For the tropical rock engineering field

ACKNOWLEDGEMENTS

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ABSTRACT

Ripping is a process of breaking harder ground by dragging tines attached to a bulldozer. Rippability of materials in moderately weathered (grade III) to completely weathered (grade V) has always been vague where the material behaviour is not fully understood due to their 'rock-soil' characteristics. This research is to examine factors that influence the rippability and establish a comprehensive method that effectively assessed the weathered sedimentary rock masses. The assessment of rock mass properties was mainly based on recording the presence, nature, orientation and occurrence of discontinuities. The information gathered from the monitoring was used for determining the excavatability of rocks. Monitored ripping tests were conducted at four different locations namely; Bukit Indah, Mersing, Kempas and Desa Tebrau which consisted of sandstone, shale and old alluvium. In order to rectify issues in different rock types, investigation was also conducted on granitic area at Masai and Ulu Tiram. Three main factors were identified to affect the rippability performance, these are; rock material, rock mass and the machine properties. Field measurements, in situ and laboratory test results are presented and their relation with the weathering grade was established. Some of the standard strength tests were not suitable to test very weak materials with weathering grade V (completely weathered), due to sampling difficulties. Thus, modifications to the test methods were done in order to get more accurate results. It is also found that there are significant relationships between productivity and the weathering grade. By measuring the ripping process, the relationships between the rock properties and the production were established. The data was analyzed statistically by using the Statistical Package for Social Science (SPSS) software regression analytical techniques to produce sets of equations for different weathering grades from which the machine performance can be predicted. It was revealed that a single parameter is not able to predict significantly the productivity but combinations of different parameters are able to predict satisfactorily the production rate. Different sets of factors were found to influence the productivity of the ripper machine for each weathering grade. By classifying and performing the tests required for that particular weathering grade, a significant correlation between the predicted and actual production rate was established. Identification of weathering grade, joint spacing, ripping direction and some measures of strength in addition to the machine properties are found to be the major factors in predicting the ripper performance. Methodology developed for predicting production rate for different weathering grades of these weathered rock masses is considered to be a significant advance as compared to the previously published methods.

ABSTRAK

Perobekan adalah suatu kaedah pengorekan di mana batuan dipecahkan dengan menggunakan mata perobek yang ditarik oleh jentera. Batuan lemah, terutamanya yang terluluhawa sederhana (gred III) ke terluluhawa lengkap (gred V) menjadi masalah dalam kebanyakan kerja pengorekan yang mana sifatnya tidak difahami dengan jelas yang disebabkan oleh ciri ‘batu-tanah’nya. Kajian ini menyingkap faktor-faktor yang mempengaruhi kerja pengorekan di dalam gred luluhawa yang berbeza dan menghasilkan kaedah komprehensif bagi menilai keberkesanan kerja perobekannya. Penilaian sifat batuan yang dilakukan juga mengambil kira kehadiran, jenis dan orientasi ketidakselanjaran yang mana hasil daripada penilaian ini diguna untuk menentukan kebolehrobekan batuan. Pemantauan kerja perobekan ini dilakukan di empat kawasan iaitu di Bukit Indah, Mersing, Kempas dan Desa Tebrau yang mana kawasan-kawasan ini mengandungi batu pasir, syal dan lanar tua. Bagi mengenalpasti isu yang berlainan di dalam batuan berbeza, maka kajian profil luluhawa juga telah dilakukan pada batuan granit di Masai dan Ulu Tiram. Tiga faktor telah dikenalpasti mempengaruhi prestasi kerja perobekan iaitu sifat bahan batuan, jasad batuan dan keupayaan mesin. Keputusan daripada kajian lapangan dan makmal berkenaan sifat bahan dan jasad batuan dipersembahkan dan hubungan mendapati terdapat di antara parameter-parameter berkenaan dan gred luluhawa batuan telah dihasilkan. Beberapa kaedah piawai ujikaji kekuatan bahan batuan tidak dapat dilakukan ke atas semua sampel terutamanya pada gred terluluhawa lengkap (gred V) kerana sukar disampel. Oleh itu, kaedah ujikaji yang diubahsuai telah digunakan bagi mendapatkan keputusan yang lebih tepat. Adalah didapati juga terdapat kaitan yang signifikan di antara produksi perobekan dengan gred luluhawa. Analisis statistik telah dibuat dengan menggunakan program ‘Statistical Package for Social Science’ (SPSS) iaitu melalui teknik regressi bagi mendapatkan persamaan terbaik bagi menganggar produksi perobekan di dalam gred luluhawa yang berbeza. Adalah didapati bahawa hubungan parameter tunggal menghasilkan anggaran produksi yang tidak memuaskan jika dibandingkan dengan hubungan regresi yang mengambil kira faktor-faktor berlainan bagi gred luluhawa yang berbeza. Dengan mengelaskan gred luluhawa dalam penilaian dengan ujikaji-ujikaji yang tertentu bagi gred luluhawa tersebut, maka keputusannya adalah sangat signifikan jika dibandingkan dengan produksi sebenar. Penentuan gred luluhawa, jarak antara ketidakselarasan, arah mesin perobek dan kekuatan bahan batuan adalah didapati sebagai faktor utama yang perlu dinilai bagi menganggar produksi mesin perobek. Kaedah penganggaran produksi mesin perobek dengan cadangan jenis ujian tertentu bagi gred luluhawa yang berbeza, adalah dianggap sumbangan yang signifikan dalam kajian ini.

UNIVERSITI TEKNOLOGI MALAYSIA
Research Management Centre

PRELIMINARY IP SCREENING & TECHNOLOGY ASSESSMENT FORM

(To be completed by Project Leader submission of Final Report to RMC or whenever IP protection arrangement is required)

1. **PROJECT TITLE IDENTIFICATION** :

____

____ Vote No: [ ]

2. **PROJECT LEADER** :

Name :

____

Address :

____

____

Tel : __________________ Fax : _______________ e-mail : ______________________

3. **DIRECT OUTPUT OF PROJECT** *(Please tick where applicable)*

Scientific Research	Applied Research	Product/Process Development
☐ Algorithm	☐ Method/Technique	☐ Product / Component
☐ Structure	☐ Demonstration / Prototype	☐ Process
☐ Data		☐ Software
☐ Other, please specify	☐ Other, please specify	☐ Other, please specify
________________	________________	________________
________________	________________	________________
________________	________________	________________

4. **INTELLECTUAL PROPERTY** *(Please tick where applicable)*

☐ Not patentable	☐ Technology protected by patents
☐ Patent search required	☐ Patent pending
☐ Patent search completed and clean	☐ Monograph available
☐ Invention remains confidential	☐ Inventor technology champion
☐ No publications pending	☐ Inventor team player
☐ No prior claims to the technology	☐ Industrial partner identified

5. LIST OF EQUIPMENT BOUGHT USING THIS VOT

6. STATEMENT OF ACCOUNT

a) APPROVED FUNDING RM : …………………………

b) TOTAL SPENDING RM : …………………………

c) BALANCE RM : …………………………

7. TECHNICAL DESCRIPTION AND PERSPECTIVE

Please tick an executive summary of the new technology product, process, etc., describing how it works. Include brief analysis that compares it with competitive technology and signals the one that it may replace. Identify potential technology user group and the strategic means for exploitation.

a) Technology Description

b) Market Potential

c) Commercialisation Strategies

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____
____
____
____

8. RESEARCH PERFORMANCE EVALUATION

a) FACULTY RESEARCH COORDINATOR

	Excellent	Very Good	Good	Satisfactory	Fair	Weak
Research Status	( )	( )	( )	( )	( )	( )
Spending	( )	( )	( )	( )	( )	( )
Overall Status	( )	( )	( )	( )	( )	( )

Comment/Recommendations :

____
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____
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____
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………………………………………….

Signature and stamp of
JKPP Chairman

Name : ………………………………………

Date : ………………………………………

b) RMC EVALUATION

	Excellent	Very Good	Good	Satisfactory	Fair	Weak
Research Status	( )	( )	( )	( )	( )	( )
Spending	( )	( )	( )	( )	( )	( )
Overall Status	( )	( )	( )	( )	( )	( )

Comments :-

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Recommendations :

☐ Needs further research

☐ Patent application recommended

☐ Market without patent

☐ No tangible product. Report to be filed as reference

……………………………………………..

Signature and Stamp of Dean /
Deputy Dean
Research Management Centre

Name : ……………………………………………

Date : ……………………………………………

Benefits Report Guidelines

A. Purpose

The purpose of the Benefits Report is to allow the IRPA Panels and their supporting experts to assess the benefits derived from IRPA-funded research projects.

B. Information Required

The Project Leader is required to provide information on the results of the research project, specifically in the following areas:

- Direct outputs of the project;
- Organisational outcomes of the project; and
- Sectoral/national impacts of the project.

C. Responsibility

The Benefits Report should be completed by the Project Leader of the IRPA-funded project.

D. Timing

The Benefits Report is to be completed within three months of notification by the IRPA Secretariat. Only IRPA-funded projects identified by MPKSN are subject to this review. Generally, the Secretariat will notify Project Leaders of selected projects within 18 months of project completion.

E. Submissin Procedure

One copy of this report is to be mailed to :

IRPA Secretariat
Ministry of Science, Technology and the Environment
14th, Floor, Wisma Sime Darby
Jalan Raja Laut
55662 Kuala Lumpur

Benefit Report

1. Description of the Project

A. Project identification

1. Project number :

2. Project title :

3. Project leader :

B. Type of research

Indicate the type of research of the project (Please see definitions in the Guidelines for completing the Application Form)

☐ Scientific research (fundamental research)

☐ Technology development (applied research)

☐ Product/process development (design and engineering)

☐ Social/policy research

C. Objectives of the project

1. Socio-economic objectives

Which socio-economic objectives are adressed by the project? (Please indentify the sector, SEO Category and SEO Group under which the project falls. Refer to the Malaysian R&D Classification System brochure for the SEO Group code)

Sector : ______________________

SEO Category : ______________________

SEO Group and Code : ______________________

2. Fields of research

Which are the two main FOR Categories, FOR Groups, and FOR Areas of your project? (Please refer to the Malaysia R&D Classification System brochure for the FOR Group Code)

a. Primary field of research

FOR Category : ______________________

FOR Group and Code : ______________________

FOR Area : ______________________

b. Secondary field of research

FOR Category : ______________________

FOR Group and Code : ______________________

FOR Area : ______________________

D. **Project duration**

What was the duration of the project ?

________________________ Months

E. **Project manpower**

How many man-months did the project involve?

_____________________________Man-months

F. **Project costs**

What were the total project expenses of the project?

RM_______________________

G. **Project funding**

Which were the funding sources for the project?

Funding sources	Total Allocation (RM)
_*IRPA*_________________________	______________________________
_______________________________	______________________________
_______________________________	______________________________
_______________________________	______________________________

ll. Direct Outputs of the Project

A. Technical contribution of the project

1. **What was the achieved direct output of the project :**

For scientific (fundamental) research projects?

- ☐ Algorithm
- ☐ Structure
- ☐ Data
- ☐ Other, please specify : ______________________________

For technology development (applied research) projects :

- ☐ Method/technique
- ☐ Demonstrator/prototype
- ☐ Other, please specify : ______________________________

For product/process development (design and engineering) projects:

- ☐ Product/component
- ☐ Process
- ☐ Software
- ☐ Other, please specify : ______________________________

2. **How would you characterise the quality of this output?**

- ☐ Significant breakthrough
- ☐ Major improvement
- ☐ Minor improvement

B. Contribution of the project to knowledge

1. How has the output of the project been documented?

- ☐ Detailed project report
- ☐ Product/process specification documents
- ☐ Other, please specify : ____________________

2. Did the project create an intellectual property stock?

- ☐ Patent obtained
- ☐ Patent pending
- ☐ Patent application will be filed
- ☐ Copyright

3. What publications are available?

- ☐ Articles (s) in scientific publications How Many: __________
- ☐ Papers(s) delivered at conferences/seminars How Many: __________
- ☐ Book
- ☐ Other, please specify : ____________________

4. How significant are citations of the results?

- ☐ Citations in national publications How Many: __________
- ☐ Citations in international publications How Many: __________
- ☐ None yet
- ☐ Not known

lll. Organisational Outcomes of the Project

A. Contribution of the project to expertise development

1. How did the project contribute to expertise?

- ☐ PhD degrees — How Many: ________________
- ☐ MSc degrees — How Many: ________________
- ☐ Research staff with new specialty — How Many: ________________
- ☐ Other, please specify: ____

2. How significant is this expertise?

- ☐ One of the key areas of priority for Malaysia
- ☐ An important area, but not a priority one

B. Economic contribution of the project?

1. How has the economic contribution of the project materialised?

- ☐ Sales of manufactured product/equipment
- ☐ Royalties from licensing
- ☐ Cost savings
- ☐ Time savings
- ☐ Other, please specify : ____

2. How important is this economic contribution ?

- ☐ High economic contribution — Value: RM________________
- ☐ Medium economic contribution — Value: RM________________
- ☐ Low economic contribution — Value: RM________________

3. When has this economic contribution materialised?

- [ ] Already materialised
- [ ] Within months of project completion
- [ ] Within three years of project completion
- [ ] Expected in three years or more
- [ ] Unknown

C Infrastructural contribution of the project

1. What infrastructural contribution has the project had?

- [ ] New equipment Value: RM ____________________
- [ ] New/improved facility Investment : RM ____________________
- [ ] New information networks
- [ ] Other, please specify: ____

2. How significant is this infrastructural contribution for the organisation?

- [ ] Not significant/does not leverage other projects
- [ ] Moderately significant
- [ ] Very significant/significantly leverages other projects

D. Contribution of the project to the organisation's reputation

1. How has the project contributed to increasing the reputation of the organisation

- [ ] Recognition as a Centre of Excellence
- [ ] National award
- [ ] International award
- [ ] Demand for advisory services
- [ ] Invitations to give speeches on conferences
- [ ] Visits from other organisations
- [ ] Other, please specify: ____

2. How important is the project's contribution to the organisation's reputation ?

- [ ] Not significant
- [ ] Moderately significant
- [ ] Very significant

1V. National Impacts of the Project

A. Contribution of the project to organisational linkages

1. Which kinds of linkages did the project create?

- [ ] Domestic industry linkages
- [ ] International industry linkages
- [ ] Linkages with domestic research institutions, universities
- [ ] Linkages with international research institutions, universities

2. What is the nature of the linkages?

- [ ] Staff exchanges
- [ ] Inter-organisational project team
- [ ] Research contract with a commercial client
- [ ] Informal consultation
- [ ] Other, please specify: ______________________________

B. Social-economic contribution of the project

1. Who are the direct customer/beneficiaries of the project output?

Customers/beneficiaries:	Number:
____________________	____________________
____________________	____________________
____________________	____________________

2. How has/will the socio-economic contribution of the project materialised ?

- [ ] Improvements in health
- [ ] Improvements in safety
- [ ] Improvements in the environment
- [ ] Improvements in energy consumption/supply
- [ ] Improvements in international relations
- [ ] Other, please specify: ______________________________

3. How important is this socio-economic contribution?

- [ ] High social contribution
- [ ] Medium social contribution
- [ ] Low social contribution

4. When has/will this social contribution materialised?

- [ ] Already materialised
- [ ] Within three years of project completion
- [ ] Expected in three years or more
- [ ] Unknown

Date: **Signature:**

End of Project Report Guidelines

A. Purpose

The purpose of the End of Project is to allow the IRPA Panels and their supporting group of experts to assess the results of research projects and the technology transfer actions to be taken.

B. Information Required

The following Information is required in the End of Project Report :

- Project summary for the Annual MPKSN Report;
- Extent of achievement of the original project objectives;
- Technology transfer and commercialisation approach;
- Benefits of the project, particularly project outputs and organisational outcomes; and
- Assessment of the project team, research approach, project schedule and project costs.

C. Responsibility

The End of Project Report should be completed by the Project Leader of the IRPA-funded project.

D. Timing

The End of Project Report should be submitted within three months of the completion of the research project.

E. Submission Procedure

One copy of the End of Project is to be mailed to :

IRPA Secretariat
Ministry of Science, Technology and the Environment
14th Floor, Wisma Sime Darby
Jalan Raja Laut
55662 Kuala Lumpur

End of Project Report

A. **Project number :**

Project title :

Project leader:

Tel: **Fax:**

B. **Summary for the MPKSN Report (**for publication in the Annual MPKSN Report, please summarise the project objectives, significant results achieved, research approach and team strucure)

C. Objectives achievement

- **Original project objectives** (Please state the specific project objectives as described in Section ll of the Application Form)

- **Objectives Achieved** (Please state the extent to which the project objectives were achieved)

- **Objectives not achieved** (Please identify the objectives that were not achieved and give reasons)

D. Technology Transfer/Commercialisation Approach

(Please describe the approach planned to transfer/commercialise the results of the project)

E. Benefits of the Project (Please identify the actual benefits arising from the project as defined in Section lll of the Application Form. For examples of outputs, organisational outcomes and sectoral/national impacts, please refer to Section lll of the Guidelines for the Application of R&D Funding under IRPA)

- **Outputs of the project and potential beneficiaries** (Please describe as specifically as possible the outputs achieved and provide an assessment of their significance to users)

- **Organisational Outcomes** (Please describe as specifically as possible the organisational benefits arising from the project and provide an assessment of their significance)

- **National Impacts** (If known at this point in time, please describes specifically as possible the potential sectoral/national benefits arising from the project and provide an assessment of their significance)

F. Assessment of project structure

- **Project Team** (Please provide an assessment of how the project team performed and highlight any significant departures from plan in either structure or actual man-days utilised)

- **Collaborations** (Please describe the nature of collaborations with other research organisations and/or industry)

G. Assessment of Research Approach

(Please highlight the main steps actually performed and indicate any major departure from the planned approach or any major difficulty encountered)

H. Assessment of the Project Schedule

(Please make any relevant comment regarding the actual duration of the project and highlight any significant variation from plan)

I. **Assessment of Project Costs** (Please comment on the appropriateness of the original budget and highlight any major departure from the planned budget)

J. **Additional Project Funding Obtained** (In case of involvement of other funding sources, please indicate the source and total funding provided)

K. **Other Remarks** (Please include any other comment which you feel is relevant for the evaluation of this project)

Date : **Signature :**

Lampiran 20

UTM/RMC/F/0024 (1998)

UNIVERSITI TEKNOLOGI MALAYSIA

BORANG PENGESAHAN
LAPORAN AKHIR PENYELIDIKAN

TAJUK PROJEK : ____

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Saya ____

(HURUF BESAR)

Mengaku membenarkan **Laporan Akhir Penyelidikan** ini disimpan di Perpustakaan Universiti Teknologi Malaysia dengan syarat-syarat kegunaan seperti berikut :

1. Laporan Akhir Penyelidikan ini adalah hakmilik Universiti Teknologi Malaysia.
2. Perpustakaan Universiti Teknologi Malaysia dibenarkan membuat salinan untuk tujuan rujukan sahaja.
3. Perpustakaan dibenarkan membuat penjualan salinan Laporan Akhir Penyelidikan ini bagi kategori TIDAK TERHAD.
4. * Sila tandakan (/)

☐	SULIT	(Mengandungi maklumat yang berdarjah keselamatan atau Kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA RASMI 1972).
☐	TERHAD	(Mengandungi maklumat TERHAD yang telah ditentukan oleh Organisasi/badan di mana penyelidikan dijalankan).
☐	TIDAK TERHAD	

____

TANDATANGAN KETUA PENYELIDIK

____

Nama & Cop Ketua Penyelidik

Tarikh : ____________________

CATATAN : ** Jika Laporan Akhir Penyelidikan ini SULIT atau TERHAD, sila lampirkan surat daripada pihak berkuasa/organisasi berkenaan dengan menyatakan sekali sebab dan tempoh laporan ini perlu dikelaskan sebagai SULIT dan TERHAD.*

CHAPTER 1

INTRODUCTION

1.1 Background

Weathering of surface rocks in tropical climates has produced thick weathering profiles that require interpretation of their characteristics for efficient excavation. The 'rock-soil' characteristics of these materials are a problem, not only in excavation issues but also in the slope and foundation construction as many civil and mining works are undertaken. A thick weathering profile normally consists of a number of sub-classifications or weathering grades which are based on their different characteristics. Thus, determining the characteristics of weathered rock masses is essential for selecting the best excavation method.

Digging, ripping, and blasting are the three main methods used for breaking or loosening ground in surface excavation. The term excavatability refers to the ability of any chosen method to break up the ground to a more manageable size. In principle, there are two main types of ground loosening mechanism used in surface excavation i.e. mechanical and blasting methods. Direct digging and ripping is referred to as mechanical excavation method, where digging is defined as the process of cutting and displacement by a blade or bucket that is usually done by excavator in softer ground (Hadjigeorgiou and Poulin, 1998). On the other hand, ripping is a process of breaking the harder ground by dragging tines attached to a bulldozer. Ripping is the ultimate mechanical method to be considered before resorting to blasting.

In mechanical excavation, energy generated by machines is transmitted into the ground by means of tines or ripping bars. In blasting, explosive energy in the form of heat and gaseous energy is the main mechanism for fragmenting the ground. There are many factors to take into account when deciding the most suitable method of excavation to be employed. These include type of project, rock mass characteristics, properties of the intact rock materials, extraction methods and the stability of exposed rock surface to be achieved. In addition, production rates, cost and environmental constraints need to be taken into account before the work commences (Pettifer and Fookes, 1994).

In construction, the major objective is to break the rock so that it can be economically removed (Atkinson, 1971). It has been a long held belief that ripping might be economical than blasting. However, the advent of inexpensive explosives such as ammonium nitrate (AnFo) and metallised slurries have considerably reduced blasting costs. In Malaysia, the cost of blasting depends on the volume of rock to be excavated, sensitivity of the surrounding area, location and method of blasting to be employed. Typically, the price of drilling and blasting is in the range of RM5 to RM10 per tonne compared to RM3 per tonne for ripping (Muhibbah, 2002). Thus, with this wide range of drilling and blasting costs, blasting can be cheaper than ripping especially when dealing with unrippable grounds.

Unclear and subjective classification of a weathered rock for surface excavation purposes can lead to different interpretations for the best selection of the excavation method. The term ‘hard material’ that is normally used in contract documents is very confusing as it covers a wide spectrum of materials ranging from dense soil to fresh rock. There are also arguments on definitions such as ‘rock’, ‘soft rocks’, ‘hard material’ and ‘soil’. The issues are even more confusing in a multi-strata environment, i.e. sites which are made up of sedimentary rocks. Shale, for example, has a lower strength and may be embedded with stronger material such as sandstone. Increase in moisture content may further reduce the shale strength so it behaves like a soil, but in dry conditions it might be difficult to rip.

The weathering grades for sedimentary rocks may not be as uniformed as for igneous rocks. The International Society for Rock Mechanics (ISRM, 1988) classified rock mass weathering into 6 grades, where grade I indicates the fresh unaltered state and becomes more weathered as the grade increases with grade VI being residual soil. Weathering grades III (moderately weathered) to V (completely weathered) are always indefinite in ripping assessments. The presence of isolated rocks or boulders and iron pan are other significant issues in tropical regions. In Malaysia, Tajul Anuar Jamaluddin and Mogana (2000); Mohd For Mohd Amin and Edy Tonnizam Mohamad (2003) and Tajul Anuar Jamaluddin and Ismail Yusuf (2003) used the evaluation of excavation methods based on Pettifer and Fookes (1994) classification. However, these evaluation criteria do not adequately address the weathering profile and nature of rock in the tropics Site experience shows that all of the existing rippability assessment methods do not give reliable results (Basarir and Karpuz, 2004). A more objective and practical rock excavation assessment method is required to effectively assessing the site during the preliminary stages of a project.

The complexity of selecting the best method to excavate weathered rocks has become one of the major issues in tropical countries. Thus, knowledge of the geology becomes an asset as this knowledge by far would be able to help engineers to determine the best excavation methods to use when faced with this problem. However, there is no exact guidance as yet to determine the type of methods to use so most would use experience and the existing assessment methods tools to determine the most suitable method for excavating weathered rocks. Methods of excavation have developed throughout the last hundred years from hand picks to bucket wheel excavators, to power shovels, bulldozer-rippers and explosives. In addition to this, the use of the correct method has also been an area of conflict between contractors and their principals. The former would always opt for the easiest methods that could be more expensive and the latter would prefer a less expensive method in order to save cost. The selection of the excavation method has to take into account the economic factors, the urgency of a project and environmental constraints.

Before commencing excavation, decisions have to be made on the excavation method to be applied. Normally, this would be a problem for most engineers since the properties of rock varies and it is not possible to specify which technique to use without studying the site first. Most of the time, there is a problem when faced with weak rocks. Weak rocks are the type of rock which would be difficult to excavate because of the nature of these rock cum soil materials. The rock is normally too soft to blast but too hard to excavate using ripper machines. Therefore, in this study this issue will be dealt with in allowing the prediction of the production performance. A second aim of this study is to create or modify the existing excavation assessments for specifically weathered rock masses.

There is a preference of applying ripping over blasting as it has the advantages in term of cost, time and environmental factors if it is applied to suitable geological materials. However, inability to assess the geological properties accurately prior to excavation might result in wasted time, effort and adoption of a cost effective method of excavation. In some cases, blasting works can be more economical in terms of cost and time. Thus, assessing the excavatability in the initial stage of a project will definitely help in choosing the most economical method; hence the overall project will progress more effectively. The geological profile and physical strength of the rock mass will determine the rate and cost of excavation.

Performance prediction therefore becomes even more important if the ripper machine is working in heterogeneous strata. This situation is further complicated for users of ripper machines by the claims for these machines made by some manufacturers. Seismic velocity is often used as the criterion, and claims such as materials with less than 2300 m/s can be ripped (Caterpillar, 2001). Unfortunately, limits for the application are not that easily defined and the seismic wave velocity is sometimes not accurate especially in heterogeneous weak strata. Some of the existing excavation assessment methods often use the compressive strength as the major parameter for evaluation. However, sometimes this parameter is not easy to measure in weak rock. The ideal test for rippability is to put a ripper on the job and to see if the material is rippable or not. However, this may not be practical in many cases due to time constraints, expenses involved and site access prior to contract award. Therefore, indirect assessment is an added advantage for knowing the geological properties and characteristics of the rock. In order to answer the questions posed by the industry, more research is needed particularly into determining the properties of rock materials and rock masses which affect and influence the performance of ripping machines.

These considerations make it essential so that effort is given to performance prediction methods in weak rock. Additionally, a limited amount of quantitative research in Malaysia on rippability of weak rock has clearly shown that geomechanical properties for excavation of rock masses must be evaluated. This research therefore, has the aims to tackle the problem of performance assessment for ripper machines and on characterizing the weathered rock mass particularly in sedimentary rock types and the effect on productivity.

1.2 Statement of the Problem

There is usually no issue if the material to be excavated is visible and understood to be a rock; however disputes often happen if the material has ‘rock-soil’ characteristics which are also known as weak rock. The problems that usually arise are:-

i) Weak rock of Grade III-V (ISRM, 1988) has often been a conflict for ripping or excavation assessment and has been vague for determining the best excavation method to be employed (JKR, 1998). The differences in weathering profile between rocks such as boulders for igneous rocks and heterogeneity for sedimentary rocks are important factors to be considered.

The extreme climate in tropical regions makes the weathering issue significant and unique from the existing assessments (e.g. presence of iron pan and the reduction of strength due to the increase of moisture content). This has caused the existing excavation assessments wrongly interpreted, as most of the existing assessments do not address the issues specifically for weathered sedimentary rock where most ripping works are employed.

ii) Arguments will arise when claiming for excavation of this material which may result in wasted time and sometimes may lead to false claims. In addition, the cost of earthwork cannot be estimated accurately during the planning stage and normally the cost is much higher that the expected costs.

iii) There is no standard method that is specially designed for excavating weathered rock masses. A thick weathering profile and the difference between the natures of the rock type often misled the assessment made. There is also no standardisation on contract documents between various parties in determining the excavation price for weak rock or normally known as 'hard material' in contract documents.

1.3 Objectives

This research will study into factors influencing ripping works concentrating on weathered sedimentary rock masses. The general terms of reference is to develop this research from ideas formulated through previous researchers and to be relevant to the present working methods, machines, conditions and requirement of the industry.

Within the overall structure a number of specific objectives were identified:

i) To review critically current methods of performance prediction for ripping machines. Examining the effectiveness of the assessments and more importantly dissecting each method into its main components. This process will enable the individual parameters that are used in the evaluation to be investigated.

ii) To examine the role of rock material and mass properties, weathering effects and the machine, contributing to the performance achieved.

iii) To analyse and rationalise the rock material indices and investigate suitable indices for classifying the weathered rock masses and the machine for rippability assessment.

iv) To use the data obtained from in situ monitoring to provide method of statement for the selection of the most effective method of rock excavation for weak rocks.

1.4 Scope and Limitation of Study

Taking into account the objectives stated above, the services and facilities available on sites and machine types examined, the research work was carried out within the following scope and limitations:

i) The work was based on assessing the ripper performance of the Caterpillar D9 tractor (Figure 1.1) for surface excavation at four construction sites in Johor, Malaysia.

ii) The monitoring of machine performance consisted of recording the different levels of production and cutting configurations in the weathered sedimentary rock masses (shale, sandstone and old alluvium) for weathering grade II to V.

iii) The assessment of rock mass properties was mainly based on recording the presence, nature, orientation and occurrence of discontinuities. Field seismic tests were also performed on selected sites before excavation was to take place. The information gathered from the monitoring was to be used for determining the excavatability of the rocks present by using existing excavation assessments proposed by previous researchers.

iv) Intact rock properties were assessed by laboratory tests for their density, strength, durability, penetration and mineralogical analysis. Some modified approaches to testing to suit the weaker materials were also carried out.

This research involves both field monitoring and laboratory investigation to establish the rock mass and material properties. Combination of these approaches will then be utilised to propose and formulate methods for the quantitative prediction of ripping performance. The performance of the ripper machines studied has also been predicted using empirical equations in which geotechnical and machine parameters are used. The performance of a ripper machine is based on the volume of material excavated per hour.

1.5 Significance of Research

The research was to develop an assessment which can be used in the construction and mining industry, particularly for assessing ripping works in the weathered sedimentary rock masses in tropical countries. By having an accurate prediction, it was hoped that the total cost of earthwork projects can be minimised due to the effectiveness in maximising the geological data gathered and making the correct machine selection.

1.6 Study Area

This study is based on case studies at four construction sites namely Bukit Indah, Kempas, Desa Tebrau and Mersing as shown in Figure 1.2. The focus would be on surface excavation and concentrating on weathered sedimentary rocks. This is due to many excavation issues involved with these rocks, such as degree of weathering, presence of weakness planes, discontinuity orientation relative to ripping direction and the presence of iron pan in softer parental materials. In addition, a study on the granitic weathering profile would be undertaken at Masai and Ulu Tiram to understand the different issues in granitic area.

1.7 Report Organization

The report is structured into three parts, which are interrelated in order to achieve the objectives.

Part 1 (Chapters 2 and 3) deals with a review of the literature on rock material, rock mass and machine related parameters which will affect the performance of a ripper machine. Appropriate reference is made to the rock mass characteristics which notably contribute to the ease of excavation. In addition, a brief history of ripping and some classical rock cutting theories are also explained. Reviews of the previous excavation assessments proposed by previous researchers are also presented for the evaluation and understanding which starts from the use of seismic velocity, graphical and grading methods.

Part 2 (Chapters 4,5 and 6) contains the nature of the experimental works including information of the studied sites and the type of rock materials present. Testing procedures applied during the research are outlined in Chapter 4. These include field testing and machine monitoring, determination of rock material properties and assessment of rock mass classification as applied to excavation. Productivity, depth of penetration of the tine and performance characteristics of ripper machines for each case is carefully recorded. Field and laboratory study results with independent analysis of the data acquired on each site is presented in later chapters. Engineering properties of rock mass and rock material are presented in Chapter 5 and 6 respectively.

Part 3 (Chapters 7 and 8) addresses the problem of performance prediction, using statistical analysis for investigating the relationships between various rock properties and the productivity. Relationships between rock properties and productivity are presented in Chapter 7 based on the rock type and the weathering grade. This enables us to see how the weathering grade may affect the productivity of ripping works. At the end of Chapter 7, proposed equations for performance prediction are presented. The predictions are based on statistical analysis and geological knowledge. In Chapter 8, the actual production measured during the direct ripping tests was compared to some rock mass classification methods and existing excavation assessment methods. The short falls of these relationships are discussed.

Finally, Chapter 9 covers conclusions made throughout the project and identifies the areas which may be rewarding for future research studies.

Figure 1.1: A CAT D9

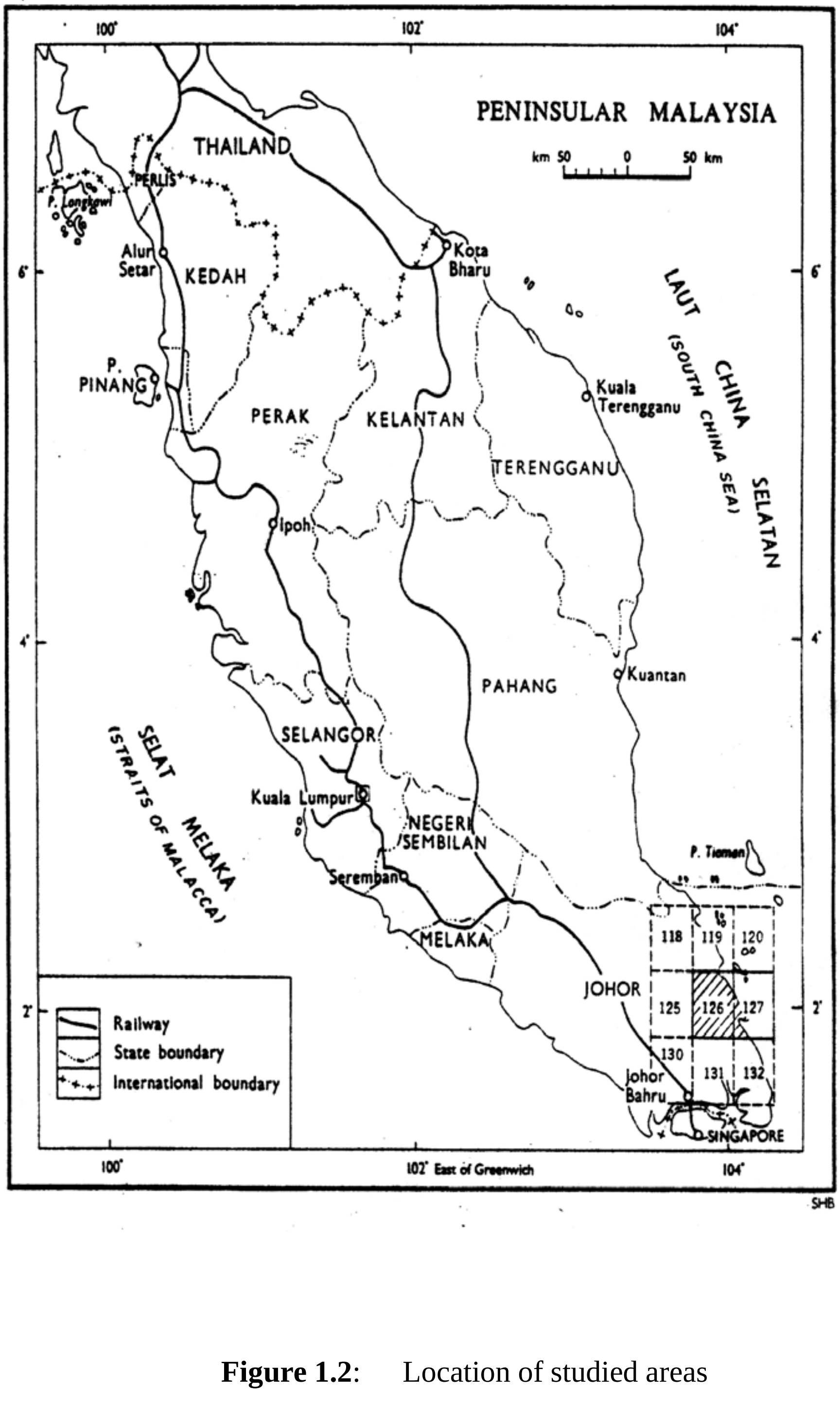


Figure 1.2: Location of studied areas

CHAPTER 2

PHYSICAL AND MECHANICAL FACTORS AFFECTING RIPPABILITY OF THE ROCK MASSES

2.1 Introduction

Previous researches have found that there are many factors affecting the rippability of ground such as the rock mass behaviour, strength of the rock material, size and power of machines employed and the economical factors. Bozdag (1988) found that among the rock mass properties involved are the rock type, strength, and degree of alteration, structure, fabric abrasiveness, moisture content and the seismic velocity. Pettifer and Fookes (1994) suggested that the ripping operations are greatly influenced by the strength of the intact rock and the joint behaviour of the rock mass. In rippability assessment, the significant rock mass and intact rock parameters should be included and examined to predict rock mass behaviour. On the other hand, Basarir et al. (2000) and Muftuoglu (1983) concluded that the characteristics of the rock, equipment, skill of operators and dimensions of the pit are the factors affecting the physical limit of ripping.

In rock engineering, the determination of the physical and mechanical properties of rock is essential to predict the behaviour of the rock mass. The best decision for the selection of the ground preparation technique is important because such activity like excavating, hauling and backfilling will be greatly influenced by the decisions made. The decision will also affect the extent of environmental impacts of the surrounding properties. The two main factors involved in determining machine performance are the rock characteristics and machine parameters (Fowell and Smith, 1993). The mass and material properties of rock must be understood before deploying any type of machine in the excavation works. Since the rock properties cannot be changed, choosing the right equipment is vital for any excavation work. Fowell and Smith (1993) also emphasized that in predicting cutting rate and tool consumption, the influence of principal variables; cuttability, cutting wear and the rock mass properties must be assessed. Clearly, it is vital to decide whether one rock mass can be excavated by a chosen method before a problem arises rather than looking at the cost first, as some inexpensive methods can be ineffective to remove certain rock masses. Hence, there is a need to understand the factors involved in ripping performance through a literature study before further research can be outlined.

2.2 Rock Mass and Material Factors Affecting Rippability

Most researchers agree that rippability depends on numerous geomechanical properties of intact rock and rock mass (Thuro and Plinninger, 2003). Factors that influence an excavating machine are suggested by the International Society of Rock Mechanics – Commision on Rock Borability, Cuttability and Drillability and other sources (Fowell et al., 1991; Bradybrooke, 1988 and Roxborough, 1987). Although most of them suggested different variables involved, most of them agree that material strength and discontinuity characteristics play an important role in rippability. Although rock mechanical properties play a key role in excavation, geological parameters are more significant than varying rock properties (Thuro et al., 2002). The influence of geology is not only relevant during the equipment selection, but also during the operations stage. Table 2.1 shows a list of variables considered relevant for assessing the excavatability by various researchers. In most of the systems proposed, uniaxial compressive strength (UCS) and seismic velocity are the two most common parameters used. These systems were proposed by Weaver (1975), Kirsten (1982), Muftuoglu (1983), Smith (1986), Singh et al. (1987) and Karpuz (1990).

2.2.1 Rock Type

In this study, focus is given to the sedimentary rocks where most ripping works are done in this rock type area. Sedimentary rocks are formed from pre-existing rock particles – igneous, metamorphic or sedimentary. Basically, the identification of basic type of rock may provide immediate indications for likely engineering behaviour of rock (Muftuoglu, 1983).

2.2.2 Strength

Compressive and tensile failures of rock are both involved in the fracture mechanism generated during ripping. Tensile strength is believed to be more significant than compressive strength when classifying rock in terms of its rippability (Singh et al., 1986). Smart et al. (1982) have found a close correlation between the uniaxial strength and quartz content. They found that the increase of quartz in rock material would increase the strength. In addition to the mineral composition of the rock material, the strength is also considerably influenced by water content. This factor can be a great challenge in weak rocks in tropical area where some of the original minerals and fabric have undergone alteration. Most of the secondary minerals will absorb water easily and will reduce the original rock strength. Heavy rainfall will increase the moisture content of the rock material especially for those in highly weathered (Grade IV) and completely weathered (Grade V) materials. This is due to loose interaction between grains as weathering has taken place.

This problem will lead to misjudgement during the rippability study as some materials can be easily ripped in the wet condition but unrippable during dry weather. The ease of excavating a highly moisturized rock could be easier compared to dry ones, even though it is of the same material. Figure 2.1 shows how moisture content would influence the rippability of material.

Figure 2.1: Grade IV sandstone can be very friable when moisture content is high

The difference in weathering grade between different rock materials though it forms in the same rock mass can be a great challenge in ripping works. Sandstone behaves differently as compared to shale to weathering agents because of their genesis. Fresh sandstone, which is well cemented, has minimal foliation and lamination as compared to shale and relatively difficult to rip. Shale is always known to have laminations, which provides spaces for weathering agents to be in contact. Furthermore, shale is composed of clay-sized material that is smaller than 0.062mm in size and some of clay types such as illite and montmorillonite may absorb water aggressively and will degrade easily on exposure to weathering agents when compared to sandstone.

Table 2.1: Summary of parameters considered for excavation assessment by various researchers

Parameters	SV	Grain size	Strength				RQD	Joint/Discontinuity								BedS	A	W
			UCS	Point Load Test	SH	TS		No of joint sets	Volumetric joint count	Joint roughness	Joint alteration	Joint orientation	Joint spacing	Joint continuity	Joint gouge			
Caterpillar (2004)	X																	
Atkinson (1971)	X																	
Franklin (1971)			X	X									X					X
Bailey (1975)	X																	
Weaver (1975)	X		X									X	X		X			X
Church (1981)	X																	
Kirsten (1982)			X				X	X	X	X	X	X	X					
Muftuoglu (1983)			X	X									X			X		X
Abdul Latif et al. (1983)				X									X					
Smith (1986)			X									X	X	X	X			X
Komatsu (1987)	X																	
Singh (1987)	X			X		X (PLT)							X				X	X
Bozdag (1988)				X									X					
Karpuz (1990)	X		X		X								X					X
MacGregor et al. (1993)	X	X	X					X		X			X			X		X
Pettifer and Fookes (1994)				X								X	X					X
Kramadibrata (1998)			X	X			X			X			X		X		X	
Hadjigeorgiou and Poulin, 1998)				X				X	X									X
Basarir and Karpuz (2004)	X		X	X	X								X					
Popularity (no)	10	1	9	9	2	1	2	3	2	3	1	4	13	1	3	2	2	9

Remarks: SV-seismic velocity; UCS-uniaxial compressive strength; PLT-point load test; SH-Schmidt hammer; TS-tensile strength; RQD -rock quality designation; BedS-bedding spacing; A-abrasiveness; W-weathering.

2.2.3 Abrasiveness

An often overlooked parameter in the rippability evaluations of rock mass is the abrasiveness of the ripped material which has importance in terms of both ripper breakdown and economics. In the study of estimation of ripper operational costs, it was shown that one of the largest portions of the expenditure was due to shank, tip and cutting edges being worn. When the tip of the ripper is worn, the force required to move the tip through the rock will be increased due to increased attack angle.

Table 2.2 depicts one of the existing classifications for rock abrasiveness, the Abrasiveness Index Classification (Singh, 1983). The rating for abrasiveness is given based on the properties of hard rock forming minerals, angularity of hard minerals, and strength of cementing material, Cechar index and rock toughness index. Toughness index is determined as Singh (1983) is shown in the following equation: -

$$T = \left(\frac{\sigma_c^{\ 2}}{2E} \right) x100 \qquad (2.5)$$

where T is Toughness index;

σ_c is Uniaxial Compressive Strength; and

E is elasticity modulus.

Table 2.2: Classification of Rock According to Abrasiveness (Singh, 1983)

Class	Cerchar Index	% Hard Mineral	Angularity	Cementing Material	Toughness Index
Very low Abrasive	<1.2	2-10	Well Rounded	Non cemented or rock with 20% voids	<9
Low Abrasive	1.2-2.5	10-20	Rounded	Ferruginous or clay or both	9-15
Moderately Abrasive	2.5-4.0	20-30	Sub-Rounded	Calcite or calcite and clay	15-25
Highly Abrasive	4.0-4.5	30-60	Sub-Angular	Silt clay or calcite with quartz overgrowths	25-45
Extremely Abrasive	>4.5	60-90	Angular	Quartz cement or quartz mozale cements	>45

2.2.4 Degree of Weathering

Weathering of rock takes place under the influence of the hydrosphere and atmosphere. Weathering can be either in the form of mechanical disintegration or chemical decomposition or both. Mechanical weathering leads to opening of discontinuities by rock fracture, opening of grain boundaries and the fracture on cleavage of individual mineral grains, whereas chemical weathering results in chemical changes in the mineral. Under the influence of weathering, the strength, density and volumetric stability of the rock will be reduced, whilst deformability, porosity and weatherability are increased. This can lead to significant reductions in rock strength and assist the excavation process (Hadjigeorgiou and Scoble, 1988). The need to establish the weathering zones in the classification was made clear by Hadjigeorgiou and Scoble (1988) to help the assessment process. The weathering classification, as recommended by the Core Logging Committee of South Africa (1976), ranks from unweathered, via slightly, medium and highly weathered to completely weathered. It is clear from the table that the classification takes extent of discoloration, and conditions of discontinuities i.e. filling and separation, into consideration.

A tropical country has sunny flux all year round (22^0-32^0C), high moisture content in the air and underground, high quantity of rain (>1200 mm) and underground water temperature of 28^0C (Thomas et al., 1992). With these characteristics, climate has a great influence to exogenic process especially to chemical weathering process where the high intensity of rain and high temperature will accelerate the weathering process.

Ibrahim Komoo (1995a) had done several studies to understand geotechnical properties of weathered sedimentary rock in Peninsular Malaysia. The results showed that material properties deteriorate from the fresher material as more intense weathering takes place. The weathered rock has less strength due to the presence of microfractures and the loosening of the bonding between grains (Fookes et al., 1988). The weathering effect can take place up to 100m down from the earth's surface in tropical areas (Hudson, 1999 and Ibrahim Komoo, 1995a,b). International Association of Engineering Geologist (IAEG, 1981) classified weak rock to have a uniaxial compressive strength from 1.5 – 50 MPa. The weak rock in moderately weathered (grade III) to completely weathered (grade V) as shown in Table 2.3, has always been an indefinite area in ripping and excavation.

Edy Tonnizam Mohamad et al. (2005a,b,c) and Tajul Anuar Jamaluddin and Mogana (2000) reported that hard material has always been an issue by contractors and clients if it cannot be classified as rock or soil. This statement always refers to grade III (moderately weathered) to grade V (completely weathered) materials in the weathering scale. Existing excavation assessments have always considered the strength factor to be one of its major factors in deciding whether the material can be ripped or otherwise. However, if strength is the only parameter considered, overall results may be ambiguous especially if sandstone and shale is evaluated separately as both materials may not have the same strength even though they are in one massive rock body. The sandstone may be in grade III but the shale may have further deteriorated to grade V as shown in Figure

2.2. Shale, which is embedded with sandstone, might have lower strength compared to sandstone and their weathering grade might vary even though they exist in the same rock mass.

In igneous origins area, we can expect an abundance of boulders, which may have similar strength, but vary in size. Small boulders can be excavated easily by normal digging, but the bigger size would need blasting for excavating them (Figure 2.3).

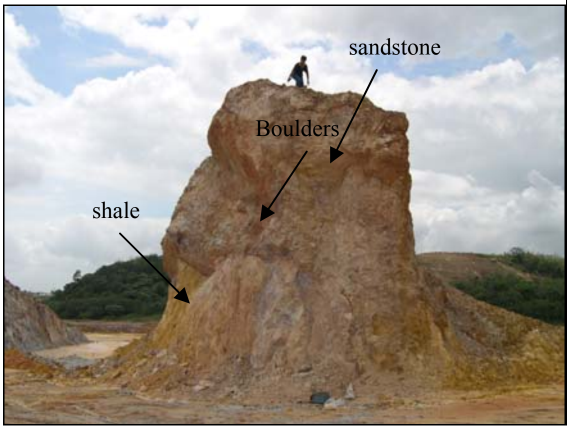


Figure 2.2: Interbedding of sandstone grade II (top layer) and shale grade V (lower layer) (Location: Bukit Indah)

Figure 2.3: Presence of boulders in a granitic area (Location: Masai)

2.2.5 Rock Structure

One of the main factors that affect the behaviour of the rock mass is the structural discontinuities such as joints, bedding planes, lamination, cleavages and faults. These factors will influence and control the rock mass behaviour. Discontinuity can be defined as a plane of weakness within the rock across which the rock material is structurally discontinuous and has zero or low tensile strength. In another words, discontinuity is used to describe any mechanical interruption of rock properties.

Table 2.3 : Description of the weathering grade (after Attewell, 1993)

Degree of Weathering	Descriptive terms	Material description and likely engineering characteristics
VI	Residual soil	Completely degraded to a soil; original rock fabric is completely absent; exhibit large volume change; the soil has not been significantly transported. Stability on slopes relies upon vegetation rooting and substantial erosion & local failures if preventive measures are not taken
V	Completely weathered	Rock is substantially discolored and has broken down to a soil but with original fabric (mineral arrangement & relict joints) still intact; the soil properties depend on the composition of the parent rock. Can be excavated by hand or ripped relatively easily. Not suitable as foundation for large structures. May be unstable in steep cuttings and exposes surfaces will require erosion protection.
IV	Highly weathered	Rock is substantially discolored and more than 50% of the material is in degraded soil condition; the original fabric near to the discontinuity surfaces have been altered to a greater depth; a deeply weathered, originally strong rock, may show evidence of fresh rock as a discontinuous framework or as corestone; an originally weak rock will have been substantially altered, with perhaps small relict blocks but little evidence of the original structure. Likely engineering characteristics are as in Zone 5.
III	Moderately weathered	Rock is significantly discolored; discontinuities will tend to be opened by weathering process and discoloration have penetrated inwards from the discontinuity surfaces;
II	Slightly weathered	Some discoloration on and adjacent to discontinuity surfaces; discolored rock is not significantly weaker than undiscolored fresh rock; weak (soft) parent rock may show penetration of discoloration. Normally requires blasting or cutting for excavation; suitable as a foundation rock but with open jointing will tend to be very permeable.
I	Fresh	No visible sign of rock material weathering; no internal discoloration or disintegration. Normally requires blasting or cutting for excavation; may require minimal reinforcement in cut slope unless rock mass is closely jointed.

2.2.5.1 Orientation

The orientation relative to direction of ripping can play a great influence to the rippability performance. The dip and orientation of discontinuities together with joint spacing are critical factors in ripping works (Brawner, 1985; Hadjigeorgiou and Scoble, 1988; Pettifer and Fookes, 1994). Ripping may prove easier and more productive if carried out parallel to such planes of weakness (Weaver, 1975). The joint spacing and orientations will determine the dimensions and shape of rock mass blocks, which will contribute to ease of excavation (Hadjigeorgiou and Scoble, 1988). Orientation of bedded structure can have a particularly adverse effect causing ripping behaviour similar to a massive rock structure for vertically inclined bedding or for horizontal bedding with wide spacing. Optimum inclination is close to 45 degrees (Weaver, 1975).

2.2.5.2 Spacing

Most researchers found that the spacing of discontinuities is an important factor in assessing rippability (Basarir and Karpuz, 2004; Kramadibrata, 1998; Pettifer and Fookes, 1994; Weaver, 1975). The presence of joints will reduce the shear strength of rock mass and their spacing governs the degree of such reduction (Weaver, 1975). Even, in most of the rock mass classifications such as Rock Mass Rating (RMR) and Q-System used in tunnelling, this factor is treated as one of the main criteria in their assessments. Classification suggested by International Society of Rock Mechanics (ISRM, 1981) was used in this joint spacing description.

2.2.5.3 Continuity

The continuity of joint or bedding planes has a significant effect on the strength of the rock mass. Penetration of the ripper shank into such joints could help to weaken the rock mass. International Society of Rock Mechanics (ISRM) Commission on Testing Methods (1981) suggested the use of volumetric joint count (Jv) as an indication of block size. Kirsten (1982) introduced the effort needed for excavation from block size by using Rock Quality Designation (RQD) divided with Joint Set Number (Jn) – (RQD/Jn). He also suggested quantitative values for the assistance provided by favourable structural discontinuity orientation.

2.2.5.4 Gouge

The gouge characteristics present in joints also plays an outstanding role in ripping. If the gouge is soft and in a large amount, the shank of ripper could penetrate this zone of weakness easily compared to spaces, which are filled by iron. Where chemical weathering is crucial in tropical climate, minerals in rock can be altered and accumulated at joints opening. Accumulation of iron pan is a good example of this secondary product. The iron pan can exist from a few mm thickness to more than 10 cm thickness. A 3 cm thick of iron pan which blankets the surface of Grade IV (which supposedly can be ripped) material is enough to resist the penetration of the ripper shank, hence not allowing ripping works.

2.2.6 Material Density

Density is also another factor to be considered in assessing the rippability of rock material. The degree of cementation, sorting of sediment, packing of the grain and the shape of the grains can be assessed by knowing the density. Higher density may associates with lesser voids within the rock and strong bonding between the mineral grains, hence stronger material.

2.2.7 Rock Fabric

Fabric is a term used to describe the micro structural and textural features of rock material. Researchers have found that rock fabric is another factor affecting the rippability (Weaver, 1975). Coarse-grained rocks (grain size > 5mm) such as pegmatite and sandstone can be ripped easily than fine-grained rocks (grain size < 1 mm) such as quartzite, basalt and limestone. It can also be generally assumed that acidic rocks are more easily ripped than basic rocks (Weaver, 1975). A most widely accepted grain size classification, based on British Standard Methods of Test for Soils for Civil Engineering Purposes (BS 1377, 1975) is given in Table 2.4.

Table 2.4: Grain Size Classification (BS 1377, 1975)

Description	**Size (mm)**	**Recognition**	**Equivalent Soil Type**	**Equivalent Rock Type**
Very grained	< 0.06	Individual grains cannot be seen with a hand lens	Clays & Silts	Claystone & Siltstone
Fine grained	0.06 - 0.2	Just visible as individual grains under hand lens	Fine sand	
Medium Grained	0.2 - 0.6	Grains clearly visible under hand lens, just visible to naked eye.	Medium Sand	Sandstone
Coarse Grained	0.6 - 2.0	Grains clearly visible to naked eye	Coarse sand	
Very Coarse Grained	> 2.0	Grains measurable	Gravel	Conglomerate

2.2.8 Seismic Velocity

This method of assessment has been widely used to predict ease of excavation. Caterpillar has used this method since 1970 and keeps updating the chart with introduction of their newer models (Caterpillar, 1985). Seismic velocity depends on a number of parameters including density, porosity, moisture content, degree of fracturing and the weathering of the rock mass (Singh et al., 1986). Hardy and Goodrich (1992) noted that seismic velocity can give a good indication of rippability in highly fractured rock masses with high intact strength. The velocity of seismic shock wave depends on the density and degree of compaction of materials. This parameter provides an indication of average conditions along the path of propagation. Relatively, higher wave velocities materials are more difficult to be ripped compared to the lower ones. Generally, a rock with seismic velocity of less than 1950 m/s is regarded as rippable, whilst a rock with 1950 – 2250 m/s is defined as marginal and rock with velocity of greater than 2550 m/s is non-rippable (Singh et al., 1986). Although these methods are widely used in ripping assessment, there are reports about the inaccuracy and setbacks of this method (Kramadibrata, 1998; Singh et al., 1986). They found that the seismic velocity alone is not sufficient to assess accurately on the rippability especially in the thin layered of rock.

2.2.9 Topography

Topography of rock mass that needs to be excavated is another important factor to be evaluated before the method of excavation is opted. However, this factor is not taken into consideration by previous researchers. Since ripping is an operation where a big bulldozer has to drive in a linear line, existence of material on the slope or unevenly protruded from the ground may not permit such work to take place. Figure 2.4 shows an example where ripping work could not be carried out at the protruded rock mass due to topographical factor.

Figure 2.4 : Protruded rock mass at a slope that could not be ripped due to topographical factor (Location: Bukit Indah)

2.2.10 Bedding Plane and Boundary of Weathered Rock

Different grade of weathering of stratigraphic rock plays an important role in ripping performance and should not be neglected in the excavation assessment study as mentioned by Barton et al. (1974) and Edy Tonnizam Mohamad et al. (2005b). They found that low strength material, which can be ripped easily if it stands independently, might not be able to rip if it is sandwiched between unripped materials. Figure 2.8 shows a significant volume of completely weathered (Grade V) shale lying under highly weathered (Grade IV) sandstone, which cannot be ripped. In addition, ripping in multi layered caused inconsistency of ripping performance as the hard layer could not be ripped as easily as the softer materials. Figure 2.5 shows an example of this situation as experienced in Bukit Indah site whereby sandstone layer could not be ripped.

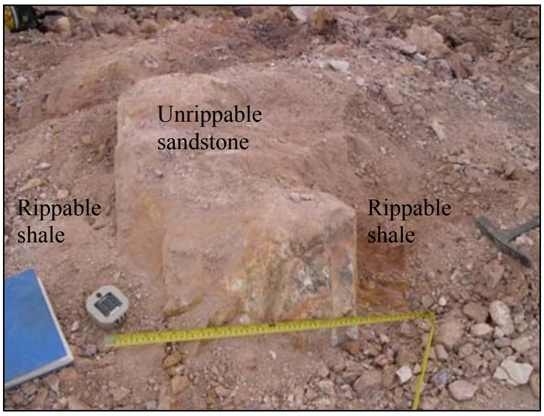


Figure 2.5: Inconsistency of ripping performance: unripped sandstone between rippable shales.

2.3 Rock Mass Classifications Related to Excavation

Several attempts have been introduced to classify the complex characteristics of rock masses into a well-organized system for easy interpretation. Listed below are the classifications related to excavation.

2.3.1 The Rock Mass Quality Rating (Q-SYSTEM)

Rock Mass Quality System or Q-System takes account of six parameters and a basic description of each parameter and their ratings are presented in Appendix A. The Q- system was developed by Barton, Lien and Lunde of the Norwegian Geotechnical Institute in 1974 (Barton et al., 1974). The concept of the Q-system is based on two requirements; to select optimum dimensions of the excavation and to estimate the appropriate permanent support requirements for such excavation. Based on more than 200 tunnel case studies, they grouped various parameters into three quotients to give the overall rock mass quality, Q, as follows,

$$Q = \frac{RQD}{Jn} \frac{Jr}{Ja} \frac{Jw}{SRF} \qquad (2.5)$$

where *RQD* is Rock Quality Designation;
Jn is Joint set number;
Jr is Joint roughness number;
Ja is Joint alteration number;
Jw is Joint water reduction; and
SRF is Stress reduction factor

Barton et al. (1974) identified six principal parameters on which to base their classification as shown in Table 2.5. The RQD value was obtained from drill core data or calculated using scan line survey data. The main poles of clusters of discontinuities were plotted on the stereonet equal area projection from which the number of discontinuity sets was obtained. The rating for Jn was thereafter estimated knowing the number of discontinuity sets present in the test block. The condition of the joint roughness was based on the recommended ISRM procedures as shown in Appendix B. The ratings for the joint alteration number were divided into rock wall contact, rock wall contact before 10cm of shear and no rock wall contact when sheared.

2.3.2 The Geomechanics Classification (RMR)

Barton et al. (1974) and Bieniawski (1974) proposed the geomechanics classification system to rate a rock mass for tunnelling by assigning values from six parameters obtained from field data and rock strength tests. The classification parameters and their ratings used in calculating the RMR values are listed in Table 2.6. In section A, five parameters are grouped into five ranges of values and their ratings are allocated to the different value of ranges of the parameters. These five parameters which are uniaxial compressive strength, RQD, spacing of discontinuities, condition of discontinuities and the ground water state, construct the basic RMR. A higher rating indicates better rock mass conditions.

Table 2.5: Parameters considered by Barton et al. (1974) - Q System

Parameter	**Description**
Rock Quality Designation (RQD)	RQD is based on the percentage of core pieces that are 100mm long or more divided with the total length of the core. A higher RQD value indicates the rock is better quality.
Joint Set Number	This is a measure of the number joint sets within the rock mass. It has a range between 1 (massive) and 20 (crushed).
Joint Roughness Number	This describes the roughness of the joint surface. It ranges from 0.5 for a planar slickensided joint to 4 for a rough and undulating joint.
Joint Alteration Number	This is indicative of the nature of any joint infill. The extremes are 0.75 for a tight joint with no infill, to 15 for a wide joint with substantial clay infill.
Joint Water Reduction Number	This factor account for the strength reducing the nature of water.
Stress Reduction Factor	Stress reduction Factor: This accounts for the stress conditions found in the rock surrounding the excavation.

The sixth parameters, the influence of strike and dip orientation of discontinuities, are included by adjusting the basic RMR according to Section B. Although RMR was introduced to assess the quality of rock for tunnelling, many researchers have used this method realizing that an inverse relationship exists between the tunnelling and ripping; that is, material classified as ‘poor’ rock for tunnelling can be ‘good’ for ripping (Kramadibrata, 1996; Singh et al., 1986). Venkateswarlu et al., (1989) have used RMR to assess excavatability whereas Abdul Latif and Cruden (1983) have adopted both RMR and Q-system in their studies in excavation and reported that RMR could give better result.

The effect of the discontinuity orientation relative to the cutting direction was determined from the stereonet equal area projections. The rating of the effect of discontinuity orientation was determined from the ones proposed by Fowell and Johnson (1991), which is more appropriate for excavation studies as shown in Table 2.7.

2.3.3 Rippability Index Classification

Realizing the importance of having classification system specially for ripping, Weaver (1975) proposed a rippability rating based on summing of seven weighted rock mass parameters similar to the geomechanics system (Bieniawski, 1974). Seismic velocity, weathering and joint continuity which were not considered in RMR are considered in this system.

A modification of Weaver's system was proposed by Smith (1986) in which the major changes were the omission of seismic velocity. The Rippability Index Classification (see Table 2.8) is the result of a broad examination of existing rippability classifications and experience gained on a number of opencast coal sites in the United Kingdom and Turkey (Singh et al., 1987). During the development of the Index Classification, a number of different rating systems have been used. Each of the four input parameters is divided into five ranges of values by taking their effect upon rock mass behaviour and ripper performance. Amongst these the highest rated parameter is spacing of discontinuities, which has been observed to be the most significant property governing rippability in all the rock units examined.

Table 2.6: Parameters in Rock Mass Rating

A. Classification parameters and their rating

	Parameter		Ranges of values						
1	Strength of intact rock	PLI (MPa)	> 10	4 -10	2 - 4	1 -2	For this low range UCS Test is preferred		
		UCS (MPa)	> 250	100 -250	50-100	25 - 50	5 - 25	1 - 5	< 1
	Rating		15	12	7	4	2	1	0
2	RQD (%)		90 -100	75 - 90	50 -75	25 - 50	< 25		
	Rating		20	17	13	8	3		
	Spacing of discontinuities		> 2m	0.6 - 2m	0.2 - 0.6m	0.06 - 0.2m	< 0.06m		
	Rating		20	15	10	8	5		
4	Condition of discontinuities		Very rough surfaces, not continuous, no separation, unweathered wall rock	Slightly rough surface, separation <1 mm, slightly weathered wall	Slightly rough surface, separation <1 mm, highly weathered wall	Slickensided surface or, gouge < 5mm thick or, separation 1 -5 mm, continuous	Soft gouge > 5mm thick or separation > 5mm, continuous		
	Rating		30	25	20	10	0		
5	Ground water	Inflow per 10m tunnel length (Lt/min)	None	< 10	10 - 25	25 -125	> 125		
		Joint water pressure/Major principal stress	0	< 0.1	0.1- 0.2	0.2 - 0.5	> 0.5		
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing		
	Rating		15	10	7	4	0		

B. Rating adjustment for discontinuity orientations

Strike & dip orientation of discontinuities		Very favourable	Favourable	Fair	Un favourable	Very Unfavourable
Rating	Tunnels	0	-2	-5	-10	-12
	Foundation	0	-2	-7	-15	-25
	Slopes	0	-5	-25	-50	-60

C. Rock mass classes determined from total ratings

Rating	100-81	80-61	60-41	40-21	<20
Class no.	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

D. Meaning of rock mass classes

Class no.	I	II	III	IV	V
Average stand up time	20 yr. For 15m span	1 yr.for 10 m span	1wk for 5 m span	10 hr for 2.5 m span	30 min for 1 m span
Cohesion of the rock mass (kPa)	> 400	300 – 400	200 - 300	100 - 200	< 100
Friction angel of the rock mass (degree)	> 45	35 – 45	25 - 35	15 - 25	< 15

Table 2.7: The effects of discontinuity strike and dip orientations in tunnelling and excavation (after Bieniawski, 1989 and Fowell & Johnson, 1991)

1	The effect of joint strike and dip orientations in tunnelling						
	Strike perpendicular to tunnel axis				Strike parallel To tunnel axis		Dip 0-20^{o} irrespective of strike
	Drive with dip		Drive against dip				
	Dip 45-90^{o}	Dip 20-45^{o}	Dip 45-90^{o}	Dip 20-45^{o}	Dip 45-90^{o}	Dip 20-45^{o}	
	Very favourable	Favourable	Fair	Un Favourable	Very unfavourable	Fair	Un favourable

2	Revised orientation for excavation using the Rock Mass Classification System (Fowell & Johnson, 1991)					
	Rock Class	I	II	III	IV	V
	Strike & Dip orientation	Very unfavourable	Unfavourable	Fair	Favourable	Very favourable
	Rating for excavation	-12	-10	-5	-2	0

(a) The remaining three parameters are given the same ratings. The sum of the weighted parameters is used to indicate the quality or rock mass in relation to its rippability. The higher the index, the more difficult the ripping operation becomes. A rock mass with final rating less than 25 will be regarded as easily rippable. A rock mass with a rating of 25-45 is expressed as moderately rippable while 45-65 suggests difficult ripping. Values between the ranges of 65-85 indicate marginal zones and over 85 suggest blasting. Tractor-rippers are recommended for operations using the rippability index. The tractor-ripper referred to each class is specified by its weight and powers that are the two most important features as far as ripping capability is concerned. Since then, the development of this rippability system is done by many researchers, as listed in Chapter 3.

2.4 Machine Characteristics

Apart from the rock parameters, machine characteristics are an important factor influencing the ripping work or excavation performance (Thuro and Plinninger, 2003). The important requirement in mechanized rock excavation is that the cutting element is capable of taking a reasonable depth of cut to gain the advantages of lower specific energy (Fowell, 1993). Specific energy is the energy required to remove a unit volume of ground and is an inverse measure of excavation efficiency. It is important to have a stable cutting machine and optimum forces to hold the cutting machine and cutting tools into the rock.

Table 2.8: Classification of Rock Mass According to Rippability Index (Singh et al., 1987)

PARAMETERS	ROCK CLASS				
	1	2	3	4	5
Uniaxial Tensile Strength (MPa)	<2	2-6	6-10	10-15	>15
Rating	0-4	4-8	8-12	12-16	16-20
Weathering Degree	Completely	Highly	Moderately	Slightly	Unweathered
Rating	0-4	4-8	8-12	12-16	16-20
Abrasiveness	Very Low	Low	Moderate	Highly	Extremely
Rating	0-4	4-8	8-12	12-16	16-20
Discont. Spacing (m)	<0.06	0.06-0.3	0.3-1.0	1.0-2.0	>2.0
Rating	0-10	10-20	20-30	30-40	40-50
Total Rating	<25	25-45	45-65	65-85	>85
Ripping Assessment	Easy	Moderate	Difficult	Marginal	Blast
Recommended Dozer	Class 1 Light Duty	Class 2 Medium Duty	Class 3 Heavy Duty	Class 4 Very Heavy Duty	-
Output (kW)	<150	150-250	250-350	>350	-
Weight (kg)	<25000	25000-35000	35000-55000	>55000	-

2.4.1 Ripper Components

Ripping is one of the mechanical excavation methods that is most widely used in surface excavation. A tine is used to penetrate the earth so that it may be pulled through the ground to loosen it for excavation. In earlier times, a ripper was used to increase the effectiveness of scrappers. However, with the development of machines in terms of weight on the ripper tooth, horsepower and design, has made working in harder ground possible. Figure 2.6 shows a schematic diagram of ripper component.

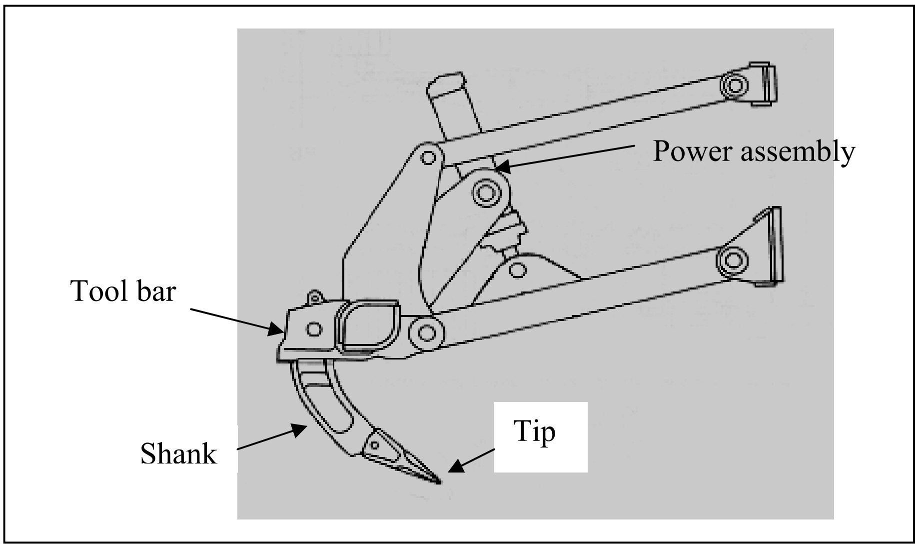


Figure 2.6: Schematic diagram of a ripper component (Caterpillar, 1994)

The main components of a ripper are: -

i) The tip:-
This enters into the rock formation by wedge action. The initial penetration is critical and may be the determining factor to see whether a material is rippable or not (Caterpillar, 1994).

ii) The shank:-
The shank is the component extending down from the ripper to which the adapter and tips are attached. In abrasive conditions, use of wear plates (protector) is recommended. These plates not only protect the shank from wear, but also reduce the traction effort due to their self-sharpening characteristics.

iii) The tool bar:-

It is the heavy transverse box section, to which the shanks are attached. The tool bar is raised and lowered by the power assembly on the tractor unit.

iv) The power assembly:-

This part consists of arms and hydraulic cylinders used for raising and lowering the tool bar. The tool bar is hinged to the tractor frame so that it swings through an arc of approximately 30^o.

2.4.2 Tip Selection

In selecting the optimum ripper tip to be used, considerations need to be given to the penetration ability, fracture characteristics and abrasiveness of the material. There are several recommended tip selections for a type of ripper.

i) Short:-

Short tip is used in high impact conditions where breakage problems occur. The shorter the tip, the more it resists breakage.

ii) Intermediate:-

Intermediate tip is used for most effective in moderate impact conditions where abrasion is not excessive. In this study, this type of tip was used.

iii) Long:-

Long tip is used in loose, abrasive materials where breakage is not a problem.

2.4.3 Matching Shank to Duty

There are varieties of ripper shanks available in the market and apparently, manufacturers will give advice on the usage of the right shank for specific applications.

The matching of the selected shank to its intended duty is essential in achieving greater production, better control of fragmentation, reduced traction effort and longer component life, which will result in economical operation and cost reductions. The optimum length of shank extended from the ripper frame is essential to pull the material efficiently and to maintain sufficient clearance under the lowered ripper frame (Caterpillar, 2001).

Straight shanks are not so popular with construction contractors but it is suitable for slabby and blocking materials and can be found in a wide range of applications for mining and quarrying. Whereas, curved shanks work well in less dense material and also produce less ripping resistance. The curved shape provides more lifting action that often results in good fracture characteristics especially in unbroken, fine grained materials. Out of these, the single shank can produce a wide fracture area and suitable for usage in easily penetrated materials. A single shank with curved shape was used in the course of this study.

2.4.4 Comparison between Multiple and Single Shank

Rippers can be equipped with two different types of shank combination, which are multiple and single shanks. Both shank combinations have special functions as listed below by Caterpillar (1985):

i) Multiple shanks:-

The shank is suitable for areas that can be ripped easily such as top soils, glacial till (without boulders) and weak sandstones. In good conditions, it can produce relatively high volumes. The distance between the tractor and shank is normally less than 900mm (36in). This characteristic makes the shank unsuitable for slabby material or occasional boulders since the large lumps can become trapped between the shank and the rear of the tractor tracks.

ii) Single shank:-

Suitable for ripping in the most difficult materials. But sometimes, adjustments need to be done at the tip for the angle of penetration during ripping, and this will result in delay due to the adjustments of the shank angle. A ripper with single shank was used in this study due to the hard ground. Table 2.9 shows the various ripping equipment problem related to shank and tip selection.

Table 2.9: Specification of Single Shank Ripper (Caterpillar, 2001)

Model	D8R	D8R Series II	D9R	D10R	D11R
Flywheel Power	228kW	231kW	302kW	425kW	634kW
Operating Weight	37580kg	37875kg	48840kg	65400kg	104600kg
Width of Standard Track Shoe	560mm	560mm	610mm	610mm	710mm
Length of Track on Ground	3.21m	3.21m	3.47m	3.88m	4.44m
Ground Contact Area	3.57m^2	3.57m^2	4.24m^2	4.74m^2	6.31m^2
Ripper Shank					
Max. Digging Depth	1130mm	1130mm	1231mm	1370mm	1612mm
Max. Reach at Ground	1.32m	1.32m	1.25m	1.50m	1.73m
Ripper Beam					
Track Clearance with Standard Shoe	76mm	76mm	71mm	97mm	141mm
Ripper with standard shank	4085kg	4085kg	4854kg	7117kg	9643kg
Ripper Forces					
Penetration Forces, shank vertical	127400N	127400N	153885N	205000N	279860N
Pry out Force, shank vertical	222800N	222800N	320511N	429000N	657840N

Table 2.10: Ripping Equipment Problems and Solutions (Caterpillar, 2001; Adam, 1983)

Problem	Possible Reason	Solution
Excessive Tip Breakage	Tip is long Too many shanks used Wrong attack angle Shank protector and/or tip stop missing or damaged Operator fault	Use shorter tip Reduce number of shanks Change attack angle Check and replace if required Lift tip before turning or moving backwards
Lack of Penetration	Wrong tip in use Material is denser Deceleration Positioning of shank	Use different tip (Guidelines are available from manufacturers) Try shallow passes Tandem rip Pre-blast Shank length selection

2.4.5 Equipment Selection

Proper selection of ripping equipment will produce optimum production and efficient excavation operation. The principal factors affecting the selection of correct ripping equipment are as follows:

i) Tractor weight:-
   This factor will determine whether the tractor has sufficient penetration and the horizontal force.
ii) Tractor power:-
   This factor will determine whether tractor can transmit the necessary force to advance the tip. A larger horse powered bulldozer will have greater drawbar pull and can easily rip harder rock material as compared to a smaller bulldozer.

iii) Down pressure on the tip:-

This factor will determine whether penetration can be initiated and then maintained throughout the ripping works.

A balance of these three factors is essential to assure successful and economical ripping (Singh, 1987). The size of the equipment defined by weight and power has been used for the selection of an optimum tractor-ripper for a given ripping operation (Church, 1981). Caterpillar (2004) noted that weight and flywheel power are the two main parameters important to ripping. To penetrate the shank into the rock, the ground weight will play an important role, whilst to drag the ripper horizontally, the flywheel power is the most important factor. The details of ripper machines manufactured by leading manufacturers, Caterpillar and Komatsu are shown in Table 2.11**.** It is estimated that 25 percent to 35 percent of the bull dozer's gross weight can be transferred to the ripper tines (Anon, 1994).

Table 2.11 : Different type of ripper machine manufactured by Caterpillar (2001) and Komatsu (Anon, 1987)

Dozer	**Flywheel Power (kW)**	**Operating Weight (kg)**
CAT D8R	305	27065
KOMATSU D155A	300	26920
CAT D9R	405	47913
KOMATSU D 355A	410	36280
CAT D10R	570	65764
KOMATSU D 375A	508	44760
CAT D11R	850	102287
KOMATSU D475A	740	63700

2.4.6 Comparison of Track Type Bulldozer with Rubber Tyre Type

The type of tyres used on the ripper is also another factor that cannot be neglected. Shand (1970) and Atkinson (1971) outlined some of the factors regarding the differences between the two types:

i) Speed and mobility:-
Rubber tyres tractors have more advantages in its mobility compared to track type of machines.

ii) Drawbar pull:-
Track type tractor has greater traction effort than the rubber tyre with comparable weight due to higher coefficient of traction of tracks. A rubber tyre unit very often has to expend a lot of rim pull in overcoming rolling resistance.

iii) Cost:-
As a rubber tyre tractor needs more weight and power than a crawler dozer of similar pushing capabilities, it is not very cost effective, unless its mobility justifies the production rate. Broken and abrasive rocks might spoil the rubber tyres easily when compared to tracks.

iv) Working condition:-
In bad and wet condition, tracks command a better working capability due to its low ground bearing pressure when compared to rubber type tyres. Tracks type also work better when working up and down a hill.

For heavy ripping application, track type tractors should be used because of the better traction and track wear and failure experienced by tyre units (Shand, 1970). In practice, most of the rippers in Malaysia use tracks. This is mainly due to the practicability of working in a tropical climate.

2.4.7 Speed

The ripper speeds are available in two directions that are forward and reverse and it has three speeds for each direction (Caterpillar, 1985). Usually in ripping work, the speed that is used to produce high force is around 2.5km/h which is in the first power speed in the forward direction. However, some consideration might also be given to the decelerator as matched drawbar pull is necessary for traction and ground condition, to prevent track spin. A constant and steady pull will maximize production and minimize wear and tear on the machine. It is advisable to rip deeper at regular speed rather than higher speed for easily rippable material (Caterpillar, 2001).

2.4.8 Pass Spacing

Wider pass spacing will help to increase the production rate. However, the spacing will depend much on the materials and optimum pass spacing is necessary to maximize production and lower the costs. As a rule of thumb, (Caterpillar, 1985) recommends that the pass spacing should be one half of the tractor width.

2.4.9 Ripping Direction Relative to Rock Structure

Ripping production is dependent upon the capability of the ripping tractor and the condition of the rock formations, fracture spacing, degree of weathering, abrasiveness, and strength (Singh et al., 1986) Production capacity of a ripper is determined by taking account of ripping depth, spacing between passes and the speed of the machine. Alternatively, ripper production can be determined by cross-sectioning and weighing methods (Caterpillar, 2001).

2.4.10 Definition of Forces

There are two forces components related in ripping work. These are:

i) "Pryout force" (Breakout):-
the maximum sustained upward force, generated by the lift cylinders measured at the ripper tip.

ii) "Penetration force":-
The maximum sustained downward force, generated by ripper lift cylinders measured at the ripper tip, which is required to raise the back end of the vehicle with the tip on ground and the shank (pinned in the top hole) vertical.

2.5 Mechanism of Failure by a Single Ripper Tooth

Being able to achieve the optimum penetration during the initial process is critical and may be the determining factor to see whether the material is rippable or not. The initial stage of the ripping procedure is the penetration of the rock by the weight on the ripper tooth causing compressive failure of the rock (Singh et al., 1986).

When ripping in easily penetrated material such as shale, the shank angle may only be slightly backward beyond vertical for initial penetration. Whereas in harder material, the rear of the tractor may be forced up as the ripper tip makes contact with the surface (Caterpillar, 2001). Similar observations have been made by a number of investigators (Dubbe, 1974 and Colburn, 1977). Dubbe (1974) also conducted finite element studies to analyze the rock failure mechanism by a ripper tip. He concluded that for only a moderate ripper load, tensile stresses produced were larger than the tensile strength of many rocks. Also, the shearing stresses associated with ripping were below the shearing strengths of most rocks. Thus, results suggested that the failure of rocks by ripping was due to tensile fracture.

The literature survey carried out revealed that limited attempts have been made to analyze the mechanism occurring in the ripping of rock. Analyses are either developed or adopted forms of Evans' Coal Cutting and Merchant's Metal Cutting theories applies to underground mine excavation (Dubbe, 1974 and Colburn, 1977). Evans's theory, which can be applied to sedimentary rocks, assumes plane strain conditions to calculate the force required to rip the rock mass (Roxborough, 1973). Tensile forces exist as the ripper tool enters the rock and fractures develop as a result of tensile stresses in the rock. These fractures cause breakout of wedge of the rock. The force to move the tip through the rock mass (ripper draft force) is given as Colburn (1977) as follows:

$$F = [2 \text{ x } t \text{ x } d \text{ x } w \text{ x } \text{Sin}\,(\text{Ø} + \varphi)]/[1 - \text{Sin}\,(\text{Ø} + \varphi)] \qquad (2.1)$$

where *F* is ripper draft force;
t is tensile strength of rock;
w is width of ripping tool;
d is depth of cut;
Ø is semi angle of ripping tool; and
φ is angle of friction between rock and tool.

Using the equation 2.1 for a given ripper, point angle, friction coefficient between the rock and the ripper point and the tractor draft force capability, a curve can be plotted relating penetration depth to rock tensile strength where the penetration is obtained (Figure 2.2). This relationship applies to ripper capability in a homogeneous or thickly laminated rock masses.

During field studies it has been noted that the penetration capability of a ripper is dependent upon the structural features of the rock mass. These features include penetration depth which is considerably increased by reduced discontinuity spacing and strength of material. When the rock is laminated some of the load is relieved, allowing the ripper point to penetrate into the next lamination (Figure 2.7).

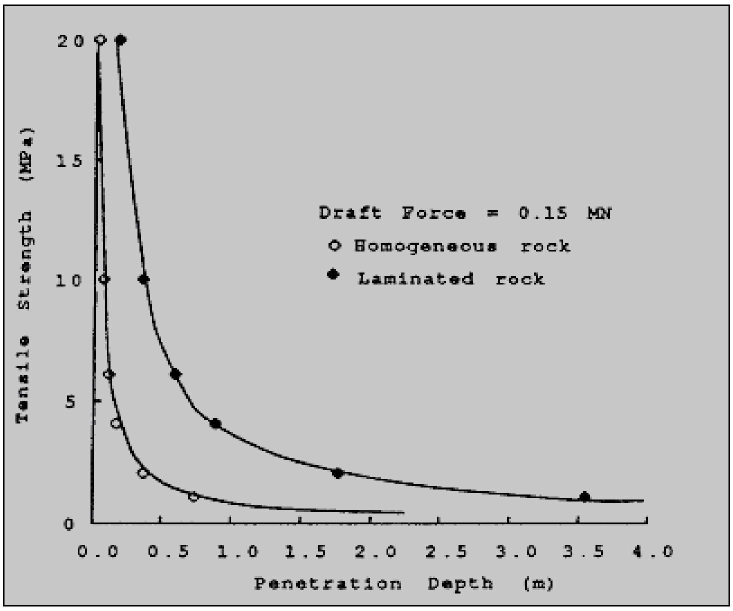


Figure 2.7: Relationship between Tensile Strength and Penetration Depth (Colburn, 1977)

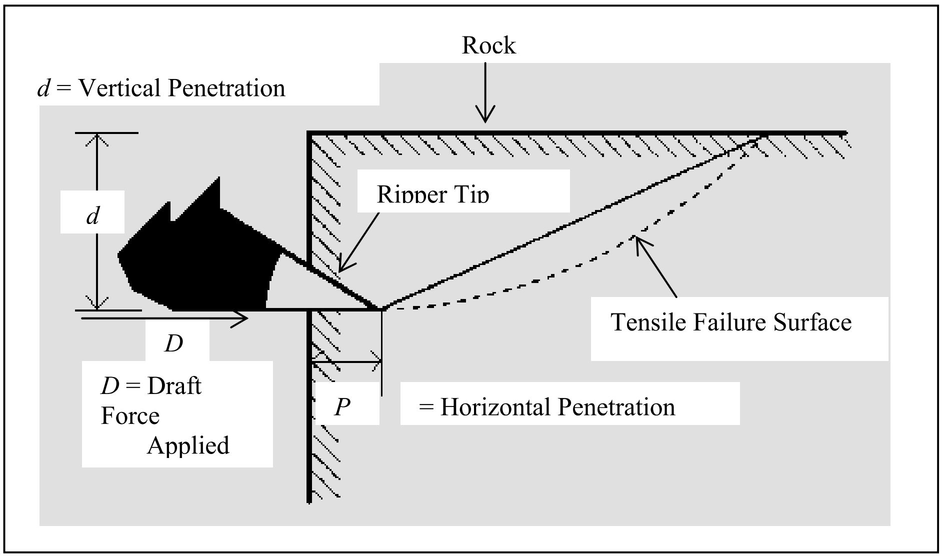


Figure 2.8: Ripper Tip Penetrating a Homogeneous Rock (Colburn, 1977)

2.5.1 Evans's Theory of Coal Cutting

The earliest recorded study of the rock cutting process was by Evans and Pomeroy (1966). They showed that during the penetration of a wedge shaped indenter into coal, cracks attributed to tensile breakage radiate from the tip of the wedge and that this breakage path took the form of a simple circle.

Considering a buttock of coal XOY (see Figure 2.4) with a wedge of angle 2θ entered at abc. It is assumed that the coal tears along a curve cd and that the curve has a horizontal tangent at c (Evans and Murrell, 1957). Assuming that there is no friction between the wedge and the coal, the forces acting on the buttock are:

i) A force R acts normal to the face of the wedge ac
ii) The resultant T of the tensile forces acting normal to the curve cd.
iii) A force, S is required to maintain the limiting equilibrium in the coal buttock.

The complete analysis is not included, but from the above three forces, the cutting force experienced was deduced as: -

$$F_c = \frac{2.t.d.\sin(\theta + \phi)}{1 - \sin(\theta + \phi)} \tag{2.2}$$

where F_c is the cutting force;
t is the tensile strength of the coal;
d is the depth of cut;
θ is the wedge half angle; and
ϕ is the angle of friction.

It should be noted that the tensile mode of breakage proposed, proceeds by the propagation of the failure surface, starting at the wedge tip and following the circular path to the crack surface point. This occurs when the wedge induces a state of stress, sufficient to the conditions governing the onset of crack propagation.

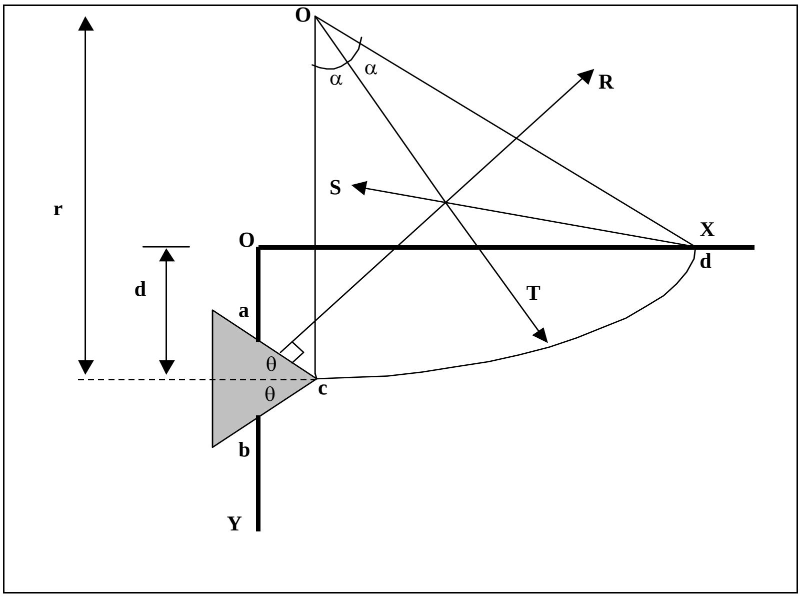


Figure 2.9 : Evans's theory of coal cutting illustrating tensile breakage mechanism (Evans and Pomeroy, 1966)

2.5.2 Nishimatsu's Theory of Rock Cutting

It was postulated by Evans and Pomeroy (1966) that only tensile failure takes place during cutting. Nishimatsu (1972) however, observed that while the failure of rocks in cutting takes place under tensile stress, compressive stresses are also induced. The model he developed from his observations involves a crushed zone forming about the tool edge as it is pushed deeper into the buttock of rock. As the tool is pushed deeper, the crushed zone tends to compact and stick against the rake face of the cutting tool. The failure of the cutting chip occurs when the depth of penetration induces a state of stress that allows the initiation and propagation of failure cracks and the formation of a coarse cutting chip. After the formation of the coarse cutting chip, the lower part of the initiation point of the macroscopic failure crack is crushed to fine cutting chips. This is known as the secondary crushed zone. Following this stage, the tool continues forward until it meets the next buttock and the process of rock cutting starts again.

Figure 2.10 shows the simplified stress distribution and cutting forces. Nishimatsu made the following assumptions about his model:

i) The stress concentration along the line AB decreases from A to B.
ii) The direction of the resulting stress is constant along the line AB.
iii) Failure takes place when the maximum stress corresponds with the criterion of failure, this being the Coulomb-Mohr failure criterion.
iv) The normal stress acting along AB is compressive.

He calculated the state of stress acting along the line AB in terms of the normal and tangential components and found their maximum and minimum values. Assuming that failure takes place in state of maximum stress, the cutting force was predicted according to the Mohr failure envelope, given by:

$$\tau_S = \sigma_S - \tan k.\sigma_n \qquad (2.3)$$

This gives:

$$F_c = \frac{2}{n+1} \cdot \frac{\sigma_S.t.\cos(k)}{1-\sin(k-\alpha+\phi)} \qquad (2.4)$$

where F_c is the cutting force at instant failure;
t is depth of cut;
n is stress distribution factor;
α is rake angle;
σ_S is the shear strength;
ϕ is angle of friction between the tool and rock; and
k is a constant of the angle of internal friction.

Nishimatsu verified his findings by a number of cutting experiments. From these he noticed the cyclic nature of the cutting fracture process and the formation of a compacted crushed zone sticking to the rake face of the cutting tool.

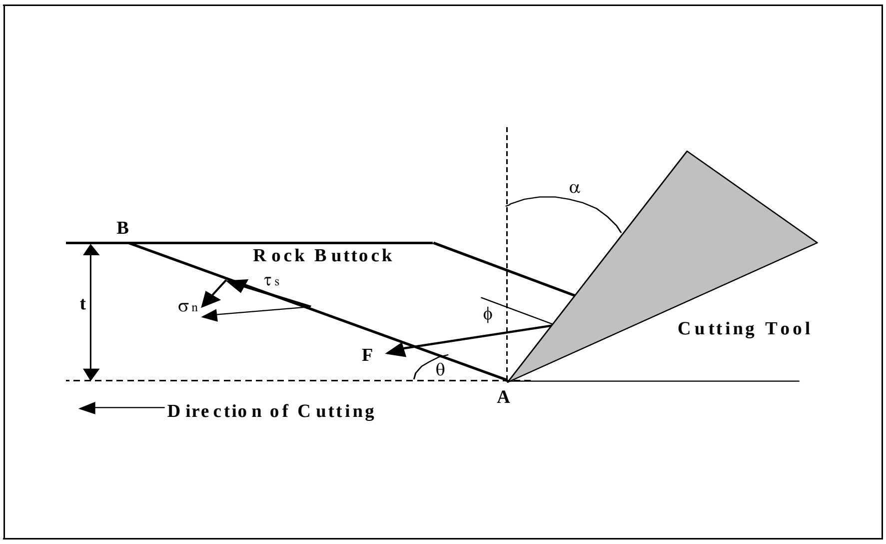


Figure 2.10: Stress distribution and cutting forces for orthogonal rock cutting (after Nishimatsu, 1972)

2.6 Ripping versus Blasting

Explosives have been an integral part of the extractive industries for more than a hundred years and today drilling and blasting techniques are commonplace in quarries and mines. But explosives bring with them variety of obvious and unseen hazards and potential problems such as fly rock and vibration. The potential hazard of flyrock can bring damage to machineries and people, are all too real, as are complaints from nearby residents because of the highly disruptive noise, dust and vibration caused by blasting.

Ripping is useful to be employed in environmental sensitive area and it is also assumed to be more economical as compared to blasting in certain rock mass. The development of more powerful ripper and advance method in blasting has triggered the needs to evaluate and compare the efficiency of these two methods. The essential difference between using blasting and ripping is the method of applying energy to break the ground; blasting uses explosive energy through expansion of gaseous whereas ripping uses mechanical energy generated by bulldozer.

Some of the advantages of ripping are:

a) **Safety**: although good working procedures can avoid most dangers in blasting, it is still more hazardous than ripping. As compared to ripping, blasting will need machines and men to be evacuated from the blasting areas, thus reducing labour utilization and machine idling. In addition, insurance premiums are higher in blasting works. These factors have made ripping more popular to be used in certain areas.
b) **Public perception**: As some of the earthworks are near to public settlements, the excavation method to be employed is worth given a greater consideration. People are highly sensitive to excessive noise, vibrations, and more importantly, their safety to fly rocks if blasting is chosen.
c) **Slope stability**: The seismic waves caused by blasting could trigger tremors in slopes and causing slope failures with the fact that slope angles are near to equilibrium.
d) **Flexibility**: the tractor ripper is a multi-usage machine which can be used for variable usage such as; dozing, hauling, and stockpiling. These factors will definitely give more advantages to the earthwork contractors.

Mechanical excavation cutting operation does not exhibit the versatility and flexibility offered by drilling and blasting the cost effectiveness of mechanical excavation is greatest in rocks of low to moderate strength. Drilling and blasting is usually preferred to mechanical excavation in strong rocks.

2.6.1 Regulations

Blasting has undesirable side effects, noise, air blast, ground vibration and fly rock. In remote areas, where such effects rarely pose any problem, competition between blasting and excavation is based solely upon cost-effectiveness. When excavating in an environmentally sensitive area, an operator may be forced to select a more costly mechanical excavation method so as to prevent the possibility of damage and the adverse response of neighbours to blast-generated vibrations. In other words, the location of the site is very important in deciding the rock cutting technique.

In Malaysian scenario, Perak Quarry Rules were introduced in 1992, to regulate the quarry industry in Perak which was enforced by the Department of Mines. This rule directly involved rules for blasting operations as well. Earlier than that, in 1987, the Department of Environment introduced the requirements for all new quarries in terms of their impact such as dust, vibration and noise generated by blasting operation.

2.6.2 Comparison of Cost

Cost is a major factor that needs to be considered by many contractors and developers when selecting the most suitable excavation method. Traditionally, researchers suggested that the cost of ripping is much lower than blasting (Hadjigeorgiou et al., 1998; Church, 1981; Caterpillar, 1983; Muftuoglu, 1983). Caterpillar (1983) noted that 2/3 of excavation cost can be saved by ripping methods as compared to blasting.

Developments in the explosive industry since the first documented use of black powder in the 1600s took place at a leisurely pace up until the middle of the last century. The last 50 years has seen many changes with the introduction of new explosive types, initiation systems and supporting accessories. The introduction of ammonium nitrate as a blasting agent has reduced blasting cost significantly, challenging the cost of the mechanical method. As a result, the combined cost of drilling and blasting is low (Mogana, 1999). That is why some of contractors will opt for blasting rather than ripping especially when dealing with boulders.

With the current development of bulk emulsion, operators can now do away with ammonium nitrate sheds, increase the ability to fire-less frequently, larger blasts and lower drilling and blasting costs. With development of more accurate delays, advances in pyrotechnic technology will allow more control of blast results and ground vibration. Risks associated with blasting and explosives have been reduced significantly over the last five decades. Safer explosives and initiation systems have been the breakthrough to this advancement.

2.6.3 The Influence of Environmental Pressure

When an explosive charge is detonated in a drill hole, there is a sudden release of the stored energy in the form of an outburst of gas at high temperature and pressure. Some portion of this energy might be wasted in the form of:

i) residual heat in the products of explosion
ii) heat expended in raising the temperature of the rock surrounding
iii) heat loss to the atmosphere

The general public is less ready to accept the effects of blasting without protest and complaint. Some of the trigger factors associates with blasting are listed below:

a) Ground vibration- when explosive charge is detonated, the energy released partially absorbed by a solid rock mass behind the row of holes. This energy has to be dissipated through the surrounding ground; the energy causes a vibration.

b) Air Blast- in addition to ground movement, blast wave travel through the air which causes the rattling of windows associated with the blast is the noise explosion.

c) Fly rock is the most hazardous effect of blasting. It is the leading cause of fatalities and damage. Excessive fly rock is most often associated by improper designed blast.

2.7 Summary

In this chapter, a brief review of ripping equipment and physical factors that influence ripping works are presented. Ripping techniques, ripper mechanisms, cost, mechanisms of rock failure and aspects of production have also been examined.

Rippability of rock mass can be determined by a number of methods. The best method to evaluate rippability of rock mass is by field trial, however this method is not always possible due to logistic and site preparation. Thus, a number of indirect methods of assessing rippability were introduced by previous researchers. Although the methods were introduced by taking into account a number of parameters that are believed to influence rippability, there is still a vacuum in assessing tropical weathered sedimentary rock masses such as the influence of moisture content, lithology, iron pan and some other factors. As rippability is greatly influenced by the rock mass condition, the field study on discontinuities is vital together with the characteristics of the machine and its direction of ripping. These data can only be gathered during the study on the actual ground and not in the laboratory alone.

The decision regarding rock rippability should be based on better understanding of the various physical and mechanical properties of rock and the machines used. Although geophysical method has been used widely in the assessment, this method is recommended to be supported by other geotechnical properties and discontinuities study as well. Rock mass classification systems appear to be an effective tool in assessing rippability as it helps to group the dominant factors in a systematic manner.

Field studies were undertaken at various sites in order to study the rippability related in situ and intact rock parameters and to create rippability data to be used for development of rippability index classification. Penetration as one of the most important factors in rippability has been stated by various researchers but were not well addressed previously will also be studied in this research (Basarir and Karpuz, 2004; Kramadibrata, 1998; Muftuoglu, 1983).

CHAPTER 3

ROCK EXCAVATION ASSESSMENT

3.1 Introduction

Work into ground preparation consists of development and application of a systematic method to be used in the classification of rock masses to ease the ground preparation. These methods are designed to assist in the selection and optimization of equipment for a given duty. For more than 40 years, there have been numerous attempts to develop systems that can predict rippability of rocks. The systems used by many researchers for determining rippabilities of rock can be grouped in two main groups:

i Direct method
ii Indirect method

Direct ripping is where field trials are employed to demonstrate or estimate the performance of ripping production for given equipment. A ripper is measured by its weight and flywheel horse power, compared with the production rate by ripper. If field trials or direct runs cannot be conducted then indirect methods will be used to estimate rippabilities. Indirect method can be grouped into three types:

i Seismic velocity based approximations
ii Graphical methods
iii Grading methods

3.2 Direct Methods

These methods are based on the field trials by actual ripper machines. This method is found to be the best method to evaluate the actual ripping performance in the selected rock masses. However, it is not always possible to perform this test due to high cost, project constraint and availability of the site. According to Anon (1994) there are three general methods to perform this type of testing; volume by weight, volume by cross sectioning and volume by length.

3.2.1 Volume by Weight

This could be the best method to evaluate the production from ripping. Ripped material will be weighed and the time spent for the ripping will be recorded. The hourly production can be found by dividing the material weight by the time spent to rip it.

3.2.2 Volume by Cross Sectioning

In this method, the area that had been ripped and removed will be cross sectioned. The volume of ripped material versus the time taken can be found by dividing the volume by the time spent.

3.2.3 Volume by Length

This method is timing the ripper over a measured distance. The length of ripped material will be recorded and the volume estimated.

3.3 Indirect Method

When a direct ripping run is not practical or during the planning stage of earthworks, indirect methods of assessment will be an alternative to evaluate the rippability of the rock mass. This method covers geophysical techniques that function to detect changes in the physical properties of rocks, which lie beneath the surface. Other than that, graphical and grading methods are also another method to evaluate the rippability of rock mass.

3.3.1 Seismic Velocity Based Method

The seismic refraction method is the most popular and useful method for the purpose of rock mass characterisation in surface mines, which can lead to the selection of an excavation system (Atkinson, 1971). Seismic velocity methods can represent several intrinsic rock properties like porosity, density, grain size and shape, anisotropy, mineralogy, degree of cementation and moisture effects of the rock material combined together (Bradybrooke, 1988). In the decade of 1920 to 1930 the seismic refraction methods were used in oil exploration and later they have been applied to earth-rock excavation. The seismic velocity method was first used by Caterpillar Company in 1958 and was also widely used in 1960s for selecting the excavation method (Pettifer and Fookes, 1994).

Snell's law of refraction as applied to seismic work can be expressed as when a shock wave passes through a layer in which its velocity is *Vu* and strikes an interface separating this upper zone of lower velocity from the lower earth-rock zone of higher velocity *Vl* at an angle *Iu* with the normal, it is bent at an angle *Rl* with the normal in the lower layer*, Vl* as derived in equation 3.1.

$$\frac{\sin Iu}{\sin Rl} = \frac{Vu}{Vl} \qquad (3.1)$$

Figure 3.1 shows ideally the path of travel of shock waves from the point of excitation to geophone through three layer of earth-rock structure. Waves from each excitation points 1 through 10 are picked up by geophone, G at different velocities at different times. By knowing the distance between the source and receiver geophone two points and the elapsed time, the velocity is calculated.

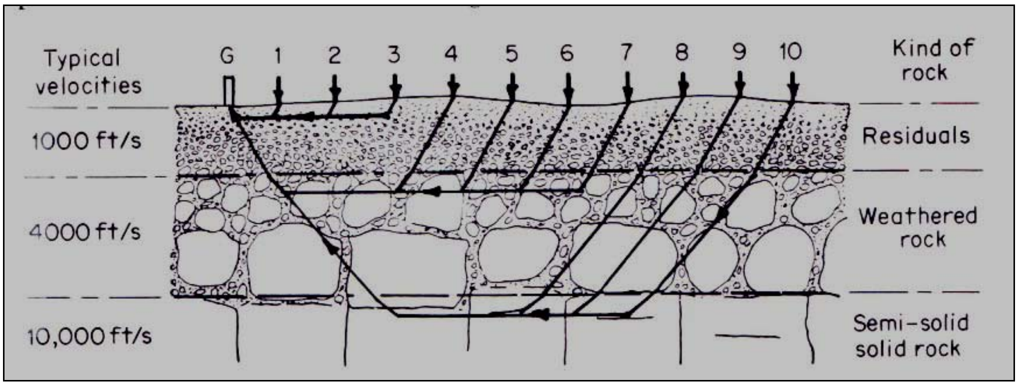


Figure 3.1: Ideal paths of travel of shock waves in an earth-rock structure according to Snell's law (Church, 1981)

Although seismic velocity is widely used, this method of assessment has some advantages and disadvantages. Other than being able to investigate large areas at low cost, the seismic method is able to determine different layers by the difference in their velocity. Figure 3.2 shows the difference gradient of velocity indicating a different layer.

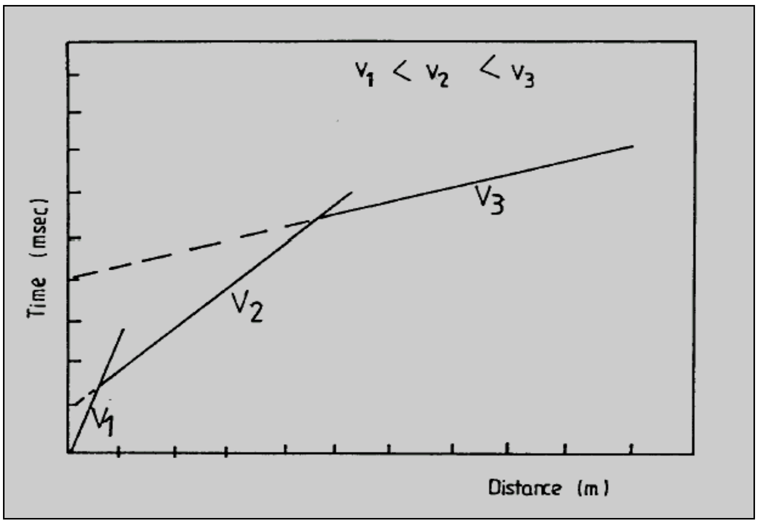


Figure 3.2: A typical distance-time relationship of seismic measurement (Bozdag, 1988)

Slopes of the curve segments representing the wave speed through each layer as shown in equation 3.2:

$$V = \frac{D}{T}.1000 \qquad (3.2)$$

where V = seismic P-wave velocity (m/s);

D = distance (m); and

T = time (ms).

According to Singh et al. (1987), abrasive material, which is also affecting the excavatability is not affected by seismic velocity. Fresh boulders and rock columns in a matrix of completely weathered material, which are normally found in granite, gabbro, basallt and sandstones, are also not clearly sensed by seismic velocity. The data obtained from the survey may lead to an incorrect excavatability assessment. Similarly, if the thickness of the high velocity layer is less than 1/3 of the overlying layer, surface seismic methods may see through the layer as the upper layer masks the lower layer (Bradybrooke, 1988).

Seismic velocity is not able to differentiate the different nature of material. For example, sandstone velocity may be the same as in granite; however the sandstone is classified as a rippable rock whereas granite is well known for its difficulty to rip. The seismic velocity will travel faster in saturated material compared to dry material as water helps in transmitting the wave. This may lead to porous rock which has a higher moisture content to give higher velocity compared to dry ones and does not represent the true strength. Due to problems in interpretation the seismic velocity data, $\pm$ 1000m/s can be observed for the same material and the accuracy can be $\pm$20% (Bilgin, 1989).

3.3.2 Excavatability Assessment by using Seismic Velocity

In assessing the excavatability, many researchers proposed different guidelines for excavation with different seismic velocities. Bulldozer manufacturers, Caterpillar and Komatsu use solely the seismic velocity to estimate the excavatability of various types of rock. Their assessments are also developing as more powerful machines are being developed. Atkinson (1971) and Bailey (1975) proposed excavation possibilities without specifying the rock type and degree of weathering.

3.3.2.1 Atkinson Method

Atkinson (1971) proposed a chart showing the diggabilities of rocks based on their P wave velocities as shown in Figure 3.3.

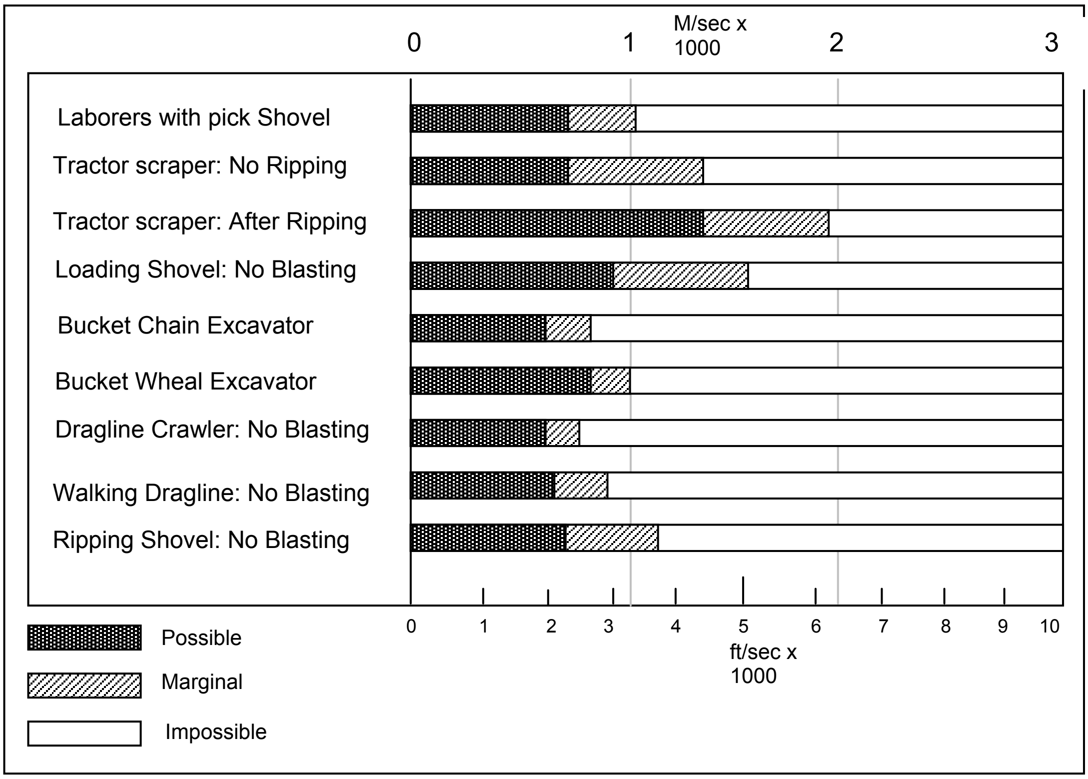


Figure 3.3: Excavation possibilities as proposed by Atkinson (1971) by using seismic velocity

3.3.2.2 Bailey Method

Bailey (1975) proposed diggability class definition and index number by using P wave velocities as shown in Table 3.1. The diggability of the rock masses is classed as very easy to extremely difficult based on the seismic velocity wave. The higher seismic wave velocity indicates the more difficult it is to be ripped.

Table 3.1: Diggability classification of rocks according to seismic velocity (Bailey, 1975)

P-wave velocity (ft/s)	**(m/s)**	**Diggability class definition**	**Index number**
1000-2000	305-610	Very easy	1-3
2000-3000	610-915	Easy	3-4
3000-5000	915-1525	Moderate	4-6
5000-7000	1525-2135	Difficult	6-8
7000-8000	2135-2440	Very difficult	6-8
8000-9000	2440-2743	Extremely difficult	8-10

3.3.2.3 Church Method

Church (1981) divided the excavatability assessment guidelines to medium-weight (200-300 engine-hp, 60,000 lb-90,000 lb working weight) and heavyweight tractor (300-525 engine-hp, 100,000-160,000 lb working weight). Table 3.2a and 3.2b show the diggability classifications proposed by Church (1981) for medium and heavy weight tractors. Similar to the other seismic velocity based assessments, the high seismic wave velocity indicates a more difficult rock masses to be ripped.

Table 3.2a: Diggability classification for medium-weight tractor-rippers (Church, 1981)

Diggability Class	**Seismic velocity, m/s**
No ripping	<455
Soft ripping	455-909
Medium ripping	909-1212
Hard ripping	1212-1515
Extremely hard ripping or blasting	1515-1818
Blasting	>1818

Table 3.2b: Diggability classification for heavyweight tractor-rippers (Church, 1981)

Diggability Class	**Seismic velocity, m/s**
No ripping	<455
Soft ripping	455-1212
Medium ripping	1212-1515
Hard ripping	1515-1818
Extremely hard ripping or blasting	1818-2121
Blasting	>2121

Church (1981) has also proposed a relationship between seismic shock wave velocities and depth below ground surface for sedimentary, metamorphic and igneous rocks for their minimum, average and maximum degrees of weathering as shown in Figure 3.4.

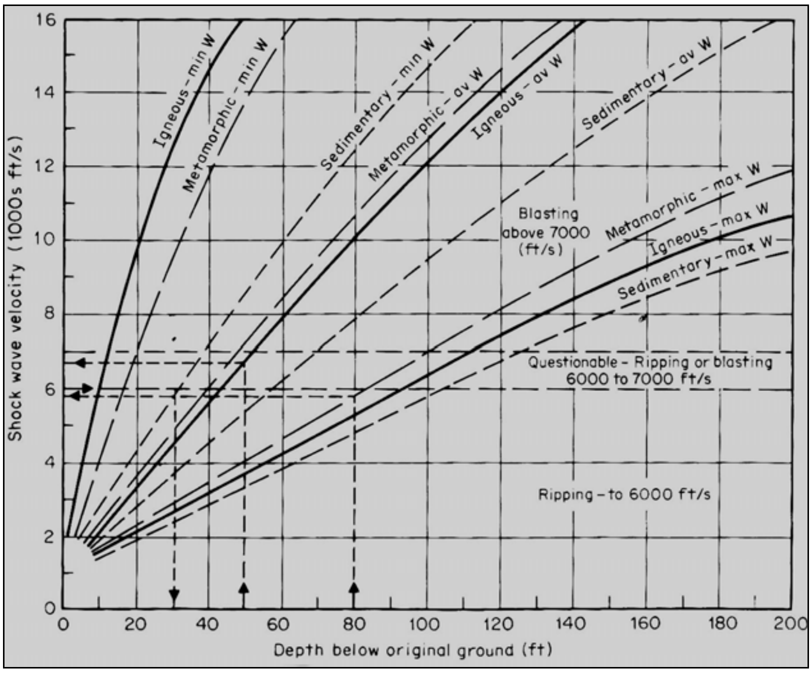


Figure 3.4: Relationship between seismic velocities and depth below ground surface for different rocks and their degree of weathering (Church, 1981)

3.3.2.4 Caterpillar and Komatsu Method

As early as 1958, the Caterpillar Company has used the seismic refraction method in assessing the excavatability of various rocks. A typical chart for a CAT D9 is shown in Appendix C. The charts used seismic P wave velocities to assess whether the material is rippable, marginal or non-rippable for various rock types. The value of the seismic velocity for the marginal to non-rippable category will be higher for bigger size dozers. Similarly, Komatsu Company has also produced a similar chart for its dozer as shown in Appendix C (Anon, 1987). Both Caterpillar and Komatsu are using solely the seismic velocity to assess the excavatability of different materials.

Even though many excavation assessment methods are using seismic velocity as an indicator, many researchers claim that this method may lead to a misleading estimation of excavation (Stacey, 1976; Kirsten, 1982; Smith, 1986 and Hadjigeorgiou & Scoble, 1988). The geological features which require different field procedures and the rock mass condition may be some factors that lead to misinterpretation. As in general, seismic velocity cannot be determined to accuracy better than 20 percent (Kirsten, 1982).

3.3.3 Excavation Assessment By Using Graphical Method

This method as proposed by several researchers provides a useful indication of excavation methods when quick assessment is needed. Franklin et al. (1971) are the pioneers in proposing such assessments followed by Bozdag (1988) and Pettifer and Fookes (1994). All these assessments use discontinuity spacing parameter and point load value to estimate excavation method without focussing on any specific rock type.

3.3.3.1 Franklin, Broch and Walton Method

Franklin et al. (1971) published a size-strength graph that relates discontinuity spacing and rock strength to the method of excavation required. The graph subdivided area of digging, scraping, ripping, blasting to loosen and blasting to fracture based on a research conducted in the United Kingdom in 1968 and 1970. In this assessment, Franklin et al. (1971) suggested two parameters namely discontinuity spacing and point load index (Is_{50}) as very important factors in excavation. Discontinuity spacing is defined as the average spacing of fractures in a rock mass whereas the value of point load index is measured by using force to break rock samples. Figure 3.5 shows the classification diagram. Four groups of zones are plotted namely digging, ripping, blasting to loosen and blasting to fracture. The rippability classes proposed did not specify machine and rock type.

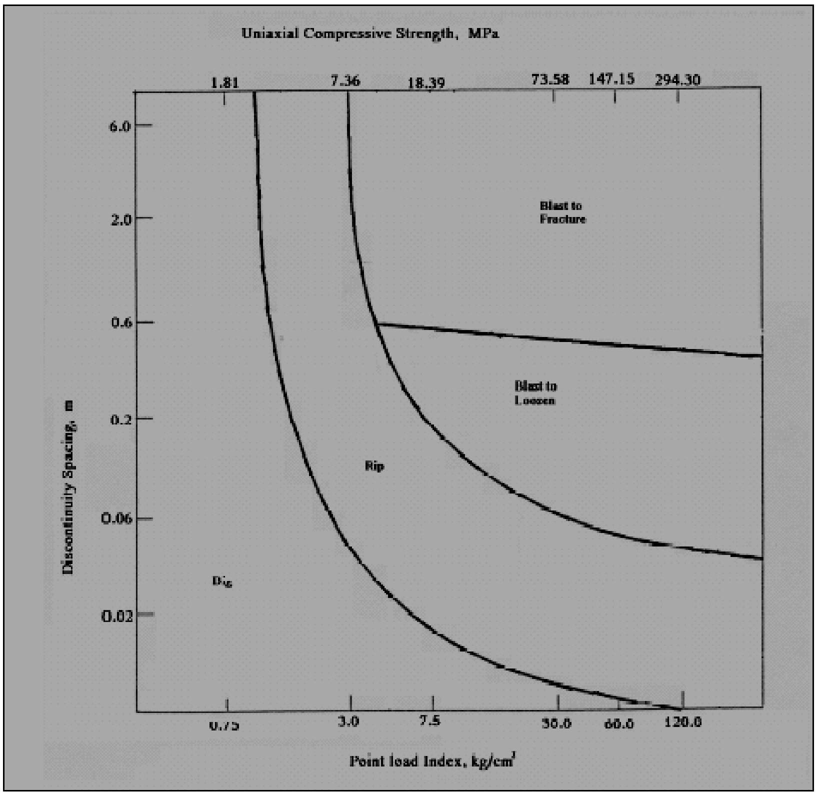


Figure 3.5: Excavation chart proposed by Franklin et al. (1971)

3.3.3.2 Bozdag Method

Based on his research in different open pits of Turkish Coal Enterprises, Bozdag (1988) modified the Franklin et al. (1971) chart. Bozdag (1988) divided the graph boundary into four parts and suggested the type of equipment to be used. The diagram is shown in Figure 3.6.

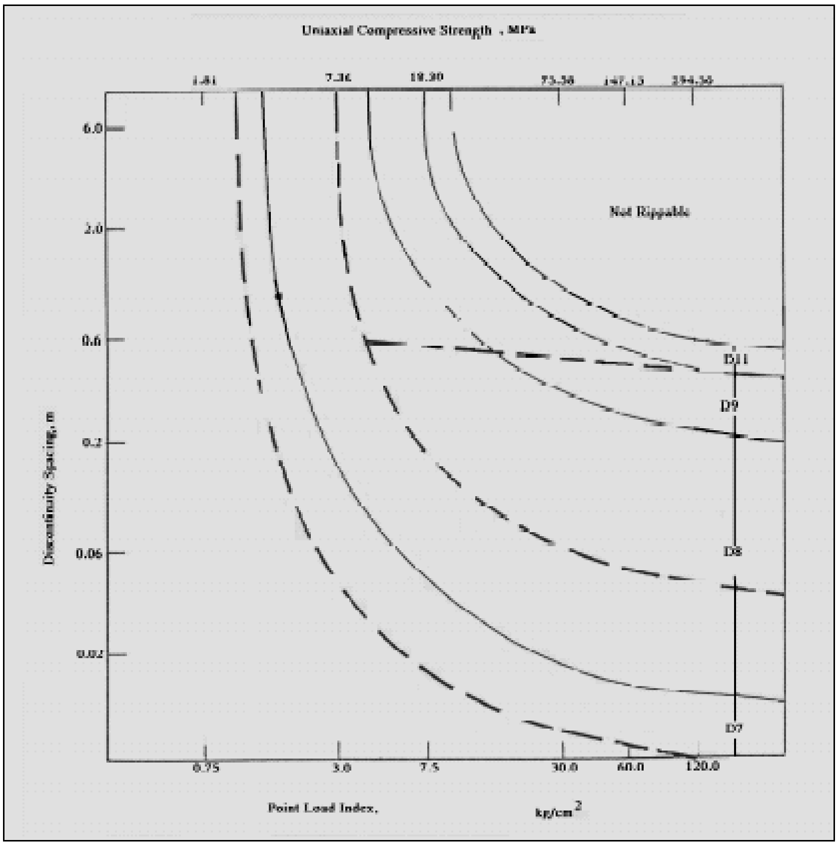


Figure 3.6: Assessment chart proposed by Bozdag (1988)

3.3.2.3 Pettifer and Fookes Method

Pettifer and Fookes (1994) used a graphical revision collected from case studies in Africa, Hong Kong, United Kingdom and through discussion with site staff and observation at a hundred sites. The summary of criteria used by other researchers is shown in Table 3.3. They found that the discontinuity spacing and strength of intact rock has the most influence to the excavation of rocks. The revised Franklin (1971) graph as shown in Figure 3.7, allows the excavation assessment to be assessed more rapidly, and is particularly suited to rippability assessments for civil engineering works. However, the graph does not necessarily resolve problems of equipment selection and cost, due to some other geological and geotechnical properties that may dictate specific working practices.

Table 3.3: Summary of Geotechnical parameters used by researchers in assessing the excavatability (after Pettifer and Fookes, 1994)

Assessment	Relative importance of each parameter[1)]									
method	SV[2)]	Σc[2)]	PLI	Hd	Ab[2)]	Wea	Dsw	Jp	Jsp	Jor.
Caterpillar (1970)	****	-	-	-	-	-	-	-	-	-
Franklin et al., (1971)	-	-	****	-	-	-	****	-	*	***
Weaver (1975)	****	-	-	**3)	-	**	****	*	*	*6)
Kirsten (1982)	-	****4)	-	-	-	-	****5)	-	*	**7)
Minty & Keams (1983)	****	-	**	-	-	**	***	*	*	-
Scoble & Muftuoglu (1984)	-	**8)	-	-	-	**	****9)	-	-	**
Smith (1986)	-	**	-	-	-	**	****	*	*	-
Singh et al., (1987)	***	-	**10)	-	**	**	****	-	-	-
Karpuz (1990)	****	***8)	-	**11)	-	**	****	-	-	-
Hadjigeorgiou & Scoble (1990)	-	-	***	-	-	**	****12)	-	-	*6)
MacGregor et al., (1994)	*	*								
Pettifer & Fookes (1994)	-	-	****	-	-	*	****	-	-	**

Notes:

1. Number of stars denotes relative importance of parameter in each assessment method.
2. Requires specialized techniques or laboratories testing.
3. Can be expressed in term of UCS.
4. Compared with dry density.
5. A function of ROD and the spacing ratio for two joint sets.
6. Compared with the spacing ratio for two joint sets.
7. Minty and Kearns also consider ground water conditions and the surface roughness of discontinue ties.
8. Can be derived from field point load values.
9. Considers joint spacing and bedding spacing separately.
10. Uniaxial tensile strength determined by laboratory testing is preferred.
11. Schmidt hammer value.
12. Expressed at the volumetric joint count, Jv.

SV = Seismic velocity   σc = UCS   PLI = Point Load Index
Hd = Rock Hardness   Ab = Abrasivity   Wea = Weathering
Dsw = Joint spacing   Jp = Joint persistence   Jsp = Joint separation   Jor = Joint orientation

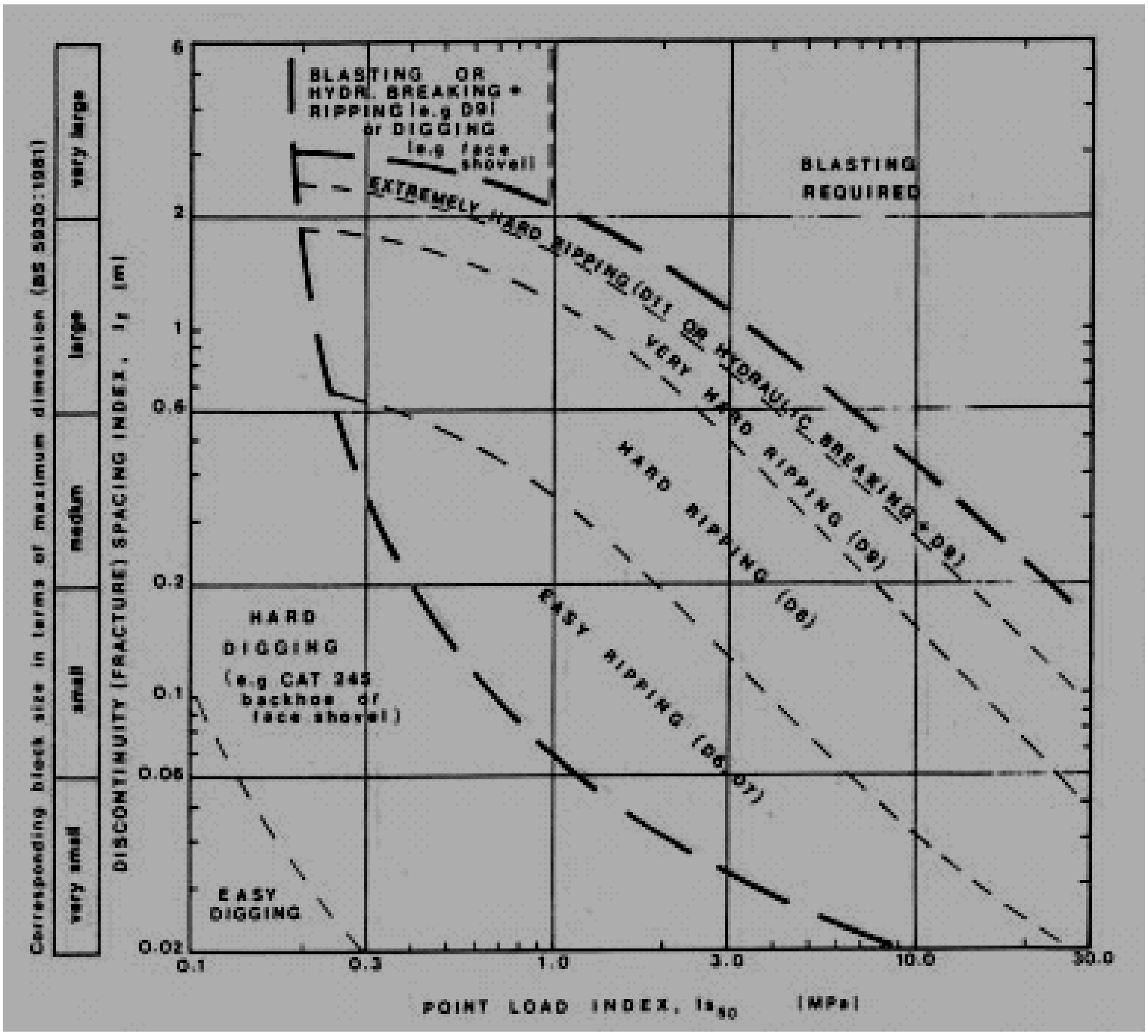


Figure 3.7: Excavatability assessment chart proposed by Pettifer and Fookes (1994)

3.3.4 Excavation Assessment By Using Grading Systems

It is noted that the excavatability of rocks depends on a number of geomechanical properties of intact rock and rock mass such as discontinuities, weathering grade, grain size and strength. The properties can be determined by rebound tests, rock strength index tests, rock mass classifications and other specific tests. Basically, no single test can uniquely define rock material properties. Instead, there are numerous tests giving either a direct or an indirect value to each property. Other than the geo-properties, working conditions and the equipment variables may also influence the excavatability. Based on these factors, rock mass and rock material properties are graded with respect to their importance in excavatability. The importance of certain parameters used for this system is noted for different researchers, perhaps due to the differences in the rocks studied. Table 3.4 lists some other factors that are considered.

Table 3.4: Summary of rock properties influencing the excavation design in surface mines

Rock Property	**Variables**	**Reference**
Physical Properties	-Moisture content -Density -Porosity	ISRM, 1981 ISRM, 1981 ISRM, 1981
Rock Substance Hardness	-Mineralogical hardness Schmidt rebound hammer Modified Schmidt hammer	N.C.B ISRM, 1981 Gehring, 1992
Standard Rock Strength	-Unconfined compressive strength (UCS) -Brazillian tensile strength	ISRM, 1981 ISRM, 1981
Rock Strength Index	-Pont Load Index-PLI	ISRM, 1981
Dynamic Property	-Laboratory seismic velocity	ISRM, 1981
Rock Mass Properties		
Mass Properties	-Discontinuity Frequency -Rock Mass Strength	ISRM, 1981 ISRM, 1981
Rock Mass Classification	-Rock Quality Designation (RQD) -Rock Mass Rating (RMR) -Rock Quality System (Q-System) -Excavatability Index	Deere, 1964 Bieniawski, 1989 Barton et al., 1974 Kirsten, 1982

Note:

EXC. = Excavation, SS = Slope study

3.3.4.1 Weaver System

Weaver (1975) used examples from South Africa to propose a rippability chart by using seismic velocity, weathering parameter and discontinuity orientation. Weaver (1975) designed a rippability prediction method based on Bieniawski's geomechanics classification system (RMR). However, ground water conditions were ignored and seismic velocity was used instead of RQD. By having an index number for each situation, a total index number will then calculated and the excavation method was proposed as shown in Table 3.5.

3.3.4.2 Kirsten System

Kirsten (1982) proposed specification classes of excavation in terms of basic characteristics and provided basic parameters of standard recognized testing standards. A classification system is proposed based on engineering properties for weakest soil to hardest rock. Kirsten (1982) parameters were based on Barton et al. (1974) Q system.

An excavatability index (N), which represents six parameters was proposed as follows:

$$N = Ms \frac{RQD}{Jn} Js \frac{Jr}{Ja} \tag{3.3}$$

where *Ms* is Mass strength number;
RQD is Rock Quality Designation;
Jn is Joint set number;
(RQD/Jn) is reducing effect of blocks;
Js is reducing effect of block shape and orientation;
Jr is Joint roughness number (Q system);
Ja is Joint alteration number (Q system); and
(Jr/Ja) is reducing effect on deformability and weakness of joints.

Table 3.5: Excavation assessment chart proposed by Weaver (1975)

Rock Mass	**I**	**II**	**III**	**VI**	**V**
Description	Very Good Rock	Good Rock	Fair Rock	Poor Rock	Very Poor Rock
Seismic Velocity (m/s)	>2150	2150-1850	1850-1500	1500-1200	1200-450
Rating	26	24	20	12	5
Rock Hardness	Extremely Hard Rock	Very Hard Rock	Hard Rock	Soft Rock	Very Soft Rock
Rating	10	5	2	1	0
Rock Weathering	Unweathered	Slightly Weathered	Weathered	Highly Weathered	Completely Weathered
Rating	9	7	5	3	1
Discontinuity Spacing (mm)	>3000	3000-1000	1000-300	300-50	<50
Rating	30	25	20	10	5
Discontinuity continuity	Non Continuous	Slightly Continuous	Continuous – no Gouge	Continuous some Gouge	Continuous with Gouge
Rating	5	5	3	0	0
Joint Gouge	No Separation	Slightly Separation	Separation < 1mm	Gouge < 5mm	Gouge > 5mm
Rating	5	5	4	3	1
Strike Dip and Orientation *	Very Unfavourable	Unfavourable	Slightly Unfavourable	Favourable	Very Favourable
Rating	15	13	10	5	3
TOTAL RATING	100-90	90-70 **	70-50	50-25	<25
Rippability Assessment	Blasting	Extremely Hard Ripping and Blasting	Very Hard Ripping	Hard Ripping	Easy Ripping
Tractor Selection	-	DD9G/D9G	D9/D8	D8/D7	D7
Horse Power	-	770/385	385/270	270/180	180
Kilowatts	-	570/290	290/200	200/135	135

* Original strike and dip orientation now revised for rippability assessment
** Ratings in excess of 75 should be regarded as unrippable without pre-blasting

The mass strength number is obtained by multiplying the average value of UCS with coefficient of relative density. The latter is obtained from dry unit weight (kN/m^3) divided by 27 kN/m^3 (Dry unit weight that is assumed for extremely hard rock). Appendix D summarized the system proposed by Kirsten (1982) and the class of excavation was proposed based on the total N number as shown in Table 3.6. The higher value of N indicates the more difficult the excavation will be.

Table 3.6: Class of rippability based on the Excavation Index (N)

Excavation Index, N	Rippability
N<0.1	Hand tools
0.1<N<10	Easy ripping, D6/D7
10<N<1000	Hand to very hard ripping, D8/D9
N>1000	Extremely hard ripping to blasting, D10

3.3.4.3 Muftuoglu System

Muftuoglu (1983) considered equipment and ground condition in proposing his excavation assessment. He developed the diggability index for sandstone and mudstone based on his experience at 6 sites. Parameters considered are weathering, rock strength, joint spacing and bedding spacing. The parameters, grades and classifications for the scheme are given in Table 3.7 and 3.8 respectively. The ease of digging was classified based on the total of the indices.

Table 3.7: Diggability Index rating method (Muftuoglu, 1983)

Class Parameter		I	II	III	VI	V
Weathering Rating		Completely	Highly	Moderately	Slight	Unweathered
	W	0	5	15	20	25
Strength (MPa)	UCS	<20	20-40	40-60	60-100	>100
	$Is_{(50)}$	0.5	0.5-1.5	1.5-2.0	2.0-3.5	>3.5
Rating	S	0	10	15	20	25
Joing Spacing (m)		<0.3	0.3-0.6	0.6-1.5	1.5-2.0	>2.0
Rating	J	5	15	30	45	50
Bedding Spacing (m)		<0.1	0.1-0.3	0.3-0.6	0.6-1.5	>1.5
Rating	B	0	5	10	20	30

Table 3.8: Diggability classification proposed by Muftuoglu (1983)

<table>
<tr><th>Class</th><th>Ease Digging</th><th>Index (W+S+J+B)</th><th>Excavation Method</th><th>Plant to be Employed (Without Resort to Blasting)</th></tr>
<tr><td rowspan="3">I</td><td rowspan="3">Very Easy</td><td rowspan="3"><40</td><td>1. Ripping</td><td>A. Ripper-Scraper Cat D8</td></tr>
<tr><td>2. Dragline Cast</td><td>B. Dragline >5m3 Lima 2400</td></tr>
<tr><td>3. Shovel Digging</td><td>c. Rope Shovel >3m3 Ruston Bucyrus 71 RB</td></tr>
<tr><td rowspan="3">II</td><td rowspan="3">Easy</td><td rowspan="3">40-50</td><td>1. Ripping</td><td>A. Ripper-Scraper Cat D9</td></tr>
<tr><td>2. Dragline Cast</td><td>B. Dragline >5m3 Marion 195</td></tr>
<tr><td>3. Shovel Digging</td><td>c. Rope Shovel >3m3 Ruston Bucyrus 150 RB</td></tr>
<tr><td rowspan="2">III</td><td rowspan="2">Moderately Difficult</td><td rowspan="2">50-60</td><td>1. Ripping</td><td>A. Ripper Shovel/F.E Ldr. Cat D9</td></tr>
<tr><td>2. Shovel Digging</td><td>B. Hydraulic Shovel > 3m3 Cat 245</td></tr>
<tr><td rowspan="2">IV</td><td rowspan="2">Difficult</td><td rowspan="2">60-70</td><td>1. Ripping</td><td>A. Ripper Shovel/F.E Ldr. Cat D10</td></tr>
<tr><td>2. Shovel Digging</td><td>B. Hydraulic Shovel > 3m3 Cat 245 or O&K RH240</td></tr>
<tr><td>V</td><td>Very Difficult</td><td>70-95</td><td>Shovel Digging</td><td>Hydraulic Shovel >3 m3 Cat 245 or O&K RH40</td></tr>
<tr><td>VI</td><td>Extremely Difficult</td><td>95-100</td><td>Shovel Digging</td><td>Hydraulic Shovel > 7m3 Demag H1111, Poclain 1000CK, P&H 1200, O&K RH75</td></tr>
<tr><td>VII</td><td>Marginal Without Blasting</td><td>>100</td><td>Shovel Digging</td><td>Hydraulic Shovel >10 m3 Demag H185/241, O&K RH300</td></tr>
</table>

3.3.4.4 Smith System

Smith (1986) proposed a systematic means with 6 rock parameters namely rock hardness, rock weathering, joint spacing, joint continuity, joint gouge and strike / dip orientation as a modification of Weaver's (1975) system. He recommended a method of correlating the rating with seismic and tractor horsepower as shown in Figure 3.8. The modified version of Weaver's (1975) chart is shown in Table 3.9.

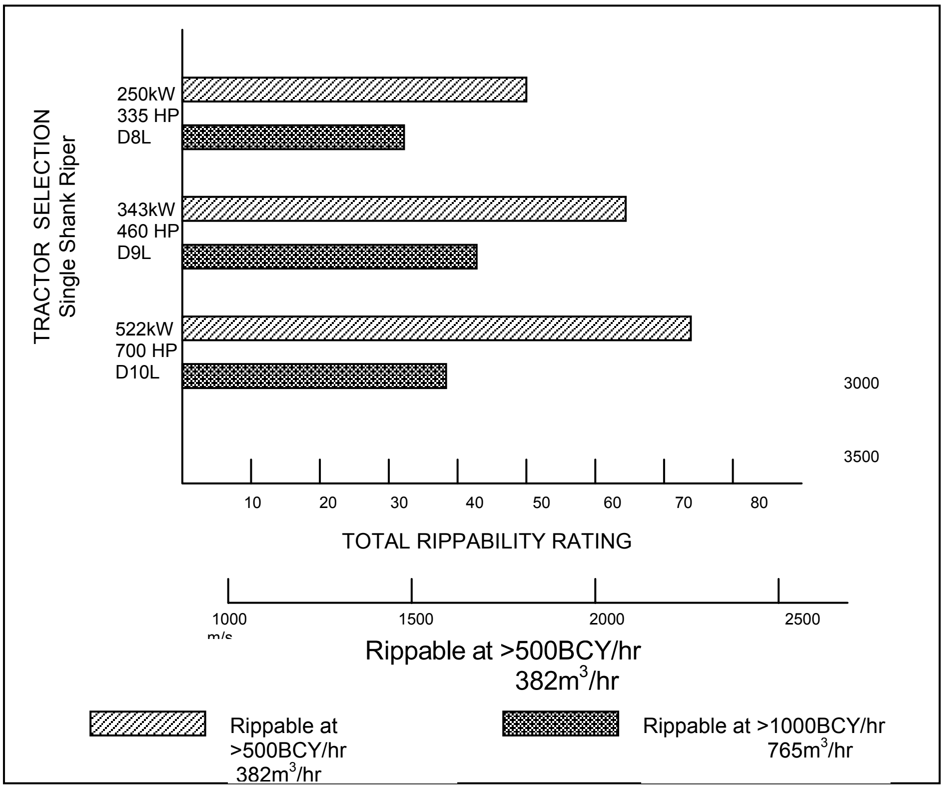


Figure 3.8: Correlation of rippability rating index with seismic velocity (Smith, 1986)

Table 3.9: Modified version of Weaver's classification (after Smith, 1986)

Descriptive Classification	**Very Good Rock**	**Good Rock**	**Fair Rock**	**Poor Rock**	**Very Poor Rock**
Rock Hardness*	Very Hard Rock ≥70 MPa	Hard Rock 70-25 MPa	Medium Hard Rock 25-10 MPa	Soft Rock 10-3 MPa	Very Soft Rock>3 MPa
Rating	≥10	5	2	1	0
Rock Weathering	Unweathered	Slightly Weathered	Highly Weathered	Completely Weathered	Complete Weathered
Rating	10	7	5	3	1
Joint Spacing (mm)	>3000	3000-1000	1000-300	300-50	<50
Rating	30	25	20	10	5
Joint Continuity	Non Continuous	Slightly Continuous	Continuous-no	Cont. some Gouges	Continuous-with Gouges
Rating	5	5	3	0	0
Joint Gouge (mm)	No Separation	Slight Separation	Separation<1	Gauge <5mm	Gouge<5mm
Ratiing	5	5	4	3	1
Strike dip and Orientation	Very Unfavorable	Unfavorable	Slightly Unfavorable	Favorable	Very Favorable
Rating	15	13	10	5	3

3.3.4.5 Abdullatif and Cruden System

Abdullatif and Cruden (1983) studied in 23 quarries involving ball clay, china clay, dolerite, gravel, limestone, sandstone and shale on the excavatability of rock mass. The rock mass were excavated by three methods; digging, ripping and blasting. The fieldwork was designed to study intact rock strength and discontinuity characteristics of different rock masses and to examine the excavation method used for the excavation. The data were obtained by carrying out scan line surveys on exposed faces and rock masses in terms of rock mass quality by using the following classification systems:

a) Point load strength index and fracture spacing
b) Q-system (Barton et al., 1974)
c) Rock mass rating (Bieniawski, 1989)

The method employed by Abdullatif and Cruden (1983) in getting the RQD value is through equation proposed by Priest and Hudson (1976) as shown in Equation 3.5.

$$RQD = 100e^{-0.1\lambda}(0.1\,\lambda + 1) \qquad (3.4)$$

where RQD is Rock Quality Designation; and
λ is Mean discontinuity frequency per metre.

Among other researchers that studied relationships between RMR and Q-system are Bieniawski (1984), Abad et al. (1983), Udd and Wang (1985) and Kramadibrata (1996). Even though Q-system was originally developed for assessing stabilisation of underground opening, its use in surface excavation is also acceptable (Kramadibrata, 1996).

Abdullatif & Cruden (1983) proposed that digging a rock mass is possible up to RMR of 30 and ripping is possible up to RMR of 60. If the value is above RMR 60, the rock mass must be drilled and blasted.

3.3.4.6 Singh, Denby and Egretli System

With an experience in 6 road construction works in coal measures rock, Singh et al. (1987) used abrasiveness of rock, discontinuity spacing, seismic velocity, weathering and indirect tensile strength to study the excavatability. They claimed current rippabilities indices fail to account for the fracture strength of the rock mass. They also noted that a rock mass is rippable if the shank can penetrate more than 0.6 m with a minimum forward speed of 2.5 km/h. Table 3.10 shows the rock rippabilities index as proposed by Singh et al. (1987).

Table 3.10: Rock index of rippability as proposed by Singh et al. (1987)

Parameters	Rock Class				
	1	2	3	4	5
UTS (Mpa)	<2	2-6	6-10	10-15	>15
Rating	0-3	3-7	7-11	11-14	14-17
Weathering	Completely	Highly	Moderately	Slightly	Unweat.
Rating	0-2	2-6	6-10	10-14	14-18
Seismic Velocity (m/s)	400-1100	1100-1600	1600-1900	1900-2500	>2500
Rating	0-6	6-10	10-14	14-18	18-15
Abrasiveness	Very Low	Low	Moderately	Highly	Extremely
Rating	0-5	5-9	9-13	13-18	18-22
Disc. Spacing (m)	<0.06	0.06-0.3	0.3-1.0	1.0-2.0	>2.0
Rating	0-7	7-15	15-22	22-28	28-33
TOTAL Rating	<30	30-50	50-70	70-90	Blast
Rippability Asses.	Easy	Moderate	Difficult	Marginal	-
Recommended Dozer	None- Class 1	Class 2	Class 3	Class 4	-
	Light Duty	Medium Duty	Heavy Duty	Very Heavy Duty	-
Output (kW)	<150	150-250	250-350	>350	-
Weight (t)	<25t	25-35f	35-55f	>55f	-

3.3.4.7 Karpuz System

Karpuz (1990) has used parameters of uniaxial compressive strength (UCS), joint spacing, P-wave velocity, weathering and hardness in evaluating the excavatability assessment. The parameters used and the classification schemes are shown in Table 3.11 and 3.12 respectively. Each parameter will be rated according to the suggested value and the total rating will be used to identify the easiness of ripping.

Table 3.11: Parameters used by Karpuz (1990)

	Excavation Class				
Parameters	1	2	3	4	5
UCS (MPa)	<5	5-20	20-40	40-110	>110
Is (50)	0.2	0.2-0.8	0.8-1.6	1.6-4.4	>4.4
Rating	2	5	10	120-200	25
Joint Spacing cm	<30	30-60	60-120	20	>200
Rating	5	10	15	2500-3000	25
P velocity m/sn	<1600	1600-2000	2000-2500	20	>3000
Rating	5	10	15	Slightly	25
Weathering	Completely	Highly	Moderately	10	Fresh
Rating	0	3	6	45-55	10
Hardness (SHV)	<20	20-30	30-45	12	>55
Rating	3	5	8		15

Table 3.12: Excavatability classification system as proposed by Karpuz (1990)

Class	Description	Rating					
			Power Shovel[1]	Hyd. Excv.[2]	Ripping	Drill Rate (m/min)	Specific Charge (kg/m^3)
1	Easy	0-25	Direct Digging	Direct Digging	D7		
2	Medium	25-45	Blast required	Direct Digging	D8/D9	1.48	130-220
3	Moderately	45-65	Blast required	Blast required	D9/D11	1.28	200-280
4	Hard	65-85	Blast required	Blast required	D11/Blast	0.57	280-350
5	Very Hard	85-100	Blast required	Blast required	Blast	<0.42	>350

3.3.4.8 MacGregor, Fell, Mostyn, Hocking and McNally System

MacGregor et al. (1994) studied geological, geophysical and ripping in mines and highways in New South Wales, Australia to estimate rippability of bulldozers. They used a quarter scale tines on rippability assessment in a laboratory and used a full-scale tine in the field. Then the relationship of force, unconfined compressive strength and depth of penetration is determined using this information and multiple variable regression analyse on their database.

They recognised that the degree of weathering is a subjective matter and found that reasonable predictions are possible even if significant parameters are not available such as seismic and UCS. Table 3.13 shows the regression equations for various rock types as proposed by MacGregor et al. (1994). To calculate production prediction, they proposed Equation 3.5 to be used.

$$Q = 0.469 - 0.00321UCS + 0.023WR - 0.0205GS - 0.00011SV + 0.0535RR + 0.0524DS + 0.0114SR \quad (3.5)$$

$R^2 = 0.58$

where UCS is uniaxial compressive strength;
WR is weathering rating;
GS is grain size rating;
SV is seismic velocity;
RR is roughness rating;
Ds is defect set; and
SR is structure rating

Table 3.13: Regression equations for sedimentary, metamorphic and igneous rocks (MacGregor et al., 1993)

Equation number	8 Sedimentary √ PROD MASS	9 Metamorphic √ PROD MASS	10 Igneous √ PROD MASS	11 Igneous √ PROD MASS
Constant	+ 0.866	+0.895	-0.138	+0.347
UCS (MPa)	-0.00736	-0.00516		-0.00118
Weathering rating		+0.00368*	+0.112	
Grain size rating		-0.254	-0.00599	
Seismic velocity	-0.000119		-0.000084	-0.00014
(m/s)	+0.0496		+0.016	+0.108
Roughness rating	-0.00004		-0.000225	
Defect spacing		+0.00132		
(mm)				
Structure rating	0.52	0.44	0.85	0.67
	0.17	0.19	0.10	0.15
R^2				
s				

Note:
R^2 = correlation coefficient of regression
s = standard error of the estimate

3.3.3.9 Kramadibrata's System

Kramadibrata (1996) studied excavatability in a limestone quarry, an open pit gold mine and an open coalmine in Austria, Australia and Indonesia. Geomechanical investigations were conducted which involved scan line mapping of rock faces and laboratory test. Rock samples were obtained from lumps of rock or on-site drilling. The writer used the RMR (Bieniawski, 1989) and the Q-system (Barton et al., 1974) to evaluate rock properties.

From the data gathered, Kramadibrata (1996) has proposed a relationship between Rock Mass Rating (RMR) and Excavatability Index and the Q-system and Excavatability Index as depicted in Figure 3.9 and 3.10. He found that the

Excavatability Index is better correlated with the Q-system as compared to RMR. For both correlations, the decrease of RMR or the Q- system rating will result in lower Excavatability Index. The Excavatability Index used by Kramadibrata (1996) was the one proposed by Kirsten (1982). Figure 3.11 shows the relationship between the production rate and the Excavatability Index which shows decrease of productivity with increase of Excavatability Index.

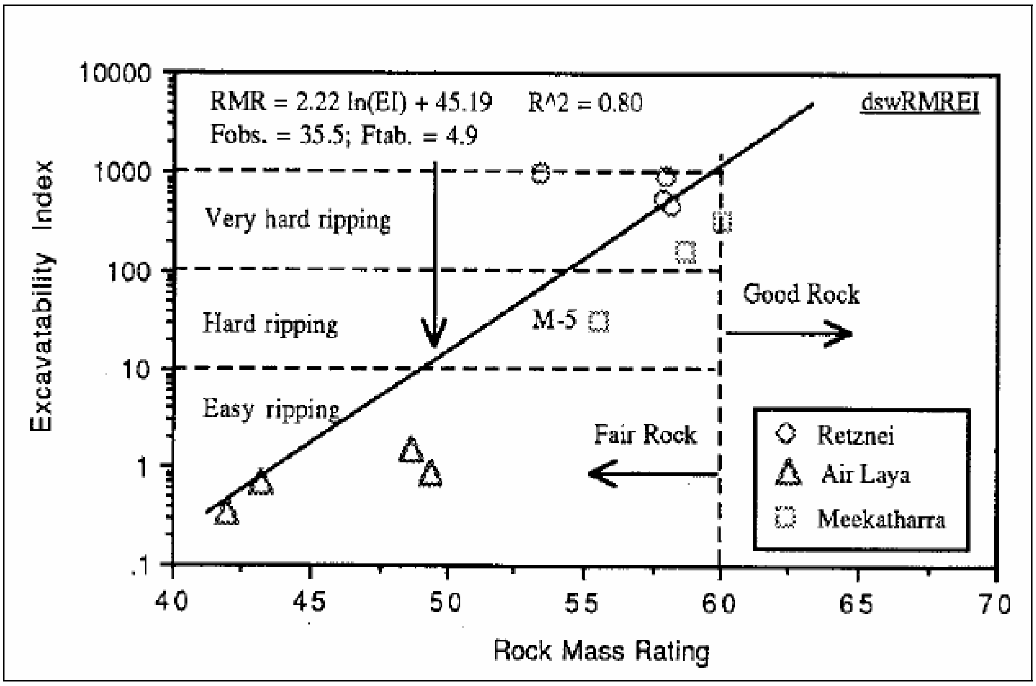


Figure 3.9: Relationship between Excavatability Index (EI) and RMR (Kramadibrata, 1996)

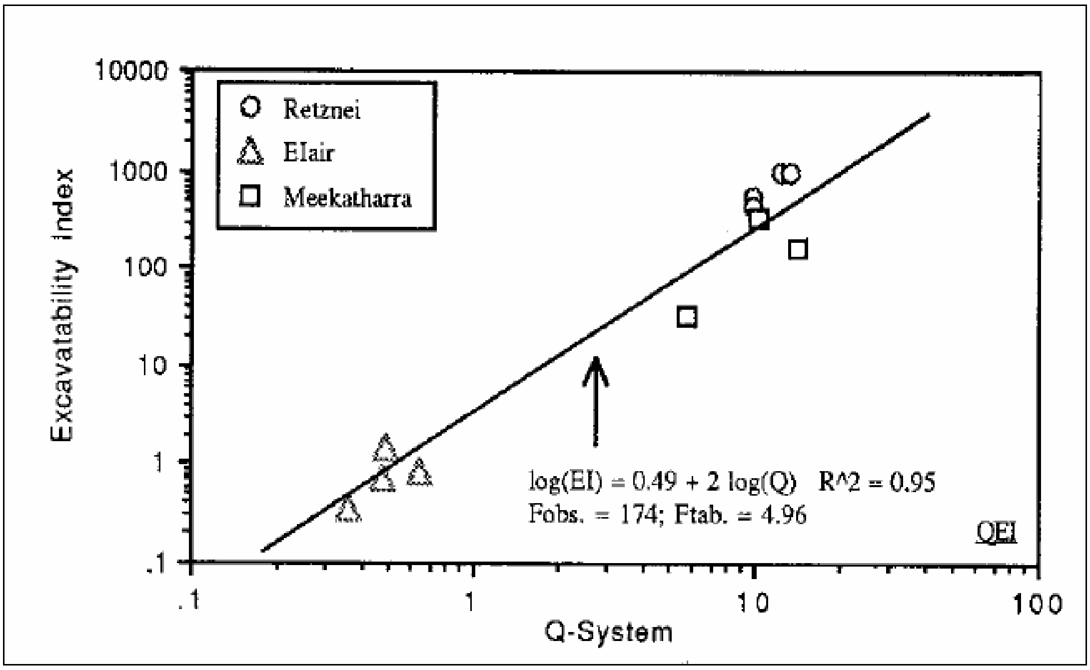


Figure 3.10: Relationship between Excavatability Index (EI) and Q-system (Kramadibrata, 1996)

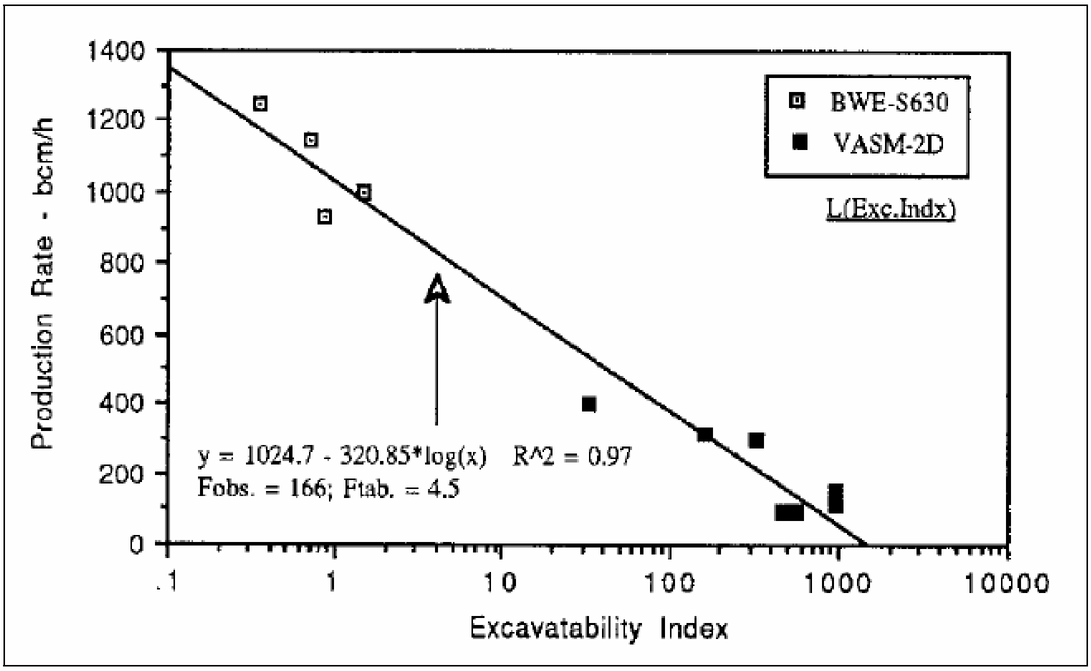


Figure 3.11: Graph showing relationship between production rate and the Excavatability Index (Kramadibrata, 1996)

3.3.4.10 Basarir and Karpuz's System

Basarir and Karpuz (2004) conducted field trials at surface coalmines in Turkey. With data, experiences and observations, he proposed a rippability assessment based on 4 parameters that are intact rock strength, seismic velocity, average discontinuity spacing and Schmidt hammer value. These parameters are then divided into five main classes with respect to their rippabilities as shown in Table 3.15 and 3.16. Research was done with D8 track dozer and the expected production by using another size of dozer performed by computer software (3DEC programme). In addition to that, Basarir and Karpuz (2004) also proposed correlation between specific energy and ripper production as shown in Figure 3.12. The specific energy is the amount of energy needed to remove 1 m^3 of rock and was based on the direct cutting test conducted in the laboratory.

Table 3.14: Rippability rating chart as proposed by Basarir and Karpuz (2004)

	Class				
Parameter	1	2	3	4	5
Seismic P Wave Velocity, m/s	0-800	800-1000	1000-2000	2000-2500	>2500
Grade	0-5	5-15	15-20	20-30	>30
Point Load Index, MPa	<0.1	0.1-0.5	0.5-1	1-2	>2
Uniaxial Compressive Strength, Mpa	<5	5-15	15-25	25-35	35
Grade	0-5	5-18	15-25	25-35	35
Average Discontinuity Spacing, m	<0.5	0.5-1	0-1.5	1.5-2.5	>2.5
Grade	0-3	3-10	10-14	14-20	20
Schmidt Hammer Hardness	<15	15-35	35-45	45-50	>50
Grade	0-2	2-7	7-10	10-15	15

Table 3.15: Rippability classification chart for D8 type dozer (Basarir and Karpuz, 2004)

Class	Description	Rating	Production for D8 dozer, m3/h	Penetration %
1	Very easy	<20	>1300	>90
2	Easy	20-55	900-1300	75-90
3	Moderate	55-70	400-900	65-74
4	Difficult	70-85	250-400	55-64
5	Very difficult	85-95	0-250	<55
6	Blast	95-100	0	0

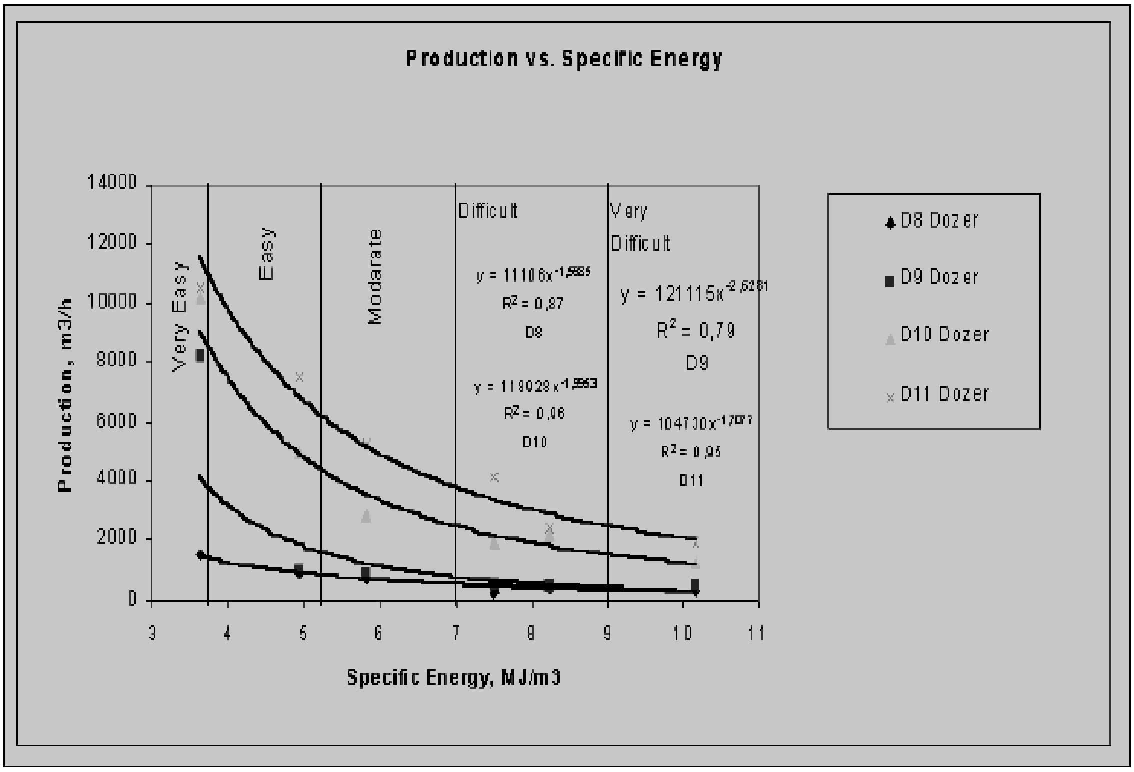


Figure 3.12: Correlation between ripper production and direct cutting specific energy (Basarir and Karpuz, 2004)

3.4 Summary

There are several methods used for assessing the surface excavation method, namely seismic velocity, graphical and grading methods. There is a need to develop a more reliable excavation assessment method to cater for technological growth in construction. A better excavation assessment would benefit people in construction as this would mean saving costs and time.

In Malaysian context, Public Works Department (JKR, 1998) does not have any specific guidelines in the indirect assessment on excavatability of weak rock. The weak rock are described and generalised as hard material. Hard material is the material that can be loosened with a tractor of 20 tonnes in weight and 200 horse power or track type hydraulic excavator (30 tonnes and minimum 165 flywheel horse power, equivalent to D7 ripper) and this includes grade III and IV rock which can be ripped and then excavated by large excavator or shovel. As no guideline is given in the indirect assessment by the JKR, this creates confusion among the contractors during the preliminary survey.

The excavation assessment can be grouped into three categories; seismic velocity method, graphical method and grading method. Generally, the assessments focused on type of excavation needed in the early years and later extended to machine type and production in recent years. The development of these assessments could be seen as early as 1958, where the Caterpillar Company used the seismic velocity as predictive tools in excavation assessment. Atkinson (1971) later classified P-wave velocity to the possibilities in excavating the material. Church (1981) has used seismic velocity in proposing type of excavation with degree of weathering for igneous, metamorphic and sedimentary rocks (Figure 3.4).

Although dozers' manufacturers i.e. Komatsu and Caterpillar Company, suggested the production and assessment for various types of rock with various sizes of dozers, they do not relate the weathering grade as factors to be considered as Church (1981) proposed. Many researchers questioned the usage of seismic velocity alone as a sole classifying criteria and the reliability of the assessment (Coon &

Merrit, 1970; Stacey, 1976; Kirsten, 1982; Smith, 1986; and Hadjigeorgiou & Scoble, 1988). Martin (1986) and MacGregor et al. (1993) reported that dozers manufacturer charts are over optimistic by predicting the rock could be easily ripped but in actual fact it was unrippable. Even though many excavatability assessments method are using seismic velocity as an indicator, many researchers claim that this method may lead to a misleading estimation of excavation (Basarir and Karpuz, 2004; Kramadibrata, 1996). The geological features which require different field procedures and the rock mass condition may be some factors that could lead to misinterpretation. Furthermore, the basic material characteristics that affect rippability is not represented in seismic velocity (Singh et al., 1987). As in general, seismic velocity cannot be determined to accuracy better than 20 percent or variance of 1000 m/s in apparently identical material (Kirsten, 1982).

In order to simplify the excavatability assessment into a simpler method, few researchers have introduced the graphical based method. The graphical method was introduced by Franklin et al. (1971) to simplify the excavation assessments so that the general public would be able to use the chart. The parameters used for the graphical methods are restricted to strength and discontinuities spacing only (Franklin et al., 1971; Bozdag, 1988 and Pettifer and Fookes, 1994). However, the excavatability of rock mass is also depending on other important factors such as joint continuity, gouge, joint set number and direction of discontinuities. The earlier assessment as proposed by Franklin et al. (1971) was then extended by Bozdag (1988) and Pettifer and Fookes (1994) by incorporating different sizes of tractors in their research.

Although the grading system tries to cover all aspects of parameters that influence the excavatability, several other factors such as moisture content, rock mass properties, topography, bedding thickness and infilled material should be incorporated for a better rock excavatability assessment. Generally, all grading assessments, except MacGregor et al. (1994), do not cover the specific rock type and being generalised by several type of geological parameters. It should be noted that each rock type displays significant differences in structure and mode of existence. Igneous rocks, for example, can have many occurrences of boulders, which may have similar parameters, but the size would differ. Normal digging could excavate small boulders easily, but a bigger size would need a different technique of excavation. These boulders may cause significant problems during excavation and normally need to be blasted to a more manageable size. MacGregor et al. (1994) found that weathering is a significant variable in the regression analysis for igneous rocks compared to other type of rocks. Even though uniaxial compressive strength (UCS) is the most popular parameter used by many researchers, the need to employ simple and practical in situ testing such as point load test and Schmidt hammer are vital. Practically, in situ testing, logistic and sampling problems may be avoided.

In sedimentary rocks, the occurrences of bedding, folding, foliation and multi layer of rock types are few distinctive differences compared to igneous rocks. Shale, which is interbedded with sandstone, would have a lower mass strength compared to the sandstone layers and from assessment; shale may be excavated by different excavation technique. However, due to its existence in the rock mass, which is interbedded between the dominancy of low or high strength of rock, the excavation method could be different from the assessment method. The varying scale of discontinuity that is always present in the sedimentary rock such as thickness of bedding, joints and foliation are not specified in most assessment systems but play a significant role in ease of excavation. The importance of integrating the homogeneity of rocks in the assessment would be important.

The mode of occurrence of the rock mass is another important factor in deciding the excavation method. The material properties might be assessed to be rippable but the topography of the rock mass would not allow such method to be effective. The ease of excavating a highly moisturized rock could be easier compared to dried ones, even though it is of the same lithologic type. Although it can be interpreted to be difficult to excavate by its strength parameter, the changes of moisture content may influence significantly to the excavatability of the weathered rock masses especially in wet weather.

CHAPTER 4

FIELD STUDIES AND TEST PROCEDURES

4.1 Introduction

In order to establish the engineering properties of weathered rock masses for surface excavation works, a study of geological properties is very important. A wide range of field and laboratory tests were employed which sought to measure rock material and mass properties to assess its excavatability. In addition to that, machine characteristics are also important to be determined before relationship between rock masses and machine performance can be established.

In terms of geological properties, studies were made into rock mass properties, which included study of the weathering profile and discontinuity characteristics. Weathering effect is crucial especially in tropical climate where it can change the various properties of the original material into different materials. Therefore, an understanding of the weathering effect on those materials is prerequisite before predicting the whole rock mass behaviour in terms of its excavatability. On the other hand, discontinuities can reduce or enhance the rock mass strength. Joints will normally reduce the rock mass strength by providing weakness planes in the rock mass whereas, accumulations of stronger material at joints surfaces such as iron pan and quartz will increase the rock material strength and resist the penetration of the ripper shank.

From the observation and field identification, extensive studies on weathering are analyzed by studying the profile, weathering grades and inhomogeneity of materials. Six sites have been selected for the study on weathering namely Bukit Indah, Mersing, Kempas, Desa Tebrau, Seri Alam and Ulu Tiram in Johor. Excavatibility by monitoring ripping machine performance was studied at all other sites except for Seri Alam and Ulu Tiram (which are granitic areas and were studied for their weathering profiles only). These sites were chosen for the study because excavation works were under progress and the actual performance of ripping could be measured. During the studies, these sites were being reduced down to the required platform level by using a ripping machine. Bukit Indah and Mersing areas are made up of sedimentary and meta-sedimentary rock masses. Sandstone and shale are inter-bedded with each other with different orientations and bedding sequences whereas Kempas and Desa Tebrau sites comprise of old alluvium (sandy silt).

Upon definition of these rock mass properties, they were further analysed to assess their influences on excavatability performance. This chapter seeks to review the methods used for the determination of rippability related to rock parameters together with factors affecting the test results.

4.2 Research Approach

The research is focussing on two issues: the geological properties of the rock mass and machine performance. The geological assessment is important to establish the ground conditions to be ripped, while the interaction with machine is carried out by measuring the production output by ripping tests. Assessments on the geological and geotechnical parameters of rock mass related to excavatability were carried out at four construction sites namely Bukit Indah, Mersing, Desa Tebrau and Kempas, Johor. The rock mass strength and other relevant engineering geology parameters were determined in order to assess excavatability. The method of assessment has been categorized into field survey of the accessible rock face exposures, weathering characteristics, in-situ testing, laboratory evaluation of the rock material and the discontinuities parameters. The purpose of the testing is to establish the material and mass properties of the rock that influence rippability. A series of new approaches in testing the weak rock were also adopted.

Field studies were carried out for geological data collection, mapping of discontinuities and assessment of rock mass conditions that include scan line surveys, hardness, strength, durability and weathering identification. In-situ testing is important, as it is relevant to the actual condition. In-situ tests that were performed on sites include seismic refraction surveys, monitored ripping tests, portable point load tests, and Schmidt hammer tests. Prior to the ripping test, discontinuities surveys were carried out. Data such as distance between discontinuities, orientation, infilling and aperture were recorded. Discontinuity measurements were carried out using scan line methods in accordance with the procedure recommended by ISRM (1981). The structural data were then analysed by using computer generated stereographic projections to determine the number of joint sets and their orientations. Degree of weathering for the rock masses was described using the modified classification scheme of Ibrahim Komoo (1995a).

Laboratory tests that were carried out to determine the physical properties of rock materials are Point Load Test, Uniaxial Compressive Strength (UCS), Brazilian indirect tensile test (ITS), density, penetration, petrographic analysis and slake durability. Laboratory work offers accuracy and more empirical results, thus act as a verification of what have been observed on site. Both field-testing on site and laboratory will be used to evaluate the rock mass properties.

To give an understanding of machine's cutting ability, a study on various rock types was performed. The interaction of the rock mass properties with the machine performance was evaluated by measuring the production rate, size of machine, width, depth of cut and the size of ripped blocks. Upon establishing the ripping performance, rock mass properties will be correlated with machine properties. A summary of the methods used in this research is summarized in the flow chart shown in Figure 4.1.

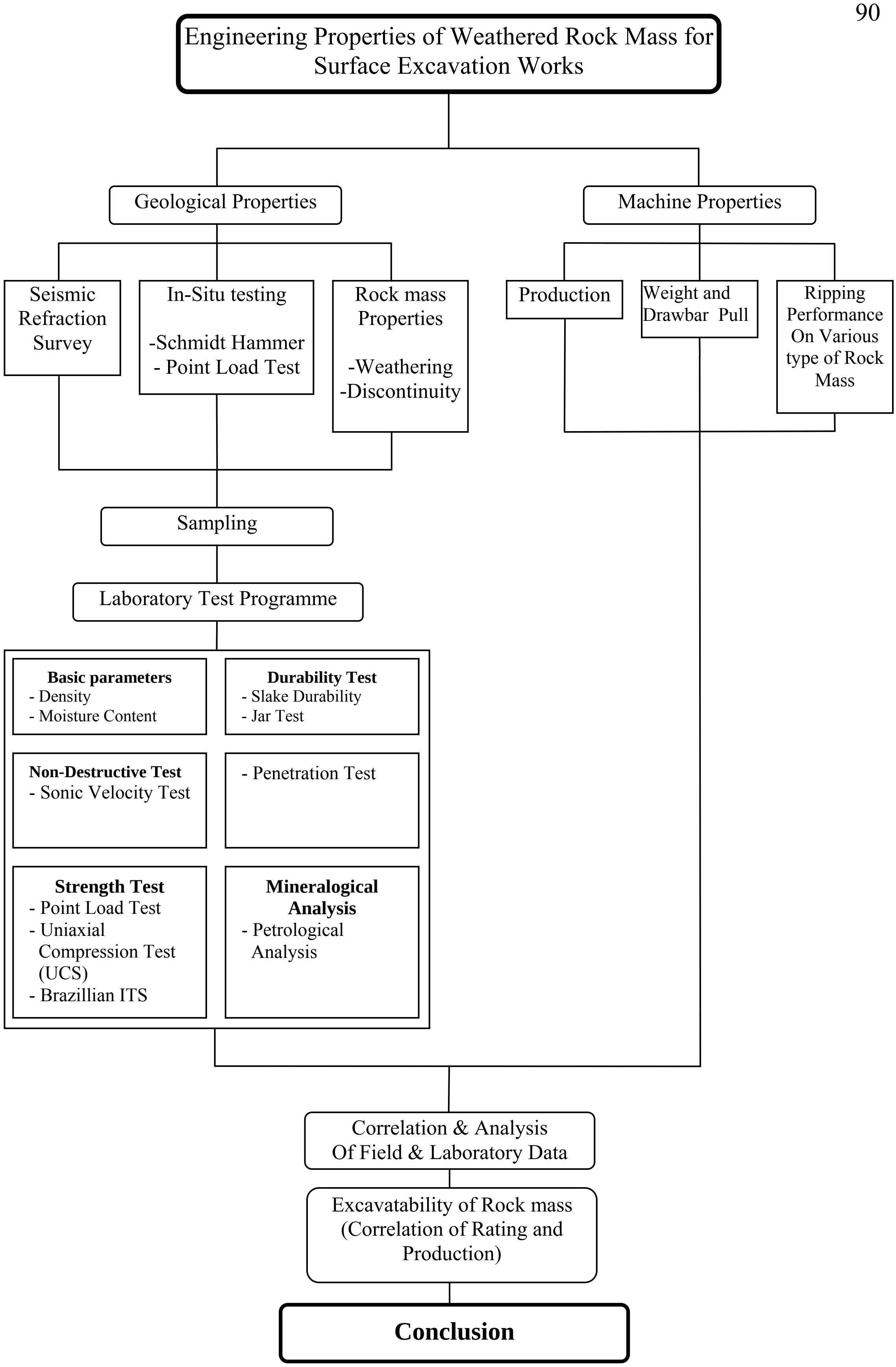


Figure 4.1: Research Methodology Flow Chart

4.3 Geological Properties

The geological properties studied involved the material and mass properties of the rock mass through fieldwork and laboratory survey and testing. The methods adopted for those procedures are listed as follow:

4.3.1 Fieldwork

In-situ tests which involved seismic velocity, portable point load testing and Schmidt hammer survey were conducted before the ripping works started. Discontinuity studies and weathering evaluation was also performed prior to the ripping works. Seismic refraction surveys were done at selected sites in order to assess the application of seismic velocity result to excavatability prediction. The seismograph used in the seismic refraction surveys is sensitive to excessive noise and vibration. In order to reduce this problem affecting the test result, surveys were performed during shift breaks, after shift hours and during weekends.

To provide appropriate sample material for the test programme, a range of rocks were collected from the ripping lines. Sample preparation involved either the production of 48 mm diameter core specimens (by using a portable coring machine) or blocks collected from the excavation sites. The purpose of in-situ testing is to evaluate whether excavatability assessment can be relied on simple and economical way. During field study, the following observation and testing were carried out:

a) Rock mass description
b) Geological structure and discontinuity survey
c) Weathering study and profiling
d) Site conditions: location and level of the ripped area; topography of the ripping area and weather conditions
e) The seismic refraction method were also used to evaluate the rock mass properties
f) In-situ testing that were carried out involved

i) Surface Hardness Survey

ii) Portable Point Load test

4.3.1.1 Rock Mass Description

The study began with the division of the rock mass into structural regions (units), in which certain features are uniformed and characteristics are similar. Major geological features such as bedding planes and joints were measured. The field mapping techniques were adopted from the proposal by the Geological Society of London Engineering Group Party (1977).

Rock type

Rock type or rock name is most significant in assessing rock as it is not only identifies the rock but it also provides an immediate picture of a likely engineering behaviour of the rock. The guideline is given by the Geological Society of London Engineering Group Working Party (1977) and the rock types at the studied sites are listed in Table 4.1.

Table 4.1: Rock type at the study sites

Site	Rock Type	Grain size	Remark
Bukit Indah	Sedimentary (Clastic)	-very fine to medium sandstone and - shale	Study on excavatability
Mersing	Meta-sedimentary (Clastic)	-very fine to medium sandstone and -shale	Study on excavatability
Desa Tebrau	Old Alluvium (sandy silt)	medium to coarse sandy silt	Study on excavatability
Kempas	Old Alluvium (sandy silt)	medium to coarse sandy silt	Study on excavatability
Masai	Granite	Medium to coarse grained	Study on weathering profile only
Ulu Tiram	Granite	Medium to coarse grained	Study on weathering profile only

Colour

Colour is one of the most obvious characteristics of a rock stratum and therefore to be one of most important criteria in rock description. Colour variation is a primary indication of weathering and therefore should be given due consideration. Yellow stained colour indicates the material has undergone slight weathering whereas darker colour such as brown shows intense weathering.

4.3.1.2 Discontinuity Characteristics

Discontinuities with the influence of frequency and orientation, within rock mass may assist and ease the excavation process in much stronger material. Discontinuity spacing measurements in orthogonal directions were made by using the scan line technique as proposed by Priest and Hudson, 1976. Scan line techniques are well known for measuring joint spacing. With this technique, a measuring tape was set up on the exposed faces of the rock mass normal to strike of the discontinuity sets. The spacing between adjacent joints is established by counting the number of joints intersecting a line of known length and expressed as mean spacing in metres. The ISRM Commission of Standardization of Laboratory and Field Test (1978) recommended a sampling length of greater than ten times the estimated spacing. In order to allow a detailed and accurate measurement, several yellow painted wood pegs were used every 0.2 m as markings.

The identification of any potentially unstable situations was carried out by using equal-area stereographical projections. In a typical field study in which structural data has been plotted on stereonet, a number of significant pole concentrations maybe present.

According to Priest and Hudson (1976) and ISRM (1981), the recommended length of a scan line has to be between 10 to 50 times the estimate mean value of discontinuity spacing. However the length of the scan lines was in the range of 10m to 40m, due to the rock exposures availability in the locations investigated. Figure 4.2 and 4.4 show the study of discontinuities at Bukit Indah site by using the scan line method.

The mean value of the discontinuity spacing was estimated by assuming that all the observations in a discontinuity class interval fall at the midpoint of it i.e. values between 0.06 and 0.07 were assumed to be 0.065. Thus;

$$MD=(F_1X_1+F_2X_2\ldots\ldots F_nX_n) / (F_1+F_2\ldots\ldots F_n) \qquad (4.1)$$

where MD is mean value of discontinuity spacing;
$F_1, F_2, \ldots\ldots F_n$ is number of observations; and
$X_1, X_2, \ldots\ldots X_n$ is the midpoint of discontinuity class interval.

Joint roughness is an important parameter in determining joint shear strength. A scheme of descriptive terms and a chart were suggested by the ISRM Commission of Standardization of Laboratory and Field Test (1978). The scheme divides surface roughness into three main groups: stepped, undulating and planar. Each group is further divided into rough, smooth and slickensided. Nature of filling and the aperture of the joints are described and recorded.

The persistence of discontinuities refers to its continuity. This is one of the most complex properties to be quantified since discontinuities frequently continue beyond the rock exposure. However, the exposed surface may practically sufficient to determine it. Mechanical behaviour and appearance of rock mass are dominated by the number of sets of discontinuities that may be intersecting one another. Thus, numbers of discontinuity sets was also recorded.

Parameters measured are listed below:

a) Type (faults, shear zones etc.)
b) Surface roughness (smooth, rough or very rough)
c) Frequency (number of joints per meter)
d) Discontinuity spacing (spacing between discontinuities)
e) Persistence of discontinuities
f) Nature of filling (clean, stained or filled)
g) Orientation (with respect to ripping direction)

A description on these parameters is discussed in Chapter 2.

a) Weathering study and profiling

The approach used to describe rock mass classification is in accordance with the approach suggested by BS5930:1999. Weathering description was carried out from the modified classification suggested by Ibrahim Komoo (1995b) as shown in Table 4.2. These classifications were chosen as they offer more detailed description and found suitable for the weathered rock masses in tropical areas (Zainab Mohamed, 2004). This field classification divides Grade IV and V into subclasses, i.e. ‘a’ and’ b’, which offers wider divisions as compared to ISRM, suggested method for classifying rock masses. The wider spectrum of material in grade IV and V need subdivision for narrowing the critical weathering zone. Degree of weathering plays an important role in determination of rippability and can be the first evaluation as to whether the material can be ripped or not.

Field identification of rock mass on weathering grade will be used as reference when testing the material properties in the laboratory. A more detailed description and classification on weathering are discussed in Chapter 6.

b) Lithology and Topography

At each case location, a description of the principal lithologies encountered was made. The key objectives of this were to identify any massive units, particularly sandstone or shale that cause difficulties in ripping. The fragmentation characteristics of a particular horizon will be noted as the nature of the fragmentation will reveal whether excavation is being carried out through joint assistance. Topography of the site will also be recorded as one of the major factors determining whether the area is accessible for a ripping machine or not.

Table 4.2: Weathering classification used to describe rock mass (modified from Ibrahim Komoo, 1995b)

DESCRIPTION	ZONE		MATERIAL				MASS			
			Colour	Texture	Slaking		Structure		Iron-rich layer	Strength (Schmidt hammer)
					In water	By hand	Condition	Changes		
Residual soil	VI		Completely changed (homogeny)	Destroyed	disintegrate	disintegrate	100% destroyed	Completely changed	None	None
Completely weathered	V	b	Completely changed (homogeny or	Half remains unchanged			<25% remains		Normally exist	
		a								
Highly weathered	IV	b	Completely discoloured	unchanged	Becomes flakes or small pieces	Becomes flakes or small pieces	>50-75% remains	Iron-rich filling in discontinuity	May exist	
		a								Less than 25
Moderately weathered	III		Slightly discoloured		Remains as Mass	Edges can be broken	100% intact		none	
Slightly weathered	II		No changes			Edges unbroken		Discolorations along discontinuity		Exceeds 25
Unweathered	I							No changes		

c) Seismic Surface Refraction Survey

A portable twenty-four-channel seismograph was used for the seismic surveys. A sledgehammer fitted with a contact switch is used as the wave trigger source. The wave is produced by striking an aluminium plate placed firmly on the ground, which then detects the frequency using a set of 24 geophones. Each geophone had a 20Hz natural frequency and was separated at 3 m intervals. The signal (which arrived at the geophone) was then stored digitally using an ABEM Terraloc MK6 24 channels seismograph. For each line, at least 7 shots were recorded, and to increase the signal to noise ratio, at least 5 records were vertically stacked. Two lines of seismic survey were carried out along the proposed area. The total spread length was 69 meters. Figure 4.3 shows a survey line was checked prior to the seismic test.

Overall, the quality of the seismic data was good, thus making the processing and interpretation relatively easy and fast. The seismic data were processed as shown in the flowchart given in Figure 4.4. The data were first filtered all the frequencies above 200Hz, using TERRALOC® MK6 v2.21a software. Then the first arrival from the filtered data was picked using FIRSTPIX™ v4.21 or PICKER™ software. To interpret and produce model for the data, OPTIM™ v2.58 software was used. The time of detection is then analysed and processed using the software Seis Opt Picker V 1.5/Seis Opt@2D V 2.8. Different ranges of velocity represent different types of material. The results are then used to determine the rippability of the material and the volume of the different materials based on depth information. Figure 4.4 shows the flowchart on how the field data were processed.

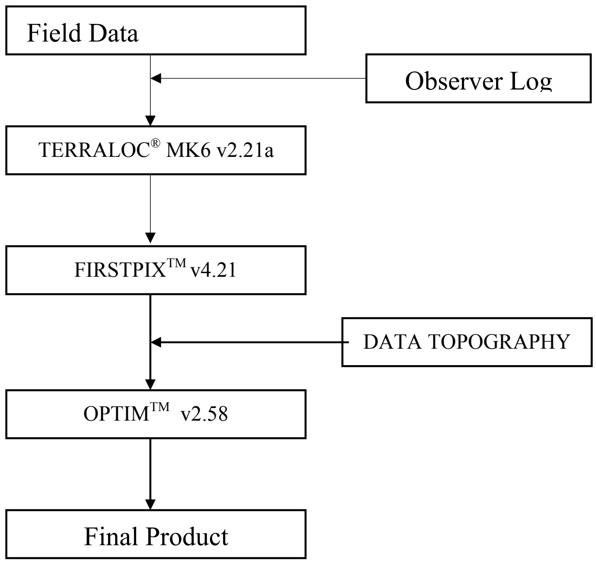


Figure 4.2: Flowchart for processing and interpretation of the seismic data.

d) In-situ Physical Testing

As one of the most common parameters used by researchers in determining the classification of rock material, simple qualitative tests on site were employed by using finger, hand and geological hammer to describe the samples.

Surface Hardness Surveys

To measure surface hardness, Schmidt hammer testing was adopted. During field studies a type L hammer was chosen due to its sensitivity to weak rocks. The hammer consists basically of a spring-loaded piston, which is projected under controlled conditions against an anvil. The domes ground end of this anvil is held in contact with the surface of the rock tested. The mechanism of the hammer is such that when operated in a given position, the thrust applied to the anvil at the time the piston is released, is constant. After striking the anvil, the piston rebounds. A purely arbitrary scale on the side of the hammer indicates the rebound distance. The harder the rock the greater the rebound energy imparted to the piston and the greater the rebound number the hammer will indicate. The Schmidt hammer number ranges 10 to 60 in practice, the lowest numbers apply to weak rocks with UCS of less than 20

MPa and the highest values indicate very strong rock with UCS more than 150 MPa. The hammer is designed for use in horizontal impact directions. When utilized in other directions, readings should be calibrated according to table provided by manufacturer (see Appendix E).

The equipment is light and easy to use in the field but care must be exercised in selecting the places at which the measurement is taken. It may be necessary to clean the surface covered with different material. It has been estimated from experience that a minimum number of 12 tests should be performed to obtain reasonable results. There are a number of Schmidt hammer reading techniques, one of which is the repeated impact technique (Muftuoglu, 1983) in which 5 continuous readings are taken on the same spot and the highest reading is accepted as the index value of a given rock. This technique as experienced by the author can provide an artificially high value of estimated UCS due to hardening of the surface. The author advocates the use of the single point technique. With this technique, as recommended by Barton et al. (1974), 10 readings are taken on a representative sample or square meter and the five lowest readings are discarded, then the mean value of the remaining five readings is accepted as the Schmidt hammer index value. Figure 4.5 shows Schmidt hammer survey at the site on grade IVa sandstone at Bukit Indah site.

Portable Point Load Test

The point load test is an indirect measure of tensile strength and involves compressing to failure a rock specimen between two points. The technique is evaluating resistance load of the sample strength at which a compression load between two cone bits loads it. Unlike the Brazillian and Uniaxial Compression Strength (UCS) which needs the samples in cylindrical shape, the point load can be applied to either rock core or irregular lumps through points of standard dimensions (Figure 4.6). Therefore, the test is appropriate for samples with weathered rock characteristic (Zainab Mohamed, 2004b).

During the test, the sample is placed between the adjustable loading frame, and the lower platen is raised by using a hydraulic ram actuated by a hand-operated jack with a quick release mechanism included. The diameter of the samples is recorded by taking the readings from a graduated scale with the pointer attached to the lower platen. The point load points 60 degree hardened steel cones with a tip radius of 5mm. After failure of the sample, the failure load on the sample is taken from reading of a gauge selected from three different ranges. The reading of the gauge is then converted to the point load strength index (Is).

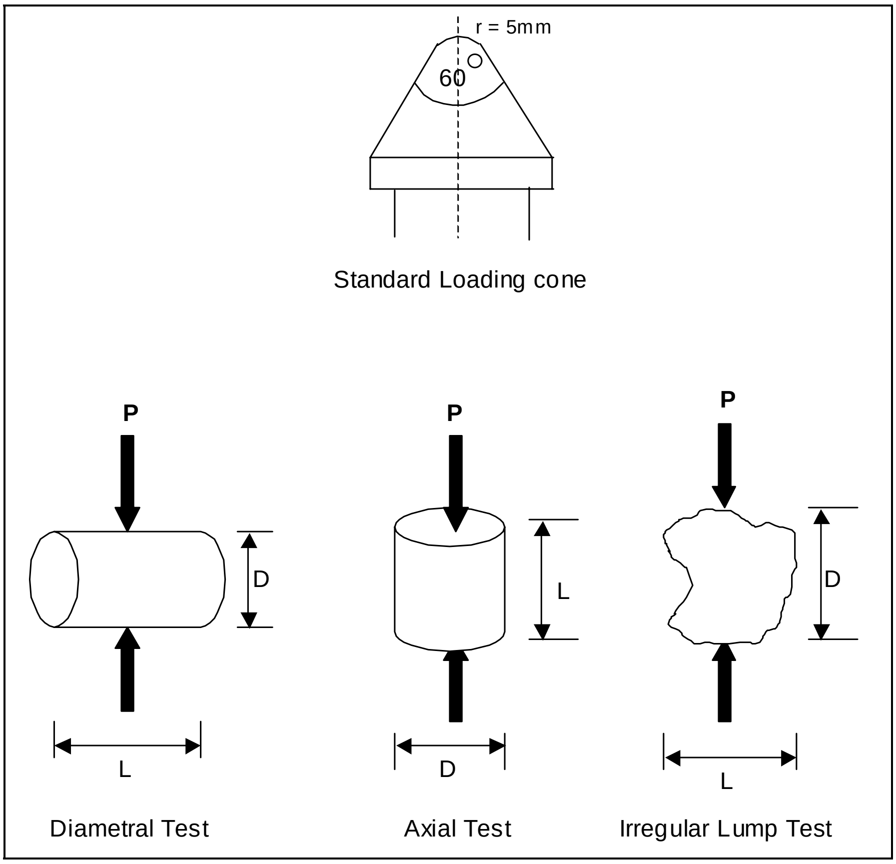


Figure 4.3: Types of Point Load Tests (Franklin, 1970)

Testing procedures as suggested by ISRM (1985) were used. Samples were taken from the site and tested in in-situ conditions. Figure 4.7 shows the portable point load tester that was used at the sites.

The popularity of the point load index must be largely credited to Franklin et al. (1971) who devised a portable testing machine and introduced the point load strength index (Is) as part of a rock classification system.

$$I_{s50} = \frac{P}{D^2} \quad (4.2)$$

where P is the point load at failure; and

D is the diametrally tested core of 50 mm diameter.

Broch and Franklin (1972) provided an alternative solution by producing a size correction chart which enables the user to convert index values for a given core diameter to his equivalent value. This size correction chart was later modified by (Hassani et al., 1980) and a mathematical equation representing the correction curves was provided for direct correction computation. The *Is* value has been transformed to a 50mm reference diameter, the strength that being known as the Is_{50} index which is expressed in MN/m^2 (MPa) as below.

Uncorrected strength,

$$I_s = \frac{P}{D^2} \quad (4.3)$$

Corrected strength, $$I_{s50} = F\frac{P}{D^2} \quad (4.4)$$

where,

$$F = \frac{(D)^{0.45}}{50} \quad (4.5)$$

For shapes other than cores an 'equivalent core diameter', *De*, is calculated such that the minimum cross-sectional area is

$$A = WD = \frac{\pi De^2}{4} \quad (4.6)$$

or

$$De^2 = \frac{4WD}{\pi} \quad (4.7)$$

The strength computation can be performed using De instead of D, that is

$$I_{s50} = F\frac{P}{De^2} \quad (4.8)$$

and,

$$F = \frac{(D)^{0.45}}{50} = \frac{(De^2)^{0.225}}{2500} \qquad (4.9)$$

For other core sizes the $\frac{P}{D^2}$ is retained and can be multiplied by a size correction factor *F*.

4.3.2 Laboratory Work

In order to analyse the rock mass character and its behaviour, a comprehensive laboratory test programme has been performed. For most tests, the moisture content of the samples was maintained by packing the samples in the plastic bags and performing the tests within 24 hours. This is to simulate the actual condition that has been experienced by the ripping works on site. Relevant samples representing the in-situ conditions were collected and brought back to the laboratory for further examinations of their material properties. Detailed characterization of rocks (strength and other physical properties) was studied. It was found that the related test for excavatability (ripping) includes the properties of strength, hardness, intrinsic and index rock parameters and texture. Some were measured through standard rock mechanics tests, which are recognized by the International Society of Rock Mechanics (ISRM, 1981), while others were measured by modified testing equipment, which might suit testing and preparation of weak rocks samples.

Testing involved are listed below:

a) Non-Destructive Test - Portable Ultrasonic Non-Destructive Digital Indicating Tester (PUNDIT)
b) Basic parameters - Density, moisture content
c) Strength Test - Point load test (by using a universal testing machine (UTM) for greater sensitivity), uniaxial compressive strength (UCS), Brazilian tensile strength
d) Durability Test - Slake durability, Jar test

e) Penetration Test - by a 10 mm probe and a point load probe

f) Mineralogical Analysis - Petrographic analysis will also be performed on suitable samples to determine the lithologic type and to study the extent of mineral changes that have taken place.

Determining the strength index of a rock material has always been a problem and standard test procedures may not fit well to assess material strength. Laboratory study may not always be possible to be carried out especially in weak or weathered rock. ISRM (1981) defined weak rock as 5.0 to 25 MPa whereas Geological Society of London adopted 1.25 to 5.0 MPa. The difference in interpretation shows that there is no clear understanding of these weak rocks. Methods of testing of weak rock depend largely on the sampling ability of these weak rocks (Zainab Mohamed et. al., 2004).

4.3.2.1 Non-Destructive Test: Sonic Measurement on Rock Material

Sonic measurements were taken on saw cut and machined rock blocks by using standard Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) equipment (Figure 4.8). The Pundit consists of a main unit that contains all the circuit boards, pulse generator and digital display unit. The whole assembly is mounted inside a P.V.C. covered aluminium and steel case. The apparatus is normally provided with two P-wave piezo-electric transducers with a frequency of 50 kHz. The shape of the specimen will not influence pulse velocity provided its least lateral dimension (i.e. its dimension measured at right angles to the pulse path) is not less than the wavelength of the pulse vibrations. For pulses of 50 kHz frequencies, this corresponds to a least lateral dimension of about 80mm. The transducers require good coupling, this may be provided by silicon or pump grease spread on the rock surface. Time measurements with this apparatus can be done in 0.5 to 999 microseconds range with units of either 0.5 or 1 microsecond. The accuracy is rated ± 0.5 microseconds and for calibration purposes the manufacturer provides a metal bar with a known transmitting time.

The velocities were obtained from the pulse transmitting time displayed on the Pundit and the distance between transmitter and receiver measured to the nearest

0.02mm. These measurements were taken in three orthogonal directions being normal and parallel to bedding. From this Velocity Ratio Index (VRI) is computed in the manner as given below:

$$VRI = \frac{Vi}{Va} \qquad (4.10)$$

where,

Vi = In-situ compressional wave velocity; and

Va = Average value of sonic measurements

Testing Procedures

The laboratory Pundit Test was carried out using the standard PUNDIT equipment. Before the testing, calibration is done by using the cylindrical steel core provided to set the wave gauge reading to zero. At both ends of the sample were supplied with grease or ultrasonic solutions to provide good coupling. Aluminium foils were placed in between the transducers and the end surfaces of the sample. The transducer and receiver are coupled neatly to the sample and the wave is applied through the sample. The wave velocity reading is taken when the reading is started to stabilize.

Figure 4.4: Measuring discontinuities in Grade IVa sandstone which could not be ripped by CAT D9, Bukit Indah, Johor

Figure 4.5 : Inspecting the seismic line before performing the test (Location: Desa Tebrau)

Figure 4.6: Performing Schmidt Hammer Test at Layer 2 (sandstone grade IVa), B7 Bukit Indah, Johor

Figure 4. 7: Testing on Portable Point Load at the site

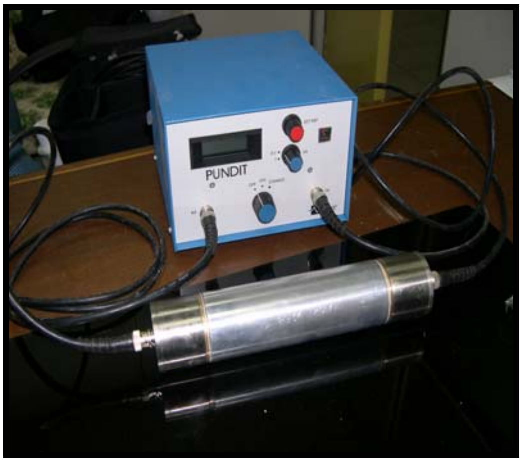


Figure 4.8: PUNDIT Test Equipment

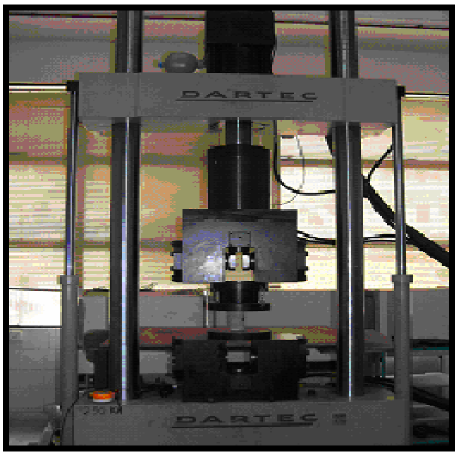


Figure 4.9: Universal Testing Machine (UTM DARTEC Model 2187)

4.3.2.2 Material Basic Properties: Density and Moisture Content

The tests for density and moisture content were carried out in accordance with the International Society of Rock Mechanics (ISRM) Standard Procedures (ISRM, 1981). Bell (1978) reported that the increase of density would also increase the strength of material. Interlocking of rock forming minerals that occur in any type of rock has the direct influence to the density of rock material. The standard method for calculating the density of a solid is to divide its mass into its volume, in this respect a rock sample is no different, except that some are porous and density will vary according to moisture content. To overcome this possible source of error, the samples were dried in an oven at 105^0C for 24 hours and placed in desiccators to cool. The volume of a rock sample was determined by measuring the amount of liquid, which the specimen displaces when placed in container of known volume. To prevent the water to get into the pores, the sample is waxed before soaking it in the water. By measuring their weight on an electronic balance to 0.1 mg accuracy, their dry density is calculated by dividing the weight recorded by the volume of the sample.

High water content will decrease the strength of material (Moon, 1993). This is due to the fact that:

i) water would soften the bonds or interact with mineral surfaces and alter their surface properties
ii) the increase of pore water pressure will cause instability of weakness plane
iii) water can cause the decrease of frictional shearing resistance and change the gouge constituents

4.3.2.3 Strength Test on Rock Material

Kate and Gokhale (1998) reported that material strength is an important parameter to evaluate the behaviour of rock material. Even in engineering design, the strength factor has always become the most important factor to be assessed may it be compressive or tensile strength. From literature, the strength parameter has also been addressed by all the researchers. In this study, the strength parameter was measured through UCS, Indirect tensile (Brazilian) and point load test by using Universal Testing Machine (UTM). The UTM machine used in this test was a DARTEC Universal Testing Machine model 2187 as shown in Figure 4.9.

Uniaxial Compression Strength Test

Uniaxial Compression Strength is the most widely used measure of strength with the method clearly standardized (ISRM 1981). This testing is probably the most universally applied rock test, but the applicability of this testing in weak rock can be very difficult. The weak rock can easily slake during the coring process, as samples are sensitive to water. In addition, this test does require a significant amount of rock in order to produce sufficient cores. This can lead to a prohibitively long preparation time and high cost. Standard Uniaxial Compression Stress Test is done by applying uniaxial compression load on cylindrical shaped sample as suggested by ISRM (1981).

This is the most common method in measuring strength, deformation and fracture characteristics of rock. The strength of the rock material is identified by the stress value at failure and given by the relationship (ISRM, 1981):

$$\sigma_c = Fc / A \tag{4.11}$$

where Fc is the failure load; and
A is the cross section area.

In order to normalize the effect of the test conditions on the test results and to reduce frictional and specimen geometry effects to a minimum, standards for the test procedure are recommended by International Society for Rock Mechanics (1981). Specimens with a height to diameter ratio of 2.5 to 3 and with diameter preferably of not less than NX core size (54 mm) are recommended. During these experimental studies, this ratio was rather difficult to establish due to the weak nature of the weathered rocks and the requirement of a substantial number of samples, either core or block for the comprehensive test programme. Especially for highly weathered (grade IV) samples, the requirements by ISRM (1981) are difficult to achieve, as samples slake easily and sensitive to water.

Therefore, where possible, a height to diameter ratio of 2 was employed for all tests which were conducted on mainly 54 mm and 38 mm diameter core samples with an aim to increase the number of core samples. Figure 4.14 shows a sample that was tested by the UCS.

The equation 4.11 is only suitable for samples that have the length (*l*) over diameter (Ø) ratio of 2 only. For samples which *l*/ Ø are not 2, Jeremic (1987) suggested the UCS value is to be calculated by

$$\sigma_c = 8\ \sigma_p \ /\ (\ 7 + 2(\text{Ø}/l)) \qquad (4.12)$$

where σ_c is the UCS value when *l*/ Ø = 2; and

σ_p is the UCS value when *l*/ Ø 1.

Testing Procedures

The testing procedures were suggested by the ISRM (1981). The loading rate used was 0.3 kN/s for lower grade samples and 0.6 kN/s for higher-grade samples. The loading rate was recommended by Zainab Mohamed (2004) in her research on weathered material. However, these rates were adjusted to suit the different materials. The changes in physical characteristics of the weathered rock mass have caused inhomogeneity of materials and the ratio of size *l*/Ø could not be held constant.

Only three types of rock material samples could be shaped into the cylindrical that are mostly, sandstones, some shale, and a few old alluvium samples. Before testing, the top and bottom surface of the samples will be grinded to make a smooth and even surface for the loading. The following is a description of the test procedure:

a) Sample parameters were inserted into existing data formats using computer software.

b) Cylindrical sample are placed on the testing platen. Both ends of the sample were ensured to be parallel to the loading plate.
c) The loading plate was lowered down slowly until it was able to hold the sample in place. This process can be controlled by ensuring the loading rate displayed on the monitor showing a value of load that does not exceed 0.05 kN. Then, both loading and displacement transducers are set to zero.
d) The sample and both of the testing plates must be in the straight upright position.
e) Loading rate was applied to the sample until it cracked.
f) Loading profiles and displacements were recorded.
g) Failure mode of sample was noted.

This test was carried out on stronger samples, which can be cut into the cylindrical shape. The weak nature of the sedimentary rock mass apart from weathering has caused the quantity of samples used for this test to be limited.

Indirect Tensile (Brazillian) Test

There are many difficulties with performing a direct uniaxial tensile test on rock and this has led to a number of indirect methods being proposed. The most common of these, the Brazilian test, involves loading a rock cylinder diametrically between two platens. The diametric loading of a small rock disc is performed by a Universal Testing Machine (UTM), which complies with the ISRM (1981) requirements for the indirect testing of tensile strength. The test method consists of loading the disc until failure occurs along its diametric axis. The disc is prepared from 48mm diameter core samples with a thickness to diameter ratio of 1:2.

In order to ensure a uniaxial failure and hence the validity of the test, the failure of the disc should initiate at the centre of the specimen. Due to the induction of high shear stresses at the point of contact, it is recommended that this test is only done on specimens with a high shear to tensile stress ratio (Aleman, 1982). Figure 4.10 shows the design of the Brazillian apparatus and Figure 4.15 shows a sample tested using the Brazillian Test apparatus.

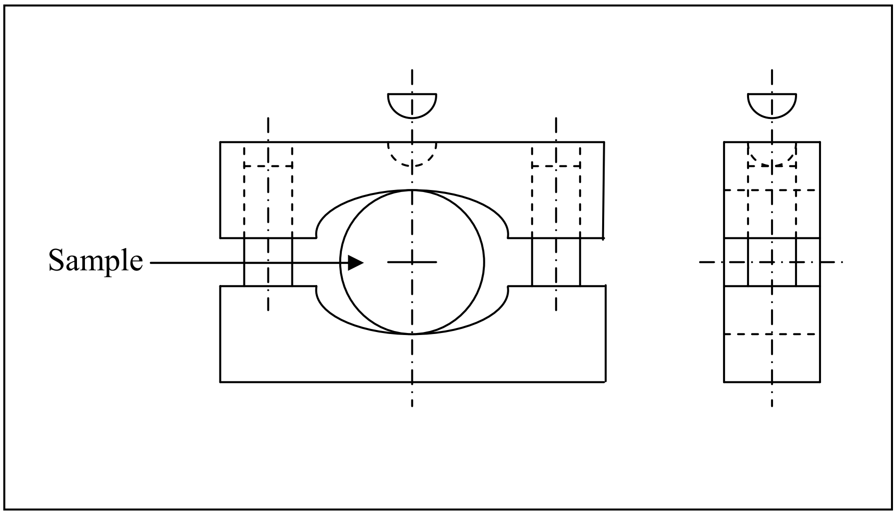


Figure 4.10: Apparatus for Brazillian Indirect Tensile Test (source: ISRM, 1981)

The measurement of the tensile strength by the Brazilian method gives reproducible results. Because of the smaller size of specimen required for the test, a smaller initial sample is required. However the necessity for machining and grinding make the preparation time inconvenient. The tensile strength of the specimen (σ_t), has been calculated using the following formula:

$$\sigma_t = \frac{0.636P}{Dt} \qquad (4.13)$$

Where P is the load at failure

D is the diameter of the test specimen (mm)

and t is the thickness of the test specimen (mm).

Testing Procedures

The testing procedures employed were as follows:

- Samples parameters were formatted using the computer software.
- Sample was placed vertically in the clamp that is fixed on the testing plate.
- The loading clamp is lowered down on to the sample slowly until it touches the loading pin on the clamp. Loading and displacement transducer are set to zero.
- Loading is applied on to the sample until it cracks
- Data profiles and displacements are recorded.
- Failure mode of the sample is noted.

Point Load Test (by Universal Testing Machine)

Description on the test has been discussed in Chapter 4,3 and 6. In the laboratory, point load measurement was made by Universal Testing Machine.

Testing Procedures

Testing procedure was carried out according to standard suggested by ISRM (1985). Universal Testing Machine (UTM) is used to perform this test. It is modified by mounting two point load bits or loading cones on to its loading platens. Loading rates were as used in previous UCS tests.

To enable all groups of samples to be tested, trapezium-shaped samples are used. Cutting was done carefully so that the samples do not break before it was tested. Width of sample does not exceed the length to ensure the failure surface is parallel and consistent. However, sizes were variable. The lamination structure of the samples was also recorded during sample preparation so that the anisotropy index for the sedimentary rock mass was determined.

Testing Procedures are as follows:

a) Width and thickness of sample was noted.
b) The sample was placed symmetrically in between two ends of the loading cones.
c) A load that did not exceed 0.01 kN was applied so that both ends of the cone can stably hold the sample.
d) Ensure that the load applied does not cause cracking to the sample.
e) The loading and displacement transducer were set to zero to start the test.
f) The loading was applied on to the sample using a loading rate of 0.03 for lower weathering grade rocks and 0.06 for higher weathering grade rocks. Load was applied until the sample failed.
g) Loading profiles and displacements were recorded.

4.3.2.4 Durability test

The resistance of a rock to short-term weathering is described as durability of the material. Thus, durability is an important engineering parameter, particularly to weathered rocks. This non-durable behaviour of these rocks is responsible for loss of strength especially when influenced by water. Two approaches were used in this study: slake durability and the jar test. The purpose of using these two different approaches was because the slake durability may not be designed to determine the durability of very weak rocks. Thus, testing by immersing the samples in water was used (jar test) for samples of a weak nature.

Slake Durability Test

The slake durability test was originally developed by Franklin and Chandra (1972), recommended by the International Society for Rock Mechanics (ISRM, 1981) and standardized by the American Society for Testing and Materials (ASTM, 1990). It measures the percentage dry weight of material retained in a steel mesh drum after rotation in a trough of water. Gamble (1971) encouraged the adoption of a second cycle after drying. The slake test was originally developed to provide an indication of material behaviour during the stresses of alternate wetting and drying, which to some degree, simulates the effects of weathering. Gokceoglu et al. (2000) used slake durability to estimate rock strength and found that slake durability can be used to determine the strength of weak rock.

The slake test was adopted because it has the advantages that it is quantitative and may be repeated as often as it is practical for several cycles. In addition, the test may be used to assess the degree and rate of weathering. However, this test has the disadvantage if fast results are expected, because it may take 2 days if 2 cycles are measured as drying of samples in an oven may take a long time. During the first wet-dry cycle, loose material and any easily slaked material will be removed from the sample. Consequently, the first cycle is a measure of the 'state' of weathering or to what extent the sample has deteriorated. For example, if sample looses 90 percent of the original weight during the first cycle, it can be interpreted that the sample is towards soil, whereas if sample only loses 5 percent of the original weight, the sample is towards rock.

Testing Procedure

In using this method, 10-rock lumps were chosen with a mass 40-60 g to give a total sample mass of 450-550 g. The maximum grain size did not exceed 3mm. The lumps are roughly spherical in shape and rounded corners during preparation. The lump is placed in a clean drum and is dried to constant mass at a temperature of 105^{o}C and requires 2 to 6 hours in an oven. The mass A of the drum plus sample is recorded. The sample is then tested after cooling.

The lid was replaced, the drum mounted in the trough and coupled to the motor. The trough was filled with slaking fluid, usually tap water at 20^{o}C, to a level 10mm below the drum axis, and the drum rotated for 200 revolutions during a period of 10 minutes to an accuracy of 0.5 minutes. The drum was removed from the trough, the lid removed from the drum, and the drum plus retained portion of the sample dried to a constant mass at 105^{o}C. The mass B of the drum plus retained portion of the sample is recorded after cooling. The steps were repeated and the mass C of the drum plus retained portion of the sample was recorded. The drum is brushed clean and its mass (D) was recorded. The slake durability index (second cycle) was calculated as the percentage ratio of final to initial dry sample masses as follows:

$$\text{Slake durability index, } I_{d2} = \frac{C-D}{A-D} x100 \qquad (4.14)$$

The report included the following information for each sample tested:

i. The slake durability index (second cycle) to the nearest 0.1 percent
ii. The nature and temperature of the slaking fluid: usually tap water at $20^{o}C$ was used.
iii. The appearance of material passing through the drum.

The second cycle slake durability index, calculated as in the paragraph above with tap water at $20^{o}C$, and was proposed for use in rock classification. However, samples with second cycle indexes from 0 to 10 percent could be further characterized by their first cycle slake durability indexes as follows:

$$\text{Slake durability index, } I_{d1} = \frac{B-D}{A-D} x100 \qquad (4.15)$$

When more than one cycle of slaking was employed, the weakening of the inter-granular bonds becomes easier, and the material was more easily removed from the original sample and this provided a better indication of durability. Indexes taken after three or more cycles of slaking and drying may be useful when evaluating rocks of higher durability. There are some researches used until the fifth cycle of slaking to characterise the strong rock material (Santi, 1995; Ulusay et al., 1995). However, two cycles of slaking was found adequate to characterize these weathered rocks. Figure 4.16 shows Slake Durability testing apparatus while Figure 4.17 and 4.18 shows the samples tested.

Jar Test

Jar test is a simple test developed to determine the reaction of rock mass to water during a certain period of time. It indicates the porosity, grain interactions and density of material. This should enable the classifying of the rock mass to be done based on the slaking index. Wood & Deo (1975) suggested the test should be completed at both 30 minutes and 24 hours by comparing the test results with the slaking index. Santi (1995) proposed to use a 30-minute period to classify the index of the material. However, these procedures are found to be less effective in very weak rock. Thus, a modification of this test was carried out by observing the samples at 4 time intervals: 10, 15, 30 and 60 minutes.

Each class of rock mass has a different reaction to water or moisture. This test enables researchers to observe and document the behaviour of these rock masses when it is immersed into water. As stated in previous assessments, the strength of rock mass is also affected by presence of moisture in the rock mass. The rock mass has variable grade of porosity and this is different between sandstone and shale. Both of these types of rock mass give certain effects when immerse in water and sandstone may decompose faster than shale as it has a larger amount of pores that can contain water. But still, shale may lose more strength than sandstone when immersed in water because of its soft and fine particles that can break down in water. After the jar test, the samples were tested using the Point load test machine to correlate the effect of moisture content to the material strength.

The assessments of behaviour and reactions of rock mass to water is very essential in determining the effects of weathering to the rock mass thus, estimates the failure mode of the rock mass. Both of these materials are tested using the same techniques as a comparison. Previous assessments found that rock mass samples mainly sandstone and shale has two modes of behavior when in contact with water. These modes are limited to the degrading of rock mass caused by weathering process before forming residual soil. As stated, shale gives different reactions to water apart from sandstone. Shale usually turns into flakes and sandstone would break into smaller pieces.

Santi (1998a,b) classified that the behavior of shale into six slaking indices. These indices were also used in a recent study as used by Zainab Mohamed (2004). However, her assessments are mainly concentrated on the reactions and behaviour of materials to water after 30 minutes. The author's experience with the jar test classified the sandstone and shale materials into six slaking indices and the samples reaction was observed for 10, 15, 30 and 60 minutes.

The reaction of the rock matter was inevitable after immersing the sample in the jar with water. The slaking index or changes in the sample also depend on the duration of the immersion time. The sample that was tested was irregular lump samples. By the observation of the changes caused by the immersing process the rock can be classified and the description for shale and sandstone are respectively shown in Figure 4.11 and Figure 4.12.

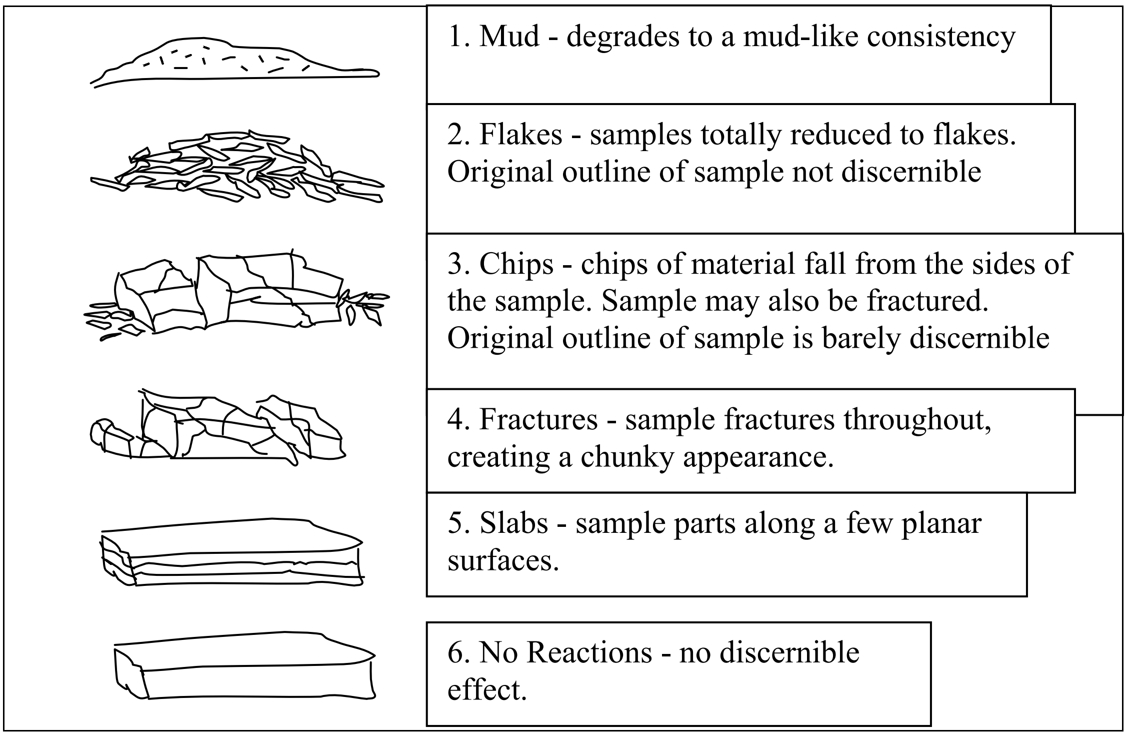


Figure 4.11: Index Classification and Slake Jar Test for shale (Santi, 1998a,b)

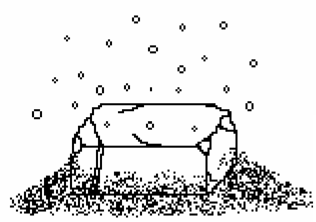
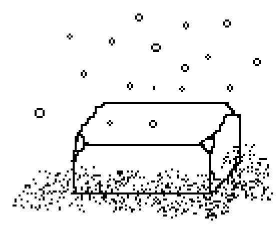
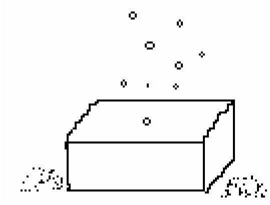
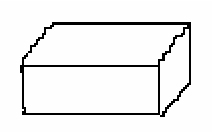
Slaking Index		Material condition
1		Sample completely deteriorated, water becomes fully diluted and very cloudy.
2		Sample extremely foamy, water becomes very cloudy
3		Sample extremely foamy, water becomes cloudy
4		Sample moderately foamy, water becomes cloudy
5		Sample slightly foamy, water becomes a bit cloudy.
6		Sample is unchanged, water unchanged.

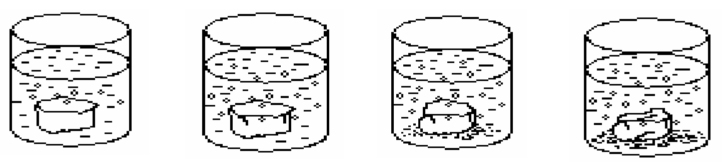
Figure 4.12: Slaking Index for sandstone (modified from Zainab Mohamed, 2004)

Testing Procedures

The testing procedures are as follows:

i. In this test, four samples were needed for each type of rock mass. Each sample is then trimmed to a suitable size (about 40 mm).
ii. Tap water was filled into 4 separate jars.
iii. The samples were then immersed into water for a period of 10, 15, 30 and 60 minutes (Figure 4.13).
iv. After the end of each period, the sample's behaviour was observed and recorded.
v. A slaking index was given to each sample for the stated period by referring to the table of slaking indices.

Sandstone and shale have different orders of slaking index. These differences are caused by the variable amount of pores and particles in each grade of rock mass. The samples that have been tested are irregular lump samples. Through observation of the changes caused by the immersing process, the rock masses were then classified according to the slaking index for shale and sandstone.



10 minute 15 minute 30 minute 60 minute

Figure 4.13: Jar slaking test were carried out (Sample B6L1)

Figure 4.14: Sample tested by UCS

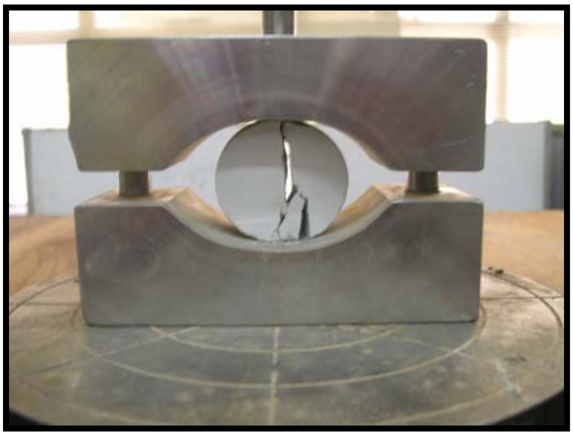


Figure 4.15: A sample tested for Indirect Tensile (Brazillian) Test

Figure 4.16: Apparatus for slake durability testing

Figure 4.17: Samples prepared for slake durability testing

Figure 4.18: Samples after being tested by the slake durability Testing

4.3.2.5 Penetration Test

Although, the mechanism of ripping involves penetration of the ripper tine in the early stages of ripping, none of the previous researchers treat this parameter on its own. Preliminary work on penetration testing was carried out by Zainab Mohamed (2004) and is further developed in this research specifically for ripping assessment. Penetration of rock is a very crucial stage during ripping and could be the determining factor whether the material can be ripped or not. Thus, a simple test by confining the rock material to simulate the actual condition on site has been developed. Tests on different moisture contents were also carried out by soaking the samples in water for 15 minutes.

This test was conducted on weathered materials as an attempt to supplement and compare with the basic tests. It is well known that sample preparation on weathered rock material sometimes creates problems if we apply standard rock mechanics testing procedures. This method is used as an indicator on the penetration behaviour of the rock material. As ripping works also involve a penetration element before the ripping process, this simple test was carried out to find if there is any relation with machine productivity.

The objective of the test is, to evaluate the strength required to penetrate the sample with a 10mm diameter of cylindrical shaped probe (Figure 4.19) until the sample fails and to compare the results with other basic test results. The second approach was by using a point load bit (Figure 4.20) and penetrates it into the samples until it fails.

So far, the confined penetration test in the laboratory has never being addressed before in rippability assessments. Therefore, this research has provided a laboratory test to define decreasing strength for weathered rock material. When the weathering degree of the samples is increased, we expect that penetration resistance to decrease, so the ability to penetrate the material is increased. The material is confined to simulate the in-situ condition during penetration of a ripper tine.

Figure 4.19: Penetration test by using a 10mm bit probe

Figure 4.20: Penetration by using a point load bit

After testing with different sizes of probe, it was found that a probe with a 10mm in diameter is the most suitable size to yield an acceptable and consistence test result. Static penetration load applied High Speed Steel (HSS) needle in cylinder shape with 10mm diameter used for a rock material sample. The needle edge is flat in shape. The static loading rate was 0.06mm/second and the limit of the penetration depth was 10mm. The highest penetration resistance load was recorded by the Universal Test Machine (UTM).

Sample Preparation

A non-uniformed cube shape with 30mm thickness, 60mm width and 60mm length was used. The sample was put into a 100mm diameter and 50mm high PVC tube. Any sample laminations are oriented perpendicular to penetration direction. Then, Plaster of Paris premix was poured into the space between the rock sample and the PVC tube. The samples were left through firming and drying process at room temperature.

Testing Procedure

The aim for the confined penetration test is to measure the penetration index of the rock materials, to allow the prediction of rock strength. A penetration probe is set on the load cell. Then, the load frame is lowered until the needle touches the sample surface. At this time, the transducer is set to zero and the load is given gradually. When the penetration reached 10mm and the machine automatically stops. The Universal Test Machine (UTM) recorded the load versus penetration resistance up to 10mm penetration

4.3.2.6 Mineralogical Analysis

The mineralogical analysis studies were based on the examinations of thin sections of rock specimens. Thin sections were made from selected samples, representing rock types and grain size. Thin sectioning involved mounting a slice of rock onto a glass slide and grinding the rock down until it becomes transparent. Determination of minerals present was established with a petrographic microscope with the point counting method. In addition, grain size, angularity and percentage of quartz present were also determined. Photographs of the thin section were taken and one representative example for each rock is provided. This test enabled the study of the mineral content, grain size and inspection of weathering effect through alteration of minerals.

Microscopic examination, evaluation and photomicrography were performed using a microscope having sub-stage illumination. When viewed in transmitted polarized light illumination originating from beneath the sample, various mineral types were identified and characterized. A Carl Zeiss Axiocam with KS300 image analyzer system (Figure 4.21) was used to determine the particle grain size and size distribution, and average porosity of the samples.

Figure 4.21: A Carl Zeiss Axiocam with KS300 image analyzer system that being used for petrographic analysis

4.4 Measurement of Machine Performance

In addition to geological properties, the machine performance was also studied to understand the correlation between the rock mass and the machine's advance. The following parameters were recorded and measured during the monitored ripping test:

a) The length of each run, m
b) Depth of ripper tine during ripping, m
c) Time taken for run for a predefined length, s
d) Change of depth during the run
e) Assessment of the ease of ripping
f) Width of ripping between lines, m
g) The average surface area of ground affected by the tine during Ripping

4.4.1 Ripper Machine

To maintain consistency of ripping result, the same class of ripper was used at all sites i.e. Caterpillar D9H (CAT D9). A photograph of this ripper machine is shown in earlier part of this thesis. The typical curves of drawbar pull for this machine against the speed are shown in Figure 6.4. These curves are already accounted for the internal losses so drawbar pull can be read directly if the speed is known. Table 6.2 shows the main specifications of the CAT D9 as given by the manufacturer, Caterpillar Tractor Company. A brief description on the terms used to describe the machine parameters have been discussed in Chapter 2.

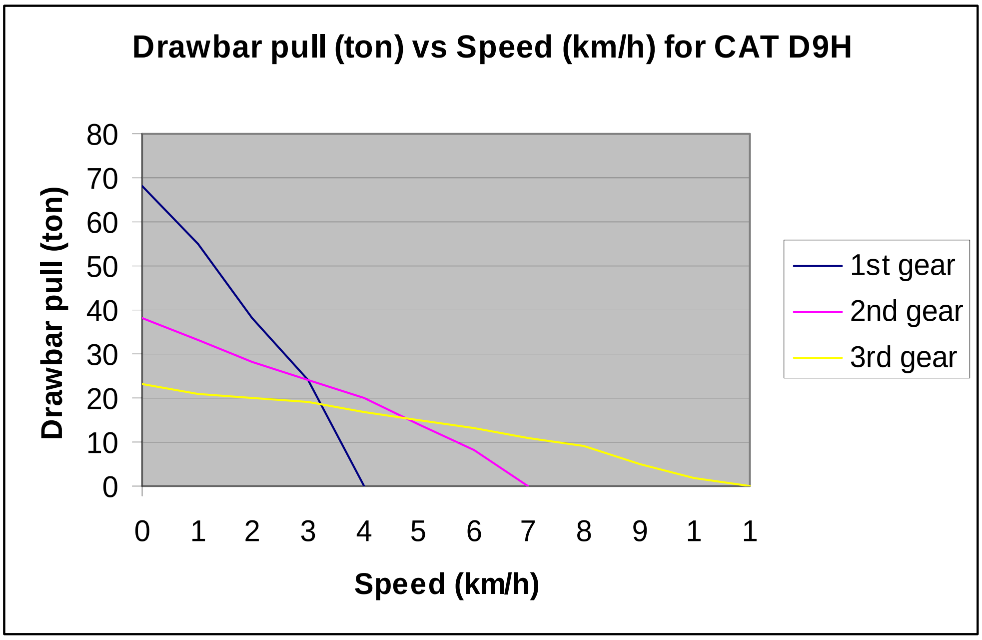


Figure 4.22: Power shift drawbar pull plotted against ground speed for Caterpillar D9H (Caterpillar Performance Handbook, 1985)

Table 4.3: Specification of Caterpillar D9 (Caterpillar Tractor Company, 2001)

Specification	**Value**
Flywheel power	410hp/ 306kW
Operating Weight	47900 kg
Ground contact area	4.24 m^2
Maximum penetration force (shank vertical)	153.8 kN
Pry out force	320.5 kN

4.4.2 Ripping Production

After ripping, the ripped material was removed to examine and measure the ripped boundaries. Figure 4.23 shows a typical measurement made on the width and depth of ripped material at the Bukit Indah site. As the shape of the ripped cross sectional area was observed as triangular in the field, an assumption of a triangular shaped cross section was made. The same assumption was reported to be viable by Bozdag (1988) and Basarir and Karpuz (2004). A simplified ripped geometry is given in Figure 6.3 where the width of ripped material was measured horizontally for the area affected by ripping and depth was measured vertically which was normally at the centre of the width line.

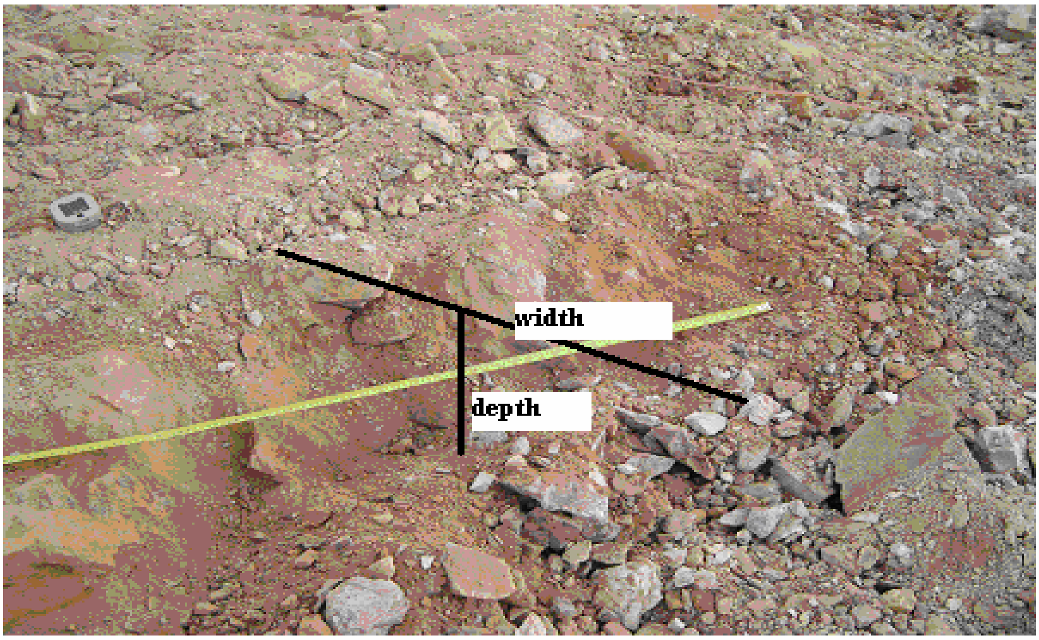


Figure 4.23: Typical measurement on the width of ripped material at Bukit Indah.

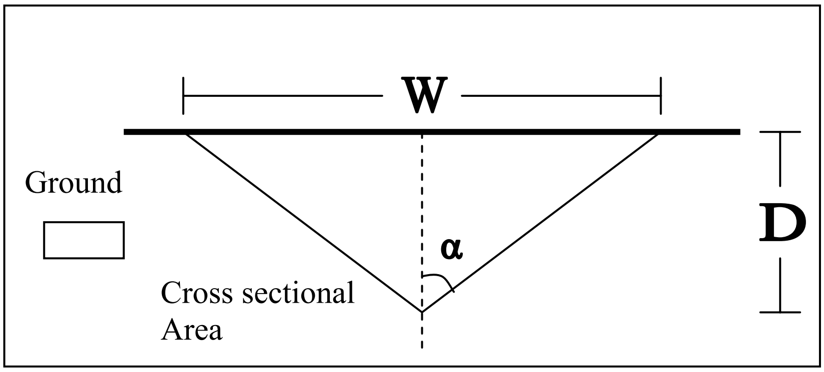


Figure 4.24. The simplified geometry of ripped material (after Basarir and Karpuz, 2004)

The cross sectional, C_{ar} area can be calculated from equation 4.16.

$$C_{ar} = \frac{DW}{2} \tag{4.16}$$

where D is Ripper depth (m); and
W is Ripping width (m)

Production per cycle is found by multiplying the cross sectional area and the ripping length.

$$q = C_{ar} \times L \tag{4.17}$$

where q is Production per cycle (m^3/cycle);
C_{ar} is Cross sectional area (m^2); and
L is Ripping length (m).

From the actual production time, the result will be converted to production per hour by using the formula as follows:

$$Q = [\ (q \times 3600) / t\ ] \times 0.75 \tag{4.18}$$

where Q : Production per hour (m^3/hour); and
t : Time taken for the ripping test (s)

The factor of 0.75 is used to estimate the actual production assuming that 25 percent of the time as non-productive (manoeuvring and turning time). This assumption was made based on data reported by Basarir et al. (2000).

4.5 Summary

In this chapter, reviews of the methods used for the determination of rock mass, rock material and machine related parameters for rippability assessment are made. In addition, description on testing equipment and procedures are also presented. Results on the testing are presented in Chapter 5, 6 and 7.

CHAPTER 5

ENGINEERING PROPERTIES OF ROCK MASS

5.1 Introduction

The main factor which influences the cutting performance of a ripper is the geological properties of the site and the machine parameters (Fowell, 1993). Geological properties can be categorized into rock mass and material properties. As for mechanical excavation, geological properties of rock masses play a significant role in determining the performance of ripper machine (Singh et al., 1987). Rock masses can be considered to be a function of a number of measurable parameters, with respect to their geomechanical properties display in massive and actual form. The properties are determined based on weathering, material strength, stratification of lithologies, frequency of jointing, discontinuities, bedding, orientation of joints, infill material and faults.

In section 2.5, a brief review of common techniques for describing rock mass structure for geomechanical purposes was discussed. This chapter aims to show how these systems of classifications were used to assess the rock mass properties for excavation. The approach to the analysis of rock mass structure for its effect on excavation performance are made by looking at the global view of rock mass structure by analysing the effects on excavation performance of various rock mass classes. In order to achieve this, classification schemes which have been discussed in section 2.5 were evaluated.

5.2 Site Location and Geology Setting

At each monitored ripping test location, descriptions of the principal lithologies were made. In the case of the Kempas and Desa Tebrau areas, the occurrence of old alluvium (sandy clay) was easily monitored because of the homogeneity of the material and the weathering grade. However, monitoring in heterogeneous materials of interbedded sandstone and shale with different weathering grades were more challenging at Bukit Indah and Mersing sites. The geology of each studied area is presented briefly in the following sections. Site locations and their general geology is shown in Figure 5.1.

5.2.1 Bukit Indah

The site is located between longitudes 103^{o}35’ E to 103^{o}36’ E and latitudes 1^{o}30’ N to 1^{o}31’ N in Johor, Malaysia. The main access to the construction site is by Second Link Plus Highway and it is located about 2 km from Sekolah Menengah Bukit Indah. During the field study, the Country View Housing Project, Bukit Indah was in the process of levelling the ground for a housing development project. A total of 1.5 million m^3 of earth was needed to be excavated. Out of this sum, 400,000 m^3 of earth could not be excavated by digging using a backacter EX200. Figure 5.2 shows the photograph of Bukit Indah site where several protruding rockmass are left behind for blasting works as it’s could not ripped by a CAT D9.

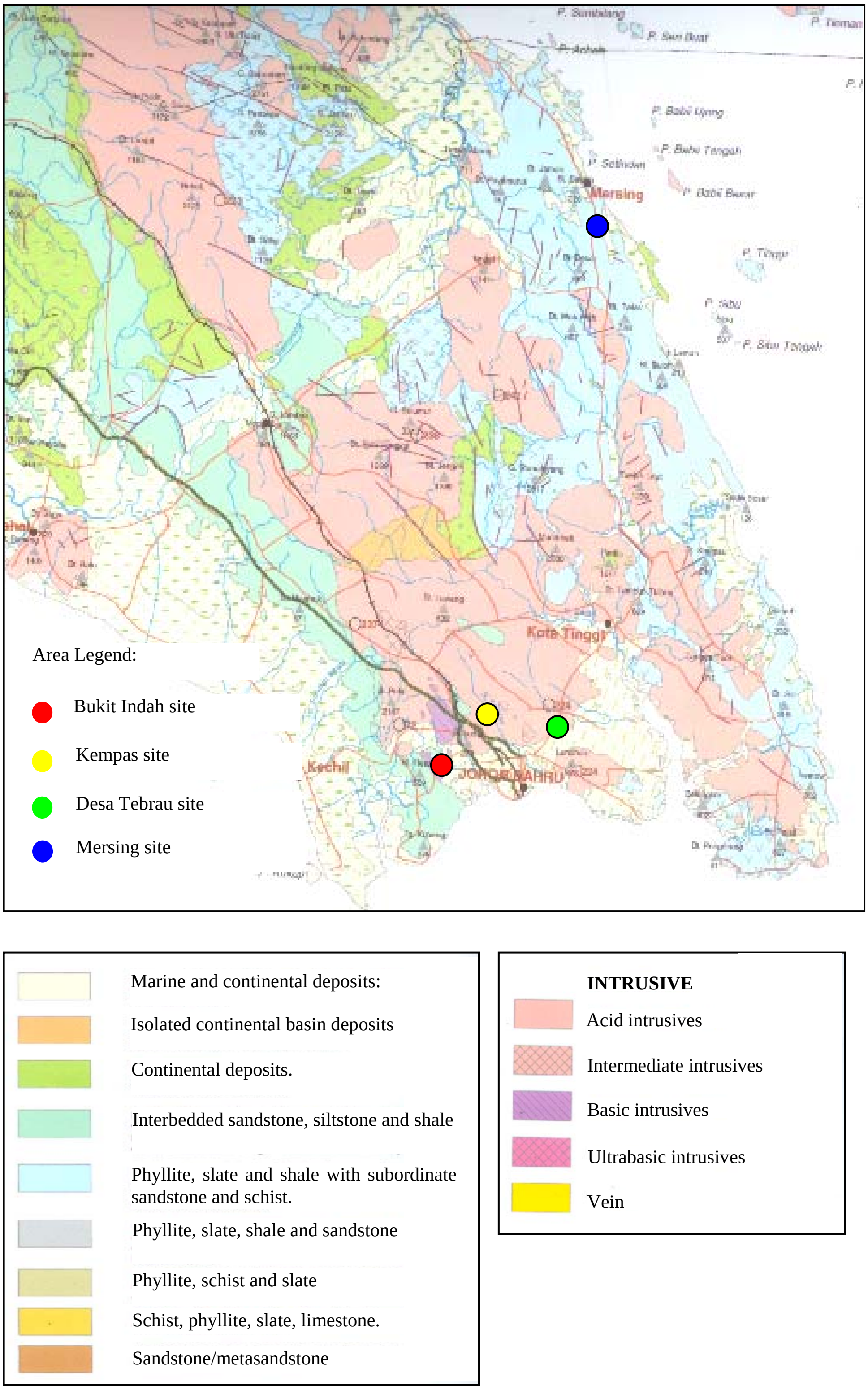


Figure 5.1: Geological map of Johor Darul Takzim (source: Mineral and Geoscience Department, 2004)

5.2.1.1 Site Geology

The Bukit Indah site comprises mainly shale and sandstone layers of Jurong Formation with thickness vary from few cm to 2.0 m. The sandstones are massive and interbedded with shale layers. Physical characteristics of the sandstone in the study area are generally light grey to yellowish in colour and have very fine to medium sized grain. Plant fossils discovered in it have not yet been determined, but a number of fossil collections from Singapore demonstrate an Upper Triassic to Mid Jurassic age for the unit (Burton, 1973).

Rock hardness varies considerably at Bukit Indah, both due to the rock type as well as the weathering grade. The upper layer is relatively more weathered compared to the bottom layer. Some material especially the shale can be excavated without ripping, whereas other areas may need ripping or blasting. The Is_{50} value for sandstones varies from 0.005 to 4.96 MPa whereas the shale has the value of 0.009 to 3.932 MPa.

The Bukit Indah site is characterized mainly by its subdued topography. The bedding strikes mainly in the north-northwest direction with dipping of 15^0-80^0. The ridge is composed mainly of argillaceous rocks and has been subjected to considerable dissection. Figure 5.3 shows a photograph showing interbedding of sandstone and shale of an outcrop at the site.

5.2.2.2 Weathering Classification

The sandstone and shale have undergone severe weathering effects and oxidation can be clearly seen from the accumulation of ferrum oxide especially at the discontinuities surface. The sandstone and shale are observed to be in the weathering grade Vb (completely weathered) to grade II (slightly weathered). Associated with the weathered sandstone and shale, many accumulation of iron pan with a few centimetres thick can be seen. A total number of 42 and 15 locations monitored during ripping test are sandstone and shale respectively, ranges from weathering grade Vb (completely weathered) to II (slightly weathered). The completely weathered (grade Vb) sandstone and shale which were found at 23 locations can be easily broken by light hand pressure and very friable. Whereas the slightly weathered (grade II) material are very hard and cannot be broken by a hammer blow. Lithology and weathering grade of each location are tabulated in Appendix G and summarized in Table 5.1. The seismic refraction survey was carried out on the dry climate and the result for line 1, 2 and 3 are presented in section 5.4.

5.2.2 Mersing

The site is lying between longitudes 103^{o} 39‘E and 2^{o} 17’ N. The main access to the construction site is Kota Tinggi- Mersing highway, which is located 5 km from Jemaluang crossroad. During the study, earthwork was in progress for the proposed Industrial Training Institute (ILP). A total of 2 million m^3 of soil needed to be removed; however 300,000 m^3 of material could not be removed by normal digging or ripping (by a CAT D9). The remaining outcrop had to be blasted. Figure 5.4 shows a typical lithology of exposed rock masses at the site where sandstone and shale are interbedded with each other.

5.2.2.1 Site Geology

The term Mersing Group is being introduced for two contiguous lithostratigraphic units, namely the Middle Permian ‘Dohol Formation and the Permian ‘Linggiu Formation’ which occur in the adjacent Gunung Belumut area. Regionally metamorphosed argillaceous and arenaceous rocks of the Mersing group occupy a large portion of the Mersing area. The age of the beds is postulated to be Late Triassic to Jurassic (Burton, 1973).

The Mersing group is essentially a monotonous sequence of predominantly shale and sandstone. The shale beds range from a few centimetres to a maximum of 2.0 m in thickness whereas the sandstones rocks are normally from 8 cm to 1.8 m thick. Some of the rocks transgressed by examining the quartz veins of various dimension and orientations. The sandstone is light grey to reddish brown in colour and has very fine to coarse grained. On the other hand, the shale is reddish brown to yellow in colour. The brownish colour is associated with the severe weathering effect. The Is_{50} for the sandstone ranges from 0.005 to 3.669 MPa and the shale ranges from 0.033 to 3.445 MPa. At the discontinuity surfaces, traces of iron pan of up to 5 cm thickness can be observed.

5.2.2.2 Weathering Classification

The exposed bedrocks which were studied at 15 locations are sandstone from weathering grade Vb to II. Grade II rocks are strong and show some discoloration along the joint surfaces. The grade II sandstone usually requires several blow of a geological hammer to break it. The grade IVa and IVb materials are substantially discoloured and the original fabric near the discontinuity surfaces has been altered. The grade IVb materials can be broken easily by hand pressure when moisturised. Table 5.2 shows a summary of locations monitored in respect to their weathering grade. Lithology and weathering grade of each location are tabulated in Appendix G.

5.2.3 Desa Tebrau

This project is developing a proposed hypermarket project and during study, earthwork was being carried out. The site is located between longitudes $103^o47'$ E to $103^o48'$ E and latitudes $1^o32'$ N to $1^o33'$ N. The main access to the construction site is using the Tebrau highway that is located about 1km from Hospital Sultan Ismail. The rock material is classified as Old Alluvium, the same as located at the Kempas site. At this site, a total of 20,000 m^3 of material had to be ripped by a CAT D9. Figure 5.5 shows a photograph of the occurrence of old alluvium in the Desa Tebrau site.

Table 5.1 Number of ripping test locations by respective weathering grade at Bukit Indah site

Rock type	Weathering Grade	Number of Locations Monitored
Sandstone	II (slightly weathered)	4
	III (moderately weathered)	6
	IVa (highly weathered)	9
	IVb (highly weathered)	7
	Va (completely weathered)	8
	Vb (completely weathered)	8
	Total	42
Shale	II (slightly weathered)	2
	III (moderately weathered)	4
	IVa (highly weathered)	9
	IVb (highly weathered)	13
	Va (completely weathered)	8
	Vb (completely weathered)	4
	Total	40

Table 5.2 Number of ripping test locations by respective weathering grade at Mersing site

Rock type	Weathering Grade	Number of Locations Monitored
Sandstone	II (slightly weathered)	1
	III (moderately weathered)	5
	IVa (highly weathered)	1
	IVb (highly weathered)	1
	Va (completely weathered)	2
	Vb (completely weathered)	5
	Total	15

5.2.3.1 Site Geology

The site is founded on massive, light grey sandy silt (Figure 5.5) which is also known as Older Alluvium (Burton, 1973). The formation was first recognized in eastern Singapore by Scrivenor (1924), who reported the presence of hills 20 – 30 m high formed of sand and clay, and named these deposits “high level alluvium: later applied the same name to similar superficial deposits in the State of Johor, across the Johor Straits from Singapore. This usage was first formalized by Willbourn (1928), who was the first to record the occurrence of this rock. Willbourn (1928) and Alexander (1950) emphasized the variable lithologies of the Older Alluvium. The most common variety is coarse feldspathic sand with occasional rounded phenoclasts, but gravelly clay, sandy gravel, sandy clay, silty clay, clayey sand, and clay are also all well represented. The common coarse feldspathic sand has obviously been derived essentially from granite, which lies at no great distance.

The rock material is fine to coarse grain, highly weathered (grade IVa), angular to sub-angular and grain supported. Under the microscope the rock is composed chiefly of quartz (70%), and feldspar/clay (15%), and iron ore mineral (15%). Cementing material consists mainly of clay and iron. The bedding planes are not clearly defined due to the thick and massive beds. At some locations, boundary of the old alluvium and the residual soil can be clearly seen as shown in Figure 5.6. At least 2 major sets of joints were identified and dipping averagely 40^0 – 80^0 S.

5.2.3.2 Weathering Classification

The weathering grade of the old alluvium was classified as grade IVa. The rock materials are generally hard, compact and difficult to be broken by the geological hammer. The value of Is_{50} ranges from 0.132 to 0.244 MPa. A total number of 10 locations which have the same weathering grade were monitored during the ripping test. Lithology of each location are tabulated in Appendix G.

For shallow engineering work, the seismic wave is normally generated from a hammer impact. For each line, at least 7 shots were recorded, and to increase the signal to noise ratio, at least 5 records were vertically stacked. Two lines of seismic survey were done along the proposed area. The total spread length was 69 meters.

5.2.4 Kempas

Earthworks were under progress at the proposed housing project in Taman Kempas Indah, Kempas. The site is located between longitudes 103^{o}43’ E to 103^{o}44’ E and latitudes 1^{o}31’ to 1^{o}32’. The main access construction is located about 0.5 km from Kempas highway exit. About 50,000 m^3 of material was ripped by a CAT D9 as it could not be excavated by a backacter EX200. Figure 5.6 shows an overview photograph of the Kempas site.

5.2.4.1 Site Geology

The Kempas site is founded by massive, light grey and coarse grained sandy silt with weathering grade Va (completely weathered). The material can be broken considerably by hand pressure during dry condition. At least one joint set was identified which most of the joints dip 40^0 - 50^0 N.

The old alluvium is the same formation as in Desa Tebrau site and can be described as partly consolidated and poor sorting sandy clay. Under a microscope, the rock has angular grained and matrix supported and composed chiefly of quartz (20-30 percent), clay (50-60 percent) and weathered feldspar (10-20 percent). Cementing material consists mainly of clay. Where the formation is exposed its feldspar content has in many places been weathered to a kaolinitic clay, and thus in the case of the common feldspathic sand type. Its surface appearance is that of a sandy clay or clayey sand.

5.2.4.2 Weathering Classification

A total number of 12 locations were monitored during the ripping test involving weathering grade Va. The material can be broken by light hand pressure and become very weak when moisturized. The Is_{50} value for these materials ranges from 0.025 – 0.066 MPa. Lithology of each monitored location is tabulated in Appendix G.

5.3 Discontinuities

Discontinuity measurements were made prior to the ripping test to mark the weakness planes that in some cases will enhance the strength of rock mass. Discontinuities include all types of mechanical break or plane of weakness in rock mass such as joints, bedding plane, fractures and shear zones that weakened the strength of rock masses. The enhancement of strength could happen through fillings of iron pan and quartz mineralization. Monitored ripping tests were carried out on massive sandstone and shale. These were achieved by ripping the rock mass through horizontal beds or when the bedding thickness permits the ripping test to be carried out. The purpose of performing testing on individual layers is to understand the ripping performance for an individual weathering grade. Discontinuity survey was conducted by using the scan line method as discussed in the Section 4.3. Based on the discontinuities data, the rock units were classified with the rock classification system: namely Rock Mass Rating (RMR), Q-system and Excavatability Index (EI) for easy interpretation. Some examples on the scan line results are presented in Appendix F and they are summarized in the following sections.

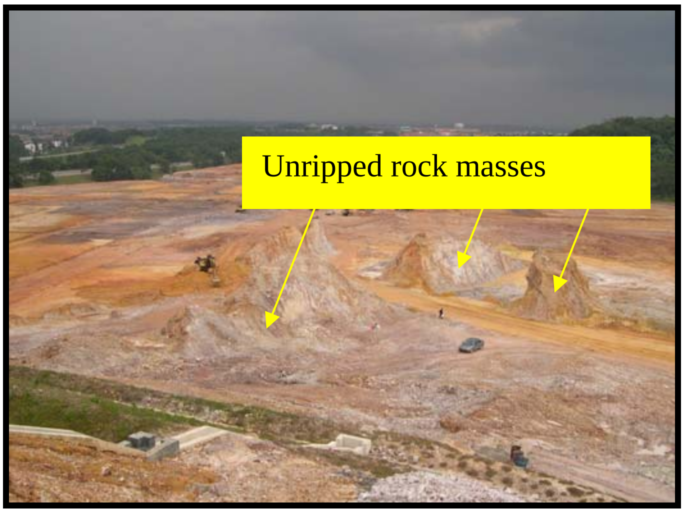


Figure 5.2: Protruding rockmass that could not be ripped by a CAT D9 in Bukit Indah site

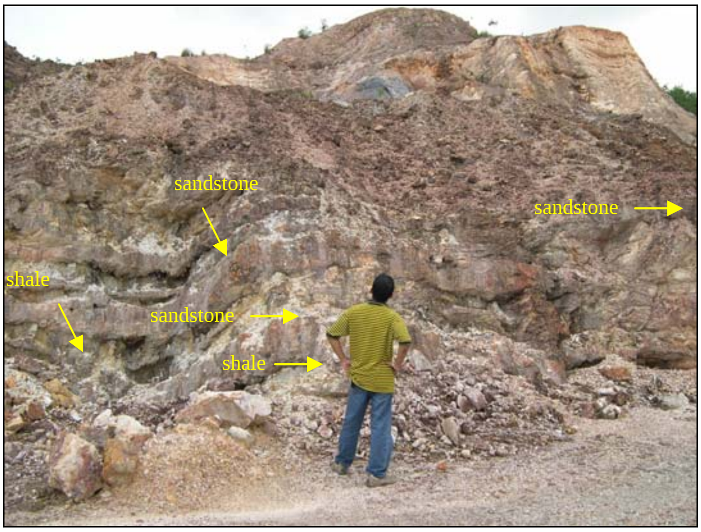


Figure 5.3: Sandstone and shale formations in Bukit Indah

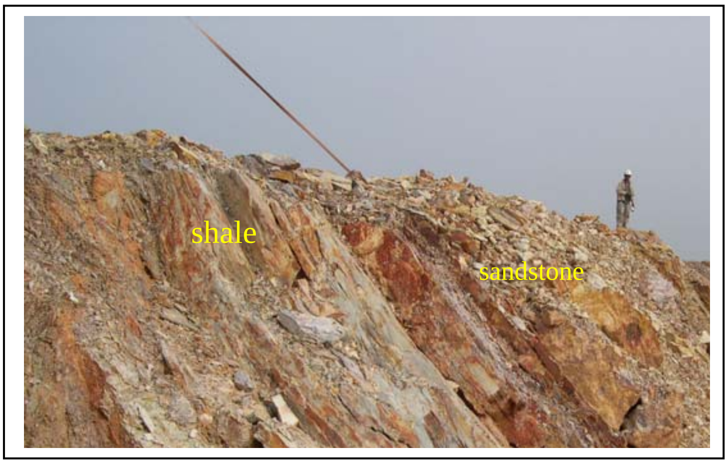


Figure 5.4: Interbedding of sandstone and shale in Mersing site

Figure 5.5: Occurrence of old alluvium at Desa Tebrau site

Figure 5.6 : Presence of old alluvium (whitish grey) in proposed site of Taman Kempas Indah

5.3.1 Bukit Indah Site

Discontinuity survey at Bukit Indah site was conducted at 57 ripping test locations. These discontinuities are predominantly found in the form of joints. These joints are generally tight, coated with iron stain or clay, with planar to slightly undulating. Scan lines were carried out at all locations and revealed that 1 to 5 joint sets are present. The discontinuity can be considered as major sets based on their density, though not all of them contribute to potential instability.

There are five major discontinuity sets are present; J1 with dip and dip direction of $50^0/280^0$, J2 ($70^0/90^0$), J3 ($50^0/210^0$), J4 ($40^0/180^0$) and J5 ($80^0/340^0$). It was observed at least one joint or maximum of three joint sets are present at each ripping location. The joint spacing ranges from a few cm to 1.5 m. The wide joint spacing of more than 1 m was found in grade IVa sandstone, grade IVb shale and Vb sandstone. At each location, an average joint spacing was calculated and summarized in Table 5.3.

The rating value for the Rock Mass Rating (RMR), Q-system and Excavatability Index (EI) are calculated for each location of ripping test. The rock mass classification systems (RMR and Q-system) and the EI were discussed in Section 2.5 and 3.3.4.2 respectively. Table 5.3 summarizes the results of RMR, Q-system and EI while Appendix G shows the detail of the results. The value of RMR ranges from 32 to 67, it indicates difficult excavation when the value is higher. The Q-system value ranges from 0.03 to 14.42. The higher value indicates the quality of rock increases thus, a more difficult excavation required. While the EI value ranges from 0 to 1189 indicates hard to extremely hard ripping when the value is more than 1000. Table 5.3 summarizes the results in relation with the weathering grade. Overall, it appears that the value of Q-system, RMR and EI show decreasing trend as the weathering grade is higher for both sandstone and shale. Rock classification according to Bieniawski (1989) suggests RMR value of more than 60 as ‘good rock’ and requires blasting, while the lower value can be treated as ‘fair rock’.

Table 5.3: Summary of scan line results for Bukit Indah site

Weathering Grade	Material	Joint Spacing (m)	Q-system	EI	RMR
II	sandstone	0.17 - 0.56	6.60 - 9.65	616 - 1165	56 - 62
	shale	0.28 - 0.29	6.99 - 9.61	442 - 1189	50 - 60
III	sandstone	0.11 – 0.39	3.77 – 9.76	95 - 433	50 – 59
	shale	0.22 - 0.60	5.97 – 9.19	147 - 387	40 – 60
IVa	sandstone	0.10 – 1.22	4.59 – 14.42	18 - 194	52 – 62
	shale	0.16 – 0.47	2.54 – 9.48	26 - 156	55 - 67
IVb	sandstone	0.19 – 0.78	3.39 – 7.78	14 - 29	44 – 51
	shale	0.17 – 1.10	0.22 – 5.55	2 - 24	39 – 50
Va	sandstone	0.09 – 0.73	0.23 – 0.70	0 - 1	32 – 42
	shale	0.20 – 0.52	0.13 – 0.75	0 - 8	37 - 40
Vb	sandstone	0.20 – 1.51	0.03 – 0.11	0 - 4	36 – 41
	shale	0.20 – 0.31	0.07 – 0.10	0	38 - 40

5.3.2 Mersing site

There are at least 6 discontinuity sets for the site. The major sets are J1 ($60^0/020^0$), J2 ($40^0/060^0$), J3 ($80^0/100^0$), J4 ($80^0/150^0$), J5 ($70^0/250^0$) and J6 ($80^0/340^0$). Similar to Bukit Indah site, the scan lines were carried out regionally along the ripping lines in order to evaluate the quality of rock mass. The joints are tight with planar and undulating surfaces. It was observed at least one joint or maximum of four joint sets are present at each ripping location. The joint spacing is in the range of 0.21 to 0.81 m. The value of the joint spacing is relatively high, thus leading to generally high value for the rock mass classification ratings. It was found that the RMR value ranges from 38 to 60, Q-system value ranges from 0.1 to 14 and the EI value ranges from 0 to 407. Weathering grade Va shows the lowest value of RMR, Q-system and EI. This is due to low quality of rock (RQD) that resulted low ground structure number. Generally, those values will decrease with the increase of weathering grade.

Excavatability Index is correlated to the Q-system because of the ratios of rock quality and joint number (RQD/Jn and Jr/Ja) are held in both systems. Table 5.4 shows the summary of the results obtained from the site and the details are shown in Appendix G.

Table 5.4: Summary of scan line results for Mersing site

Weathering Grade	Material	Joint Spacing (m)	Q	EI	RMR
II	sandstone	0.21	9.07	313	57
	shale	0.83	9.80	407	55
III	sandstone	0.24 – 0.80	6.97 – 9.30	86 - 303	50 – 60
	shale	0.44 - 0.81	9.30 – 9.70	306 - 378	53 – 54
IVa	sandstone	0.41	14.00	206	59
	shale	0.68 – 0.81	3.30 – 9.78	70 - 171	54 - 59
IVb	sandstone	0.56	7.40	21	48
Va	sandstone	0.27 – 0.33	0.49 – 0.50	0	38 - 40
	shale	0.20 – 0.57	0.49 - 0.50	0	40 - 41
Vb	sandstone	0.24 – 0.56	0.10 – 0.20	0	38 - 42

5.3.3 Desa Tebrau site

At least 6 discontinuity sets present at this site i.e. set J1 ($80^0/140^0$), J2 ($80^0/100^0$), J3 ($80^0/170^0$), J4 ($70^0/320^0$), J5 ($50^0/200^0$) and J6 ($60^0/240^0$). Most of the joint shows dipping of around 70^0 - 80^0. It was observed at least one joint or maximum of three joint sets are present at each ripping location. The discontinuities surfaces are rough and tight. The joint spacing is moderate to wide with value of 0.68 – 1.13 m. The RMR value calculated at the location ranges from 45 to 73 indicating fair to good rock. The high value of RMR is contributed by the wide joint spacing. The EI and Q-system value ranges from 18 to 274 and 1.65 to 15 respectively suggesting hard to very hard ripping. The summary of the results are shown in Table 5.5 and the scan line measurements are presented in Appendix G.

Table 5.5: Summary of scan line result for Desa Tebrau site

Weathering Grade	Material	Joint Spacing (m)	Q	EI	RMR
IVa	Old alluvium	0.68 – 1.13	1.65 – 15.00	18 - 274	45 - 73

5.3.4 Kempas site

There are 3 discontinuty sets for this site i.e. set J1 ($50^0/300^0$), J2 ($40^0/140^0$) and J3 ($50^0/210^0$). Most of joint shows dipping around 40^0 to 50^0. At least one joint set present at the ripping location. The joints surface is tight and rough with some iron stains. A total of 12 locations were measured by the scan lines. The joint spacing is wide with the value of 1.14 to 1.59 m. However, due to the weak material (grade Va) the RMR was found to be in the range of 39 to 42, Q-system value in the range of 0.38 to 1 and the EI value ranges from 39 to 42. These values suggest hard ripping is necessary to excavate the rock. The summary of the results are shown in Table 5.6 and the detailed results are presented in Appendix G.

T**able 5.6**: Summary of scan line result for Kempas site

Weathering Grade	Material	Joint Spacing (m)	Q	EI	RMR
Va	Old alluvium	1.14 – 1.59	0.38 – 1.00	0 - 1	39 - 42

5.4 Seismic Survey Result

The seismic survey tests were carried out at selective sites namely Bukit Indah, Mersing, Desa Tebrau and Kempas. Their results are presented in the following sections.

5.4.1 Bukit Indah Site

Three seismic lines were surveyed at Bukit Indah area namely Line 1 (unripped by a CAT D9), Line 2 (rippable by a CAT D9) and Line 3 (unripped and rippable by a CAT D9) as presented in the following section.

5.4.1.1 Bukit Indah Line 1

Figure 5.7 is a model diagram of seismic velocity for Bukit Indah Line 1. Geophone spacing was 4 m and 7 stroke points. It shows that the first layer in blue to green colour is about 14 m thick is rippable layer (seismic velocity below 2300 m/s). The second layer in light green to yellowish colour is about 7 m thick is marginal (seismic velocity 2300 to 2900 m/s). And the third layer in yellow to reddish colour is about 20 m deep is the non rippable layer (seismic velocity more than 2900 m/s). Estimated about 46 percent of this area is rippable rock mass, 24 percent is marginal, and 30 percent is non rippable rock mass.

During the monitored ripping test, it shows that the layers were unripped by a CAT D9. The material consist of grade IVb sandstone which can be broken by strong hand pressure. Discontinuity spacing measurements were made with scan line technique. In this line, discontinuity measurements revealed that there are 4-6 discontinuities per metre square with average spacing of 0.25 m. Material has to be broken by drill and blast method. At least 46 percent of this area that is supposed to able to be ripped by manufacturer’s recommendation could not be ripped in the actual ripping works.

5.4.1.2 Bukit Indah Line 2

Figure 5.8 shows the seismic velocity for Bukit Indah Line 2. It shows that the first layer in blue to light green colour is about 7 m thick is rippable layer (seismic velocity below 2300 m/s). The second layer in green colour is about 8 m thick is marginal (seismic velocity 2300 to 2900 m/s). And the third layer in greenish yellow to pink colour is about 15 m deep is the non rippable layer (seismic velocity more than 2900 m/s). From the diagram, it is known that most material in this area is marginal rock mass that is in green colour zone. It is estimated about 35 percent of this area is rippable rock mass, 40 percent is marginal, and 25 percent is non rippable rock mass.

During the monitored ripping test, it shows that the layers were rippable by a CATD9. The material consist of grade III sandstone which can only be broken by strong hammer blow. Part of the material as marked on the diagram, is Grade IVb shale which is easily rippable. Discontinuity spacing measurements were made with scan line technique. In this line, discontinuity measurements revealed that there are 12-15 discontinuities per meter square with average spacing of 0.05 m for moderately weathered sandstone and 6-8 discontinuities per metre with average spacing of 0.20 m for the grade IVa shale.

5.4.1.3 Bukit Indah Line 3

Figure 5.9 is the model diagram of seismic velocity for Bukit Indah Line 3. The area is a cut through of a small hill. Seismic test was done with 7 stroke points and 4 m geophone spacing. From the diagram, it shows that the first layer in blue to light orange colour is about 5 m thick is the rippable layer (seismic velocity below 2300 m/s). The second layer in light orange to reddish colour is also about 5 m thick is marginal (seismic velocity 2300 to 2900 m/s). A small part in red to pink colour is about 10 m deep is the non rippable layer (seismic velocity more than 2900 m/s). Most rock mass in this area is marginal and non-rippable rock mass. Percentage estimated for this area is about 30 percent of this area is rippable rock mass, 35 percent is marginal, and 35 percent is non rippable rock mass.

During the direct ripping test, it shows that the lower layers that consist of grade IVa shale was rippable by Caterpillar D9 but the protruded rock (sandstone grade III) was unrippable. Discontinuity spacing measurements were made with scan line technique. Along this line, discontinuity measurements revealed that there are 10-18 discontinuities per meter square with average spacing of 0.15 m for grade IVa shale where as 6-13 discontinuities per metre with average spacing of 0.20 m for the grade III sandstone.

5.4.2 Mersing Site

Seismic velocity test were carried out at 2 locations namely Line 1 and Line 2. Their results are presented as follows.

5.4.2.1 Mersing Line 1

Figure 5.10 indicates that the first layer in blue to yellowish orange colour and about 14 m thick is the rippable layer (seismic velocity below 2300 m/s). The second layer in orange to reddish colour and about 2 m thick is marginal (seismic velocity 2300 to 2900 m/s). And the third layer in red to pink colour and about 16 m deep is the non rippable layer (seismic velocity more than 2900 m/s).The small area in blue is possibly a rippable rock or a boulder. It is estimated about 78 percent of this area is rippable rock mass, 11 percent is marginal, and another 11 percent is non rippable rock mass. During ripping test, it was noted that the top rock mass was rippable. The material is grade IVb sandstone with joint spacing of 0.3 m.

5.4.2.2 Mersing Line 2

Figure 5.11 is the model diagram of seismic velocity for Mersing Line 2 area. Seismic test at this area was done using 4 m geophone spacing but only 6 stroke points. The first layer in blue to green colour and 9 m thick is the rippable layer (seismic velocity below 2300 m/s). The second layer in green colour and about 5 m thick is marginal (seismic velocity 2300 to 2900 m/s). A small part in green to pink colour and also about 14 m thick is the non rippable layer (seismic velocity more than 2900 m/s). Most material in this area is rippable which is in blue zone. It is estimated about 47% of this area is rippable rock mass, 26% is marginal, and another 26% is non rippable rock mass.

5.4.3 Desa Tebrau Site

The seismic section shown in Figure 5.12 shows a significant different in changes of colour. The top part shows dark blue in colour with the velocity of 550 m/s and the velocity of the second layer marked by green and red in colour ranges between 1800 to 2200 m/s. This can be interpreted that the top layer is made up of highly weathered material which is soft and the second layer is stronger and harder.

5.4.4 Kempas Site

The test result is shown in Figure 5.13. The top layer has a velocity value of 500 m/s and the second the layer has velocity value between 2000 to 2200 m/s. Similar to Desa Tebrau site, the top layer is made up of softer material and the second layer is made up of stronger material. From the field survey, it was noted that the top layer consist of grade Va old alluvium which can be ripped.

5.4.5 Discussion on Seismic Velocity Test Results

The result shows that for sandstone of weathering grade III, the discontinuity spacing plays an important factor to determine whether the material is rippable or not. Material with this high strength (grade III) can be ripped as compared to lower strength (grade IV) with assistance of discontinuity spacing. Discontinuity spacing of 0.05 m could help sandstone grade III to be ripped but spacing of 0.2 m (Line 3) would resist the ripping work. However, for sandstone in grade IVb with discontinuity spacing of 0.25 will not permit ripping work. Although, its (sandstone grade IVb) lower strength of material would be of help, the wide spacing will resist the breakage of material through ripping. The grade IVa shale with spacing of 0.15 and 0.20 is able to be ripped. This might be due to the lower strength of shale as compared to sandstone. Thus, discontinuity spacing and material strength of rock mass play significant factors in determining the rippability of rock.

Both parameters of spacing and strength could not be interpreted separately on its own, but need to be considered together. The seismic velocity chart of Caterpillar (2001) only provides guidelines to a certain extent. There are two cases shown that the Caterpillar (2001) suggested chart could not correlate well to the actual rippability performance if solely based on a single parameter, i.e. seismic velocity. This result support the findings of McCann and Fenning (1995) on the use of seismic velocity as rippability assessment tool.

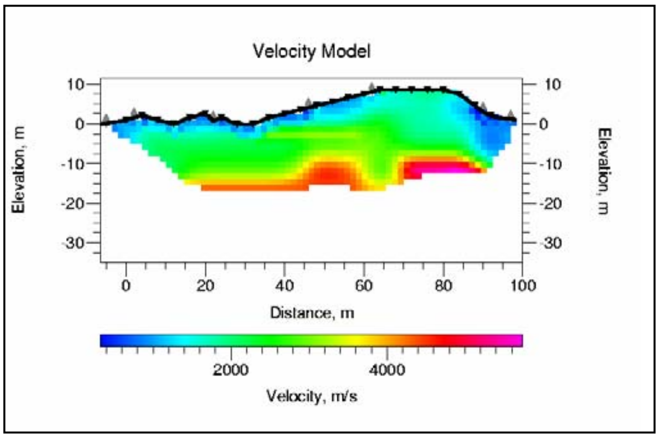


Figure 5.7: Model diagram for Bukit Indah Line 1

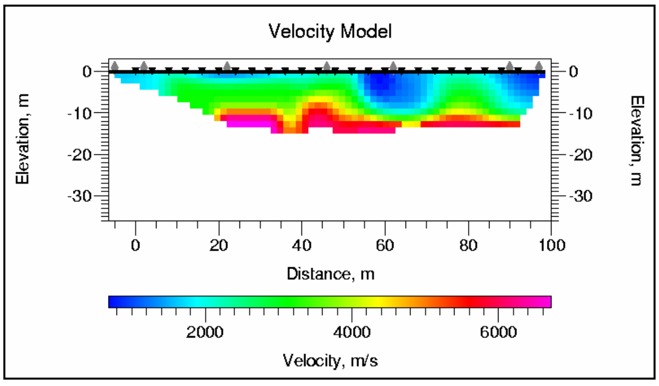


Figure 5.8 : Model diagram for Bukit Indah Line 2

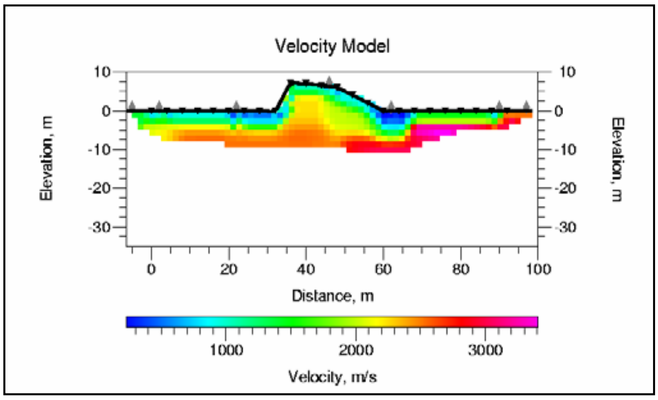


Figure 5.9 : Model diagram for Bukit Indah Line 3

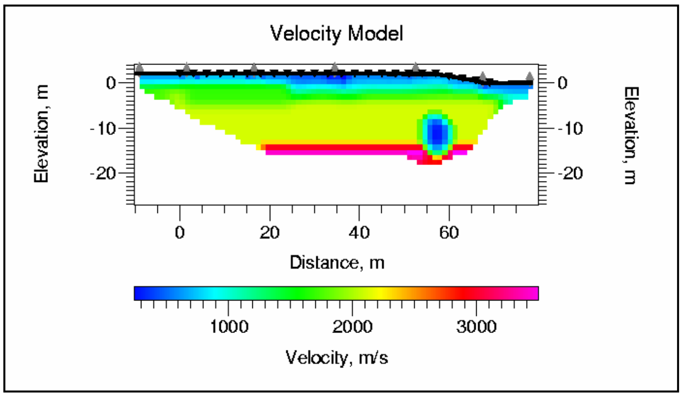


Figure 5.10 : Model diagram for Mersing Line 1

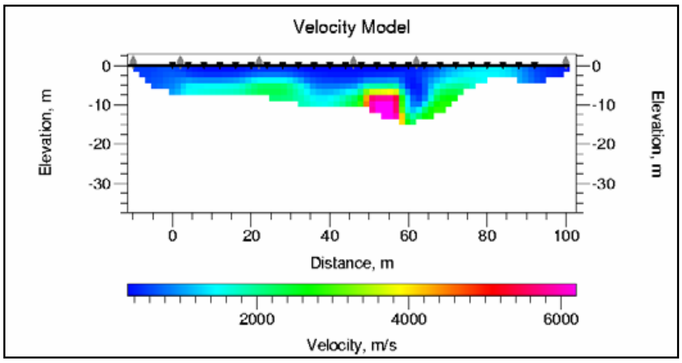


Figure 5.11 : Model diagram for Mersing Line 2

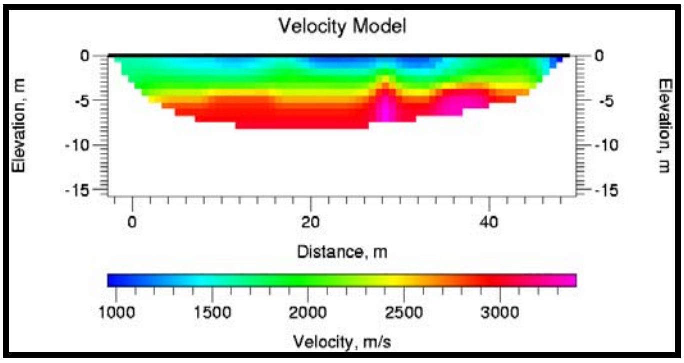


Figure 5.12: Model diagram for Desa Tebrau

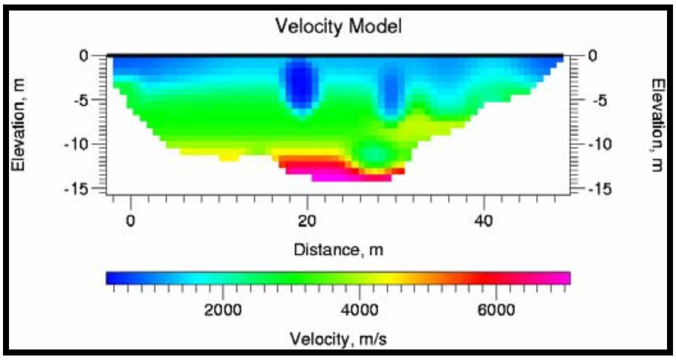


Figure 5.13: Velocity model for Kempas Site

5.5 A Comparative Study of Weathering Profile in Granitic and Sedimentary Rock Masses

Since excavatability of weathered rock masses are very dependant on weathering profile, it is therefore necessary to understand the different characteristics of the general weathering profile in granitic and sedimentary areas. A study of weathering profile of granite was carried out in a road cutting in Seri Alam, Masai and Khoo Soon Lee Housing Development, Ulu Tiram. In general, the area of weathered granites is covered with boulders and soil (overburden) whereas the study areas in Bukit Indah, Mersing, Kempas and Desa Tebrau involved sedimentary rock.

This section presents the results of the field study on the weathering profile at various locations. For the purpose of this study, indices are given for each weathering grade as shown in Table 5.3. The criteria used to grade the material are discussed in Chapter 2.

Table 5.7: Classes of different weathering grades used to classify the rock masses

Grade	I	II	III	IV		V		VI
Sub grade				a	b	a	b	
Index	1	2	3	4	5	6	7	8

5.5.1 Taman Bestari Indah, Ulu Tiram

During profiling works, drilling activities for subsequent blasting operations were carried out. Studies were made on two exposed areas namely BI-1 and BI-2 are presented in the Figure 5.14 and 5.15.

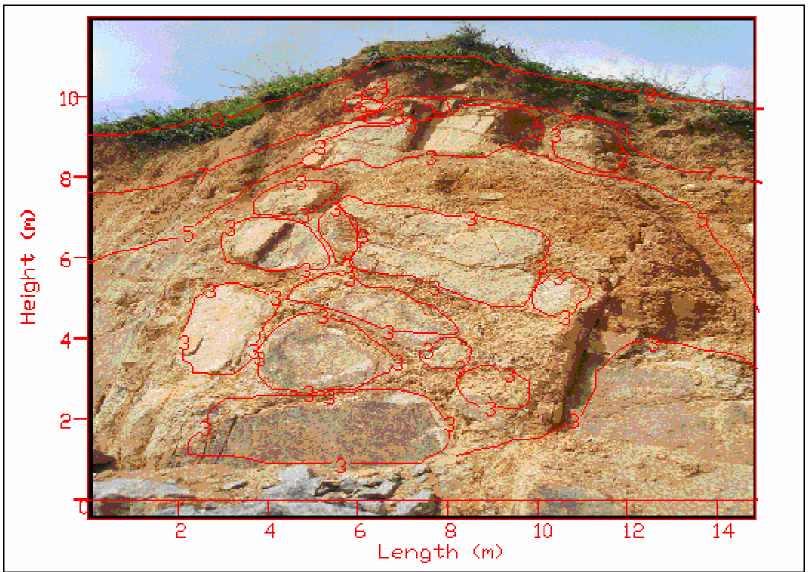


Figure 5.14 : Photo and sketch of weathering profile on an exposed rock face (BI-1) in Ulu Tiram

It can be observed from the profile, a large amount of angular shaped boulders exist 10 meters from the surface. A thin layer of residual soil (grade VI) of about 1 meter thick is the uppermost material. Beneath the residual soil is the completely weathered zone which is marked as number 7 whereas highly weathered zone is marked as number 5. Boulders can be found abundant in these zones (completely and highly weathered) with sizes ranges from 0.3m to 5m. The material strength of boulders is much higher (grade III) as compared to the surrounding material (matrix). Towards the bottom part of the exposed face, bedrock can be found at about 10m from the surface.

In BI-2, the residual soil (grade VI) is about 1m from the surface. Grade IVb (highly weathered) material is below the residual soil. In these zones, boulders of 0.3 to 1m in sizes can be found. The boulders have higher strength and cannot be broken by geological hammer.   Bedrock is not visible in this exposed area.

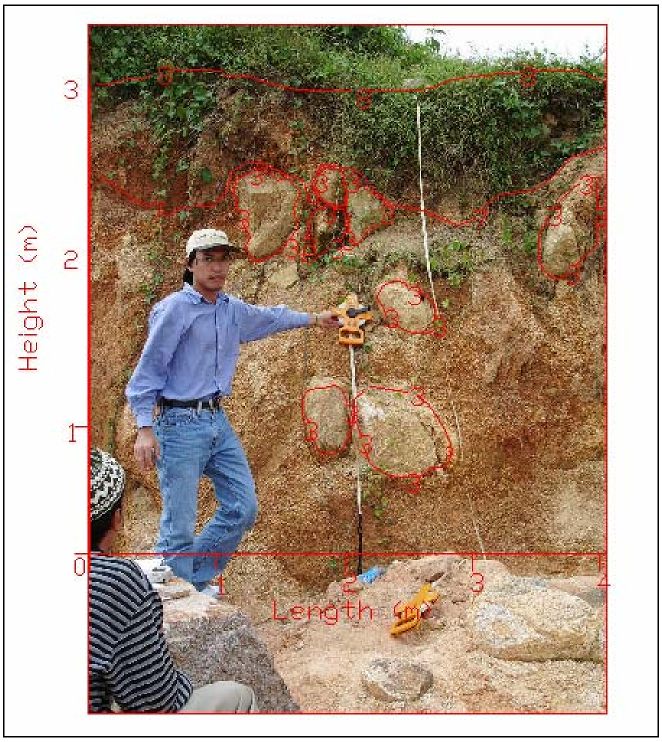


Figure 5.15: Photo and sketch of weathering profile at BI-2, Ulu Tiram

5.5.2 Bandar Sri Alam, Masai

A study on an exposed slope along the main road in Seri Alam Township, Masai, Johor was carried out. Studies were made at two different locations namely SA-1 and SA-2. From field examination, the rock can be classified as granite. The photographs and their sketches on weathering profile are shown in Figures 5.16 and 5.17.

The top layer is grade IVa material. Three discontinuity sets are identified in this zone. Discoloration on the surface of the rock shows the effects of weathering. On the right side, materials are in grade III, where texture and minerals are still preserved. No discolorations can be seen. Tests carried out using the Schmidt hammer produced readings ranges from 40 to 50 with an average of 45. Weathering effects can be observed in discontinuity spacing. Boulders of 1m to 2 m in sizes are present in the highly weathered zone.

In SA-2, at least 2 discontinuity sets striking along a W-WSW orientation and dip 15 – 30^0 N can be observed. At the joint surfaces, evident of weathering has taken place can be seen from the discoloration and decomposition of minerals. Previous rock breaking or blasting works may have caused the large numbers of discontinuity in this area. The upper part is classified as grade IVa. Beneath this part is material of grade III and the lower part is classified as grade II. Most rock in this area is still in the original state with slight effects of weathering.

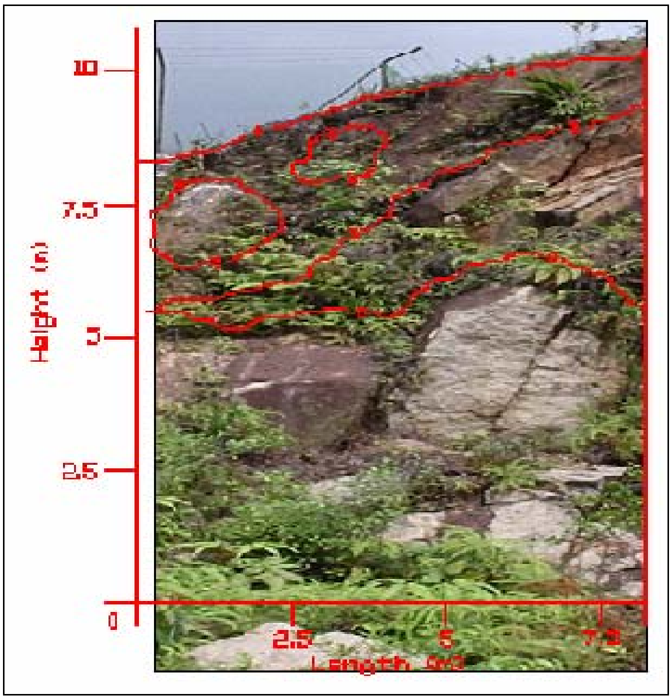


Figure 5.16: Photo and sketch of weathering profile on an exposed slope at SA-1 (Seri Alam, Masai)

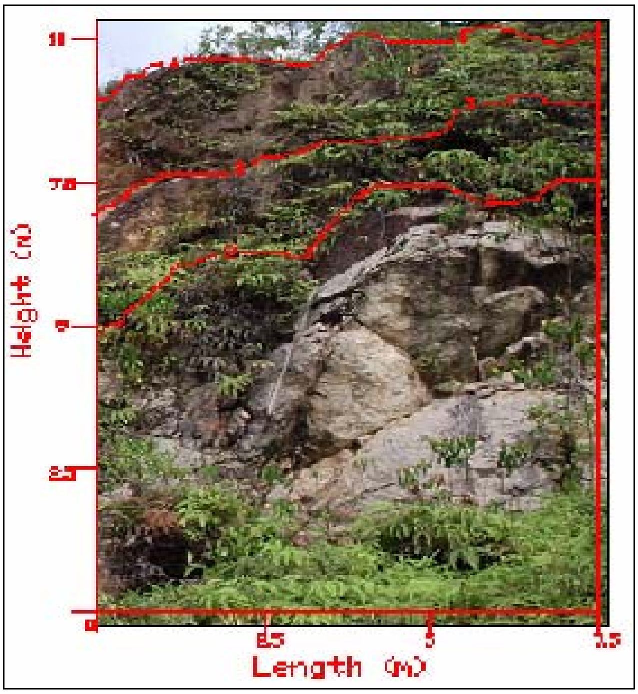


Figure 5.17 : Photo and sketch of weathering profile at SA-2, Seri Alam, Masai

5.5.3 Bukit Indah

Bukit Indah is a sedimentary area where rock materials are sandstone and shale. Materials of different grades are inter-bedded as one rock mass. Studies were made at two different sites namely BK-1 and BK-2. Figure 5.18 and 5.19 show the photographs and sketches of the weathering profile of the outcrops.

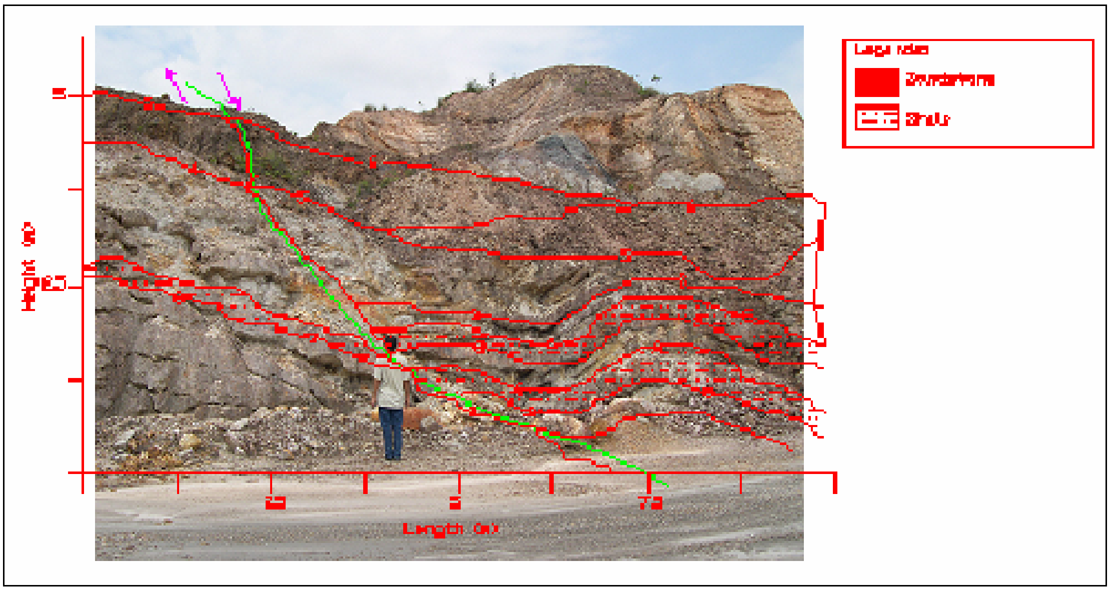


Figure 5.18: Photo and sketches of weathering profile at BK-1, Bukit Indah

The top left layer consists of grade IVb sandstone as marked by number 5. The second layer is of grade IVa sandstone materials and the lower layer is made of grade III sandstone. On the lower right, series of inter-bedded materials of grade III (sandstone) and V (shale) can be observed. A large numbers of discontinuity are visible to indicate that this area is exposed to extreme weathering process. In this sedimentary rock mass, we can see a distinctive difference compared to the granitic rock mass where inter-bedding of different rock types is the major characteristic. Each rock type may have different weathering grades due to the mineralogy and susceptibility to weathering agents. In this example, the majority of shale has a lower strength (grade Va) as compared to sandstone, which is mainly in grade III.

In Figure 5.19, a large rock mass consists of two type of materials of sandstone grade IVa (upper layer) and shale Vb (lower layer) are found. A lower strength material of grade Vb shale is inter-bedded with higher strength sandstone of Grade IVa on the top. The sandstone shows some changes in colour, proving that oxidation of iron has taken place. Along the discontinuities some changes of mineralogy and accumulation of iron pan has occurred. Although the lower strength shale should be easy to excavate by an excavator, the occurrence of higher strength of material sitting on top of it makes the whole material unrippable. This is a good example where lithology plays an important role especially in sedimentary area.

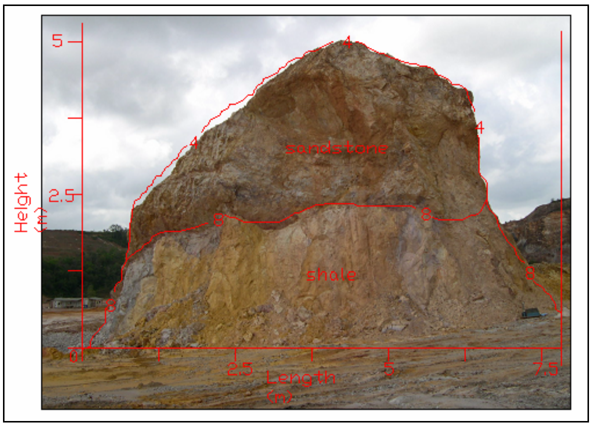


Figure 5.19 : Photo shows significant amount of shale (Grade Vb) lying under Grade IVa sandstone

5.5.4 Industrial Training Institute, Mersing

This site consists of sandstone and shale which has undergone low grade metamorphism. A photograph is shown in Figure 5.20 shows a weathering profile encountered at the site namely M-1.

Figure 5.20 shows the bedding is inclined and rock material on the right is sandstone of grade Va and IVb. Sandstone material of grade Va can be easily broken by hand pressure whereby grade IVb can only be broken by strong hand pressure. Both materials are inter-bedded to each other and the sandstone of grade IVb needs blasting to be excavated.

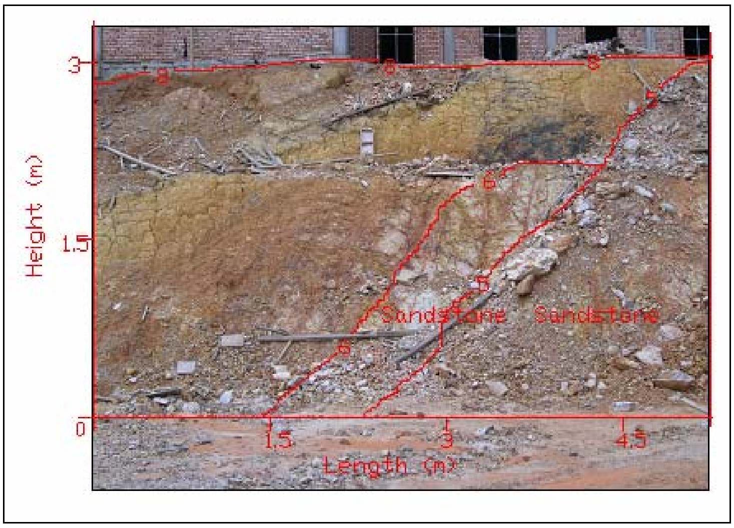


Figure 5.20: Photograph and sketch of weathering profile at M-1, Mersing

5.5.5 Discussion on Weathering Profile in Respect to Its Excavatability

The granite rock formations showed in section 5.5.1 and 5.5.2 do not consist of uniformed boundaries and layers. It was observed that the formation layers varied significantly within a small area, in terms of mineral composition, extent of weathering, rock texture and other features. This proves the fact that the characteristics of the rock's vertical profile are not identical to adjacent areas, even though just a short distance away.

Rocks with coarser textures are actually weaker in terms of strength in comparison with fine textured rocks. This was proven when observing that the former could be easily broken by hand or geological hammer. The outer surface of the rock formation and areas along the joints were observed to consist of a coarser texture. Apart from that, this also indicates that fine textured rocks have greater strength due to strong interlocking and bonding between the particles.

As reported by Ibrahim Komoo (1995a), chemical weathering in tropical areas has resulted in a thick weathering profile with abundant of boulders to be expected in granitic areas. Granite boulders have higher strength when compared to the surrounding material. Almost all the studied sites at BI-1, BI-2 and SA-1 show occurrence of boulders at highly and completely weathered zones. The changes of weathering grade can be also rapid in granitic areas. The high strength of the rock material and boulders are the factors that make ripping works unpopular as an excavation method in Malaysia. In igneous origin areas, we can expect abundant of boulders that may have similar strength, but vary in the sizes (Figure 5.21). Normal digging can excavate small boulders easily, but the larger size (normally greater than 1 m^3) may need blasting to break them.

Figure 5.21: Presence of boulders with different sizes in granitic area (Location: Masai)

The blasting method is always opted in this granitic area due to occurrence of boulders and sharp boundary between the weathering grades. Thus, it is more economical to use the blasting method in such cases. Figure 5.22 shows an example where blasting works were carried out to remove protruding granitic rock in the Puteri Wangsa Housing Project.

Generally, sedimentary rock mass consists of more than one type of rock and always forms alternate layer because of the natural forming process and are also exposed to tectonic effects and pressure. The weak rock in moderately weathered (grade III) to completely weathered zone (grade V) has often been the 'grey' area for excavation.

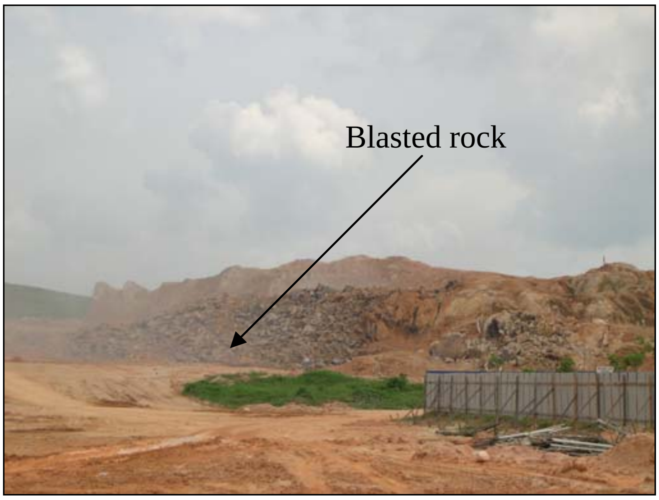


Figure 5.22 : Blasting works is opted for excavation in granite (Location: Ulu Tiram). Traces of blasted rock can be seen at the bottom of rock face.

Fresh sandstone, which is well cemented, has minimal foliation and lamination as compared to shale and relatively difficult to rip. Shale is always known to have laminations or a fissile nature, which provides spaces for weathering agents to be in contact. Furthermore, shale composed of clay size material smaller than 0.062mm in size and some of clay types such as illite and montmorillonite may absorb water and will degrade easily on exposure to weathering agents as compared to sandstone.

Existing excavation assessments have always considered the strength factor to be one of the major factors in deciding whether the material can be ripped or otherwise. However, if strength is the only parameter considered, overall results may be ambiguous especially if sandstone and shale is evaluated separately as both materials may not have the same strength even though they are in one massive rock body. The sandstone may be in grade III but the shale may have further deteriorated to grade V as shown in Figure 5.19. Shale, which is inter-bedded with sandstone, might have lower in strength compared to the sandstone and their weathering grade might vary even though they exist in the same rock mass.

In sedimentary rock, the occurrence of bedding, folding, foliation and inhomogeniety of rocks are few distinctive differences compared to igneous rock. Shale, which is inter-bedded with sandstone, would have lower in strength when compared to sandstone and from the assessment; shale could be excavated by a different means of excavation technique. However, due to its existence in the rock mass which is inter-bedded between the dominancy of low or high strength of rock, the excavation method could differs from the assessment method. The small and larger scale of discontinuity that are always present in the sedimentary rock such as thickness of bedding, joints and foliation are not specified in the assessments but found to play significant role in assisting excavation. The percentage of dominancy of low or high strength of rock need to be assessed in advance as it may cause problems in ripping and during the preliminary excavation assessments. A more specific approach for ripping assessment specially for sedimentary area is needed as the assessments of material properties alone does not give accurate results to assess the whole rock masses rippability.

5.6 Conclusion

In this chapter, a review of the geological properties of sites were made which include the rock type, mineral composition, weathering state and the discontinuities analysis. In order to evaluate the quality of the rock masses, scan lines methods were employed at each ripping location. From the scan lines result, the data were evaluated by the rock mass classifications to define the ease of excavation.

The RMR, Q-system and the EI values suggested the type of excavation needed to remove the rock materials. The fractures or discontinuities normally aid the excavation by providing planes of weakness. However, the actual performance of ripping on those rocks was monitored and will be discussed in Chapter 7. At the end of this chapter, a comparison on weathering profile of granitic and sedimentary rock was made. Granitic areas are prone to have boulders and sharp boundary whereas the sedimentary areas may be influenced by the bedding, foliation and other type of discontinuities. The structural and stratigraphy of the sedimentary rocks play an important role in ripping performance and should not be neglected in any excavation assessment study. Low strength material, which can be ripped easily if it stands independently, might not be able to be ripped if it is sandwiched between unrippable materials.

CHAPTER 6

ENGINEERING PROPERTIES OF ROCK MATERIAL

6.1 Introduction

The mechanical properties of rock materials depend upon the interaction between the minerals, particles and cementations material of which it is composed. However, the physical and chemical weathering causes disintegration of original fabrics and changes in mineralogy. The rock that has been altered by weathering processes generally shows some anomalous engineering characteristics in comparison with fresh rock or residual soil. Variations in weathering grade usually result in varying engineering properties of rock. Thus, it is important to recognise the role played by weathering process in the performance of rock in engineering application.

From the literature review, it was found that in the field of rock cutting, the relevant parameters involved are strength, abrasiveness and index of machinability. In this chapter, rock material properties of the relevant site will be presented. Rock material properties were obtained from in-situ and laboratory testing from areas where ripping works had been observed and recorded. During a break in operations, samples representative of the ripped material were taken for in-situ and laboratory testing.

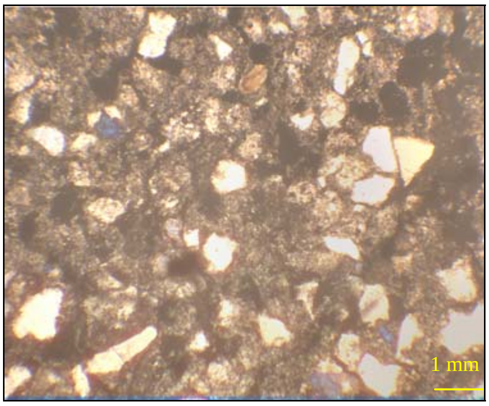
In-situ tests that were undertaken were selected as they are easy and quick to perform. The properties that were measured during in-situ testing are surface hardness and material strength. Whereas for laboratory testing, the properties that were measured were basic parameters of material strength, durability, mineralogical analysis and penetration test as described in Chapter 4.

6.2 Test Results

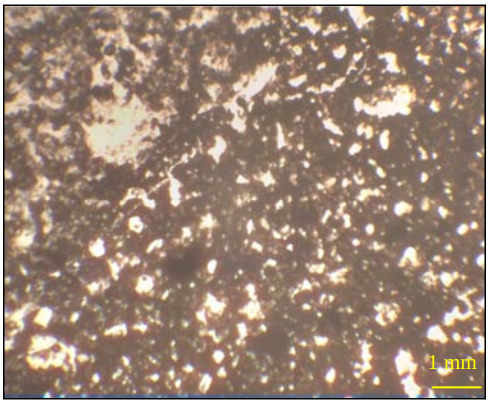
The strength behaviour evaluations of the weathered sedimentary rock mass that consists of sandstone and shale materials in this research are concentrated on tests that will determine strength and physical qualities of materials. These laboratory tests were carried out on samples from Bukit Indah, Mersing, Desa Tebrau and Kempas. The assessment of weathered materials becomes more challenging with the increase of weathering. It was found that the weathered sandstone and shale experienced decreasing physical qualities thus causing the materials difficult to be sampled. The results presented in the following sections show the results of each testing in relation to the weathering grades. The detail results for all the testing are presented in Appendix H.

6.2.1 Petrographic Study

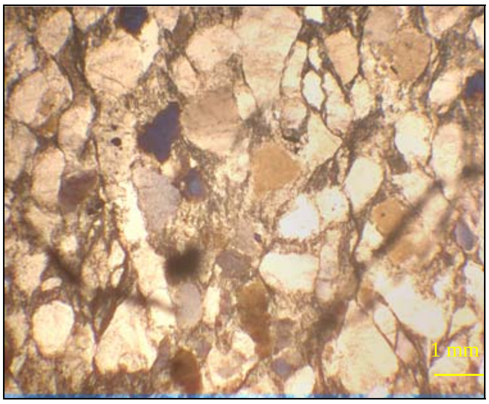
The results of petrographic analysis showed that the sandstone was mainly formed from quartz, feldspar, clay, mica and iron minerals. There was a wide range of pore sizes in the weathered sandstone due to grain size variations. Grade II fine sandstone had a fine grained, dense, generally, tightly interlocked structure with a mixture of platy minerals and quartz grains (Figure 6.1a). The pores were irregular in shape and generally less than 0.5μm in diameter, though some pores with 2-3 μm did occur. Pores exceeding 10 μm were occasionally found as evidence and generally associated with inter-granular spaces between the coarse grains. Coarser grained material has higher porosity than the fine grained material.



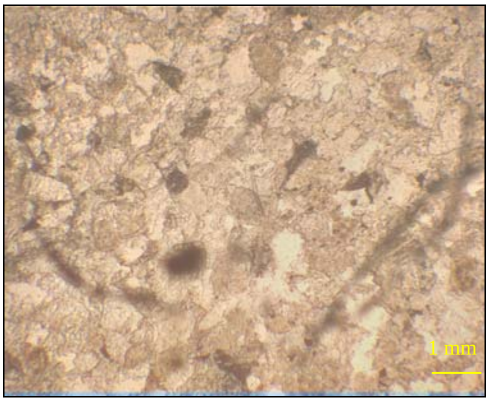
a) fine sandstone, grade II (sample B8L3)



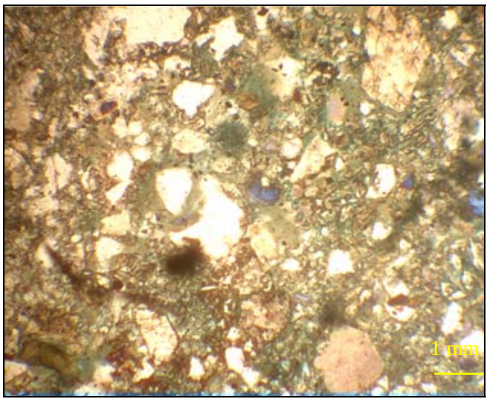
b) Shale, grade II (sample R4L9)



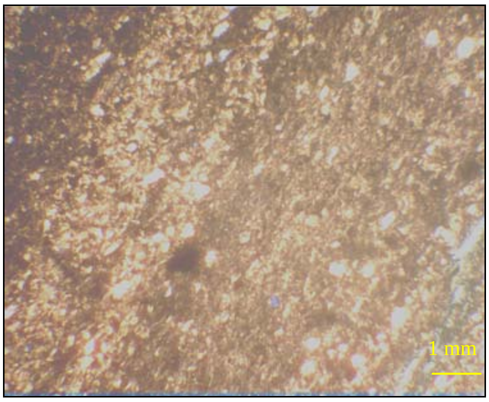
c) medium grained sandstone, grade III (sample RL3EL1)



d) Shale, grade III (sample LN7R2)



e) fine grained sandstone, grade IVa (sample LN8R3)



f) Shale, grade IVa (sample LN8R2)

Figure 6.1: Photomicrographs of sandstone and shale

High rock density was achieved due to the wide range of grain sizes present, in which fines infilled gaps between the coarser grains. Figure 5.1 (a) – (f) shows the variations in grain size as observed under the microscope. Shale has the finest grain size and lower porosity compared to sandstone. When the materials are more weathered, it was found the feldspar minerals decomposed to clay as can be seen in Figure 5.1 (c) – (f). Porosity observed in the petrographic study reflects the real change in void spaces due to weathering. It was found that in stronger sandstone (grade II) there is an absence of clay minerals and the material has good interlocking texture. On the other hand, where there was an increase of clay minerals and the material has poor interlocking texture. The presence of clay minerals can be an indicator of the role of water absorption and swelling in the rock material (Franklin et al., 1971).

6.2.2 Dry Density

Table 6.1 shows the mean of dry density, number of samples (N) and standard deviation for each weathering grade. The results are also presented graphically as plotted in Figure 6.2. The box plot shows the upper and lower value of dry density while the 25 and 75 percentiles are marked by the upper and lower part of the box. The mean is marked by the thick black line. Grade II materials show a mean of 2609 kg/m^3 with standard deviation of 131. Grade III materials show a mean of 2426 kg/m^3 with standard deviation of 114. The mean values for material in grade IVa, IVb and Va show a decreasing trend with higher weathering grades. Grade IVa has a mean value of 2241 kg/m^3 and grade IVb shows a mean of 2150 kg/m^3 while grade Va has a mean value of 1851 kg/m^3.

Table 6.1 : Table showing the mean value of dry density (kg/m^3) for respective weathering grade

Weathering Grade	**Mean (kg/m^3)**	**N**	**Standard Deviation**
Grade II	2609	8	131
Grade III	2426	17	114
Grade IVa	2241	32	120
Grade IVb	2150	21	162
Grade Va	1851	32	203
Grade Vb	2121	17	159
Total		127	

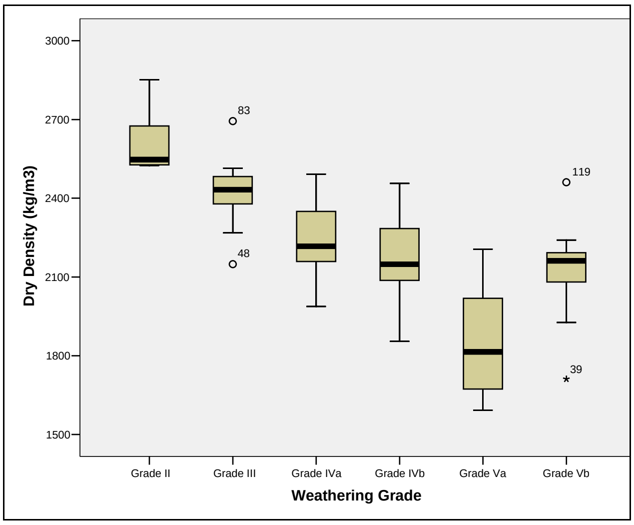


Figure 6.2 : Box plot of dry density versus weathering grade

The dry density values for grade II sandstone are in the range of 2500 to 2700 kg/m^3 and grade III to IVb were found to be in the range of 2000 to 2500 kg/m^3 while the value for grade Va and Vb are in the range of 1500 to 2200 kg/m^3. Samples of Kempas have the lowest dry density that is in ranges of 1500 to 1800 kg/m^3. In general, sandstone materials showed a dry density value of more than 1500 kg/m^3.

Grade II shale has a density value of 2500 to 2900 kg/m^3; Grade III : 2200 to 2700 kg/m3; Grade IVa : 1900 to 2900 kg/m^3; Grade IVb : 1800 to 2500 kg/m^3 and Grade Va : 1600 to 2300 kg/m3. However, the values are higher for grade Vb where the value ranges 1900 to 2500 kg/m^3. Generally, both sandstone and shale density results do not show good indicators for the weathering grade of the material.

From the results, it can be seen that dry density has a general trend of decreasing with the increase of weathering grades. However in grade Vb, it was found that the mean of the materials were higher than grade Va sample. This might due to material compactness and mineralogy changes in the rock material. Decreasing in dry density value with weathering grade can be explained by the pore enlargement where the loose debris (by weathering) might be flushed away from the pore throats in the saturating medium (Fitzner, 1988).

6.2.3 Strength Test

Test results of point load test, uniaxial compressive strength and indirect tensile (Brazillian) are presented in this section.

6.2.3.1 Point Load Index (Is_{50})

A total number of 127 samples were tested with the portable point load test at the site. The trends of Is_{50} for sandstone materials in Bukit Indah, Mersing, and Desa Tebrau show decreasing values with the increase of weathering grades. For grade II samples, the Is_{50} values are in range of 3 to 5 for both Mersing and Bukit Indah sandstones whereas Is_{50} value for grade III is in the range of 1 to 3. For grade IVa, Is_{50} values are in the range of 0 to 1 and samples from Desa Tebrau has lower values than Bukit Indah and Mersing. The Desa Tebrau alluvium samples show a value of 0.2 to 0.6. With the Universal Testing Machine (UTM) used to obtain Is_{50}, the failure load can be read sensitively, thus giving values of 0.15 to 0.91 for grade IVb sandstone.

Shale has lower strength and durability compared to sandstone. Is_{50} index shows trends of decreasing with increase of weathering grades. Materials tend to have lower strength with higher weathering grades. Materials in grade II are in ranges 3 MPa to 4 MPa; grade III is in ranges 1 MPa to 3 MPa and grade IVa in ranges 0.3 MPa to 1 MPa. Materials from grade IVb to Vb have the lowest value. The range of the point load index is shown in Table 6.2.

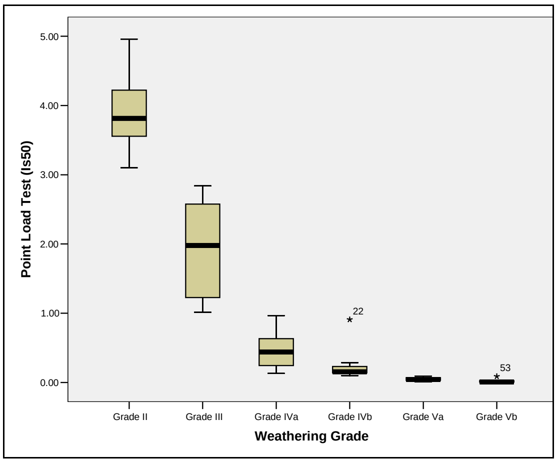
Table 6.2: The range of point load index (Is_{50}) value for the respective weathering grade

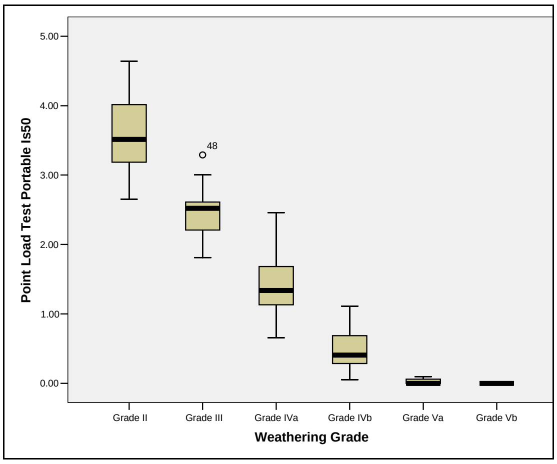
Type	Location		Range of Is_{50} value (MPa)					
			II	III	IVa	IVb	Va	Vb
Sandstone	Bukit Indah		3 to 5	1 to 2.7	0.2 to 0.9	0.1 to 1	0.05 to 0.09	0 to 0.015
	Mersing		3 to 4	1 to 3	0 to 1	0 to 0.2	0 to 0.05	0 to 0.09
	Desa Tebrau	Fine	-	-	0.1 to 0.3	-	-	-
		Coarse	-	-	0.1 to 0.2	-	-	-
	Kempas		-	-	-	-	0.02 to 0.07	-
Shale	Bukit Indah		3.6 to 4.0	1 to 2.8	0.3 to 0.7	0.1 to 0.3	0 to 0.08	0 to 0.03
	Mersing		3 to 3.5	1 to 2.7	0.4 to 1	-	0 to 0.04	-

Box plots of point load index (Is_{50}) versus weathering grades for both measured by the UTM and the portable tester are shown in Figure 6.3 (a) - (b) and their mean values are shown in Table 6.3. As for material in grade II, the point load index value (Is_{50}) range from 2.6 to 4.7 with mean of 3.59. The value decreases with higher weathering grade. When the material deteriorates to grade Va, the mean is 0.0244 and no value is detected for materials in grade Vb. When compared to the point load index measured by universal testing machine (UTM), materials in grade Vb shows mean of 0.0172 and 0.0493 for grade Va. These values can be measured by UTM machine and could not be measured by the portable point load tester. The portable point load tester could not measure the failure load of materials in grade Vb due to the insensitivity of the gauge compared to those being measured by the UTM machine. Strength of most of grade IVb, Va and Vb materials were difficult to be measured by the portable tester as the materials failed to give any reading on the gauge. Figure 6.6(a) – (b) show photographs of sample being tested with the UTM machine.

Table 6.3: Mean value of Point Load Index (Is_{50}) for respective weathering grade

Weathering Grade	Mean	N	Standard Deviation
Grade II	3.9061	8	0.59
Grade III	1.9790	17	0.67
Grade IVa	0.4111	32	0.21
Grade IVb	0.2042	21	0.17
Grade Va	0.0493	32	0.02
Grade Vb	0.0172	17	0.02
Total		127	





(a) (b)

Figure 6.3: Boxplot of Point Load Index (Is_{50}) versus Weathering Grade (a) measured by the portable point load (b) by the UTM machine

6.2.3.2 Uniaxial Compressive Strength (UCS)

The Uniaxial Compression Strength Test (UCS) is one of the tests often used in assessing the maximum strength of rock materials when compression load is applied in the unconfined condition. Maximum stress recorded at failure limit is defined as the UCS index. This index is normally used to represent index strength of material in rock mass classification systems.

The ranges of the UCS values of the rock materials in relation to their weathering grades at each site are tabulated in Table 6.4. The UCS value for grades IVb, Va and Vb are not available as it is not possible to prepare standard UCS samples. The UCS for sandstone show decreasing in value in respect to the increase of weathering grades. Values for grade II are in ranges of 50 MPa to 85 MPa. Grade III has values in ranges 20 MPa to 40 MPa showing a gap of 10 MPa from grade II. The alluvium samples of Desa Tebrau which are in Grade IVa have values of 3 MPa to 15 MPa. The UCS values for sandstone in Bukit Indah, Mersing and Desa Tebrau can only be obtained up to grade IVa. As for grade IVb to Vb the testing could not be carried out due to problems in sample preparation. Desa Tebrau fine grain samples show a higher result compared to the coarser grained materials, indicating that the interaction between grains contributes to the strength factor.

As for shale, the UCS value cannot be determined for grade IVb, Va and Vb samples as samples from these grades cannot be prepared. Similarly, the trend of UCS value decreases with the increase of weathering grade.

Table 6.4: Ranges of UCS values respective to weathering grades for each location

Type	Location		Range of UCS value (MPa)					
			II	III	IVa	IVb	Va	Vb
Sandstone	Bukit Indah		55 to 83	19 to 40	3 to 13	-	-	-
	Mersing		52 to 53	20 to 39	9 to 12	-	-	-
	Desa Tebrau	Fine	-	-	10 to 15	-	-	-
		Coarse	-	-	8 to 11	-	-	-
	Kempas		-	-	-	-	-	-
Shale	Bukit Indah		47 to 56	16 to 42	5 to 12	-	-	-
	Mersing		52 to 53	28 to 37	8 to 20	-	-	-

Table 6.5 shows the mean value of the UCS respective to the weathering grades while Figure 6.5 shows the boxplot. The mean value for each grade shows a decreasing trend when the weathering grade increases. Grade II materials show mean of 58.41 MPa, grade III of 29.63 MPa and the grade IVa materials show mean of 9.9 MPa. Figure 6.6(a) – (b) show photographs of samples tested for the UCS.

Table 6.5: Mean value of UCS for respective weathering grades

Weathering Grade	**Mean**	**N**	**Standard Deviation**
Grade II	58.41	7	11.66
Grade III	29.63	15	7.86
Grade IVa	9.90	30	3.15
Total		52	

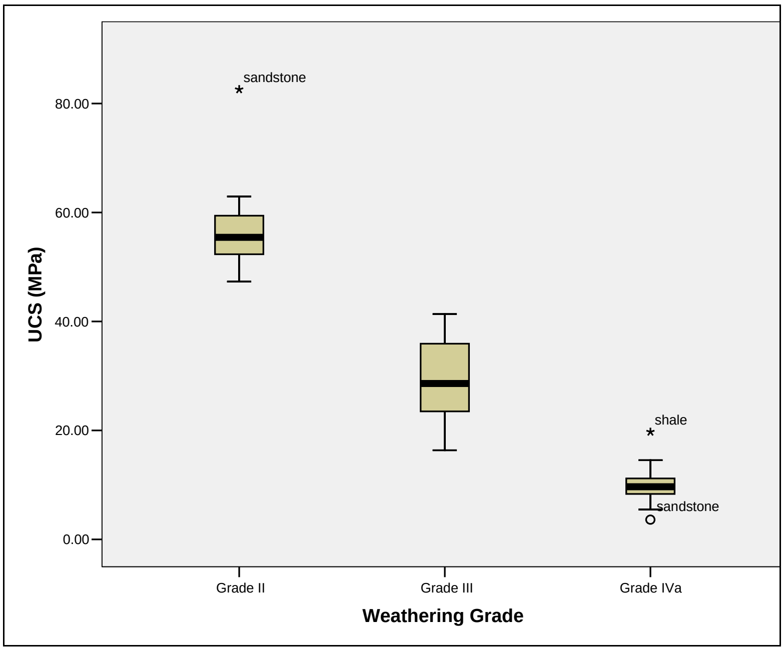


Figure 6.4: Boxplot of UCS versus the weathering grade

6.2.3.3 Brazilian Indirect Tensile Strength (ITS)

The test is all about applying load on to a small diametric rock disc. A rock mass sample is cut to a size ratio of about 1:2. Normally the size used is 50 mm diameter and 25 mm thick. The objective of this test is to obtain the tensile strength of a specified rock sample and to determine its deformability. In this laboratory test, Brazillian tests were carried out by the Universal Testing Machine (UTM). The range of the ITS values are tabulated in Table 6.6.

Table 6.6: Range of ITS values for respective weathering grade for each location

Rock Type	Location		Range of ITS value (MPa)					
			II	III	IVa	IVb	Va	Vb
Sandstone	Bukit Indah		2.7 to 4.4	1.9 to 2.8	1.1 to 2.2	-	-	-
	Mersing		4 to 4.1	1.5 to 3.9	1.4 to 1.9	-	-	-
	Desa Tebrau	Fine	-	-	1.5 to 2.5	-	-	-
		Coarse	-	-	0.6 to 2.0	-	-	-
	Kempas		-	-	-	-	-	-
Shale	Bukit Indah		3.7 to 3.8	1.6 to 3.6	0.8 to 1.7	-	-	-
	Mersing		3.7 to 3.8	1.9 to 3.5	1.6 to 1.7	-	-	-

ITS results for Bukit Indah, Mersing and Desa Tebrau show that samples of grade II to IVa decreases with weathering grade. Grade II values are in the range of 5 MPa to 3 MPa while samples in grade III have values that overlapped with grade II which ranges from 1.5 MPa to 4 MPa. Values for grade IVa are also overlapping to grade III in ranges 1 to 2.5 MPa. No samples of grade IVb to Vb were carried out for this test due to sampling problems.

Boxplot in Figure 6.7 shows that grade II has a high tensile strength and the value decreases with weathering grade while Table 6.7 shows the mean values. The mean value for grade II samples is 3.65 MPa, a mean value of 2.62 MPa for grade III samples and a mean value of 1.53 MPa for the grade IVa samples. Grade IVa has the lowest tensile strength and for grade IVb to Vb, tensile strength could not be tested by the Brazillian method because the samples were broken during preparation. Figure 6.8(a) – (b) show photographs of samples tested for the ITS.

Table 6.7: Mean value of ITS for respective weathering grade

Weathering Grade	Mean	N	Standard Deviation
Grade II	3.65	8	0.50
Grade III	2.62	17	0.68
Grade IVa	1.53	31	0.46
Total		56	

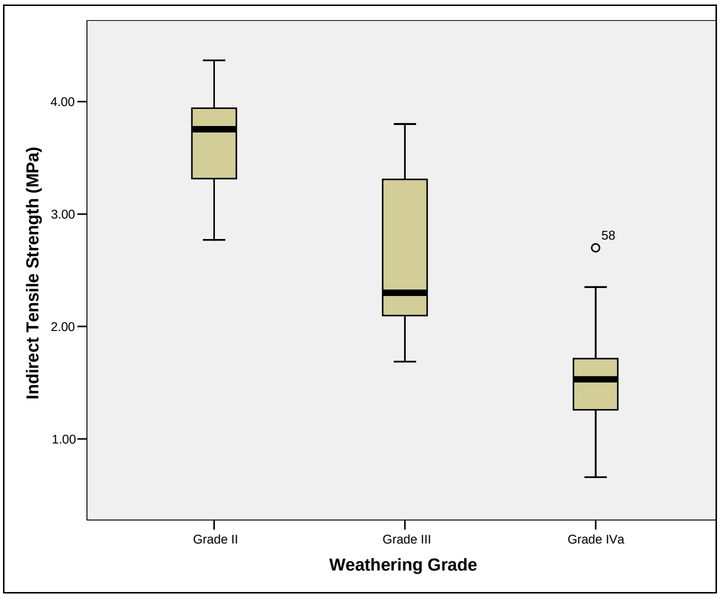


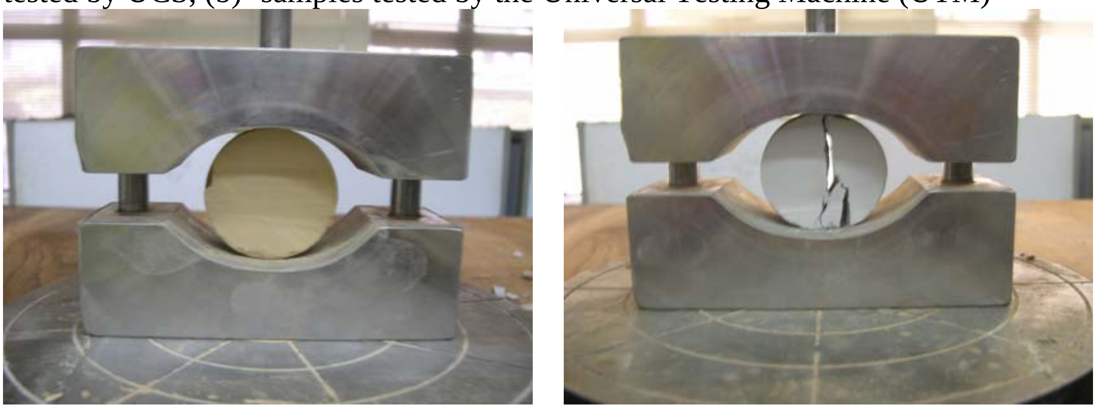
Figure 6.5: Boxplot of ITS versus weathering grade

(a) (b)

Figure 6.6: Photographs showing samples tested by the point load test (by UTM): (a)-(sample R2L1), (b)- sample B8L9 tested by UTM

(a) (b)

Figure 6.7: Photographs showing samples tested for UCS: (a)- some samples being tested by UCS, (b)- samples tested by the Universal Testing Machine (UTM)



(a) (b)

Figure 6.8: Photographs showing samples tested for the Brazillian Indirect Tensile Test: (a)- (sample R6L1), (b)- (sample LN4R4)

6.2.4 Surface Hardness

Table 6.8 shows the range of surface hardness values for respective weathering grade and Table 6.9 shows their mean value. In general, Schmidt hammer values decreased with the increased of weathering grades as shown in Figure 6.9. However, a broad range of values overlaps in grade II, III and IVa. Grade II shows values in ranges between 35 MPa to 95 MPa with a mean value of 55 MPa. Grade III values are lower than grade II, with a range from 25 MPa to 83 MPa with a mean value of 37 MPa. Whereas grade IVa is in the range of 10 MPa to 40 MPa with a mean value of 22 MPa which is much lower than grade II and grade III. No Schmidt hammer values can be obtained for grade IVb to grade Vb. These shows that in-situ Schmidt Hammer strength test is not very suitable for determining hardness and strength of sandstone materials. It is only suitable for a rough estimation on those parameters. Furthermore, readings are directly influenced by the joints present on site and results can be inaccurate.

Table 6.8: Range of surface hardness value for respective weathering grade

Type	Area		Ranges of surface hardness (MPa)					
			II	III	IVa	IVb	Va	Vb
Sandstone	Bukit Indah		38 to 92	28 to 82	10 to 28	-	-	-
	Mersing		48	28 to 44	26 to 40	-	-	-
	Desa Tebrau	Fine	-	-	21 to 22	-	-	-
		Coarse	-	-	18 to20	-	-	-
	Kempas		-	-	-	-	-	-
Shale	Bukit Indah		31 to 35	30 to 39	20 to 35	-	-	-
	Mersing		31	19 to 25	17 to 25	-	-	-

Table 6.9: Mean value of surface hardness for respective weathering grade

Weathering Grade	Mean	N	Standard Deviation
Grade II	55	8	25.52
Grade III	37	17	14.19
Grade IVa	22	32	4.70
Total		57	

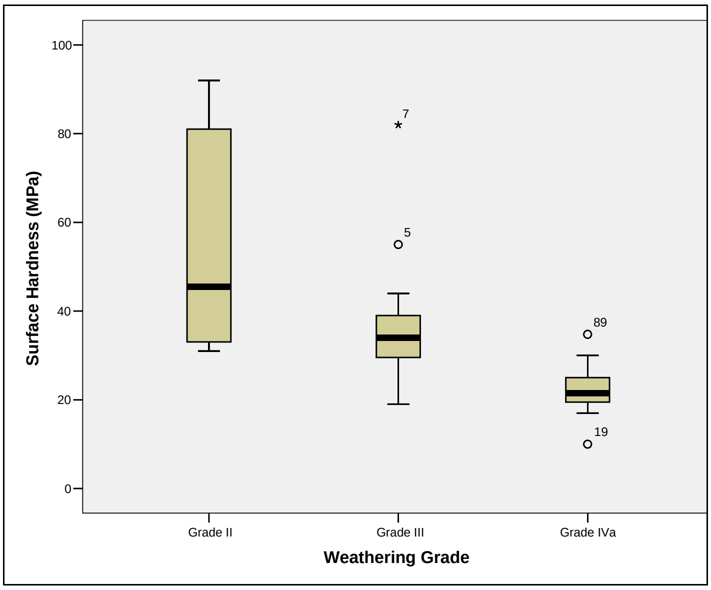


Figure 6.9: Boxplot of surface hardness versus weathering grade

6.2.5 Durability Test

The tests for durability of rock material include the slake durability test and the jar slake test and the results are presented in this section.

6.2.5.1 Slake Durability

The Slake Durability Test was originally developed by Franklin and Chandra (1972). This test aims to assess the resistance of rock material to weathering and disintegration when subjected to two standard cycles of drying and wetting. Table 6.10 and 6.11 show the results of Id_1 and Id_2 by weathering grades. The mean values for the Id_1 and Id_2 are shown in Table 6.12 and 6.13 respectively.

Table 6.10: Summary of slake durability Id_1 result for respective weathering grade

Type	Area		Range of Id1					
			II	III	IVa	IVb	Va	Vb
Sandstone	Bukit Indah		94% to 99%	91% to 99%	74% to 96%	25% to 33%	-	-
	Mersing		98% to 99%	91% to 98%	61% to 62%	18% to 19%	-	-
	Desa Tebrau	Fine	-	-	73% to 76%	-	-	-
		Coarse	-	-	71% to 73%	-	-	-
	Kempas		-	-	-	-	-	-
Shale	Bukit Indah		95% to 97%	92% to 98%	68% to 98%	21% to 39%	-	-
	Mersing		94% to 95%	87% to 90%	46% to 76%	-	-	-

Table 6.11: Summary of slake durability Id_2 result for respective weathering grade

Type	Area		Range of Id_2					
			II	III	IVa	IVb	Va	Vb
Sandstone	Bukit Indah		90% to 98%	73% to 91%	38% to 73%	-	-	-
	Mersing		94% to 95%	78% to 91%	49% to 50%	-	-	-
	Desa Tebrau	Fine	-	-	40% to 44%	-	-	-
		Coarse	-	-	32% to 40%	-	-	-
	Kempas		-	-	-	-	-	-
Shale	Bukit Indah		90% to 92%	80% to 92%	39% to 86%	-	-	-
	Mersing		91% to 92%	82% to 88%	30% to 63%	-	-	-

Table 6.12: Mean value of Id_1 for respective weathering grade

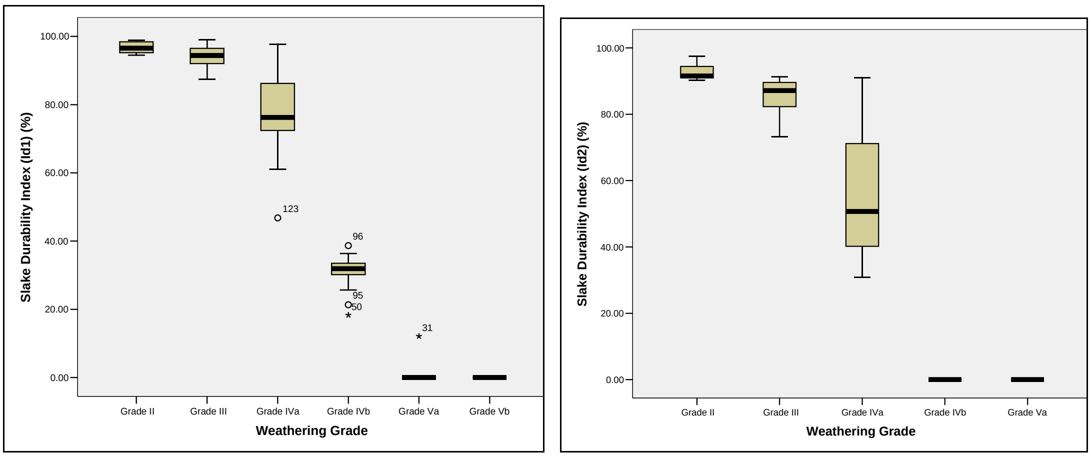
Weathering Grade	**Mean**	**N**	**Standard Deviation**
Grade II	97	8	1.74
Grade III	94	17	3.03
Grade IVa	80	32	11.05
Grade IVb	31	21	4.86
Grade Va	0	32	2.14
Grade Vb	0	17	0
Total		127	

Table 6.13: Mean value of Id_2 for respective weathering grade

Weathering Grade	**Mean**	**N**	**Standard Deviation**
Grade II	93	8	2.51
Grade III	86	17	4.96
Grade IVa	56	32	18.00
Grade IVb	0	21	0
Grade Va	0	32	0
Grade Vb	0	17	0
Total		127	

Slake Durability Index Id_1 and Id_2 are determined and presented in the graphs as shown in Figures 6.10(a) and (b) respectively. The durability index Id_1 and Id_2 generally shows increase of deterioration percentage with increase of weathering grade. Id_1 values cannot be used to distinguish grade Va and Vb materials. Grade Va to Vb has 0 percent value which means that these samples are totally destroyed in the test. Figure 6.10(a) shows the result of Id_1 that is graphically illustrated. It shows a rapid decrease in values from grade IVa to IVb. This shows that shale materials in grade Va and Vb could not even retain their structure in the first cycle of slake durability test.

As samples are further tested in the second cycles (Id_2), results show a clearer division for samples in grade II, III and IVa. However, samples in grade IVb, Va and Vb will further destroyed in the second cycle. For both Id_1 and Id_2, the alluvium samples in Desa Tebrau for grade IVa show a difference in the result for its different grain size. The coarse material shows lower values as compared to the finer ones. This signifies that coarser material is destroyed faster than the finer grain size.



(a) (b)

Figure 6.10: Boxplot of (a) Id_1 and (b) Id_2 versus weathering grade

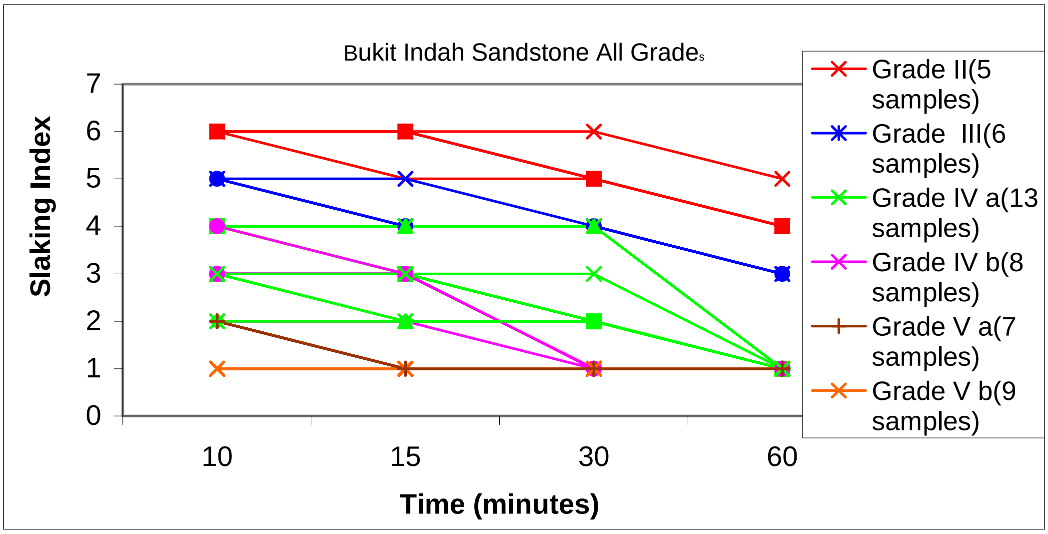
The Id_2 results are shown graphically in Figure 6.10(b). From the boxplot, we can see that grade IVb to Vb materials could not survive the second cycle of the test and has a zero value.

It was found that slake durability test is primarily influenced by rock properties which allow ingress of water into the rock material. The presence of clay minerals enhanced rock susceptibility to slaking as can be seen in the higher weathering grades materials.

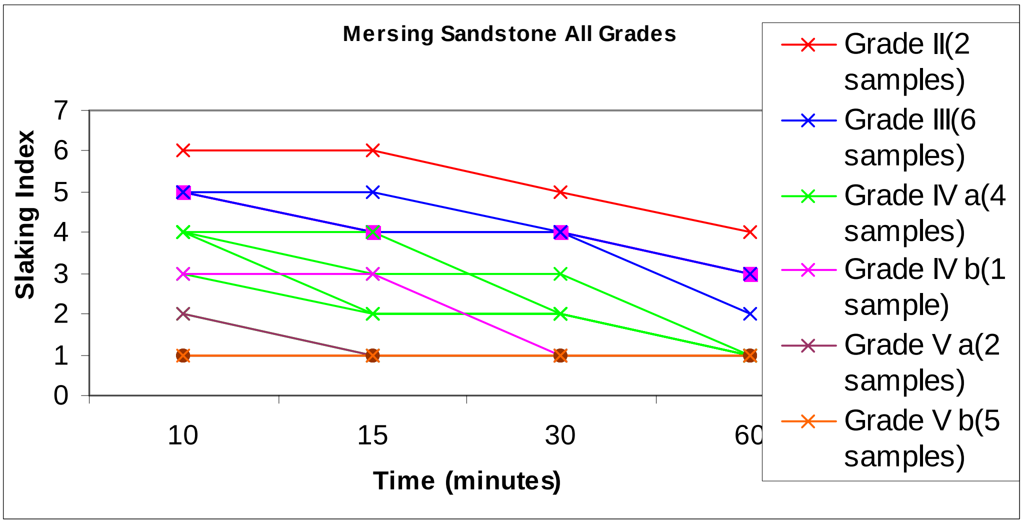
6.2.5.2 Jar Slaking Test

The objective of Jar test is to observe the reactions of the rock material to water in terms of weathering (Santi, 1998 a,b). The test is done by immersing the samples. The samples are placed in jars filled with tap water for a period of 10 minutes, 15 minutes, 30 minutes and 60 minutes. Slaking index is given to each sample based on the behaviour of samples after each period of time. This test can be carried out at the site or in the laboratory.

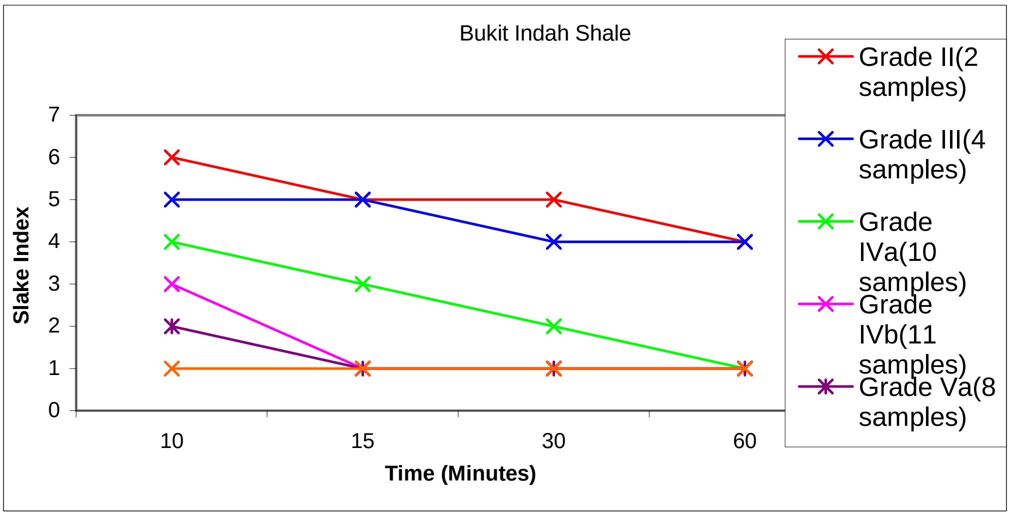
The rock samples for the test were classified as their respective weathering grade as what have been determined at the site. The rock samples were immersed in water and their slaking behaviours were noted. For each observation, an index was given based on Figures 4.16 and 4.17. Test results for jar slaking are presented in Figure 6.11(a) – (f). Figure 6.11(a) and (b) shows the jar slaking index for Bukit Indah and Mersing sandstone respectively. Grade II samples were found intact for the first 10 minutes. After 30 minutes of immersion, the samples deteriorated to index number 5 and few samples were still intact as index 6. At the end of the 60 minutes immersion, the samples showed index 4 as the lowest index. As for grade III sandstone, the samples were observed to be of index 5 after 10 min of immersion in water. As the immersion was prolonged for another 20 minutes, the samples broke down to index no 4. At 60 minutes, the samples were observed to show number 2 as the lowest index.


Bukit Indah Sandstone All Grades
Slaking Index
Time (minutes)
Grade II(5 samples)
Grade III(6 samples)
Grade IV a(13 samples)
Grade IV b(8 samples)
Grade V a(7 samples)
Grade V b(9 samples)

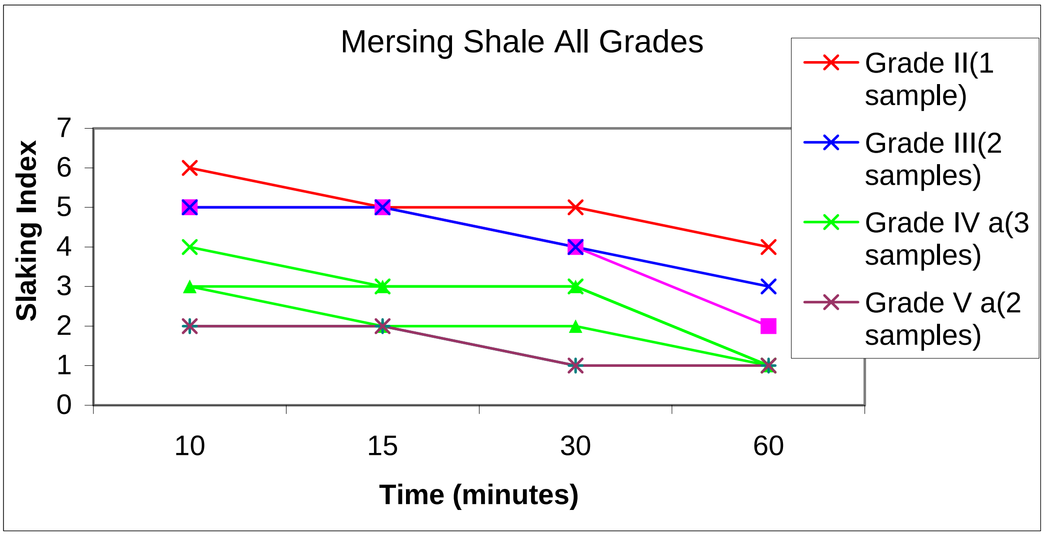
(a)


Mersing Sandstone All Grades
Slaking Index
Time (minutes)
Grade II(2 samples)
Grade III(6 samples)
Grade IV a(4 samples)
Grade IV b(1 sample)
Grade V a(2 samples)
Grade V b(5 samples)

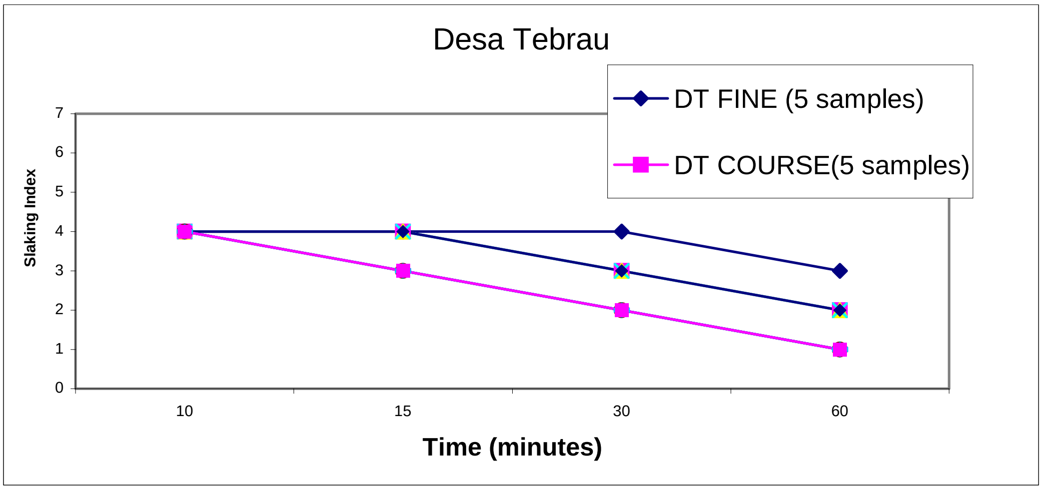
(b)


Bukit Indah Shale
Slake Index
Time (Minutes)
Grade II(2 samples)
Grade III(4 samples)
Grade IVa(10 samples)
Grade IVb(11 samples)
Grade Va(8 samples)

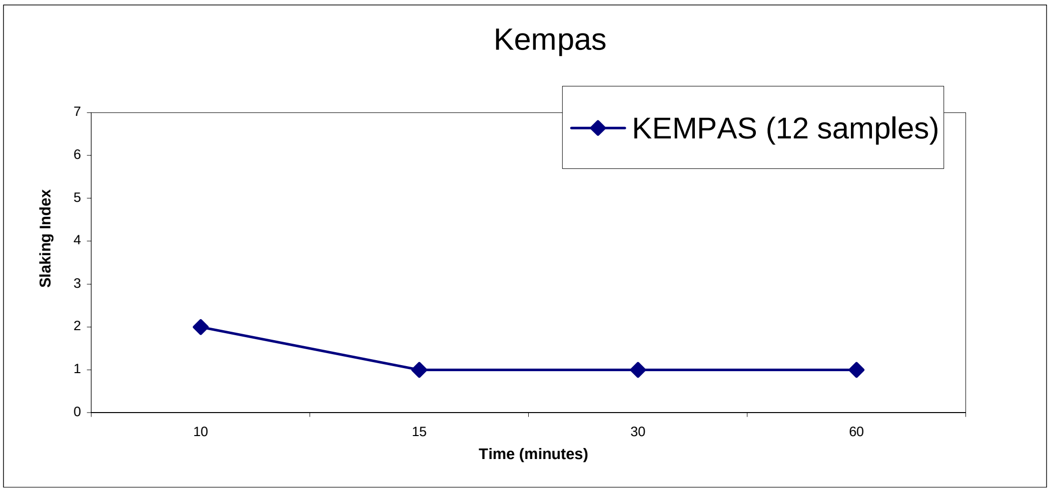
(c)



(d)



(e)



(f)

Figure 6.11 (a) – (f) : Test results of jar slaking index for various locations

Grade IVa samples showed index numbers 2, 3 and 4 for the first 10 minutes of immersion. The range of slaking index for sandstone grade IVa after 30 minutes was observed to be 2, 3 or 4. At the end of the test (60 minutes) all samples showed index of number 1. For grade IVb samples, they were observed to show index number of 3 or 4 after 10 minutes of immersion in water. All the samples broke down to index number 1 after 30 minutes. Fine and coarse grained materials from Desa Tebrau (grade IVa) showed index number of 4 after 10 minutes of immersion in water (Figure 6.11e). The coarser grained materials broke down faster than the finer grained ones due to the higher porosity that was detected after 15 minutes. Subsequently, the coarse grained materials showed index numbers of 1 and 2 after 60 minutes while the fine grained showed index number of 2 and 3. As for grade Va samples, it showed index number 2 after 10 minutes and all samples showed index number 1 after 15 minutes. The same results were also observed for Kempas materials as shown in Figure 6.11(f). As for the grade Vb sandstone, the materials broke down to the lowest index of number 1 after 10 minutes.

Figure 6.11 (c) – (d) show the jar test result for shale. Grade II shale showed index number 6 after 10 minutes of immersion in water for both Bukit Indah and Mersing materials. The index dropped to number 5 after 15 minutes and maintained at the same index after 30 minutes immersed in water. At the end of 60 minutes, the materials showed index number 4. As for grade III shale, samples from Bukit Indah and Mersing showed index number 5 after 10 minutes. After 15 minutes, they showed index number 4 and after 60 minutes the samples finalized at index number 2, 3 and 4. The grade IVa materials showed a lower index when observed after 10 minutes which was index number 4. In 15 minutes, the materials broke down to index number 2, 3 or 4 depending on the porosity of the samples and their strength. Higher porosity samples with lower strength broke down faster than high strength lower porosity samples. After 30 minutes, samples showed index number 2 and 3. At the end of the test period (60 minutes), the samples showed index number 1. Grade IVb samples showed index number 3 after 10 minutes and subsequently after 15 minutes immersion, the samples broke down to index number 1. The shale of grade IVb broke down faster as compared to sandstone in the same grade as the shale has clay constituents that swelled when immersed in water. The findings in the rate of deterioration in shale were also reported by Santi (1995). Samples Va showed index number 2 after 10 minutes and completely broke down to index number 1 in 30 minutes. Samples Vb showed index number 1 after 10 minutes of immersion. Table 6.14 and 6.15 show the summary of the results and the lowest index observed during the study respectively.

Table 6.14: Summary of jar test results for respective weathering grade

Type	Area		Range of Jar Slaking Index					
			II	III	IVa	IVb	Va	Vb
Sandstone	Bukit Indah		20 to 23	16 to 17	8 to 13	8 to 9	5	4
	Mersing		21	16 to 17	11	8	5	4
	Desa Tebrau	Fine	-	-	13 to 15	-	-	-
		Coarse	-	-	10	-	-	-
	Kempas		-	-	-	-	5	-
Shale	Bukit Indah		20	16 to 18	7 to 13	6 to 9	5	4
	Mersing		20	16 to 17	10 to 11	-	6	-

Table 6.15: Summary of the lowest index observed

Material type	**Weathering grade**	**10 min**	**15 min**	**30 min**	**60 min**
Sandstone/shale	II	6	5	5	4
	III	5	4	4	3
	IVa	2	2	2	1
	IVb	2	2	1	1
	Va	2	1	1	1
	Vb	1	1	1	1

The indices were used to produce the total jar slake index by adding the index observed in 10, 15, 30 and 60 minutes. The result of the jar slake index with regard to the weathering grade is shown by boxplot in Figure 6.12. The boxplot showed the decrease of total jar slake index with the increase of weathering grade and the mean value for respective weathering grade is shown in Table 6.16. Figure 6.13 (a) to (f) show the typical slaking indices observed during the test.

Table 6.16: Mean value of jar slaking index for respective weathering grade

Weathering Grade	Mean	N	Standard Deviation
Grade II	21	8	1.04
Grade III	16	17	0.71
Grade IVa	10	32	1.99
Grade IVb	7	21	1.20
Grade Va	5	32	0
Grade Vb	4	17	0
Total		127	

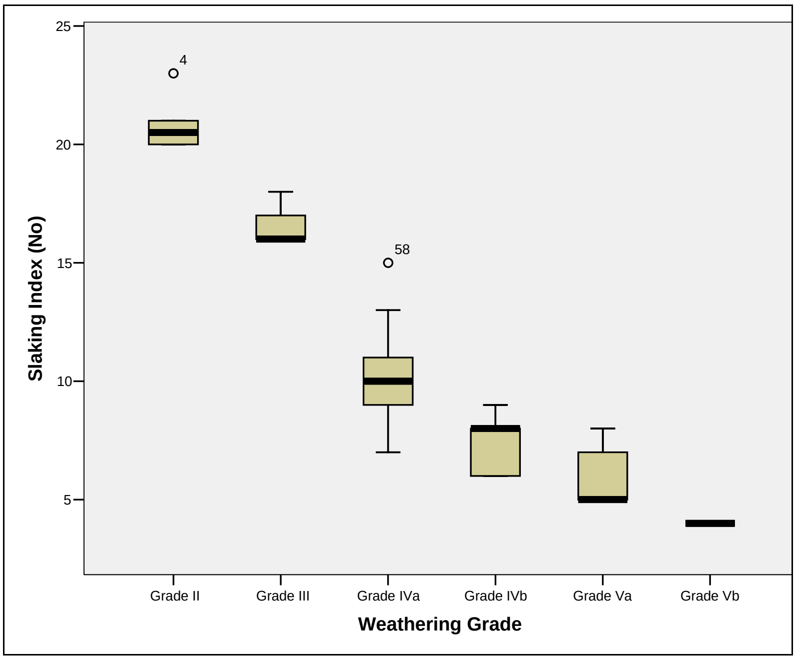


Figure 6.12: Boxplot of slaking index versus weathering grade

(a) (b)

(c) (d)

(e) (f)

Figure 6.13: Typical jar slake result: (a) index no. 6 (sample R8LN6R2S- 15 min), (b)- index no 5 (sample RL1L5- 15 min), (c)- index no. 4 (B1L3- 10 min), (d)- index no. 3 (B7L2- 10 min), (e)-index no. 2 (sample B1L3- 30 min), (f)- index no 1 (sample B6L2- 10 min)

6.2.6 Sonic Wave Velocity Test

This method involves the theory of elastic wave propagation in which a mechanical impulse is imparted to the samples and the time required to send the wave pulse through the sample, is recorded and used to calculate the velocity of the wave by using formulas discussed in the Pundit test theory. Sonic velocity (PUNDIT) test gives good correlations with weathering grade. It shows that the values decrease steadily with weathering grade. The range of the sonic velocities in respect to the weathering grades are summarized in Table 6.17 and their mean values are tabulated in Table 6.18. The results are illustrated in a boxplot in Figure 6.14 and it shows a decreasing trend of sonic wave velocity values with weathering grades. It was found that the sonic wave velocity results were overlapping in grade IVa, IVb, Va and Vb. These results indicate that sonic wave velocity is unable to classify the higher weathering grades of material.

Table 6.17: Range of sonic velocity (m/s) result for respective weathering grade

<table>
<tr><th rowspan="2">Rock Type</th><th rowspan="2" colspan="2">Location</th><th colspan="6">Range of sonic wave velocity (m/s)</th></tr>
<tr><th>II</th><th>III</th><th>IVa</th><th>IVb</th><th>Va</th><th>Vb</th></tr>
<tr><td rowspan="5">Sandstone</td><td colspan="2">Bukit Indah</td><td>2600 to 3000</td><td>2000 to 3000</td><td>1600 to 1900</td><td>1300 to 1800</td><td>1200 to 1700</td><td>1200 to 1700</td></tr>
<tr><td colspan="2">Mersing</td><td>2800 to 3000</td><td>2500 to 2700</td><td>1800 to 2000</td><td>1400 to 1500</td><td>1300 to 1400</td><td>1200 to 1400</td></tr>
<tr><td rowspan="2">Desa Tebrau</td><td>Fine</td><td>-</td><td>-</td><td>1900 to 2000</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Coarse</td><td>-</td><td>-</td><td>1800 to 2000</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td colspan="2">Kempas</td><td>-</td><td>-</td><td>-</td><td>-</td><td>1100 to 1200</td><td>-</td></tr>
<tr><td rowspan="2">Shale</td><td colspan="2">Bukit Indah</td><td>2800 to 3000</td><td>2400 to 3000</td><td>1200 to 2600</td><td>1300 to 1900</td><td>1100 to 1800</td><td>1100 to 1300</td></tr>
<tr><td colspan="2">Mersing</td><td>2800 to 3000</td><td>2400 to 2600</td><td>1800 to 1900</td><td>-</td><td>1300 to 1400</td><td>-</td></tr>
</table>

Table 6.18: Mean value of sonic wave velocity (m/s) for respective weathering grade

Weathering Grade	Mean	N	Standard Deviation
Grade II	2829	8	79
Grade III	2546	17	234
Grade IVa	1952	32	290
Grade IVb	1610	21	181
Grade Va	1294	32	164
Grade Vb	1332	17	138
Total		127	

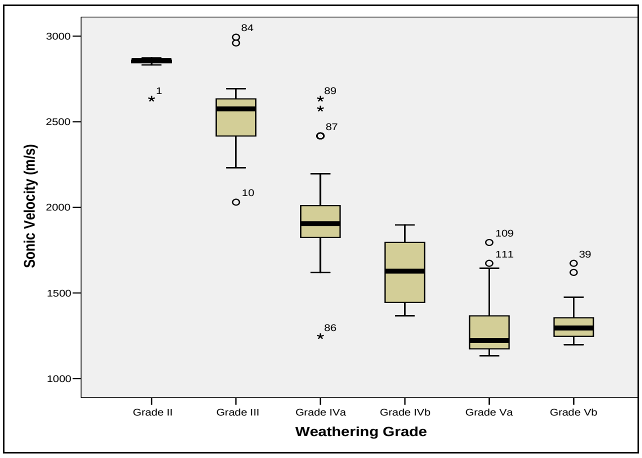


Figure 6.14: Boxplot for sonic wave velocity versus weathering grade

6.2.7 Penetration Test

The results of the penetration test with a 10 mm probe and point load bit probe are described in this section. Figures 6.15 (a) and (b) show the boxplot of the results of penetration with a 10mm probe and point load bit probe respectively. Their means based on weathering grade are tabulated in Table 6.19 and 6.20. Both penetration results showed decreasing load value with the increase of weathering grade.

Figure 6.16(a) - (f) show the photograph of typical failure observed in different weathering grades. It was observed that the material was broken by radial cracking or chip formation in stronger samples (grade II – III). Stronger samples showed little indentation before the failure took place. As materials are softer (grade IVa – IVb), the indentation was deeper as can be seen in Figure 6.16 (c) to (d). As the probe penetrated down into the sample and after some indentation on the material, the material failed by radial cracking or sometimes by chipping. This mechanism was not observed in samples in grade Va and Vb as these samples were only penetrated without initiating cracks as shown in Figure 6.16 (e) – (f).

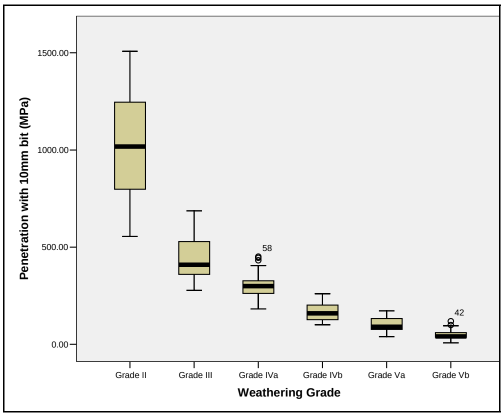
The penetration results with the point load bit are shown in Figure 6.15 (b). Figure 6.17 (a-i) to (a-v) show the sequence of typical failure mode in grade II sandstone. Similar to the failure mode by using the 10 mm probe, there was a very little indentation before the samples created minor cracks. This mode can be seen in Figure 6.17 (a-ii) where hairline radial cracks were observed. As load increased, the cracks became larger (Figure 6.17 a-iii) before chipping took place (Figure 6.17 a-iv) and finally the sample failed as can be observed in Figure 6.17 a-v. For softer material, there was some indentation before failure as can be observed in Figure 6.17 a-ii. Figure 6.18 (b-I to ii) show the radial cracking in grade III sample during the failure. Figure 6.18 (c) showed failures in shale grade IVa. Similarly as in sandstone, there is some indentation before the radial crack or chipping took place. The sample tends to fail along the foliation or through the existing weakness plane as well. Figure 6.18 (d) show deeper indentation before failure by radial cracking in grade IVb sandstone. In softer materials (regardless the material type), no cracking was observed as the probe penetrated the material as observed in Figure 6.18(e) and 6.18 (f).

Table 6.19: Mean value for penetration load with 10 mm probe (MPa)

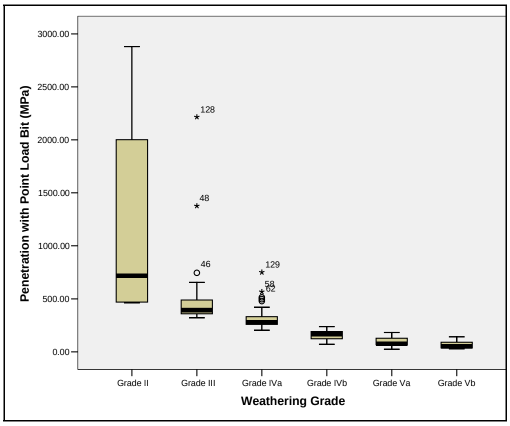
Weathering Grade	**Mean**	**N**	**Standard Deviation**
Grade II	1023	8	318
Grade III	440	17	121
Grade IVa	303	32	73
Grade IVb	167	21	49
Grade Va	102	32	36
Grade Vb	52	17	30
Total		127	

Table 6.20: Mean value of penetration load for point load bit (MPa)

Weathering Grade	**Mean**	**N**	**Standard Deviation**
Grade II	715	8	943
Grade III	490	17	255
Grade IVa	294	32	82
Grade IVb	166	21	43
Grade Va	95	32	43
Grade Vb	65	17	36
Total		127	



(a)



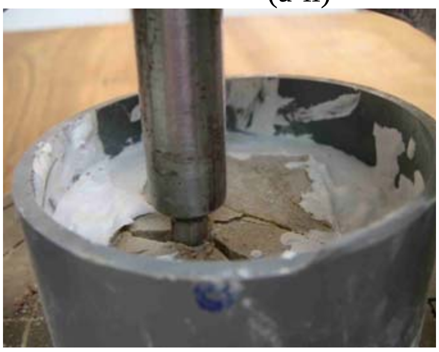
(b)

Figure 6.15: Boxplot of penetration load of (a) 10 mm probe (b) point load bit vs weathering grade

(a-i)

(a-ii)

(b-i)



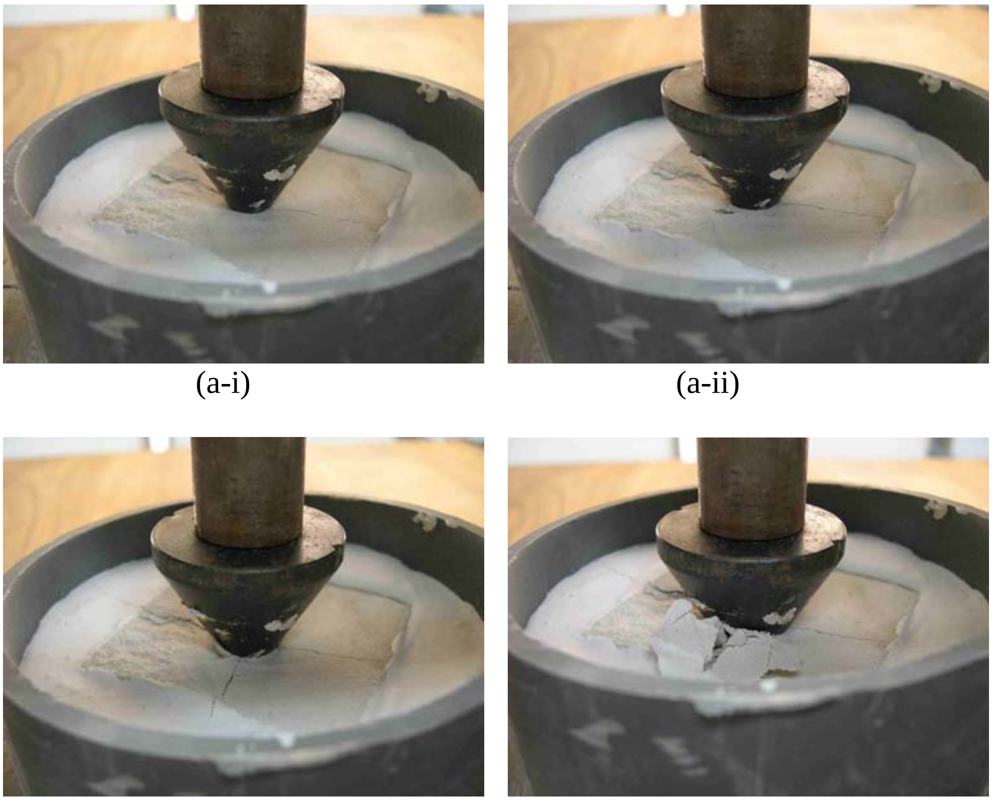
(b-ii)

(c)

(d)

(e) (f)

Figure 6.16 : Photographs showing the typical failure mechanism for penetration test by10mm probe: (a-i) and (a-ii)- Grade II (R8LN2UR1), b(i) and (b(ii)- Grade III (sample R6L1), (c)- grade IVa (sample B1L3), (d)- grade IVb (sample B4LA), (e)- grade Va (sample B2SH4) and (f)- grade Vb (sample B6L2).



(a-i) (a-ii)

(a-iii) (a-iv)

(a-v)

Figure 6.17 : Sequence of failure mechanism for grade II sandstone (sample: B8-L3)

(b-i)

(b-ii)

(c)

(d)

(e)

(f)

Figure 6.18 : Photographs showing the typical failure mechanism for penetration test by point load bit: b(i) and (b(ii)- Grade III (sample LN8R3), (c)- grade IVa (sample R8LN1R2), (d)- grade IVb (sample R4L8), (e)- grade Va (sample R4L4) and (f)- grade Vb (sample LN6R5).

6.2.8 Effects of Moisture Content

Results of the penetration load test (by using a 10 mm probe) on rock samples when soaked in water for 15 minutes and the initial moisture content are shown in Appendix I. The summary of the result is tabulated in Table 6.21. All samples were tested normal to the foliations (if any).

Generally, the result shows decreasing of penetration load with increase of weathering grade. The results also showed increased of moisture content with the increased of weathering grades. The results indicated the susceptibility of water on weaker samples is more compared to the fresher samples. The increased of moisture content helped in reducing the penetration load. Moisture content that were measured on Bukit Indah and Mersing sandstones increased less than 5 percent for grade II samples but the grade Vb showed increasing of up to 35 percent of moisture content. The same phenomena can be seen on old alluvium from Desa Tebrau and Kempas. Samples from Desa Tebrau which has weathering grade IVa showed reduction of 38 to 69 percent of the penetration load while the Kempas samples (grade Va), showed reduction of 77 to 94 percent of the penetration load.

It was revealed from petrographic analysis that rock samples will have more clay minerals and pores in higher grade of weathering. These clay minerals and pores help the absorption of water, thus reducing the penetration load. Broch (1974) explained that the reduction of strength with increase of moisture content is due to the reduction in the internal friction and their surface energy. The moisture within the grains acts as grease and reduces the strength of the material. The pores within the grains will assist the absorption of moisture within the rock material, thus porous rock especially in grade IV and V showed significant reduction on penetration load.

Table 6.21: Summary of the penetration load result

Rock Type	**Location**	**Weathering Grade**	**Increase of Moisture Content (%)**	**Decrease of Penetration Load (%)**
Sandstone	Bukit Indah and Mersing	II	<5%	6 - 13
		III	<5%	16 - 20
		IV a	<5%	22 - 41
			5-10%	44 - 49
		IV b	5-10%	51 - 61
			10-15%	62 - 70
		V a	10-15%	70 - 82
			15-20%	83 - 84
		V b	15-20%	85 - 92
			20-25%	92 - 94
			25-30%	94 - 97
			30-35%	98 - 100
	Desa Tebrau	IV a	5-10%	38 - 48
			10-15%	46 - 69
	Kempas	Va	<5%	77 - 90
			5-10%	92 - 94
Shale	Bukit Indah and Mersing	II	<5%	13 - 22
		III	<5%	24 - 29
		IV a	<5%	37 - 49
			5-10%	50 - 51
		IV b	5-10%	36 - 57
		V a	<5%	54 - 58
			5-10%	59 - 70
		V b	<5%	79 - 83
			5-10%	95

6.2.9 Effects of Iron Pan on Rock Material Properties

Results on the effects of iron pan on the rock material properties by Is_{50} and penetration (by 10 mm probe) testing are tabulated in Table 6.22 and 6.23 respectively. Generally, the Is_{50} increased with the thickness of iron pan as shown in Table 6.22. It was found that the increase of Is_{50} was up to 83 percent when the iron pan thickness was 0.5 cm. When the iron pan is 0.5 to 1 cm, the increment of Is_{50} was 80 to 480 percent. The high percentage of increment was detected on grade IVa sandstone which initially showed Is_{50} of 0.384 MPa without the iron pan but was increased to 2.246 MPa with the presence of iron pan. Significant increase of Is_{50} was observed in grade Va sandstone which was 0.044 MPa without iron pan to 6.636 MPa with iron pan with a thickness of 1 cm.

Table 6.22: Comparison of point load index (Is_{50}) values for materials with iron pan

Weathering grade	**Sample**	**Is_{50}**			**% Increase of Is_{50}**
		Without Iron Pan	With Iron Pan		
III	R6 L1	2.672	<0.5cm	3.283	22.85
III	RL 1 L6	1.028		1.371	33.32
IVa	B1 L1	0.827		1.331	60.90
III	B8 L9	1.025		1.687	64.58
IVa	RL 3 Slope Area 1 L5 (Zone B)	0.852		1.412	65.72
IVa	LN8 UR1	0.592		1.016	71.61
III	B6 L1	1.053		1.832	73.99
IVa	B1 L3	0.581		1.042	79.40
III	RL 3 C L2	1.977	0.5-1.0cm	3.930	98.80
IVa	LN4 R3S	0.433		1.099	153.76
III	LN8 UR2	1.288		3.305	156.60
IVa	LN3 R3S	0.794		2.138	169.30
IVa	R7 L1	0.763		2.108	176.32
III	R3 L1 R4S	1.288		3.891	202.13
IVa	B1 L2	0.407		1.241	204.82
IVa	RL 3 Slope Area 1 L5(a)	0.491		1.569	219.51
IVa	LN8 R3	0.493		2.392	385.18
III	RL 1 (b) L2	1.166		5.722	390.72
IVa	LN3 UR1	0.739		3.732	405.01
IVa	B2 L3	0.384		2.246	484.90

The results of penetration test by 10 mm probe on materials with iron pan are tabulated in Table 6.23. Both Is_{50} and penetration tests results agreed that the thickness of iron pan that coated the surface of rock materials resulted in increase in the strength of the rock material. A study of the properties of iron pan was carried out and it was found that the iron pan has a density of 4.5 t/m^3, Is_{50} value of 19 MPa and a Schmidt hammer value of 40.

Table 6.23: A comparison of penetration load for materials with iron pan

Weathering grade	**No Sample**	**Penetration Load (MPa)**			**% Increase of Penetration Load**
		Without Iron Pan	With Iron Pan		
V a	R7 L2	118.97	<0.5cm	218.460	83.63
Vb	RL 3 A L4	60.84		160.726	164.16
V a	R4 L7	60.47		187.715	210.42
V b	B6 L2	49.46		172.374	248.52
IV b	B7 L2	37.30	0.5-1.0cm	171.610	360.07
V b	R8 LN1 R1	36.16		171.101	373.24
IVa	RL 3 Slope Area 1 L5 (Zone C)	36.16		187.460	418.49
Va	RL 3 Slope Area 1 L1	22.98		159.962	596.12
IVb	RL 3 A L1	16.87		183.514	987.92

6.3 Summary

The test results indicate that the strength, durability and density of rock materials deteriorate with the increase of weathering grade. As strength of rock material is a function of several properties including the hardness of the mineral constituents, degree of compactness, texture and inter-granular bonding material (Matsuoka, 1990) their inter relation can be expected. Petrographic analysis revealed that feldspar and biotite minerals decomposed to clay as weathering takes place.

Various tests were adopted in this study to determine the material properties. However, it was found that certain tests were only suitable to be adopted for certain weathering grades. Table 6.24 shows the test that was found suitable for various weathering grade. The Brazilian ITS, UCS and Id_1 were found suitable to be used to test grade II, III and IVa materials. This was because weaker samples tend to break down during sample preparation for UCS and Brazilian ITS testing. For grade IVb, Va and Vb materials broke down during the first cycle of slake durability test. Thus, Id_1 cannot be measured. The Id_2 was found only suitable to measure stronger rock materials in grades II and III, which can sustain the first cycle (Id_1).

Table 6.24: List of testing that were found suitable for various weathering grade

Testing		Weathering Grade					
		II	III	IVa	IVb	Va	Vb
1	Brazillian ITS	■	■	■			
2	UCS	■	■	■			
3	Point Load Strength Test (PLT)-UTM	■	■	■	■	■	■
	Point Load Strength Test (PLT)-Portable	■	■	■	■		
4	Confined Penetration Test		■	■	■	■	■
5	Sonic WaveVelocity (PUNDIT) Test	■	■	■	■	■	■
6	Slake Durability Test (Id_1)	■	■	■			
7	Slake Durability (Id_2)	■	■				
7	Schmidt Hammer Test	■	■	■			
8	Jar Slaking Test		■	■	■	■	■
9	Dry density	■	■	■	■	■	■

Although the sonic wave velocity and dry density can be tested on all materials, the results for the weathering classification can be widely scattered. The density can be found higher in grade V compared to grade IV materials due to the compactness of minerals. For example, shale, which is of finer grain, was more compact than the coarser grained sandstone in grade IV.

The point load test is suggested to be more useful than UCS (Singh, 1987). The test concept is to evaluate limits of strength in the rock sample when compression load is applied between two loading cones or bits. Although point load index can be a useful parameter in determining the strength properties of rock materials, it was found that the portable point load has a limitation. It was found the portable point load tester could be used to test materials in grade II to IVb only. There will be no gauge reading detected in very weak materials in grade Va and Vb.

Jar slaking test and Schmidt Hammer can be carried out in the field for fast identification of the material properties. However, the Schmidt hammer test was found not to be suitable for grades IVb and V. Table 5.10 summarizes the list of testing that was found suitable for various weathering grade.

The occurrence of iron pan can increase the strength of the parent material. It was noted that the thickness of iron pan on the rock surface would increase proportionately the strength. A sufficient thickness of iron pan may stop the penetration of ripper tine due to the hardness of this material.

Moisture content will be another factor that can affect the strength of the material. The effect is greater on grade IV materials where the dry and wet materials can be significantly affecting the productivity of ripping works. Thus, it should be carefully taken into account that the same materials that were tested during the initial assessment may have a different strength after heavy rain or during dry conditions.

It has been reported that the UCS value is closely related to other properties such as texture, mineralogy, cementing material, density and porosity (Allison and Goudie, 1994). Thus, it is expected that the material strength deteriorate with the increase in weathering grade. Generally, high strength rocks are more durable than the weaker rocks.

It is clear that no single testing method can be used to explain properties of rock materials and to measure for all weathering grades. Thus, careful selection of the properties and tests that are useful for a particular purpose is essential.

CHAPTER 7

MACHINE PERFORMANCE AND RIPPABILITY ASSESSMENTS OF ROCK MASSES

7.1 Introduction

Monitored ripping tests were conducted at four sites namely Kempas, Desa Tebrau, Bukit Indah and Mersing where ripper performance was measured together with various laboratory and field tests relating to the material. In this chapter, the results of monitored ripping tests are presented. The parameters measured during ripping tests are depth, width, length of run and time of cutting to measure the productivity. Various rock materials and mass properties that have been presented in Chapter 5 and 6 will then be analyzed and compared with the production rate for ripping.

The rock mass and material properties were then predicted in respect to the production rate. At the end of the chapter, prediction equations for production rate are proposed based on the best combination of the predominant field and laboratory parameters. These parameters have been observed to control both rock mass behaviour and ripper performance.

7.2 Measurement of Direct Ripping Runs

A total of 127 tests were conducted for sandstone and shale. During monitored ripping runs, the following parameters were recorded: length of run, depth of tine during ripping, time taken, assessment on ease of ripping, width of ripping and the average surface area affected. In order to maintain the consistency of data, only initial ripping will be measured and not the cross ripping. Detail results are presented in Appendix J and the summary of the monitored ripping tests at each location are presented in Table 7.1.

Table 7.1: Summary of monitored ripping tests conducted at various locations

Location	Rock Type	No. of Test	Length of ripping run (m)
Kempas	Old Alluvium (sandstone)	12	17.2-30.28
Desa Tebrau	Old Alluvium (sandstone)	10	17.2-31.52
Bukit Indah	Sandstone	47	1.72-24.35
	Shale	40	2.4-25.4
Mersing	Sandstone	19	4.3-15.8
	Shale	8	8.0-14.52

The width of the ripped material was done by measuring the breakage observed from left and right of the ripping line. Figure 7.1 shows the monitoring of direct ripping run in Kempas by a CAT D9 ripper. The photo shows the ripper tine fully penetrating into the rock material (old alluvium) in ripping line number 1.

To avoid inconsistency of ripper performance due to the operator performance, assessment of ripping was done in one ripping run without taking maneuvering time into account. Hence, ripping performance was based solely on the machine and rock mass properties without any human factor. During ripping, the change in the shank position, depth and the loss of traction were all noted to assess the ease of ripping.

Figure 7.1: Ripping process at Line 1, Kempas

7.3 Direction of Ripping

In relation to any excavation work in strong rock, the most important of all the properties measured is the joint set spacing and their orientation with respect to the machine (Fowell, 1993). A schematic diagram showing the effects of joint orientation to the machine advance is shown in Figure 7.2.

Ripping tests were conducted at various directions of joint orientation to the machine advance. Discontinuity orientations were analysed using a stereonet projection and the discontinuity effect on ripping direction was evaluated from the results as shown in Appendix K. In order to evaluate the discontinuity direction effect, Georient V6 software was used. The effects of discontinuity strike and dip orientations to the direction of ripping were based on recommendations made by Fowell and Johnson (1991) as shown in Table 2.10. These recommendations were made after modifying Bieniawski's (1989) rock mass classification to suit excavation works. The modifications were made based on reversal of the joint orientation rating; favourable orientation for stability can be unfavourable for excavation.

7.4 Monitoring of Direct Ripping Test

A brief description on the monitored ripping test results are presented in this section.

7.4.1 Kempas Site

Ripping performances were measured from 12 ripping runs. The test site was located on even ground namely line 1,1a, 2, 3,4, 5, 6, 7, 8, 9, 10 and 11. The hard ground could not be excavated by a back acter Excavator E200 (engine output power of 110kW and weight 19400 kg) as the bucket teeth could not penetrate the material. The tests were carried out on a sunny day where the ground was dry and firm. The material was in weathering grade Va, dense sandstone (old alluvium) and can be broken easily by strong hand pressure when loosened from ground.

During the ripping tests, the ripper operator was told to rip as deep as possible with the shank vertically and to maintain a constant speed. He was also told to keep the machine advancing with the same power in first gear without stalling.

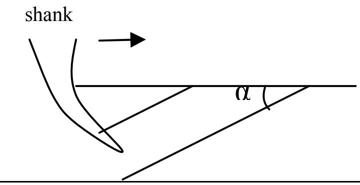
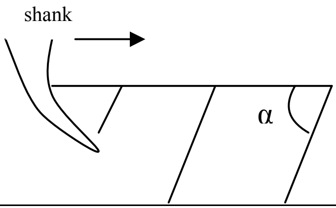
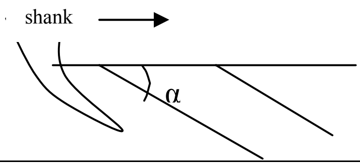
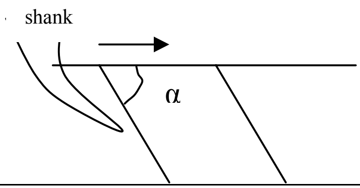
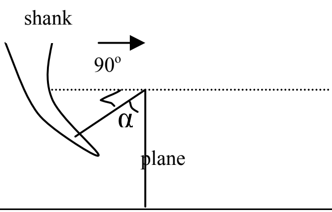
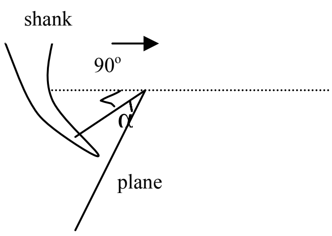
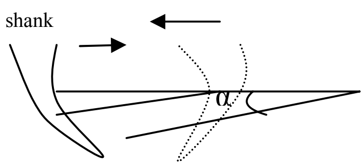
Strike Direction	Diagram	α	Ripping Direction
Perpendicular to Ripping Direction		20°-45°	Unfavorable
		45°-90°	Fair
		20°-45°	Favourable
		45°-90°	Very Favourable
Parallel to Ripping Direction		45°-90°	Very Unfavourable
		20°-45°	Fair
Any Ripping Direction		0°-20°	Unfavourable

Figure 7.2: Schematic diagram on the effect of Ripping Direction (after Fowell and Johnson, 1991)

At Kempas site, the ripping speed was constant throughout the trials. The ripper shank was able to penetrate to the maximum (99%) and consistently embedded to a depth of 1.2 m through out the test. An average speed was 6.5 km/hr in first gear. The material at Kempas site was easily ripped. It can be concluded that in this type of material with a low strength and wide discontinuity spacing, ploughing and lifting mechanisms were observed. Shank tips were replaced every 2 days after 10 hours of working.

7.4.2 Desa Tebrau Site

A CAT D9 ripper machine was deployed at this site with 10 lines of ripping tests monitored. This hard ground could not be ripped by a back acting E200 excavator and the ground appeared denser than the Kempas site. There was no blasting conducted at this site prior to the ripping tests, thus the ground condition was in its original state with no new joints developed by blasting. At this site, ripping works were relatively more difficult compared to the Kempas site, though the material type is the same. The sandy silt (old alluvium) at Desa Tebrau is denser and firmer (Grade IVa) as compared to Kempas's sandy silt. The material could only be broken by a hammer blow. The ripper advanced on average 6.17 km/hr in first gear, was slower than Kempas site. It was noted that the ripper shank penetrated less in Desa Tebrau site as compared to Kempas.

There were 2 different grain sizes encountered in Desa Tebrau; fine grains and coarse grains. The ripper shank was seen to penetrate deeper in coarser grained material by 14 percent, i.e. an average of 68.4 percent penetration of shank into the coarse material as compared to 59.8 percent for finer grain material. In this type of homogeneous material with medium strength and generally small discontinuity spacing, the crushing and lifting mechanism was observed. The tips of the shank were aggressively worn at this site, with an average of one tip to be replaced after 10 hours of working compared to 16 hours in Kempas site. The materials were also grouped under sandstone materials for analysis purposes due to their similar characteristics.

7.4.3 Bukit Indah Site

This site consists of heterogenous material of sandstone and shale, with different weathering grades. A total of 47 direct ripping tests were conducted on sandstone and 40 tests were for shale with various weathering grades. Fragmentation characteristics of a particular horizon were noted, as there can be a fundamental link to its cuttability. Table 7.2 summarizes the materials that are being tested by direct ripping. Test results are presented by material type with the respective weathering grades.

Table 7.2 : Monitored ripping tests at Bukit Indah

Material type	Weathering grade	No of test
Sandstone	II	4
	III	7
	IVa	12
	IVb	8
	Va	8
	Vb	8
Shale	II	2
	III	4
	IVa	9
	IVb	13
	Va	8
	Vb	4

7.4.3.1 Monitoring of Ripping Test in Sandstone

For sandstone of weathering grade II, the penetration depth depended much on the joint spacing. With joint spacing of 0.17 m, the penetration of the ripper shank can reach 0.9 m, whereas if the joint spacing is more than 0.3 m, there will be no penetration observed. As for grade III sandstone, 3 out of 7 lines were unrippable. The condition of discontinuities also play an important role in determining whether it is rippable or not, particularly the joint spacing. It was found that joint spacing of more than 0.34 m did not permit penetration of shank into these materials; however joint spacing of less than 0.29 m could allow penetration of shank for up to 0.7 m. It was noted that the width of the ripping line increases with the depth of the penetration. For this type of material with higher strength, the discontinuity characteristic particularly the joint spacing plays an important role in determining whether the material is rippable or not. Other factors that influence rippability of these materials are direction of ripping and the joint fill material. The crushing mechanism was observed in low discontinuity spacing material.

When it comes to weaker material in grade IVa, penetration depth depended mostly on the joint spacing and the discontinuity characteristics. A joint spacing of more than 1.09 m did not permit any ripping works as shown in Figure 7.3. Discontinuities that were filled by more than a 4 cm thick of iron pan minerals did not permit penetration of ripper shank and no production was monitored. The joint spacing of 1.09 m in this type of material can still be ripped provided that the direction of ripping favours the ripping process and there is no hard material such as iron pan and quartz present. In this medium strength material with wide joint spacing, crushing and lifting mechanisms were observed. For grade IVb material with joint spacing of more than 0.55 m with iron pan of 5 cm thick, penetration could not take place. Penetration of the shank was observed at 0.8 m for material with 0.49 m discontinuity spacing with no presence of iron pan.

As for material in weathering grade Va and Vb, all of the lines can be penetrated by the ripper shank throughout the ripping process. It seems that for these weathering grades, joints do not influence much the productivity. The weak material alone is enough to help the ripping works.

Figure 7.3: Unrippable sandstone of weathering grade IVa with joint spacing more than 1 m.

7.4.3.2 Monitoring of Ripping Test in Shale

Relatively, shale was found to be easier to rip compared to sandstone. In weathering grade II, the ripping tine was able to penetrate up to 0.5m with the assistance of joints spacing of 0.28 m. Generally, the penetration of tine increased in weaker material. The wider joint spacing may give higher resistance, thus lower productivity can be expected. In low strength material with low joint spacing (less than 0.5 m) the mechanism of ploughing and lifting was observed especially in grades IVb, Va and Vb. The ripper tine produced a uniform depth of rip throughout the ripping run in these weak materials.

As for higher strength shale in Grade IVa and lower, it was found that joint spacing and direction of ripping plays a significant role by observing whether the tine can penetrate or not. These cases are similar to sandstone with similar weathering grade.

Sometimes the ripper tine could not penetrate the material initially in the stronger material, however once the machine has advanced, the weight of machine together with the penetration force of the tine, helped the ripping process with the joints assisting. However, in the lower strength materials, this process may not be required as the initial penetration force of the tine alone is able to penetrate the material.

7.4.4 Mersing Site

This site consists of sandstone and shale that needed to be levelled for construction works. A total number of 27 ripping tests were conducted with 19 tests for sandstone and 8 for shale with various weathering grade. The details are listed in Table 7.3.

The presence of iron pan and quartz veins along the discontinuities was found to be one of the important factors that will determine whether ripping is possible or not. There were 3 cases where ripping works were not possible even though the host material is in weathering grade IVa, which logically can be ripped. Figure 7.4 shows an example where iron pan of a 4 cm thick over capping the sandstone grade IVa and resisting penetration of the ripper shank. Whenever ripping works were not possible, blasting methods were employed to break the rock.

Table 7.3: Number of ripping test on various weathering grades in Mersing

Material type	Weathering grade	No of tests
Sandstone	II	1
	III	6
	IVa	4
	IVb	1
	Va	2
	Vb	5
Shale	II	1
	III	2
	IVa	3
	Va	2

Figure 7.4: Presence of thick iron pan (4 cm) on grade IVa sandstone resisting the penetration of ripper tine

7.5 Relationship of Ripping Depth and Width

The ripper depth and width were found to be closely associated with the production rate. Hence, these parameters were analysed to determine their relationship. In general, the ripper depth ranges from 0 to 1.2 m, whereas the ripping width is in the range of 0 to 1.6 m. A summary of ripping depths and widths obtained are tabulated in Table 7.4 and the details of the results are shown in Appendix M. The relationship between ripper depth and width was examined and it was noted that the width increased with deeper ripping depths as shown in Figure 7.5. The relationship was found to be very significant and the best-fit line gave the coefficient of determination of 0.965 with a regression equation as follows:

$$RD = 1.414RW - 0.075 \qquad (R^2 = 0.965) \qquad (7.1)$$

where RW is ripping width (m); and
RD= ripping depth (m)

It was also noted that the weathering grade has significant effects on the ripping depth. When it is a very weak rock (weathering grade Vb), the maximum ripping depth is 1.2 m. The ripping depth and width were found to decrease when the weathering grade is lower; marking that there is a relation between the weathering grade and the ripping depth. It is interesting to note that the data for materials in weathering grade IVb to II are more scattered compared to grade Vb to Va suggesting that there could be other parameters such as discontinuity characteristic that can influence the excavation rate.

The relationship between ripper depth and production is plotted in Figure 7.6. From the graph it shows that the ripping width increased with the ripping depth in a quadratic relationship with a regression equation 7.2 in Table 7.6 for both shale and sandstone. When assessing the shale alone, it gives a lower value when compared to sandstone with the same ripper depth as shown in equations 7.3 and 7.4 in Table 7.5. In general, a rule may be postulated that the production rate will depend on the ripper depth throughout the ripping works. However, the production rate will also depend on other factors such as the discontinuity characteristic. Thus, care must be taken when assessing the productivity, as the ripper tine may not give the same depth throughout the ripping works.

Figure 7.7 shows the same data marked by their weathering grade. Materials with weathering grade of Vb show the highest production and the maximum value of ripping depth. As the materials become stronger (lower weathering grade), the ripper depth and production value decreases. Material from grade IVb and lower seems more scattered suggesting that the materials from these grades depend on other factors in assessing productivity.

Table 7.4: Summary of ripping depth and width

Weathering Grade	Sandstone			Shale		
	Ripping Depth (m)	Ripping Depth (%)	Ripping Width (m)	Ripping Depth (m)	Ripping Depth (%)	Ripping Width (m)
II	0-0.5	0-42	0-0.5	0-0.5	0-42	0-0.5
III	0.4-0.9	33-75	0.4-0.9	0-0.8	0-67	0-1.1
IVa	0.6-1.0	67-83	0.6-1.0	0.8-1.0	67-83	1.0-1.5
IVb	0.9-1.0	75-83	0.9-1.0	0.8-1.2	67-100	1.0-1.6
Va	1.0-1.2	83-100	1.0-1.2	1.1-1.2	92-100	1.4-1.6
Vb	1.2	100	1.2	1.2	100	1.6

Table 7.5: Correlation between production rate (m^3/hr) and ripping depth (RD)

Production (m3/hr)	**Equation**	**R^2**	**Equation No.**
Production (Q)	$891.583RD^2 - 115.780RD + 24.536$	$R^2 = 0.832$	7.2
Production (shale)	$1054.945RD^2 - 316.308RD - 0.117$	$R^2 = 0.853$	7.3
Production (sandstone)	$814.910RD^2 - 3.585RD + 25.893$	$R^2 = 0.841$	7.4

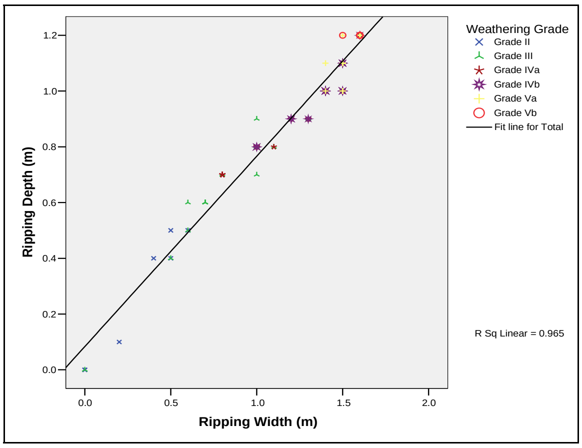


Figure 7.5: Ripping depth (m) versus ripping width (m) marked by weathering grade

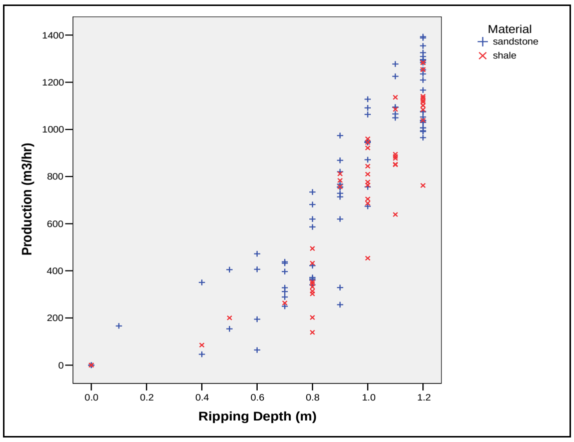


Figure 7.6: Relationship between Production (m^3/hr) versus Ripping Depth (m) marked by material

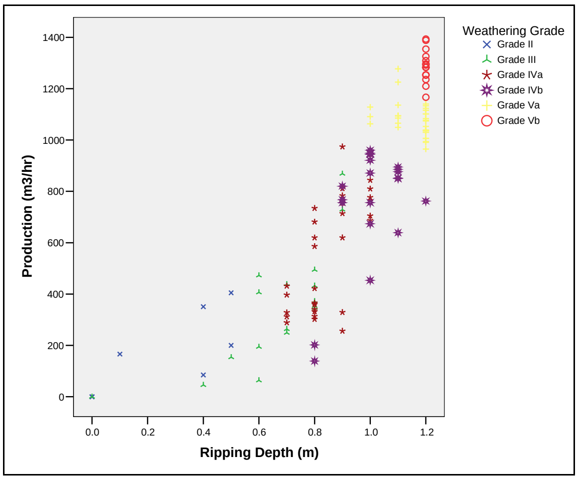


Figure 7.7: Production (m^3/hr) versus ripper depth (m) marked by weathering grade

7.5.1 Ripping on Iron Pan

There were 9 cases where the material could not be ripped due to a capping of iron pan on the rock surface. Table 7.6 shows the results of direct ripping on these materials. It was noted that a 2 cm thick of iron pan is sufficient to resist the penetration of the ripper tine into the ground in weathering grade III materials. Whereas in grade IVa and IVb, 3 cm and 5 cm thick of iron pan respectively did not permit the penetration of tine. It was found that the occurrence of a certain thickness of iron pan with the respective weathering grade prevented the penetration of the ripper tine. Iron pan is a very dense material and a thick layer may enhance the ripping resistance.

Most of the dissolved iron in sedimentary rock is derived from the decomposition of iron-bearing minerals (Prothero and Schwab, 2004). However, it was observed that the ripper tine could rip the weak rock material if it managed to break the iron pan. A schematic diagram showing this phenomenon is shown in Figure 7.8.

Table 7.6: Monitored ripping test on iron pan materials

Sample	Location	Weathering Grade	Width (m)	Depth (m)	Iron Pan (cm)
RL 1 (b) L2	Mersing	III	0	0	2
RL 3 A L3	Mersing	IVa	0	0	3
RL 3 Slope Area 2 L2	Mersing	IVa	0	0	3
RL 3 Slope Area 1 L5 (Zone B)	Mersing	IVa	0	0	4
B6 L1	Bukit Indah	III	0	0	2
B1 L1	Bukit Indah	IVa	0	0	3
LN8 UR1	Bukit Indah	IVa	0	0	3
LN3 UR1	Bukit Indah	IVa	0	0	4
B3 L1	Bukit Indah	IVb	0	0	5

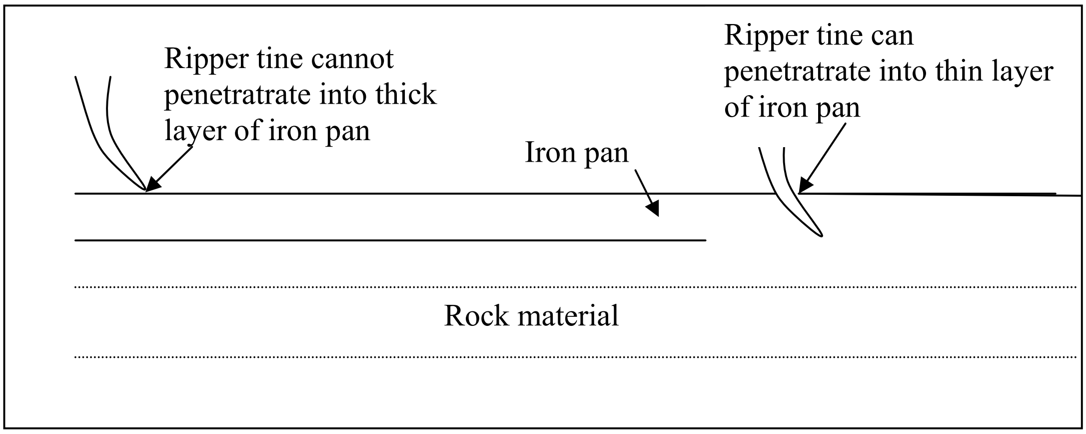


Figure 7.8: Schematic diagram of a capping of iron pan that resists penetration into the rock material below.

7.6 Analysis of Relationships of Machine Performance and Individual Properties

As reported by previous researchers, the production rate of excavating machines depends on the rock mass and material properties. Consequently, an attempt was made to examine the form of the relations between these variables. This section presents the relationship of production rates with various properties of rock material and mass properties. The results are presented in two ways i.e. by material and weathering grade. The relevant experimental results can be found in Appendix H. The analysis was conducted by plotting graphs of the individual properties against machine performance (production). Then a statistical analysis was carried out by a multi linear regression technique to predict machine performance.

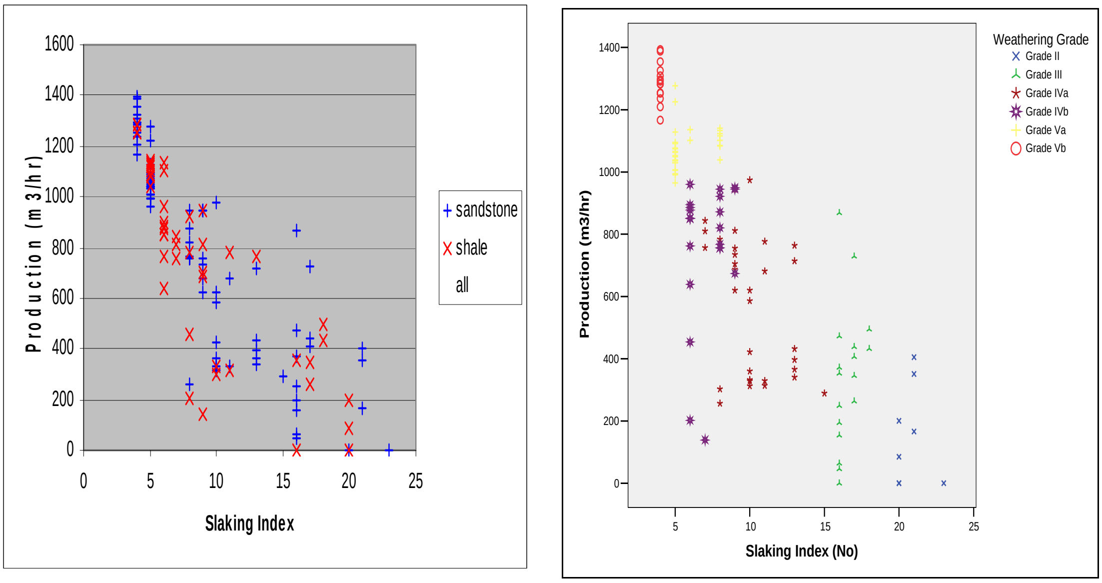
7.6.1 Relationship Between Rock Material Properties and Production

Diagrams showing the influence of various parameters on the productivity are shown in Figures 7.9 to 7.21. Parameters included in these relationships are penetration tests, point load index, slake durability, slaking index, UCS, indirect tensile test, density, sonic velocity, joint spacing, Schmidt hammer and moisture content. However grain size, joint spacing, moisture content, dry density and Schmidt hammer equations are not included as the R^2 for these parameters was less than 0.3. However these parameters are believed to have significant relationship with production and will be analyzed with weathering grade in the later section. The lower percentage of number of cases (N) is due to samples being too weak for that particular test.

The intact properties for both sandstone and shale which are best correlated with production are slaking index, point load index, slake durability (Id_1), penetration by a 10mm probe, penetration by point load bit, sonic velocity, slake durability (Id_2), indirect tensile strength, UCS and dry density. Their correlations with weathering grades are covered in Section 7.8.

7.6.1.1 Jar Slaking Index

Figure 7.9(a) shows the production rate decreases with the increase in slaking index. A total number of 127 tests were conducted on all samples, from which 79 samples are sandstone and 48 are shale. The data for shale material is more scattered especially when the slaking index is high of more than 10. This might be attributed by other factors such as discontinuity characteristics that might influence the production for stronger materials. In addition, the mineralogy of shale that absorbs water significantly also contributes to the lower slaking index. Santi (1998) has found a good correlation between the jar test and weathered shale and marked the results by slaking index for 30 minutes and 24 hours. Zainab Mohamed (2004) has also adopted the procedure using 30 minutes and noting the index as discussed in Chapter 4. However, due to the wide range of weathered sandstone and shale materials, the author has introduced the sum of slaking indices at 10 minutes, 15 minutes, 30 minutes and 60 minutes. The sum of slaking indices was noted to correlate well with the productivity rate especially for the weak material. As can be seen in Figure 7.9(b), the trend of correlation is more accurate when the weathering grade of Vb and Va with production is above 1000 m^3/hr and the slaking index is less than 7 or these materials disintegrated completely within 10 minutes.



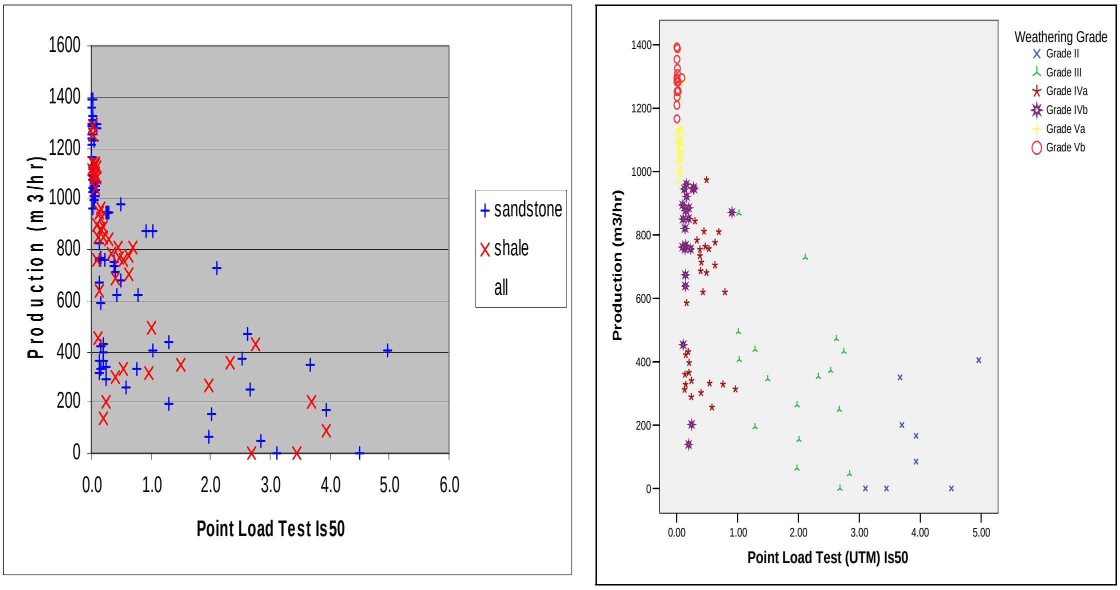
(a) (b)

Figure 7.9: The relationship of production rate and the jar slaking index (SI) marked by: (a) type of material and (b) weathering grade

7.6.1.2 Point Load Index (Is_{50})

Point load index (Is_{50}) is one of the most popular indices for excavation assessment as reported by previous researchers (Kramadibrata, 1996; Basarir and Karpuz, 2004; Muftuoglu, 1988). Figure 7.10(a) and (b) shows correlation between Is_{50} and the production rate marked by type of material and weathering grade respectively. Plotting the Is_{50} against machine performance produced a negative log function, which shows that productivity decreases with the increase of Is_{50} value. A Is_{50} value of less than 1 represents materials in weathering grade

IVa or a weaker material. It is important to note that the Is_{50} value used in this correlation is from the test using a universal testing machine (UTM) and not from the portable point load machine used at the site. The portable testing machine shows less sensitivity for the weakest material especially those in weathering grade IVb and higher (as discussed in Chapter 6).

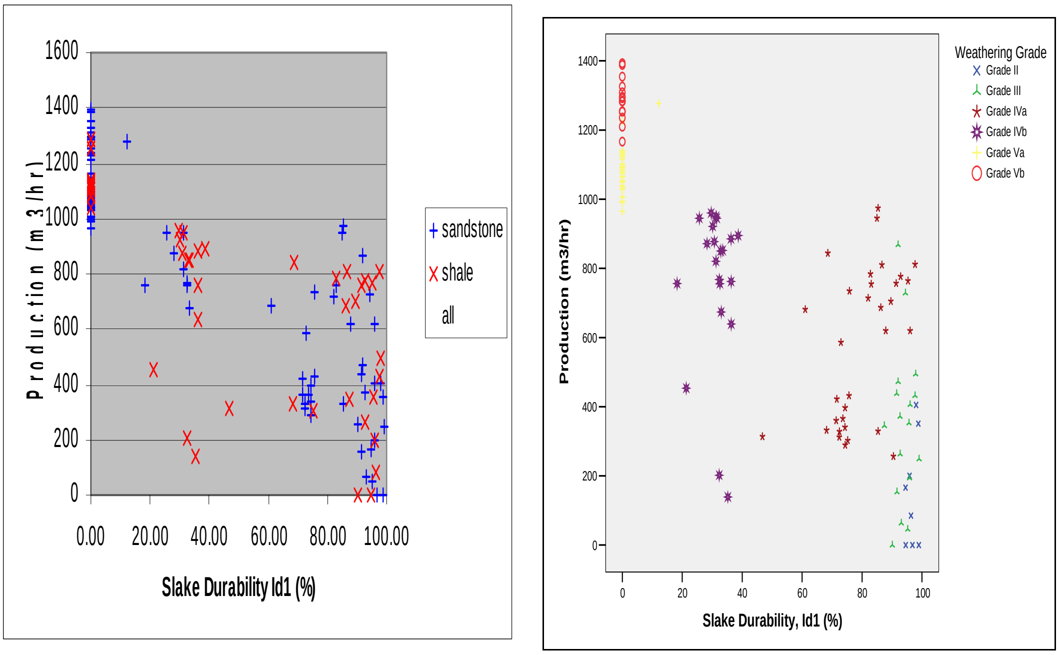


(a) (b)

Figure 7.10: The relationship of production rate and the point load index (Is_{50}) marked by: (a) type of material and (b) weathering grade of material

7.6.1.3 Slake durability Index (Id_1)

Figure 7.11(a) and (b) show the relationship of slake durability (Id_1) with production rate marked by material and weathering grades respectively. Materials from grades Va and Vb show the lowest slaking index value and give a higher value of production rate. Materials from grade IVb and lower, show a variation in production suggesting that other factors might influence the production rate. Id_1 is a parameter measured by one cycle and all materials can be tested in this procedure. There are some materials in weathering grade IVa, IVb and III that generated 800 m^3/hr of production. Stronger materials could produce high productivity through assistance of other factors that will be discussed later in this report.



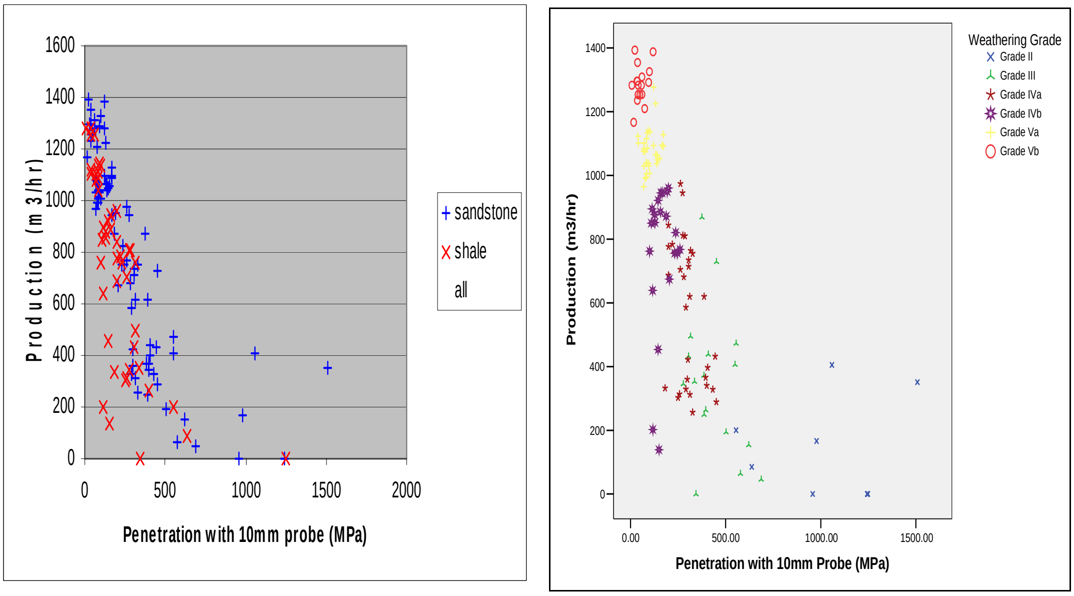
(a) (b)

Figure 7.11: The relationship of production rate and the slake durability (Id_1) marked by: (a) type of material and (b) weathering grade of material

7.6.1.4 Penetration test

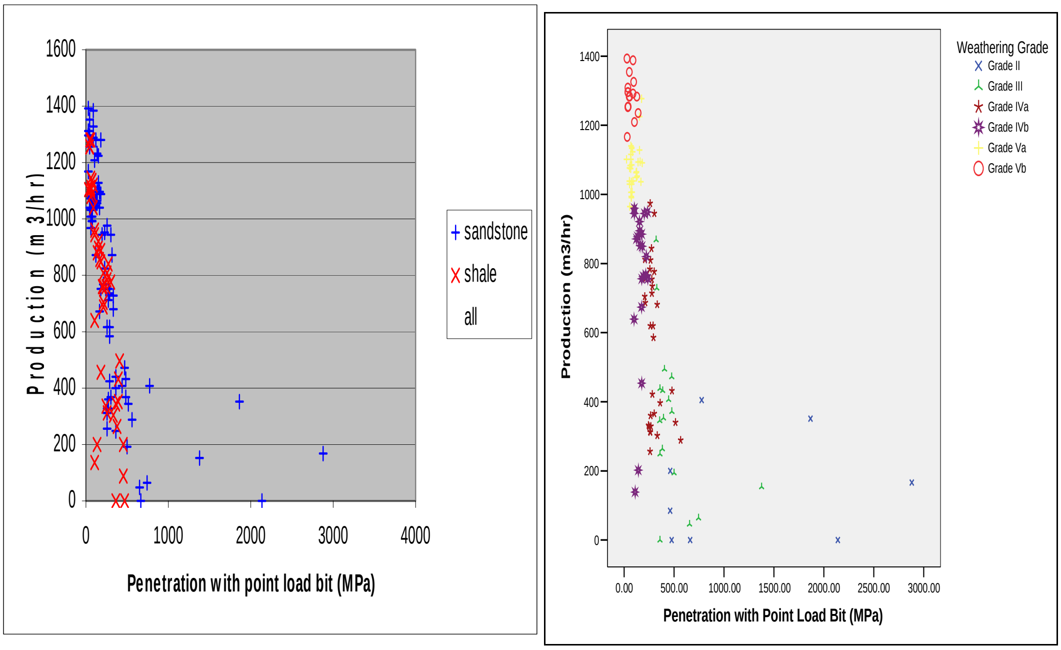
It was found that production rate decreases with the increase of penetration force to break samples through penetration of the 10mm probe and point load bit as materials become harder. These relationships can be seen in Figure 7.12 and 7.13. The relationship of the penetration test with ripping depth can also explain this phenomenon, where higher penetration forces generally will result in a shallower depth for the ripper tine. As the depth of penetration is linearly related to productivity, thus increase of the penetration force may decrease the overall production. Figure 7.12(b) and 7.13(b) show lower weathering grades of material will result in higher penetration forces both with the 10 mm probe and with the point load bit.

The forces needed to penetrate the samples correlates well with the initial ripping depth by the tine. These tests were conducted in an attempt to produce a relatively small scale test that can be used for excavatability prediction. The confinement of materials by using PVC pipe and plaster of Paris has been found satisfactory to replicate actual conditions. The material penetrability can be used to evaluate satisfactorily on the ripping depth. Penetration by the 10 mm probe is seen to correlate satisfactorily to the ripping depth (Figure 7.14) with the regression equation as tabulated in Table 7.7. The probe penetrated easily into these materials. A similar mechanism was also observed during initial penetration of the ripper tine at the site.



(a) (b)

Figure 7.12: The relationship of production rate and the penetration with 10mm probe (Pen_{10}) marked by: (a) material type and (b) weathering grade



(a) (b)

Figure 7.13: The relationship of production rate and the penetration with point load bit (Pen_{Plb}) marked by: (a) type of material and (b) weathering grade

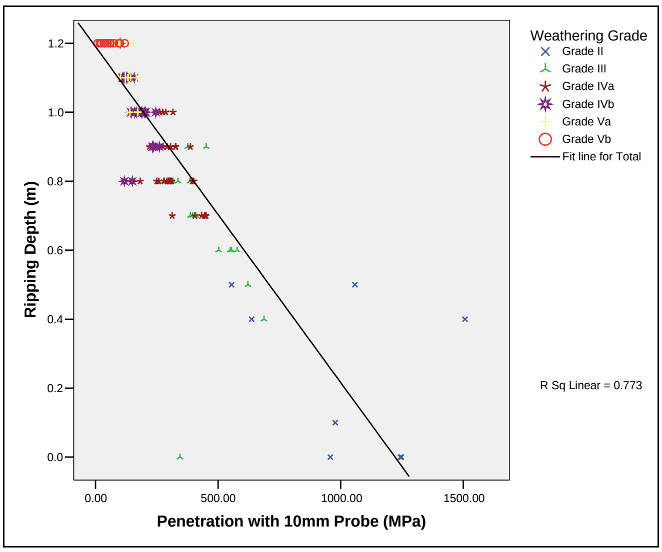


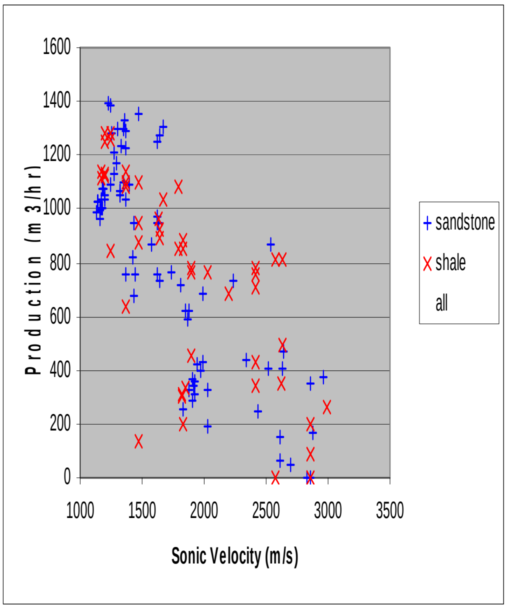
Figure 7.14: Relationship of ripping depth and the penetration of 10mm probe

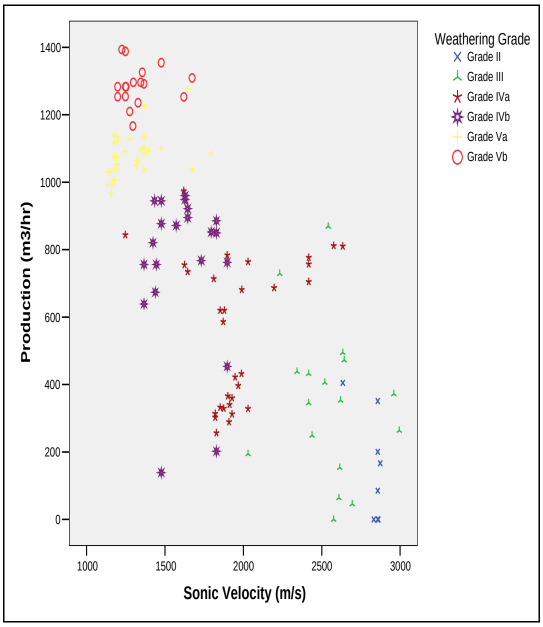
Table 7.7: Regression equations of relationships between ripper depth and penetration of 10mm probe

No	Independent variables	Regression equations	R^2	N	Equation no.
1	Penetration by 10 mm Probe (P_{10})	RD= -0.001 P_{10} + 1.19	0.773	127	7.5

7.6.1.5 Sonic Velocity

A similar trend of decreasing in productivity with higher sonic wave velocity is shown in Figure 7.15(a) and (b). The results are scattered and no clear relationships for the respective weathering grades.



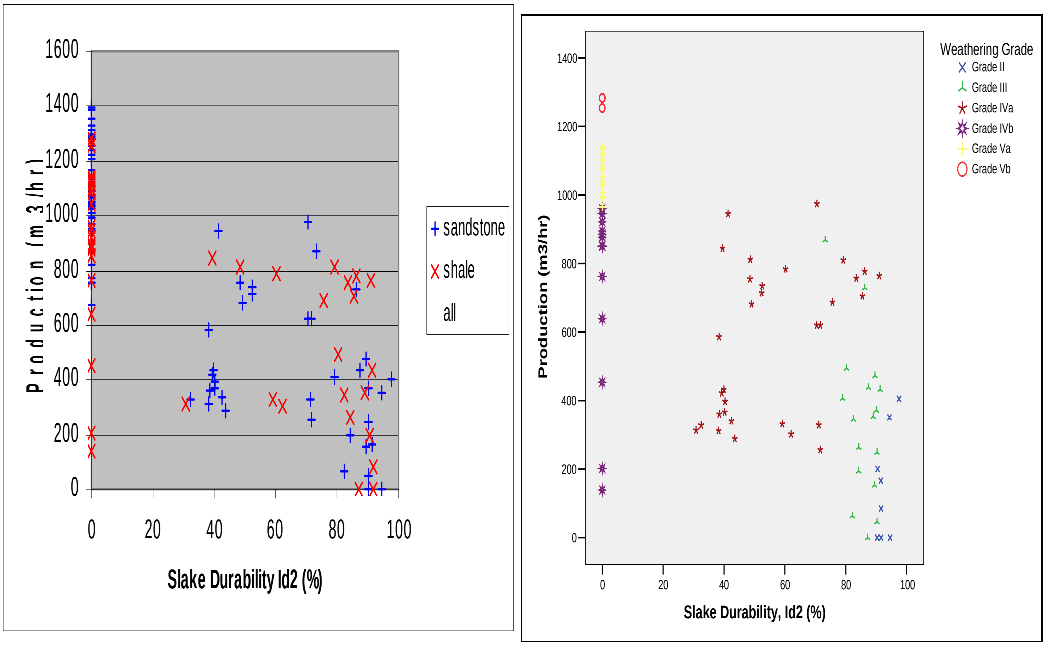


(a) (b)

Figure 7.15: The relationship of production rate and sonic velocity marked by: (a) type of material and (b) weathering grade

7.6.1.6 Slake Durability Index (Id_2)

Figure 7.16(a) and (b) show the relationship between slake durability (Id_2) with production. The R^2 of this relationship is less than the first cycle of slake durability (Id_1) for weak rock. This can be explained because only 64 percent number of materials could be measured by the second cycle of this test as 36 percent of the original materials had fully disintegrated during the first cycle. Only stronger materials in grade IVa and lower can undergo the second cycle. Thus, by adopting only the first cycle for slake durability is adequate to assess the excavatability of these weak rocks.

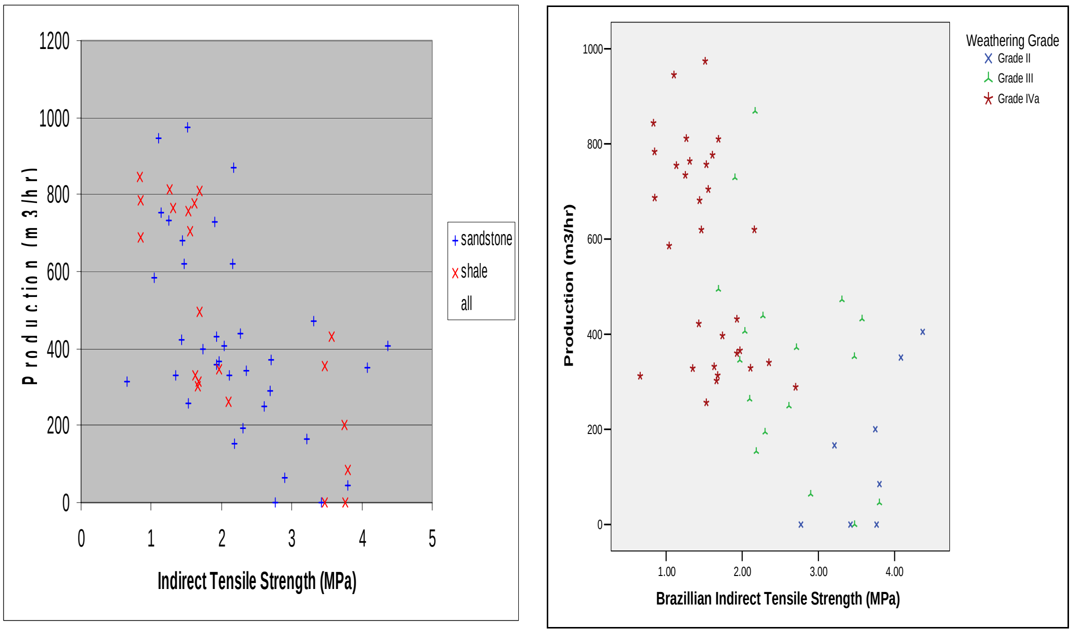


(a) (b)

Figure 7.16: The relationship of production rate and Id_2 marked by: (a) type of material and (b) weathering grade

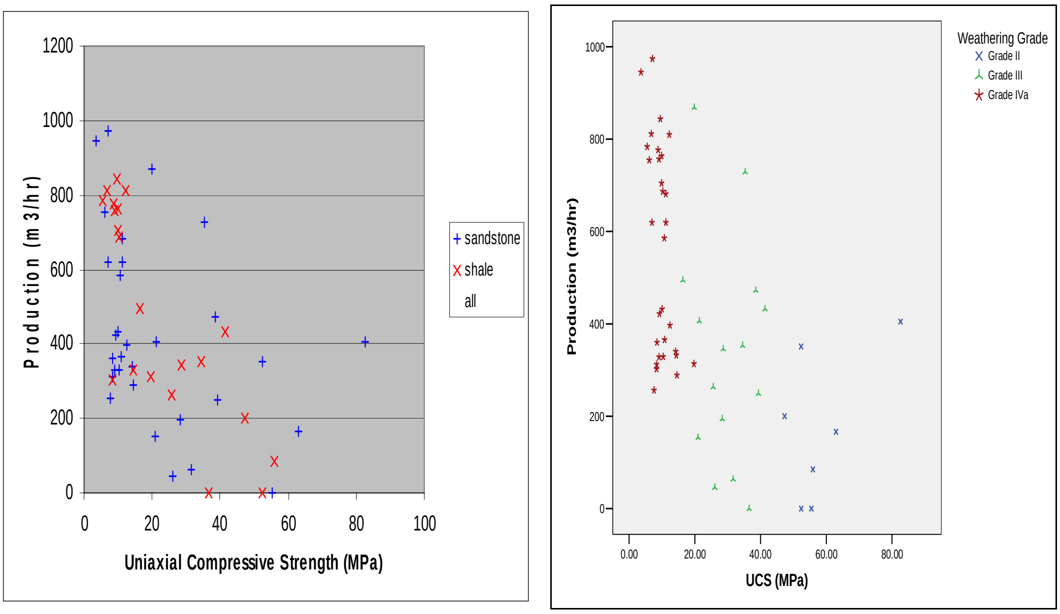
7.6.1.7 Indirect Tensile Strength and Uniaxial Compressive Strength

The relationship of Brazillian indirect tensile strength (ITS) and production is displayed in Figure 7.17. Values of the tensile strength ranges from 0.6 to 4.3 MPa and generally shows an overall increase for a decrease in productivity, however, there was a wide scatter in the results. Total of 56% from the total number of samples were managed to be tested by ITS while only 52% for the UCS. The number of tests carried out by Brazillian test is more than the UCS as the samples are easier to be prepared. The trend for UCS values to the production as shown in Figure 7.18 are also scattered and show decreases of production with the increase of the UCS value. The strong samples (Grade IVa and above) depend much the discontinuity characteristics to ease the excavation. These findings suggested that the use of a single variable of UCS or ITS alone for assessing excavatabiliy is not a sound judgement as numbers of other factors might contribute to the productivity. The low coefficient R^2 for ITS and UCS are supported by Bradybrooke (1988) and Poole & Farmer (1978) which reported R^2 value of less than 0.5 for relation of UCS and machine performance.



(a) (b)

Figure 7.17: The relationship of production rate and indirect tensile strength (ITS) marked by: (a) type of material and (b) weathering grade

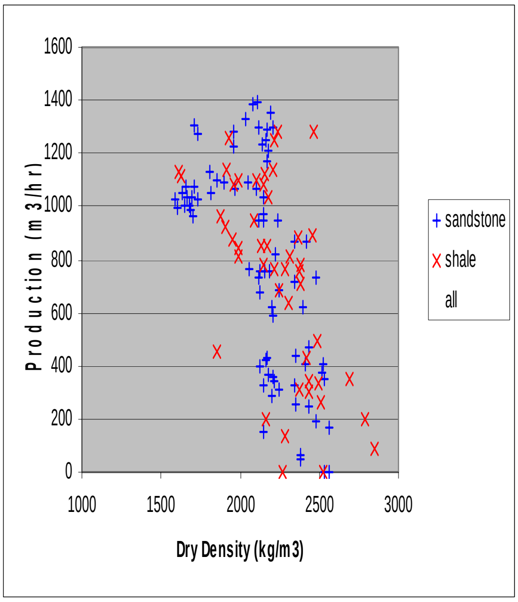


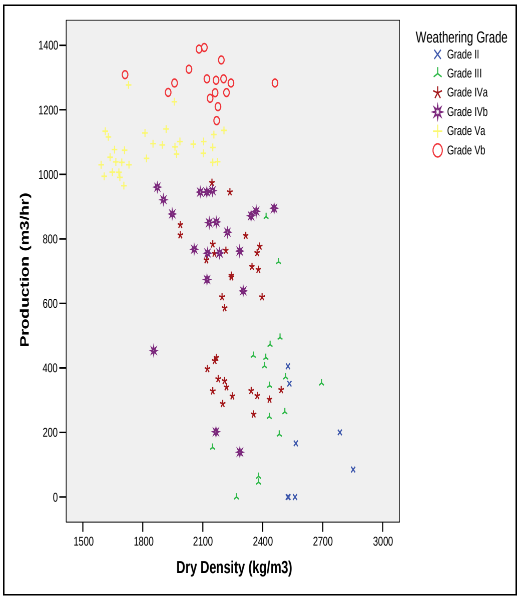
(a) (b)

Figure 7.18: The relationship of production rate and UCS marked by: (a) type of material and (b) weathering grade

7.6.1.8 Dry Density

Figure 7.19 shows the influence of dry density of rock materials on the production rates. The trend of the data shows that when density increases, the productivity will decrease. The R^2 for this correlation is poor as the data are scattered with no clear difference of values between sandstone and shale. Wide variations of density data from 1500 to 2400 kg/m3 can be seen generating production of 1000 m3/hr. This is due to several other factors such as discontinuity characteristics that affect the material for excavation.



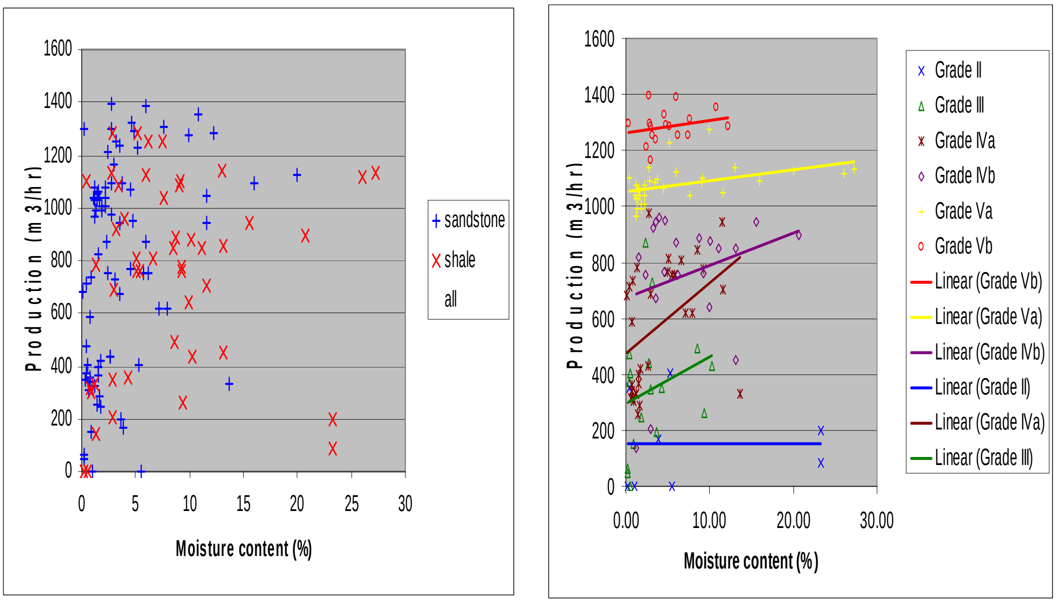


(a) (b)

Figure 7.19: The relationship of production rate and dry density marked by: (a) type of material and (b) weathering grade

7.6.1.9 Moisture Content

Interestingly, the relation of moisture content with production rate does not give clear correlation if it is plotted by material (Figure 7.20a). However, if the data is analyzed by weathering grade as shown in Figure 7.20(b), significant relationships can be seen. However the analysis needs to be done together with the weathering grade to see a significant relationship. The weakness in strength of the material is sufficient to generate productivity of more than 1000 m^3/hr. Figure 7.20(b) shows the correlation of each weathering grade with regards to moisture content and productivity. Low R^2 value of the correlation suggests that there is some other factors affecting the productivity other than moisture content. All lines except grade II shows an increase of productivity with increase of moisture content. Grade Vb and Va shows the increment is not that significant as compared to grade IVb, IVa and III. Grade IVa and III shows the steepest slope of lines suggesting that materials in these grades would be affected significantly with changes of moisture content. Grade II materials has strong bonding and cementation making the moisture difficult to absorb, thus no significant changes in the strength.

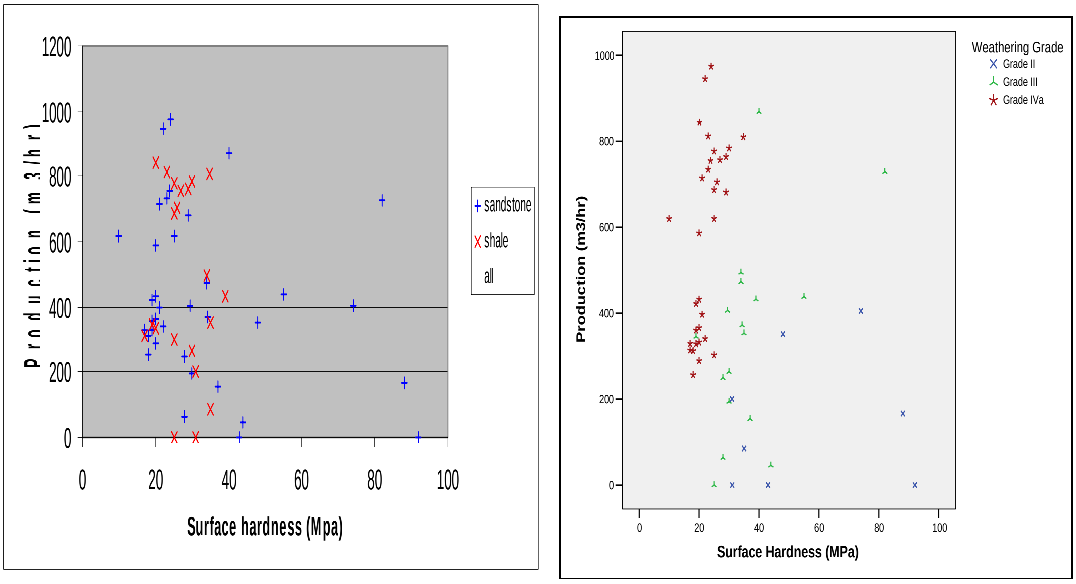


(a) (b)

Figure 7.20: The relationship of production rate and moisture content marked by: (a) type of material and (b) weathering grade

7.6.1.10 Surface Hardness

The Schmidt hammer was used to measure surface hardness with 46% from the total number of samples gave rebound value. Figures 7.21(a) and (b) show the data plotted between surface hardness value with the production rate marked by type of material and weathering grade respectively.



(a) (b)

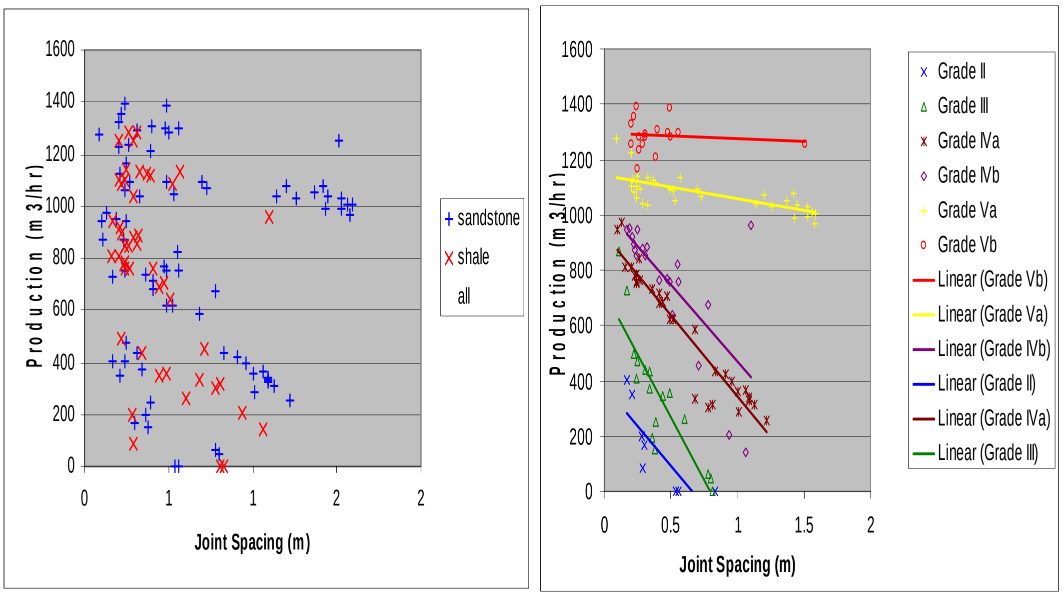
Figure 7.21: The relationship of production rate and surface hardness marked by: (a) type of material and (b) weathering grade

7.7 Relationship Based on Discontinuity Characteristics

This section presents the influence of the discontinuity characteristics on the production rate of the ripper.

7.7.1 Joint Spacing

Figure 7.22(a) and (b) show relationship of joint spacing measured in the direction of machine advance to productivity marked by material and weathering grades respectively. No significant relationships can be observed if it is based on materials but significant relationships can be seen if it is based on weathering grades. It can be noted that productivity decreases with the increase of joint spacing. In the weakest materials of grade Vb, joint spacing does not seem to influence the productivity. When the materials are stronger or when the weathering grades get lower, the influence of joint spacing will greatly influence the productivity as marked by the inclination of regression lines. Materials in grade IVb shows slight influence of joint spacing whereas materials in grade IVa show a steeper line indicating that the joints greatly influence the productivity for this grade. Materials in grade III show the steepest inclination suggesting that any slight change of joint spacing will greatly affect the productivity. The respective regression equation for each weathering grade is shown in Table 7.8.



(a) (b)

Figure 7.22: The relationship of production rate and joint spacing marked by: (a) type of material and (b) weathering grade

Table 7.8 : Regression equations of productivity (y) with joint spacing (x) for respective weathering grade.

Weathering Grade	**Regression equation**	**R^2**	**Equation No.**
Va	Y = -84.596x + 1141.7	0.512	7.6
IVb	Y = -554.67x + 1022.5	0.485	7.7
IVa	Y = -589.61x + 932.8	0.910	7.8
III	Y = -907.45x + 932.8	0.736	7.9
II	Y = -581.75x + 382.2	0.669	7.10

7.7.2 Influence of Iron Pan

In tropical weathered rock mass, accumulation of iron pan in the discontinuities can be one of a major problem in surface excavation. From the field study, it shows that 2 cm of iron pan on Grade III and 3 to 5 cm in Grade IVa/b materials are sufficient to resist the penetration of a ripper tine. Table 7.9 shows the direct ripping result of materials coated with iron pan depending on the thickness of iron pan in each case. In each case, there was no penetration of the ripper tine into the material, thus no production was observed. For example the grade IVb material with the same strength and discontinuity characteristics but without iron pan could produce more than 800 m^3/hr as compared to zero production when capped with 5 cm thickness of iron pan.

Table 7.9: Results of direct ripping tests for materials with iron pan.

Sample	Location	Weath. Grade	Iron Pan (cm)	Js (m)	Depth (m)	Production (m3/hr)
RL 1 (b) L2	Mersing	III	2	0.49	0	0
RL 3 A L3	Mersing	IVa	3	0.83	0	0
RL 3 Slope Area 2 L2	Mersing	IVa	3	0.39	0	0
RL 3 Slope Area 1 L5 (Zone B)	Mersing	IVa	4	0.45	0	0
B6 L1	Bukit Indah	III	2	0.29	0	0
B1 L1	Bukit Indah	IVa	3	0.22	0	0
LN8 UR1	Bukit Indah	IVa	3	0.76	0	0
LN3 UR1	Bukit Indah	IVa	4	0.67	0	0
B3 L1	Bukit Indah	IVb	5	0.16	0	0

It can be seen that presence of iron pan can increase the strength of the material and also coat the host material and resist the penetration. A study on the point load index (Is_{50}) on materials with and without iron pan is shown in Table 7.10. For materials in Grade IVa with iron pan of less than 0.5 cm thick have shown increase of 60 to 80 percent of the original material strength without iron pan. These results show that the iron pan would strengthen the parent material thus resisting ripper penetration.

Table 7.10: Point load index (Is_{50}) results for different thickness of materials with iron pan

<table>
<tr><th rowspan="2">Materials</th><th rowspan="2">Weath. Grade</th><th rowspan="2">No Sample</th><th colspan="3">PLT Is(50)</th><th rowspan="2">% Increase of Is50</th></tr>
<tr><th>Without Iron Pan</th><th colspan="2">With Iron Pan</th></tr>
<tr><td>sandstone</td><td>IVa</td><td>B1 L1-IP</td><td>0.827</td><td rowspan="8"><0.5cm</td><td>1.331</td><td>60.90</td></tr>
<tr><td>sandstone</td><td>IVa</td><td>RL 3 Slope Area 1 L5 (Zone B)IP</td><td>0.852</td><td>1.412</td><td>65.72</td></tr>
<tr><td>sandstone</td><td>IVa</td><td>LN8 UR1IP</td><td>0.592</td><td>1.016</td><td>71.61</td></tr>
<tr><td>sandstone</td><td>IVa</td><td>B1 L3IP</td><td>0.581</td><td>1.042</td><td>79.40</td></tr>
<tr><td>sandstone</td><td>III</td><td>R6 L1IP</td><td>2.672</td><td>3.283</td><td>22.85</td></tr>
<tr><td>sandstone</td><td>III</td><td>RL 1 L6IP</td><td>1.028</td><td>1.371</td><td>33.32</td></tr>
<tr><td>sandstone</td><td>III</td><td>B8 L9IP</td><td>1.025</td><td>1.687</td><td>64.58</td></tr>
<tr><td>sandstone</td><td>III</td><td>B6 L1IP</td><td>1.053</td><td>1.832</td><td>73.99</td></tr>
<tr><td>sandstone</td><td>IVa</td><td>LN4 R3SIP</td><td>0.433</td><td rowspan="15">0.5-1.0cm</td><td>1.099</td><td>153.76</td></tr>
<tr><td>sandstone</td><td>IVa</td><td>LN3 R3S IP</td><td>0.794</td><td>2.138</td><td>169.30</td></tr>
<tr><td>sandstone</td><td>IVa</td><td>R7 L1IP</td><td>0.763</td><td>2.108</td><td>176.32</td></tr>
<tr><td>sandstone</td><td>IVa</td><td>B1 L2IP</td><td>0.407</td><td>1.241</td><td>204.82</td></tr>
<tr><td>sandstone</td><td>IVa</td><td>RL 3 Slope Area 1 L5(a)IP</td><td>0.491</td><td>1.569</td><td>219.51</td></tr>
<tr><td>sandstone</td><td>IVa</td><td>R8 LN2 R1IP</td><td>0.251</td><td>0.984</td><td>292.03</td></tr>
<tr><td>sandstone</td><td>IVa</td><td>LN8 R3IP</td><td>0.493</td><td>2.392</td><td>385.18</td></tr>
<tr><td>sandstone</td><td>IVa</td><td>LN3 UR1IP</td><td>0.739</td><td>3.732</td><td>405.01</td></tr>
<tr><td>sandstone</td><td>IVa</td><td>B2 L3IP</td><td>0.384</td><td>2.246</td><td>484.90</td></tr>
<tr><td>sandstone</td><td>III</td><td>RL 1 (b) L2IP</td><td>1.166</td><td>5.722</td><td>390.72</td></tr>
<tr><td>sandstone</td><td>III</td><td>RL 3 C L2IP</td><td>1.977</td><td>3.930</td><td>98.80</td></tr>
<tr><td>sandstone</td><td>III</td><td>LN8 UR2IP</td><td>1.288</td><td>3.305</td><td>156.60</td></tr>
<tr><td>sandstone</td><td>III</td><td>R3 L1 R4SIP</td><td>1.288</td><td>3.891</td><td>202.13</td></tr>
<tr><td>sandstone</td><td>II</td><td>R8 LN6 R2SIP</td><td>4.96</td><td>19.307</td><td>289.25</td></tr>
<tr><td>sandstone</td><td>IVb</td><td>RL 3 A L1IP</td><td>0.141</td><td rowspan="2">>1.0cm</td><td>1.628</td><td>1054.43</td></tr>
<tr><td>sandstone</td><td>Va</td><td>RL 3 Slope Area 1 L1IP</td><td>0.044</td><td>6.636</td><td>14980.75</td></tr>
</table>

7.7.3 Influence on Direction of Ripping

Direction of ripping to joint orientation is found as one of the important parameters that influence the productivity. Although the direction of ripping towards the discontinuity orientation can influence the productivity, not many researchers have included this parameter in their assessments. Figure 7.23 is the result of productivity in relation to the direction of ripping marked by weathering grade of materials.

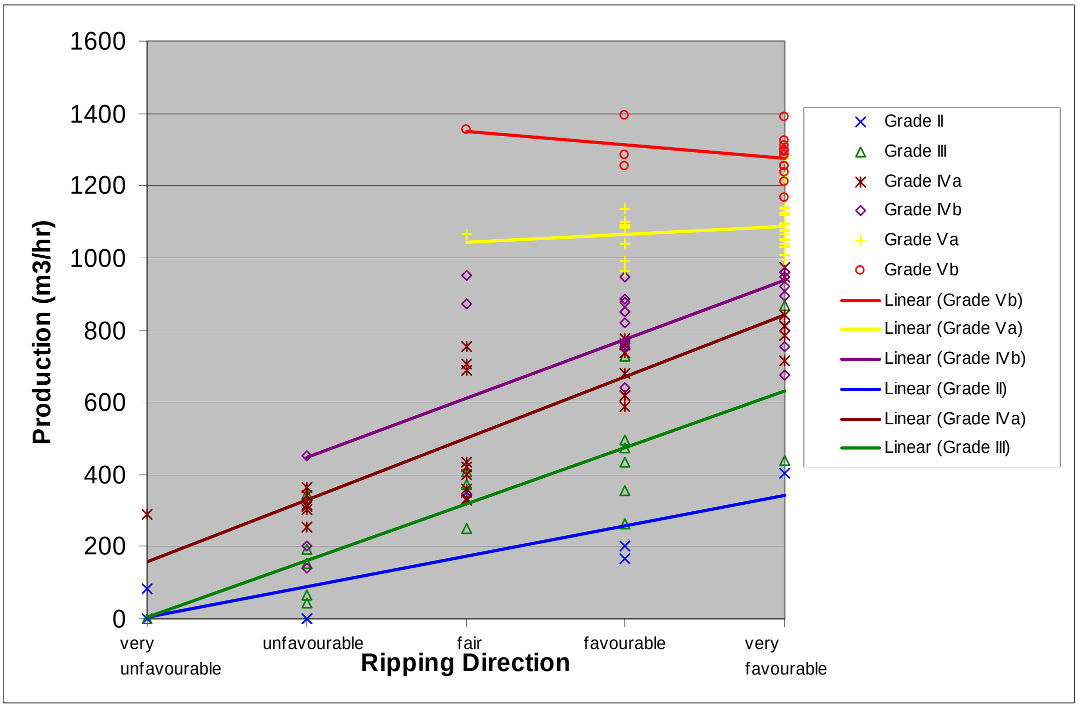


Figure 7.23: The relationship of production rate and ripping direction marked by weathering grade

It is found that ripping direction has an influence on the productivity based on the material's weathering grade. However, the ripping direction must be assessed together with joint spacing and the condition of discontinuity, in order to evaluate the actual influence on the productivity. Depending upon the joint spacing and their conditions, ripping direction might increase or decrease the productivity.

7.8 Statistical Analysis for Prediction of Machine Performance

From the graphs in Figure 7.9 to 7.23, it was apparent that the machine performance is dependent on the power of ripper machine and is also dependent on some of other rock material and mass properties. In analysing the available data, the influence of these properties on the excavation rate is examined.

The form of prediction for machine performance used in this research is by the prediction equation. The individual rock properties results have been analysed using a step-down multi-linear regression programme with the aim of relating the measurements of rock strength to machine performance. The equation allows the minput of a number of predictor variables, parameters which have been found from empirical observation to affect the production rate. In general these equations take the form;

$$V_r = f\Sigma(b_i V_i^n) \qquad (7.11)$$

where b is a constant; and

V (I = 1 … z) are the predictor variables

Generally, in order to facilitate computational computation of a multi predictor variable equation, linear functions are arranged, such that n=1. In order to achieve this, occasional transmissions are permitted. Thus, the final form of the ideal predictive equation is;

$$Vr = b_o + b_1V_1 + b_2V_2 \ldots. + b_nV_n \qquad (7.12)$$

Multiple regression analysis using Statistical Package for Social Science (SPSS) software was adopted for this purpose in evaluating the influence of these parameters on the productivity. The simplest case would be where the number of predictor variables to be regressed is all highly correlated with the response variables. The best predictor would probably include all the predictor variables. However this situation does not always arise, hence the stepwise regression technique was adopted.

Stepwise was employed in this analysis by including all predictor variables and allowed the stepwise method to eliminate the predictors until the best and most economic equation is found, conversely, when predictor variables are added the best equation would be found.

The data evaluated in the stepwise regression analysis were: weathering grade, penetration by 10 mm probe, penetration by point load bit, point load index (Is_{50}), slake durability one and two cycles (Id_1 and Id_2), sonic velocity, dry density, UCS, Indirect tensile strength, surface hardness, jar slaking index, joint spacing, grain size and ripping direction. The dependent variable entered is the production rate. The cases examined include sandstone, shale and overall rock types with classes of weathering grade. Before the stepwise regression was done, an evaluation on the individual rock mass properties with regard to the weathering grade was carried out to gain a better idea on the influences. This was to ensure the relevant parameters are included and to avoid dependence on the statistical analysis alone. Once the parameters were identified to have great influence on the productivity, the regression analysis was employed. Analyses were done on 3 different cases. These are:

a) if only field data are available: field data includes: weathering grade, portable point load (Is_{50}), jar slaking index, surface hardness (Schmidt hammer), joint spacing, grain size and ripping direction.
b) If only laboratory data are available: laboratory data includes point load index (Is_{50}), slake durability (Id_1 and Id_2), penetration with 10 mm probe, penetration with point load bit, grain size, sonic velocity, dry density, UCS, and Brazillian indirect tensile strength.
c) Both field and laboratory data are available: this includes all of the field and laboratory parameters listed above.

The significance of each regression was assessed by calculating the correlation coefficient (R). R, the multiple correlation coefficient, is the linear correlation between the observed and model-predicted values of the dependent variable. Its large value indicates a strong relationship. R^2, the coefficient of determination, is the squared value of the multiple correlation coefficient. The R^2 statistic is a measure of the strength of association between the observed and model-predicted values of the dependent variable. The large R^2 values indicate strong relationships and are therefore an important measure of the usefulness of the model. Degree of association of coefficient of determination used in this study is shown in Table 7.11.

Table 7.11: Degree of association of coefficient of determination

R^2	**Degree of association**
0.85 - 1	Very significant
0.70 – 0.84	Significant
0.60 – 0.69	Fair
0.50 – 0.59	Poor
< 0.50	Very poor

The significance value of the F statistic is less than 0.05, which means that the variation explained by the model is not due to chance. The prediction method that was used in this study i.e. by prediction of an index, which then relates empirically with the machine performance have also been reported by Fowell et al. (1976). Machine performance prediction requires not only a scheme based on the rock material properties, but also the rock mass structure and machine characteristics.

7.9 The Rock Mass Properties Affecting Machine Performance

Analysis conducted on the individual intact and mass test results were found to be insufficient to accurately predict productivity as a whole. Thus it is believed that a combination of several factors might affect the production rate as a rock mass characteristic consists of a number of parameters: intact strength, discontinuities etc. These factors plus the machine advance direction may also influence the productivity. The prediction of advance rate is based on basic information that undergoes complex processing with the aid of computer software. It is the combination of the art and science where mathematical tools for prediction need the experience of the engineer with an understanding of the whole spectrum of rock masses with respect to their weathering grade will produce a successful prediction of production rate. The factors may vary from different weathering grades as it has been noticed that some factors are not significantly affecting the production in a particular grade, but affects greatly production in other grades. Indices used to predict the machine performance in this study is shown in Appendix L.

7.9.1 Field Data Assessment

The prediction equations in this section are only based on field-collected data. The analyses were separated into Grade II/III, Grade IVa/IVb and Grade Va/Vb materials. The reason for doing this is to evaluate factors that may influence the production rate for wider spectrum of weathering grades.

7.9.1.1 Grade II and III

Closer examination of the partial correlation coefficients reveals that joint spacing, weathering grade, point load index and ripping direction are heavily weighted contributors. Hence, to confirm these, stepwise regression was adopted and the regression equation obtained is as shown in equation 7.7. The result show R value of 0.905, R^2 of 0.820 and the significant value of 0.00. This result shows that these four parameters are adequate to predict the productivity satisfactorily. The significant value shows a value of 0% indicating variations explained in the model is 0% due to chance. As for materials in grade II and III, grain size parameter, moisture content, slaking index and surface hardness measured by Schmidt hammer are not significant in affecting the production prediction. Please note that the point load index considered in this prediction is measured by the portable point load tester. Equation 7.13 is suitable to be used for both sandstone and shale as the grain size parameter was found not to be significantly affected by the production prediction in grades II and III.

$$Q = -0.28 + 181.03WG + 3.90Is_{50} - 553.72JS + 64.12RD \quad (7.13)$$

Multiple R = 0.905, R^2 = 0.820, Significance = 0.00

A forward stepwise regression, reaffirmed conclusions made from the partial correlation coefficient that among the four predictors mentioned in equation 7.7 the most significant contributor is the ripping direction followed by joint spacing. It is noted that this evaluation is only made for materials in grade II and III. When Is_{50} is replaced by SI, the R is reduced to 0.753 indicating that SI is not as suitable when compared to Is_{50} to be used for predicting performance in grade II and III materials.

The equation resulted from the single predictor is shown in equation 7.14.

$$Q = -128.24 + 135.49RD \qquad (7.14)$$

Multiple R = 0.762, R^2 = 0.581, Significance = 0.00

Thus, 58 percent of the production rate for grade II and III material is explained by the ripping direction. These results conclude that the direction advancement of the ripping machine is the most important parameter to be considered in stronger material for the case where only field data are available. In addition, joint spacing is equally important. The classification of weathering grade and the strength index is important to establish the parameter that will have the most influence.

7.9.1.2 Grade IVa/IVb

This class of weathering grade was analyzed separately from grade V materials as this class creates the most problematic materials in excavation assessment. Instead of only classed as Grade IV, the materials were divided into Grade IVa and IVb because of the wider class of material in this grade (Ibrahim Komoo, 1995a). Please see section 4.3 on the weathering grade classification.

From the results of all the field predictors, it was found that the six variables below give very significant results as presented in equation 7.15. As seen in the equation, there is the grain size parameter that has been included that signifies the equation is mainly for sandstone where grain size can be determined at site.

$$Q = 580.76 + 99.35\,WG - 15.687Is50 - 520.232\,JS + 25.16RD - 6.21GS - 1.74SI \quad (7.15)$$

Multiple R = 0.989, R = 0.978, Significance = 0.00

Without grain size parameter, the regression equation produced a coefficient of determination of 0.86 as shown in equation 7.16. It can be seen that the grain size parameter is such an important parameter when evaluating the excavatability in grade IV materials especially for sandstones. The bonding between the grains in grade IV is already weakened and the coarser grains further reduce the strength of the bonding. It can also be noted that coarser grain will break down easily compared to the finer materials in the jar slaking test.

$$Q = 252.51 + 87.43RD - 398.04JS + 88.09WG - 27.10Is_{50} + 0.96SI \quad (7.16)$$

Multiple R = 0.927, R = 0.86, Significance = 0.00

Equation 7.15 and 7.16 were further examined by not taking slaking index (SI) or point load index (Is_{50}) into account. This is in consideration to reduce possibility of repetition of material's strength measurement by performing point load and jar slaking tests together. The result shows R^2 of 0.978 for both equations when excluding the Is_{50} values and SI from equation 7.9, implying that neither parameter, Is_{50} or SI is enough to predict the productivity satisfactorily. The regression equations given are shown in equations 7.17 and 7.18.

by excluding Is_{50} from equation 7.9

$$Q = 519.44 + 25.39RD - 515.87JS - 3.70GS + 112.13WG - 2.47SI \quad (7.17)$$

Multiple R = 0.989, R^2 = 0.978, Significance = 0.000

by excluding SI from equation 7.9

$$Q = 557.65 + 25.68RD - 523.07JS - 5.66GS + 101.24WG - 17.35Is_{50} \quad (7.18)$$

Multiple R= 0.989, R^2 = 0.978, Significance = 0.000

By excluding Is_{50} or SI from equation 7.16, the regression equations showed R^2 of 0.859 for both cases as shown in equations 7.19 and 7.20 respectively. Again, this proves that either Is_{50} or SI can be used satisfactorily in the prediction.

by excluding Is_{50} from equation 7.10

$$Q = 208.38 + 88.95RD - 391.32JS + 94.83WG + 1.30SI \qquad (7.19)$$

multiple R = 0.927, R^2 = 0.859, Significance = 0.00

by excluding SI from equation 7.10

$$Q = 208.84 + 88.81RD - 388.80JS + 96.34WG + 5.15Is_{50} \qquad (7.20)$$

multiple R = 0.927, R^2 = 0.859, Significance = 0.00

It is interesting to note that by closer examination of the partial correlation the most influential factor in assessing rippability in Grade IV materials is the joint spacing and ripping direction. Surface hardness measured by Schmidt hammer was found not to be a good indicator for the assessment on the weak rock mass. When the assessment is made with rock mass weathering classification and some materials strength parameter (Is_{50} and SI), the R^2 value will further improved to 0.859.

7.9.1.3 Grade Va/Vb

Materials in grade V are considered as the weakest materials in this study. Materials in this grade are subdivided into Va and Vb according to Ibrahim Komoo (1995a) because of the wider range of these materials in this grade. During field testing, some of the materials especially in grade Vb could not be measured by portable point load tester due to insensitivity of the pressure gauges. Thus, jar slaking index was proposed to classify these materials. In this production prediction, variables included in the regression analysis were joint spacing, ripping direction, moisture content, grain size, slaking index and weathering grade. Surface hardness and point load index (portable) were not possible to be measured during the field test as no reading was detected.

The regression equation from field studies is shown in equation 7.21.

$$Q = 656.77 + 1.97MC - 21.87SI + 109.62WG - 5.33JS + 11.04RD \qquad (7.21)$$

Multiple R = 0.886, R^2 = 0.784, Significance = 0.00

The coefficient of determination of 0.784 shows that there is a significant relationship of the selected variables with productivity. In this equation, discontinuity characteristic, weathering classification and material characteristic are evaluated. Further examination by using stepwise regression method on these variables reaffirmed that weathering grade, jar slaking index and moisture content are enough to predict the productivity with a coefficient of determination of 0.782 as shown in regression equation 7.22. It was found that discontinuity characteristics (joint spacing and ripping direction) do not significantly affect the production prediction in materials in weathering grade V.

$$Q = 665.65 + 115.92WG - 21.71SI + 2.46MC \qquad (7.22)$$

Multiple R = 0.884, R^2 = 0.782, Significance = 0.000

Without moisture content, but with only slaking index and weathering grade as the predictors, this will give the regression equation as shown in equation 7.23 with coefficient of determination of 0.766. This equation suggests that jar slaking index and weathering grade are important parameters for materials in grade V.

$$Q = 407.37 + 151.90WG - 8.01SI \qquad (7.23)$$

Multiple R = 0.875, R^2 = 0.766, Significance = 0.000

The results suggested that in very weak rock masses, discontinuity characteristic do not influence significantly on the production. Moisture content also does not greatly influence the productivity as the materials are already weak for the ripping machine to work on.

7.9.1.4 All Grades

Closer examination found that certain predictor variables have better correlation as compared to other variables. In order to quantify the significant contributors, stepwise regression analyses was adopted. The equation required only four predictor variables that are: weathering grade, joint spacing, ripping direction and slaking index with R^2 improved to 0.93 as shown in equation 7.24. An interesting point here was that slaking index was found to be one of the best predictors in assessing excavatability in weak rock. It is because in this type of materials, it is important to further classify the broader class into sub-classes. However, analysis was done further to evaluate the effect of standard testing i.e. point load indices on their effect on the prediction. The regression equation if point load index replaced the jar slaking index is as in equation 7.25 with the same coefficient of determination. This result suggested that the slaking index and point load index can both be good predictors in assessing excavatability in weak rock. Both equation 7.24 and 7.25 show significance level of 0.000 indicating variations explained in the model is very unlikely due to chance.

$$Q = -246.26 + 176.49WG - 156.28JS + 118.36RD - 3.53SI \quad (7.24)$$

Multiple R = 0.964, R^2 = 0.93, Significance = 0.000

$$Q = -386.20 + 197.40WG + 15.41Is_{50} - 150.61JS + 120.60RD \quad (7.25)$$

Multiple R = 0.964, R^2= 0.93, Significance = 0.000

Overall results show that the classification of weathering grade is essential. In addition, some measures of intact strength by either point load index or slaking index and also the discontinuity spacing and orientation. The regression coefficient also suggested that the field data only is able to predict very significantly of the actual production performance.

7.9.2 Laboratory Data Assessment

In the case where only laboratory data are available, the same regression analysis using field analysis was adopted. The materials were analyzed according to the respective weathering grades as follows.

7.9.2.1 Grade II and III

The first step is to enter the whole laboratory predictors into the regression analysis. In the case of the penetration test, only the penetration test with a 10mm probe was chosen because it gave a better correlation with productivity as compared to the point load probe (see section 7.3). This is to avoid duplication in the assessment.

By adopting the stepwise regression, it was found that slake durability (Id_2) and penetration with 10mm probe produced R^2 of 0.236 and significance level of 0.052 as shown in equation 7.26. The significance level indicating 5% of the model is due to chance while the R^2 value indicating a very poor relationship to predict the production rate.

$$Q = 1666.15 - 14.87Id_2 - 0.12Pen_{10} \qquad (7.26)$$

Multiple R = 0.486, R^2 = 0.236, Significance = 0.052

If point load index (Is_{50}) is used to replace the penetration with 10 mm probe (Pen_{10}), the R^2 will be 0.226 with equation 7.27. It can be seen that penetration with 10mm probe test gives a slightly better result than the Is_{50}.

$$Q = 1420.32 - 11.66Id_2 - 43.141Is_{50} \qquad (7.27)$$

Multiple R = 0.476, R^2 = 0.226, Significance= 0.06

The equation with a single predictor of Id_2 is shown in equation 7.28.

$$Q = 1983.28 - 19.33Id_2 \qquad (7.28)$$

Multiple R = 0.464, R^2 = 0.215, Significance= 0.019

Based on this result, it shows that stronger materials particularly in weathering grade II and III, the laboratory result alone will give poor predictions for the productivity. In this case, only 23 percent of the productivity variability is explained. When we compare the result by field data alone can give more a better prediction as compared to the laboratory data alone.

7.9.2.2 Grade IVa/IVb

From the regression method, it was found that Id_1 is a better predictor compared to Id_2. Please note that Id_2 is one of the major contributors for grade II and III. As for grade IV, most of materials in grade IVa have disintegrated in the first cycle. Hence, it was not possible to carry out the second cycle. Possibly Id_2 is not meant to further classify these materials but is suitable to classify stronger material.

By adopting the stepwise method, the number of predictors is reduced to three. These are: moisture content, dry density and penetration with 10mm probe, giving the $R^2 = 0.325$ with significance of 0.00 as in equation 7.29.

$$Q = 1707.49 + 16.13MC - 0.44DD - 0.69Pen_{10} \qquad (7.29)$$

Multiple R= 0.57, $R^2 = 0.325$, Significance= 0.00

The regression was further examined by replacing the Pen_{10} with Is_{50} parameter. By adopting this, the R^2 reduced from 0.325 to 0.282 if Is_{50} to replace the penetration data as shown in regression equation 7.30. This case is not obvious in Grade II and III but quite significantly in grade IV material. Probably, because the penetration test can produced better result in moderately to weak materials. In strong material, the penetration test is not significantly a better test than the Is_{50}.

$$Q = 1731.23 + 23.12MC + 126.38Is_{50} - 0.57DD \qquad (7.30)$$

Multiple R = 0.531, $R^2 = 0.282$, Significance= 0.001

7.9.2.3 Grade Va/Vb

The laboratory data was analyzed and all data were entered into the regression model. The regression was further analyzed by not incorporating the Pen_{10} parameter and the result is shown in equation 7.31.

$$Q = 1367.93 - 2.6MC - 0.08SV + 0.02DD - 1714.37Is_{50} \quad (7.31)$$

Multiple R = 0.623, R^2 = 0.388, Significance= 0.024

Further work was done by adopting the stepwise method. The result shows that a single variable of Is_{50} can predict 89 percent of the laboratory result with R^2 of 0.345 as compared to 0.388 by adopting four variables (equation 7.32). The significance level show very minimal value, indicating the model is adequate.

$$Q = 1282.83 - 1914.34Is_{50} \quad (7.32)$$

Multiple R = 0.587, R^2 = 0.345, Significance= 0.001

7.9.2.4 All grades

In this prediction where only laboratory data is available, two steps of analysis were conducted: firstly was for materials with UCS, Indirect tensile strength and Id_2 predictors that are referring to grade II, III and IVa; and secondly was for the whole range of materials (without UCS, ITS and Id_2). This method of analysis is important as some of the predictors such as UCS and Indirect tensile strength are not able to be carried out on the weaker materials (grade IVb and higher). The regression analysis with stepwise method gave the best equation as shown in equation 7.33 and 7.34.

$$Q = 384.72 - 118.52ITS + 7.89Id_1 - 27.06SI \quad (7.33)$$

Multiple R = 0.707, R^2 = 0.5, Significance= 0.00

$$Q = 1103.41 - 84.33Is_{50} - 6.32Id_1 \quad (7.34)$$

Multiple R = 0.841, R^2 = 0.707, Significance= 0.00

From equation 7.33, further analysis was done on examining the most influential predictor. The partial correlation shows that Brazillian indirect tensile strength is the most influential predictor with a coefficient of 0.382 or 76% from the total coefficient with equation as in 7.35.

$$Q = 813.68 - 172ITS \qquad (7.35)$$

Multiple R = 0.618, R^2 = 0.382, Significance= 0.00

The result shows that ITS can be a better predictor than the UCS which most of previous researchers predicted (Singh, 1987; Basarir and Karpuz, 2004). ITS has an advantage of where the sample preparation for Brazillian testing was easier than the preparation for UCS because the thickness required on the cylindrical samples is only 25 mm as compared to about 80 mm for the UCS. Thus, a wider range of samples can be prepared for this test. The prediction of Brazillian testing result alone can be improved by the best curvilinear relationship to coefficient of 0.4133 (Equation 7.36).

$$Q = 696.73 - 379.1\ln(ITS) \qquad (7.36)$$

Multiple R^2 = 0.4133, Significance= 0.00

7.9.3 Field and Laboratory Data Assessment

The third case is when the data available comprised of both field and laboratory data. This condition is believed to give the best relationship as compared to field or laboratory only.

7.9.3.1 Grade II and III

The best predicted variables in the field and laboratory results are used in this analysis. The regression equation when the selected laboratory and field predictors are used, is shown in equation 7.37.

$$Q = 1140.07 – 17.04Id_2 + 0.14Pen_{10} + 255.51WG – 561.57JS + 64.59RD + 59.94Is_{50} \quad (7.37)$$

Multiple R = 0.931, R^2 = 0.867, Significance= 0.00

Instead of Pen_{10}, only the Is_{50} is used, the equation will be as follows in Equation 7.38.

$$Q = 1177.32 – 14.46Id_2 + 166.22WG – 536.54JS + 63.89RD + 47.63Is_{50} \quad (7.38)$$

Multiple R = 0.923, R^2 = 0.853, Significance= 0.00

The inclusion of laboratory data from the field data in the final examination only improves by 5 percent of the explanation of production from the field data i.e. from 82 percent to 87 percent. As discussed earlier, the Pen_{10} looks like giving a better result than the Is_{50} alone. Overall, it can be concluded that field data is sufficient to assess the materials in grade II and III for the ripping works.

Figure 7.24 shows the influence of individual predictors to the predicted production equation when all predictors were selected. The R^2 when all predictors were selected gives a value of 0.872 or 87.2 percent accuracy of actual production. However, it was found that only a few predictors could be used to predict the production satisfactorily marked by the dotted line. There are RD, JS, WG, Is_{50} and Id_2 as shown in equation 7.328 with R^2 of 0.853. This equation is satisfactorily for both sandstone and shale.

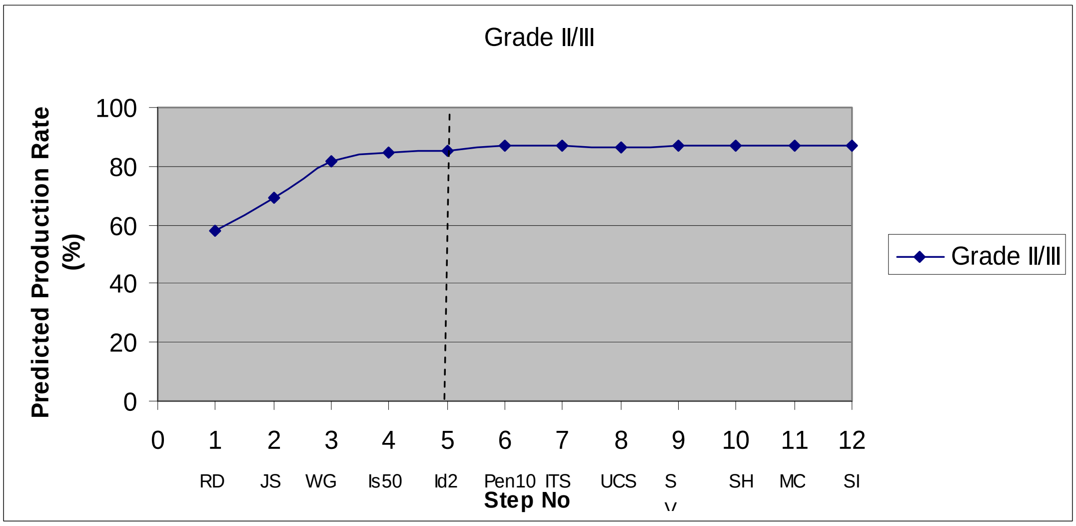


Figure 7.24: Graphical interpretation of accuracy of predicted production rate for grade II/III materials

7.9.3.2 Grade IVa/IVb

When field and laboratory results are combined, the results show that a combination of these parameters gave a very significant relation of coefficient of determination of 0.98 and siognificance of 0.00. The regression equation is as follows (equation 7.39) for sandstone:

$$Q = 416.85 - 531.83JS - 7.63GS + 24.61RD + 113.78WG - 60.11Is_{50} - 0.86MC + 0.05DD \quad (7.39)$$

Multiple R = 0.99, R^2 = 0.98, Significance= 0.00

If Pen_{10} is substituted for Is_{50}, the equation will be as follow with R^2 of 0.983 as shown in equation 7.40.

$$Q = 1055.10 - 490.27JS - 12.90GS + 19.95RD + 72.34WG - 2.03MC - 0.12DD - 0.41Pen_{10} \quad (7.40)$$

Multiple R = 0.991, R^2 = 0.983, Significance= 0.00

If SI is chosen as one of the predictors, the following equation was obtained (Equation 7.41)

$$Q = 616.46 - 515.28JS - 7.14GS + 25.59RD - 4.02SI + 107.93WG - 2.24MC - 0.02DD \quad (7.41)$$

Multiple R = 0.989, R^2 = 0.979, Significance= 0.00

However in the case of shale, where grain size is not a predictor, the equation will be as in 7.42 with a coefficient of determination of 0.872. It shows that grain size is an important predictor for material in this grade. The coarser material is easier to be ripped due to the grain-interlocking factor. The contact areas between grains are lesser in coarser grained than the finer grained, thus lower force is required to break the material as the resistance between the grains is lesser. For material in grade II and III, the grain size is not that important predictor as grains in these grades are well cemented, thus grain size will not affect excavatability so much.

$$Q = 784.84 - 392.54JS + 81.17RD + 73.59WG + 1.86MC - 0.22DD + 26.70Is_{50} \quad (7.42)$$

Multiple R = 0.934, R^2 = 0.872, Significance= 0.00

Is_{50} in Equation 7.42 was replaced with SI resulting in the regression equation of Equation 7.43. The R^2 suggested that the SI or Is_{50} can be satisfactorily used as one of the predictors.

$$Q = 774.50 + 70.20WG - 398.52JS + 80.66RD + 0.55SI + 1.89MC - 0.21DD \quad (7.43)$$

Multiple R = 0.934, R^2 = 0.872, Significance= 0.00

By replacing the Is_{50} parameter with Pen_{10}, the R^2 improved to 0.882 with equation 7.44.

$$Q = 400.55 - 430.44JS + 80.63RD + 124.94WG + 2.80MC - 0.16DD + 0.44Pen_{10} \quad (7.44)$$

Multiple R = 0.939, R^2 = 0.882, Significance= 0.00

When the stepwise regression method was employed on all field and laboratory data, the predictors were further reduced to four parameters that are: joint spacing, ripping direction, weathering grade, dry density and penetration by 10mm probe. The regression equation is (equation 7.45):

$$Q = -69.87 - 437.74JS + 86.26\,RD + 154.16WG + 0.50Pen_{10} \quad (7.45)$$

Multiple R = 0.934, R^2 = 0.873, Significance= 0.00

The result showed that significant correlation can be predicted by using only four parameters. It is also found that the penetration test by using a 10mm probe can produce better result than by Is_{50}. In this equation, weathering grade, discontinuity characteristic, weathering grade classification and some parameters related to material strength are needed to produce significant relationship. For sandstone, grain size would be an additional parameter, which would produce a better prediction.

Figure 7.25 shows the influence of individual predictors to the predicted production equation for materials with grain size parameter (sandstone) and without the grain size parameter (shale). The pink line shows the prediction with grain size and the black line shows prediction without the grain size parameter. With the input of grain size parameter, a more accurate prediction can be expected as coarser grain size will be easier to break as compared to finer grain size. Equation 7.41 gave a R^2 value of 0.98 or 98 percent of the actual production (pink line) while the equation 7.43 produce estimation of 87.2 percent from the actual production.

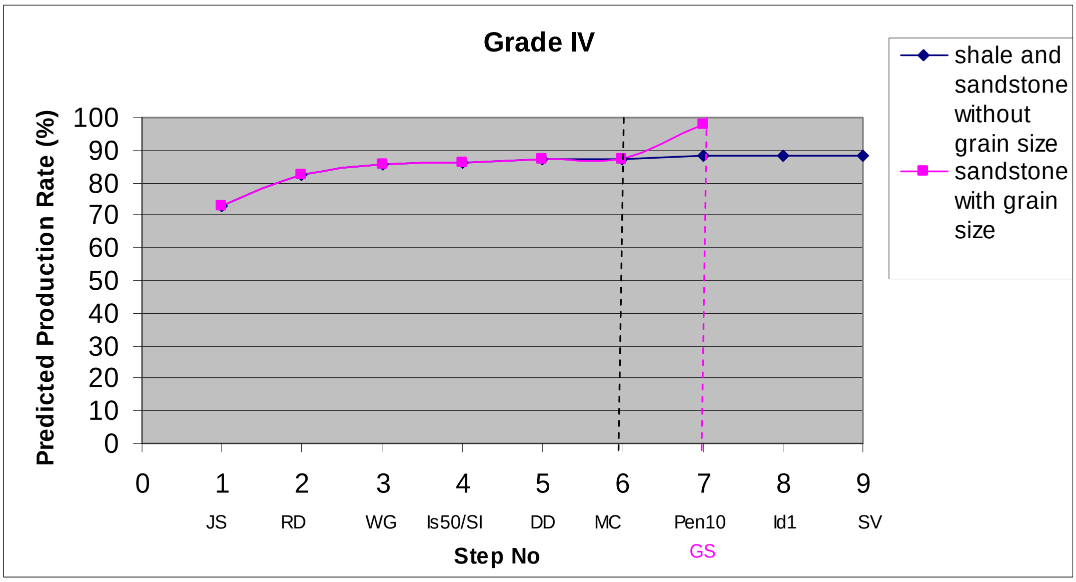


Figure 7.25: Graphical interpretation of accuracy of predicted production rate for grade IV materials

7.9.3.3 Grade Va/Vb

Both field and laboratory data are used in this analysis. When the Is_{50} value was added and left behind WG and SI, the regression equation had a coefficient of determination R^2 of 0.766 and significance of 0.00 as shown in equation 7.46. With significant relationship, this model is adequate as shown by the significance level.

$$Q = 414.62 + 151.08WG + 47.01Is_{50} - 8.79SI \qquad (7.46)$$

Multiple R = 0.875, R^2 = 0.766, Significance= 0.00

The coefficient does not suggest that any significant contribution when all the field and laboratory data are evaluated. Thus, a stepwise regression was done to see if there is any particular variable that might contribute significantly to the productivity. The result shows that weathering grade and jar slaking index can produce a R^2 of 0.766 for equation of 7.47.

$$Q = 407.37 + 151.90WG - 8.01SI \qquad (7.47)$$

Multiple R = 0.875, R^2 = 0.766, Significance= 0.00

This suggests that the determination of weathering grade (WG) and jar slaking index (SI) are very important factors especially for weaker materials. In such weak material (grade IVb and higher), other factors such as discontinuity characteristics do not play a significant role when compared to stronger materials (grade IVa and lower).

However, if Is_{50} is selected to replace the SI, the regression equation will be as in Equation 7.48. The result suggested that either SI or Is_{50} can be used to predict productivity for this grade of materials.

$$Q = 207.65 - 19.68Is_{50} + 179.90WG \qquad (7.48)$$

Multiple R = 0.874, R^2 = 0.764, Significance= 0.00

A graphical interpretation of the prediction equation is shown in Figure 7.26. When three numbers of predictors were entered, the predicted production rate was 77 percent of the actual production. It shows that by only having two predictors as shown in equation 7.48, the prediction managed to produce 76 percent of the actual production as marked by the dotted line.

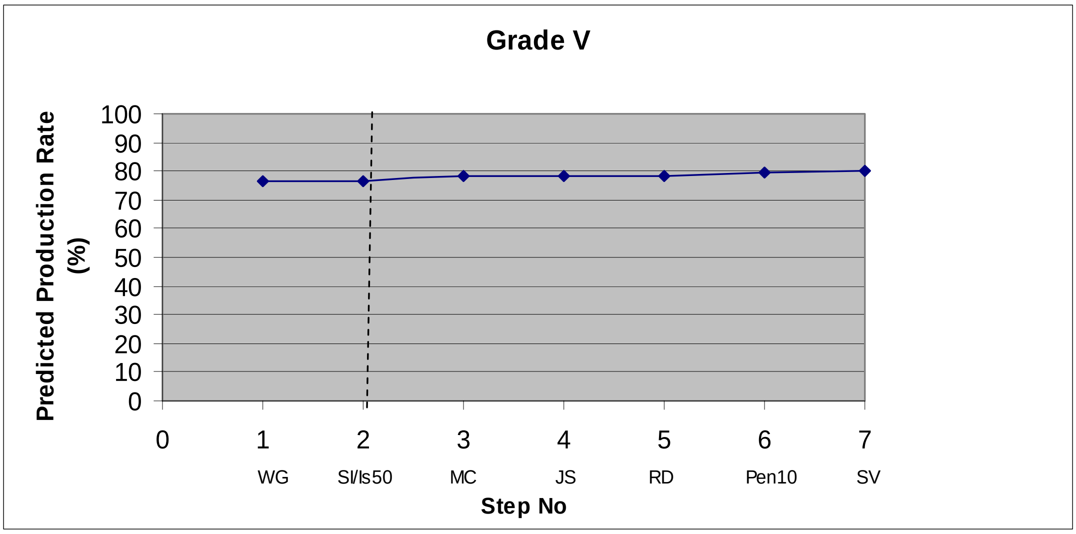


Figure 7.26: Graphical interpretation of accuracy of predicted production rate for grade V materials

7.9.3.4 All grades

With field and laboratory data available, the regression was further analyzed and the regression equation result is presented in 7.49 and 7.50 for the predictors chosen: Is_{50} or jar slaking index (SI).

$$Q = -330.94 + 187.72WG - 153.66JS + 119.6RD + 0.126Id_1 - 4.37Is_{50} \quad (7.49)$$

Multiple R = 0.964, R^2 = 0.93, Significance= 0.00

$$Q = -259.8 + 178.72WG - 155.7JS + 118.44RD - 3.39SI + 0.07Id_1 \quad (7.50)$$

Multiple R = 0.964, R^2 = 0.93, Significance= 0.00

From the equations, it suggested that either the Is_{50} or the SI as the input will give similar prediction of productivity. Further analyzed showed that the weathering grade governed the prediction by up to 85 percent. Hence, it again shows that identification of weathering grade is important in weak rock excavatability assessment. Logically, these variables make sense. Observation at the sites showed that the ripper machine performance depended greatly on the rock mass quality which can be explained by weathering grade, slake durability index, jar slaking index and the point load index. As it is commonly recognized, the advanced stages of weathering cause a reduction in the intact rock strength. With the closer joint spacing, the discontinuity strength within such a rock mass would be considerably reduced; hence the penetration of ripper tine and its advancement can be achieved with less effort. The joint spacing parameter can also indicate the block size that can be excavated. This does not mean that the other variables are not so important but the predictor variables listed above significantly governed the production rate in weak sedimentary rock. For all the above equations the residuals were checked for scatter and normality. In general, the checks proved satisfactorily and none of the regressions challenged the basic assumptions behind the statistics used.

7.10 Discussion

It is evident from the analysis of the results that the use of laboratory determined rock properties by themselves do not give an accurate prediction of machine performance. When these laboratories determined properties are combined with some measure of rock mass structure, the accuracy of prediction is greatly improved.

In the case of the analysis of machine performance and laboratory determined properties the amount of data regressed was quite significant in giving higher coefficient. This tends to indicate that if more results were available relating to rock structure, the accuracy of prediction will be more. However, it is also important to simplify the prediction by having minimum input parameters but could produce significant result.

In the earlier chapters, the material and mass properties with regard to the productivity were presented. This includes the influence of iron pan on the ripping depth. It was found that 2 cm to 5 cm thick of iron pan could resist the penetration of ripper tine on the surface of materials in weathering grade III to IVb. Thus, no production was observed in such cases.

The effect of moisture content was found to affect the productivity especially for materials in grade IV as compared to materials in weathering grade II, III and V. This is due to the strong interlocking of grains with strong cementation in grade II and III with the moisture having difficulty to seep between the grains. In weathering grade V, materials are already weak and such decrease in strength value will not affect the productivity significantly.

At the end of the chapter, the various parameters that were measured in the field and the laboratory were analyzed for the best combination to predict productivity. It can be seen that reasonable predictions are possible with relevant parameters as listed in section 7.6 and 7.7. However, for the best result, prediction should use weathering grade classification, material strength and the discontinuity characteristics depending on their respective weathering grade. Analysis found that, for each weathering grades, the properties that most influence the productivity are not the same.

For materials in grade II and III, the regression equation suggested that rock mass classification in terms of their weathering grades, discontinuity characteristics (joint spacing and ripping direction), material durability and strength will be combined to predict productivity satisfactorily. This result is in line with observation during the monitored ripping test that the rock would break along the existing discontinuity planes. It was therefore apparent that strong rocks might need jointing sets to assist in the excavation. From observations also, it was found that closed fractures did not assist breakage to the same degree as open fracture and in some cases provided no assistance whatsoever especially in the presence of quartz veins and iron pan. The frequency of joints has been covered by measuring the joint spacing. Higher frequency of joints will produce closer joint spacing and this parameter will also aid in the productivity. There is no significant difference between sandstone and shale materials in terms of their productivity in this grade, thus the same equation can be used.

As for materials in grade IV, two different sets of equations are proposed; firstly for sandstone and secondly, for both sandstone and shale (without the grain size parameter). The grain size parameter was found to significantly improve the prediction as indicated by the coefficient of determination (R^2) for sandstone. Coarser grained rock was found to give better productivity as compared to the finer grain material due to the loose grain interlocking. The penetration test with the 10mm probe was found to be an alternative predictor to be used instead of the Is_{50} value and their predictions involved these parameters are presented in Equation 7.44 and 7.45. Jar slaking index was also found to be a reliable predictor for this weathering grade and the equation is shown in 7.43. Jar slaking index has the advantage that this procedure can be conducted on site without requiring sophisticated equipment.

Productivity of sandstone and shale materials in weathering grade V can be predicted by using a single equation. The grain size and material type are found not significantly affecting the productivity. The slaking index or Is_{50} can both produce satisfactory predictions as shown in equations 7.24 and 7.25. The discontinuity characteristics are found not to be important parameters to be included in this grade. This is mainly due to the fact that the material is already weak, hence productivity does not depend much on joint assistance.

An alternative production prediction equation is also given without pre-determining the weathering grade. The regression equations are shown in Equations 7.47 and 7.49. The equation consists of rock mass classification by the weathering grade, discontinuity characteristic measured by joint spacing and ripping direction, material's strength and durability. The use of SI parameter instead of Is_{50} is also given in the equation. Please note that for all the predictions, it is assumed that the materials are not over capped by iron pan or any harder material such as quartz veins. If there are cases where the materials are over capped, the thickness of the hard materials should be considered as in section 7.7.2. A summary of equations with respect to their weathering grade are tabulated in the Table 7.12. The interesting finding is that Is_{50} can be replaced by slaking index or the Pen_{10} parameter. While Pen_{10} could produce a better R^2 than the Is_{50}, the SI is easy to conduct and can produce as good a result as the Is_{50} value.

Table 7.12: Summary of production performance prediction equations

Weathering Grade	**Equations**	R^2	**Equation No.**
II and III	Q = 1177.32 – 14.46Id_2 + 166.22WG – 536.54JS + 63.89RD + 47.63Is_{50}	0.853	(7.38)
IVa and IVb	*For sandstone*		
	Q = 416.85 – 531.83JS – 7.63GS + 24.61RD + 113.78WG – 60.11Is_{50} – 0.86MC + 0.05DD ; *or*	0.98	(7.39)
	Q = 1055.10 – 490.27JS – 12.90GS + 19.95RD + 72.34WG – 2.03MC – 0.12DD – 0.41Pen_{10} ; *or*	0.983	(7.40)
	Q = 616.46 – 515.28JS – 7.14GS + 25.59RD – 4.02SI + 107.93WG – 2.24MC – 0.02DD	0.979	(7.41)
	For shale and sandstone (without grain size parameter)		
	Q = 784.84 – 392.54JS + 81.17RD + 73.59WG + 1.86MC – 0.22DD + 26.70Is_{50} ; *or*	0.872	(7.42)
	Q = 774.50 + 70.20WG – 398.52JS + 80.66RD + 0.55SI + 1.89MC – 0.21DD ; *or*	0.872	(7.43)
	Q = 400.55 – 430.44JS + 80.63RD + 124.94WG + 2.80MC – 0.16DD + 0.44Pen_{10}	0.882	(7.44)
Va and Vb	Q =407.37 + 151.90WG – 8.01SI	0.766	(7.47)
	or		
	Q = 207.65 – 19.68Is_{50} + 179.90WG	0.764	(7.48)
General equation	Q =-330.94 + 187.72WG – 153.66JS + 119.6RD + 0.126Id_1 – 4.37Is_{50}	0.93	(7.49)
	or		
	Q = -259.8 + 178.72WG – 155.7JS + 118.44RD – 3.39SI + 0.07Id_1	0.93	(7.50)

7.11 Summary

This chapter has presented the analysis of machine performance working towards the combining of results from the field and laboratory monitoring undertaken for this study. From the results of these tests a relationship was sought, using a multi-linear regression technique, whereby the expected production rate could be predicted from the rock properties measured. Several prediction equations were derived based on:

a) a number of laboratory determined properties

b) field measurement, this gave a better correlation with machine performance compared to laboratory data alone

c) a combination of laboratory properties and measurement at field, this gave the most significant relationship, making it the most suitable method to predict the machine performance.

d) prediction was made based on different weathering grade and the type of materials to be excavated

From these prediction equations the optimum cutting performance of a CAT D9 ripper may be calculated.

CHAPTER 8

A COMPARATIVE STUDY WITH OTHER SUGGESTED METHODS FOR EXCAVATABILITY ASSESSMENTS

8.1 Introduction

The aim of this section is to compare the results of actual productivity rates measured at the sites in this study with other excavatability assessments proposed by other researchers. While all the previous researchers have produced different type of proposals, the ultimate aim was to predict as accurately as possible the excavation rate. However, it is generally understood that some modifications need to be made to suit any particular geological situation. The production rates from the case studies are compared with other methods of assessment namely RMR, Q system, Excavatability Index (EI), Singh et al. (1987), MacGregor et al. (1994), Karpuz (1990), Pettifer and Fookes (1994) and Basarir and Karpuz (2004). These types of assessments were chosen as they are widely accepted as classification assessments particularly for tunnelling (RMR and Q-system) and to evaluate whether the classifications can be used in rippability assessment for weak rock. The Excavatability Index developed by Kirsten (1982) was chosen because this system had been modified for excavation purposes from the Q-system thus it was considered important to use it in this study. In addition, the actual direct ripping test results will be compared with the established rippability assessments namely Pettifer and Fookes (1994), Singh et al. (1987), MacGregor et al. (1994), Karpuz (1990) and Basarir and Karpuz (2004) assessment methods.

The results of the rock mass properties for each location are given in Appendix A and were used as the input parameters in these comparisons. In order to describe the ease of ripping in an actual situation, classification based on production rate as suggested by Basarir and Karpuz (2004) was used as listed in Table 8.1.

Table 8.1: The suggested production for the assessment of ease of rippability (Basarir and Karpuz, 2004)

Production of D9 (m^3/hr)	**Descriptive terms**
0 – 285	Very difficult
285 – 450	Difficult
450 - 1000	Moderate
1000 – 1500	Easy
> 1500	Very Easy

Details of the parameters used and their ratings for the respective assessments have been discussed in Chapter 3.

8.2 Relationship between Productivity and RMR, Q System and EI

Comparisons of production rate were made with the rock mass classification that was designed for tunnelling works to compare whether there are any relations to ripping works. The relationship between the production rates of the ripping works and the RMR, Q-system and the Excavatability Index are shown in Figure 8.1.

The RMR values are formed by simply adding up the six parameters rating: UCS, RQD, discontinuity spacing, condition of discontinuity, groundwater conditions and orientation of discontinuities. In assessing the effect of discontinuity orientation for RMR, a revised version of the ratings proposed by Fowell and Johnson (1991) was used. The RMR ratings show a minimum value of 30.47 and the maximum value of 72.56. Bieniawski (1989) suggested that value of more than 60 indicating good rock and lower than 60 as fair rock for support applications.

While Abdullatif & Cruden (1983) reported that ripping works are possible up to an RMR of 60. Above this value, the rock needs to be blasted. However, these findings show that about 20 percent of the cases below 60 (especially grade II and III materials) are very difficult to rip and blasting is needed to excavate these materials.

The RMR has a poor coefficient of determination (R^2) of 0.5024 on the weathered rock in contrast with findings by Fowell and Johnson (1991) where they found a fair relation to stronger rock used for machine tunnelling. These findings were supported by Tallon (1982) where he reported that the RMR method exhibits a prediction for the central class, i.e. fair rock. The grade Vb and Va materials which are very weak rock have almost the same RMR value, but their production varies from 1000 to 1400 m^3/hr. There are more scatter of data for grades IVa and IVb materials ranging from moderate and very difficult ripping with production of 200 to 1000 m^3/hr. As for stronger materials in grade II and III, data are also scattered with RMR values of 40 to 65 with production from 0 to 900 m^3/hr.

Rowlings et al. (1995) reported that RMR system overemphasised the discontinuities parameter by having RQD and joint spacing separately (receiving up to 50 percent of the total rating) at the expense of other parameters. In addition, Bieniawski (1989) recommended the joint spacing ratings should be increased by 30 percent when less than three joint sets are present, giving more emphasis on block size. These reasons could contribute to the wide scatter for stronger materials as found in the grade II and III materials, which have lower values of RMR.

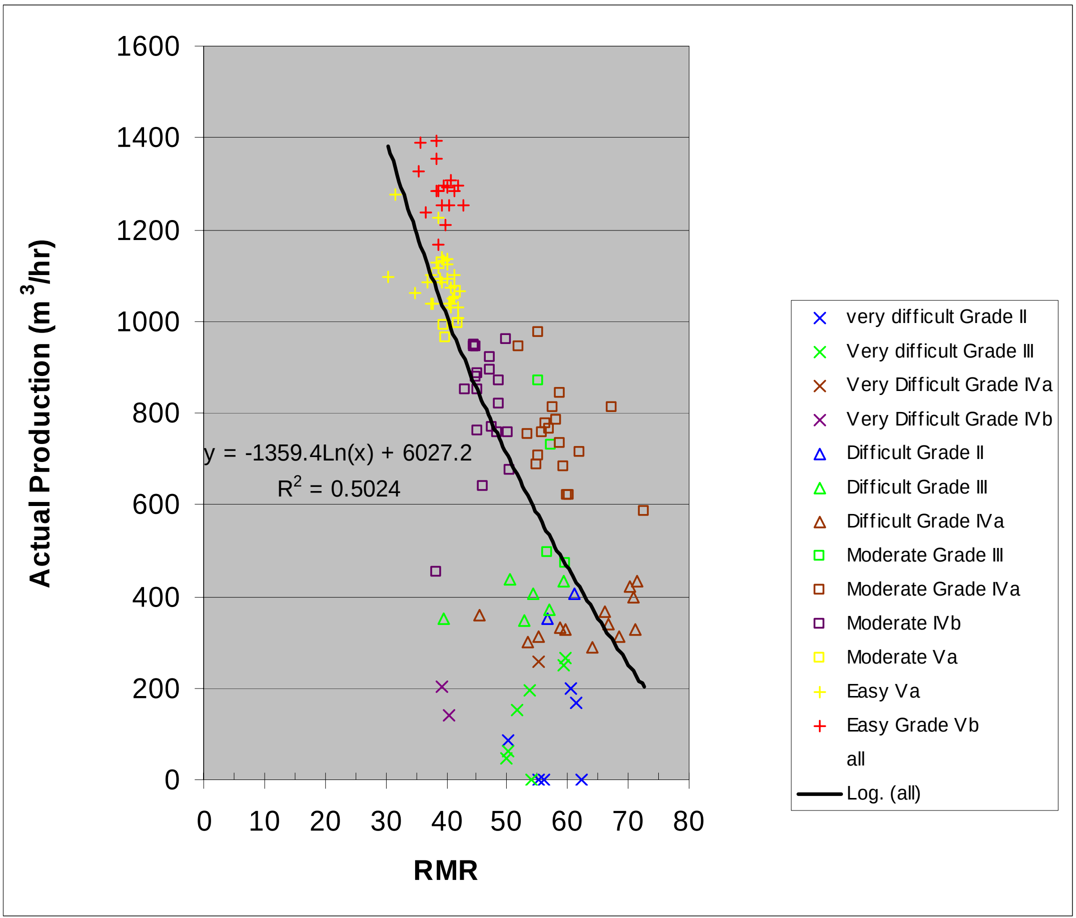


Figure 8.1: The relationship between production rates and RMR values

Figure 8.2 shows the relationship of Q-system and the productivity. The Q-system ratings were discussed in Chapter 3. Basically this system considers six parameters: RQD, number of joint sets, roughness of joints, degree of joint alteration, water inflow and stress condition. The value of Q ranges from 0.001 to 1000 which indicates exceptionally poor conditions for the lowest value and exceptionally good for the highest value. Abdullatif & Cruden (1983) suggested that easy digging can be expected when Q value is less than 0.14 and ripping is required for values greater than 1.05. If the value of 0.14 applies to the current study, a Q value of less than 0.14 indicates the grade Vb material, which could not be excavated by the EX200 excavator and needed ripping works to be carried out. The Q value of more than 1.05 indicates that the grade IV and lower materials which were moderately and difficult to rip and had production of less than 1000 m^3/hr by ripping with CAT D9.

The R^2 using Q-system to predict production rate is 0.6394, which is considered as a fair value as shown in Figure 8.2. The coefficient value using Q-system seems better than using RMR for the prediction of productivity. The data ranges from 0.03 to 15 on the Q-system rating. However, there is a wide scatter of data for grade IV, III and II materials. Grade IV materials can be considered as the most problematic materials in assessing the excavatability due to the materials exhibiting a 'soil-rock' behaviour. A better prediction of productivity was obtained using the Q-system as compared to RMR has also been reported by Kramadibrata (1996). Rogers (1991) has also noted that Q-system provides better definition of weak rocks and the RMR makes good distinction between the medium and strong rocks.

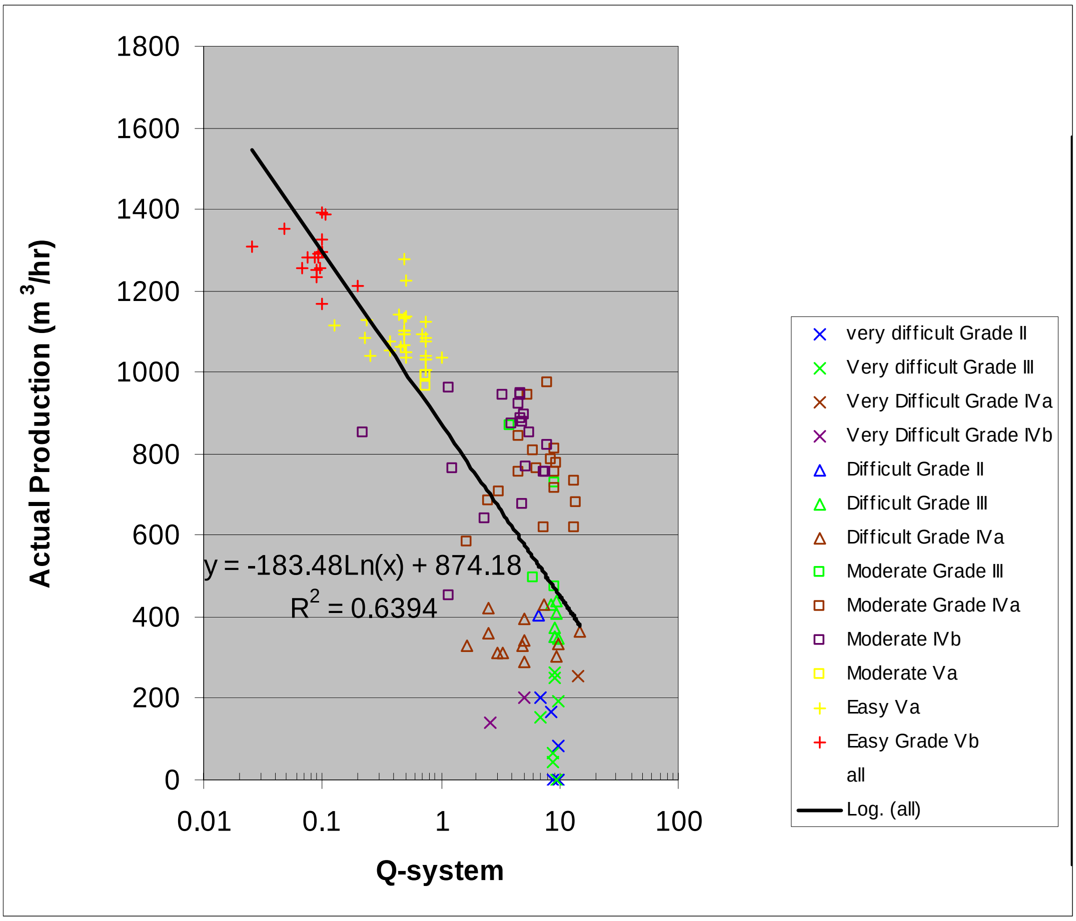


Figure 8.2: The relationship between the production rate and the Q-system

Excavatability Index developed by Kirsten (1982) was a modification from the Q-system and allows another comparison to be made. Parameters considered in the EI are mass strength number, joint spacing, RQD, joint set number, joint roughness and joint alteration that have been discussed in Chapter 3. It is shown in Figure 8.3 where EI offers more significant coefficient of determination (R^2) of 0.7134 and it is higher than RMR and the Q system. The use of the Excavatability Index as a measure to predict the productivity rate appears to be more appropriate than the RMR and Q-system. This may be due to the fact that RMR and Q-system were not developed as predictive tools for assessing excavatability particularly in the weak rocks. The findings have also been supported by Kramadibrata (1996) who found that EI gave a better assessment as compared to RMR and Q-system in assessing productivity.

The EI rating ranges from 0.01 to 1189 for the studied cases. The grade IV materials show some scatter. This is because EI considers the mass block size (Ms) to be significant. The higher the value of EI when the block size is larger, suggests productivity is expected to be lower. However, in grade V materials, the joint spacing or the block size alone does not significantly affect the production. This is because the material itself is already weak and is not subjected to assistance from the jointing. That is why grade V material data show some scatter. More scattered data can be seen for grade IV materials where moderate to very difficult ripping was noted. With the same value of EI of 100, the production rate varied from 200 to 1000 m^3/hr.

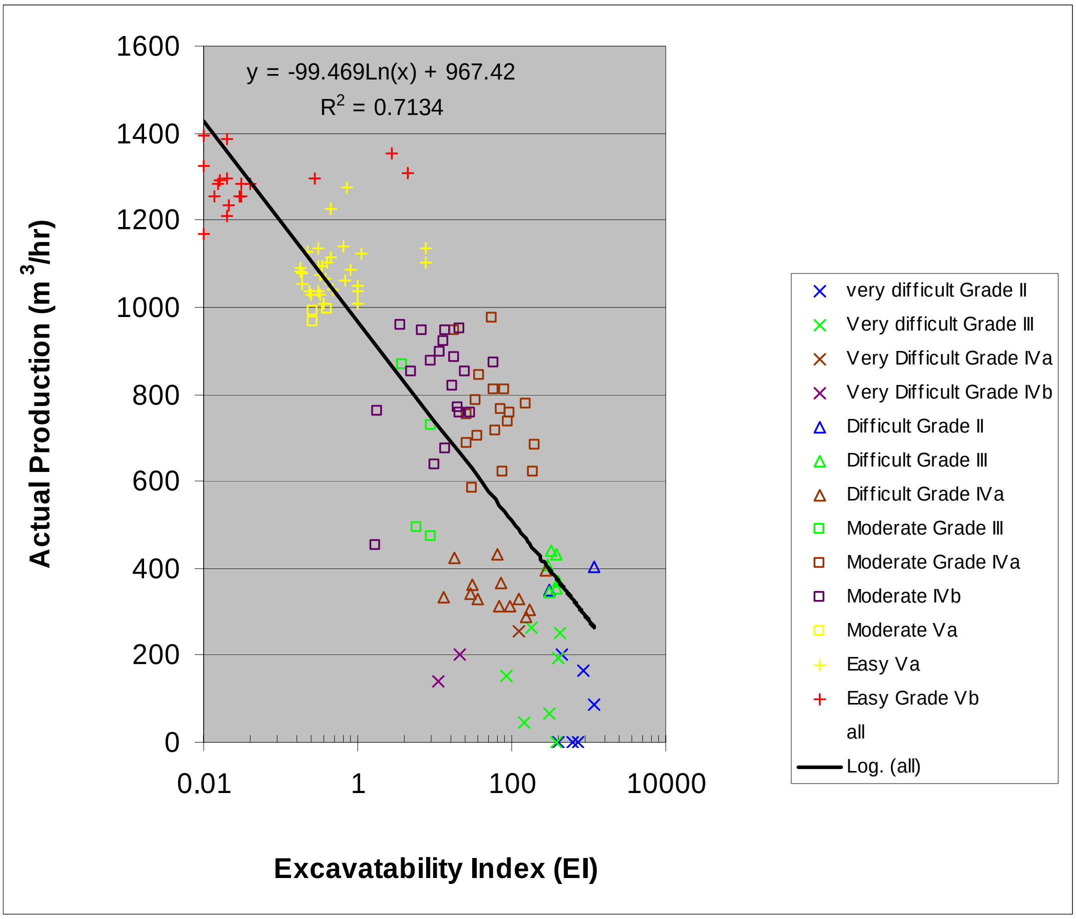


Figure 8.3 : The Relationship between Production rate and Excavatability Index (EI).

It appears from the evidence that classifications of ease of excavation by using RMR, Q-system and EI can be carried out with varying degrees of confidence. The use of EI to predict production rates appears to give a better assessment as compared to the Q-system and RMR. This is because EI was designed as predictive tools for excavation whereas RMR and Q-system were for rock mass support. The results showed similar weathering grades are plotted together for Vb, Va and IVb materials. Thus, it is worthwhile to further analyse the weathering effect of the rocks to its excavatability to provide a more precise prediction.

8.3 Graphical Method – Pettifer and Fookes

The evaluation of the sites was carried out using the Pettifer and Fookes (1994) recommended chart. This method of assessment is based on point load index and the joint spacing. The diagrams are divided into Easy digging, Easy rip (by D6/D7), Hard rip (by D8), Very hard rip (D9), Extremely hard rip (D11) and blasting required. The data of the direct ripping results were plotted and is presented in Figure 8.4 which shows that 90 percent of the data are found in the hard rip (D8), easy rip (D6, D7) and hard digging. Only about 10 percent of the result lies in the very hard ripping zones that require a D9 ripper.

The actual ripping test found that grade Va and Vb materials needed ripping works and were not able to be excavated easily as assessed in the assessment. It can be concluded that this method of assessment was too optimistic for these grades. Most of grade IVb materials can be found in the hard digging zone where materials in this zone are assessed to be able to be excavated by a shovel. However, in actual tests, these materials were classified as moderate ripping by a CAT D9. The same trend can be found in grade IVa materials, which lie in the hard ripping zone. However, in the actual situation, the materials were classified as moderate and difficult ripping by a CAT D9.

In the easy rip zone (materials that can be ripped by D6 or D7), materials from grade IVa and III dominated this area. In the actual ripping test, materials in this category were found to be moderately rippable by D9. This current study shows that materials in these grades are influenced much by the joint spacing and the ripping direction. However, no ripping direction is considered in this assessment. It is also noted that this assessment is too optimistic in the prediction for these types of weak materials. It is also found that in this assessment method the point load index is one of the parameter needed. However, the point load index in the weak rock was found to be very low, thus the assessment is found to be optimistic.

In the very hard, extremely hard zones and blasting zone, materials of grade II and III were found to be very difficult to rip. The materials in this zone can be regarded as acceptable in the assessment. The stronger materials in weathering grade II and III have a higher point load index and larger spacing. However, the materials with smaller joint spacing falls in the hard and easy rip zones.

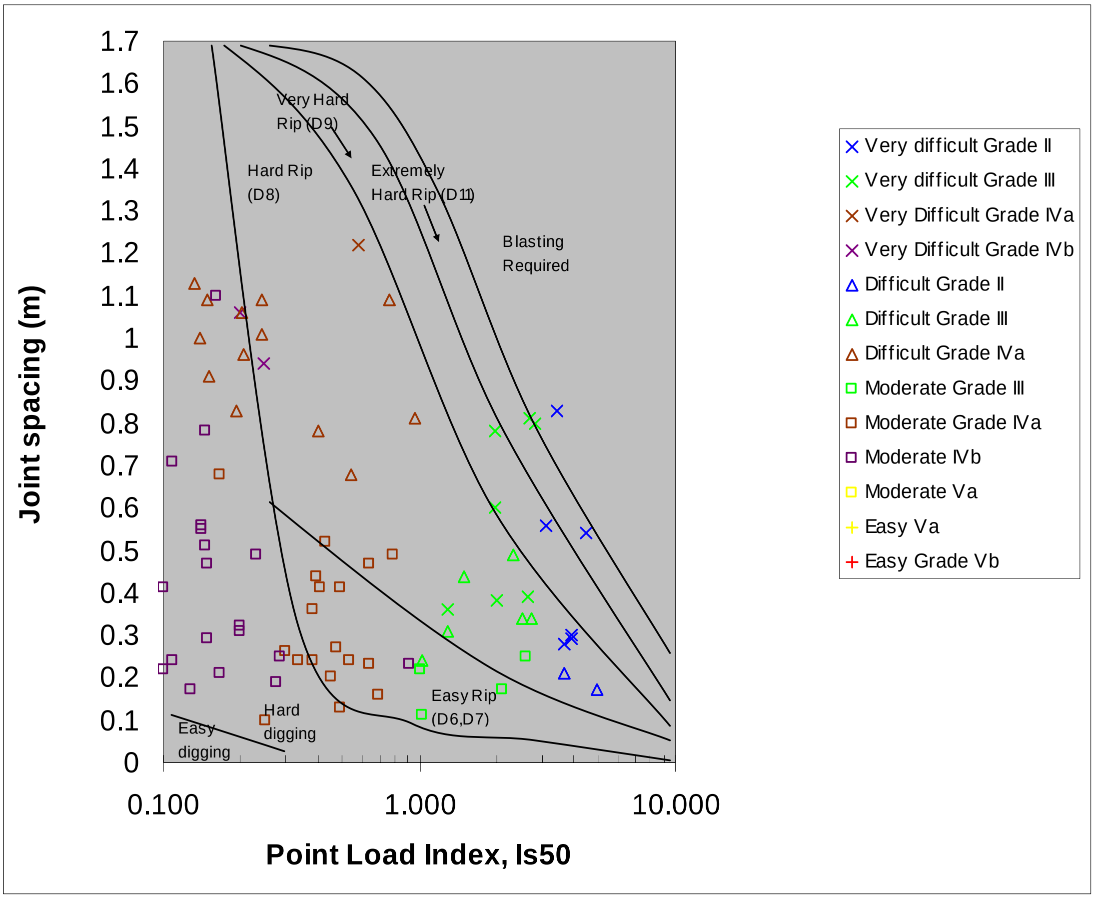


Figure 8.4: Rippability classes of rock according to Pettifer and Fookes (1994)

8.4 Comparison by Grading Methods

Grading methods are used to evaluate the excavatability of rock mass by giving points to the parameters that are considered. These systems have been introduced by many researchers as discussed in Chapter 3. For this comparison Singh et al. (1987), Karpuz (1990), Excavatability Index (1982), MacGregor et al. (1993) and Basarir and Karpuz (2004) were chosen for their reputation in Malaysia.

8.4.1 Singh, Denby and Egretli Assessment

In this assessment, parameters of tensile strength, weathering grade, sonic wave velocity, abrasiveness and discontinuity spacing were rated. The ratings were based on Singh et al. recommendations as presented in Chapter 3. Singh et al. (1987) gave emphasis to the discontinuity spacing followed by sonic velocity, abrasiveness, weathering and strength. The total rating is categorized by the ease of excavatability: easy, moderate, difficult and marginal, based on the size of machines. The difficult section means that the rock mass can only be ripped by a CAT D9 while the moderate and easy columns indicate that it should be easy ripping as these columns suggest that the task can be done by a smaller size of ripper. The marginal column indicates that the rock mass may need to be blasted. These sections are marked according to their range of ratings and shown in Figure 8.5.

Grade Vb materials showed production of more than 1000 m^3/hr but from the Singh et al ratings showed that it ranges from easy to difficult columns. The moderate and easy columns indicate that the material can be ripped relatively more easily than the difficult column and logically it can produce more. However, the production rates were found to be similar in the difficult or moderately column than the easy column. In this assessment, all rock materials used the same method of assessment without specifying the weathering grade where all the five parameters considered (tensile strength, weathering grade, sonic velocity, abrasiveness and discontinuity spacing) were evaluated and were heavily weighted. However, in this current research it was found that grade Vb materials are not very dependant on the parameters except for the weathering grade and the slaking index (Equation 7.35). The same situation also applies to the grade Va materials where two outliers were detected in the moderate column that showed production of more than 1200 m^3/hr but classified in the moderate column while the data in easy column shows a lower productivity.

Grade IVa and b materials show generally decreasing values when the rating increased. The findings confirm that these materials are subjected to the influence of weathering grade, joint spacing, density (measured by sonic velocity in this evaluation) and strength. However, a few outliers showed production of less than 400 m^3/hr in the difficult column and an outlier fell in the easy column, which was found difficult to rip in practice. The problems associated with these weaker rocks when using this assessment were also addressed by MacGregor et al. (1994) where they found a very wide scatter of data in the easy, moderate and difficult columns that could not be classified satisfactorily for rippability. These results give evidence that ripping direction is one of the important parameters that influenced the productivity in grade IV materials, which was not accounted for in Singh et al.'s assessment.

The findings in this study show that ripping direction, joint spacing and some measures of strength affect the productivity in grade II and III materials. Out of these parameters, ripping direction and joint spacing was found to be the most influential parameters (equation 7.3) in assessing productivity. The trend for this grade was more scattered with some data which were found to be very difficult to rip (less than 200 m^3/hr which required blasting) lies in the difficult column but some data that produced about 400 m^3/hr fell in the marginal or very difficult column. The ripping direction parameter, which influenced much on these materials was not included and could be the cause of this anomaly.

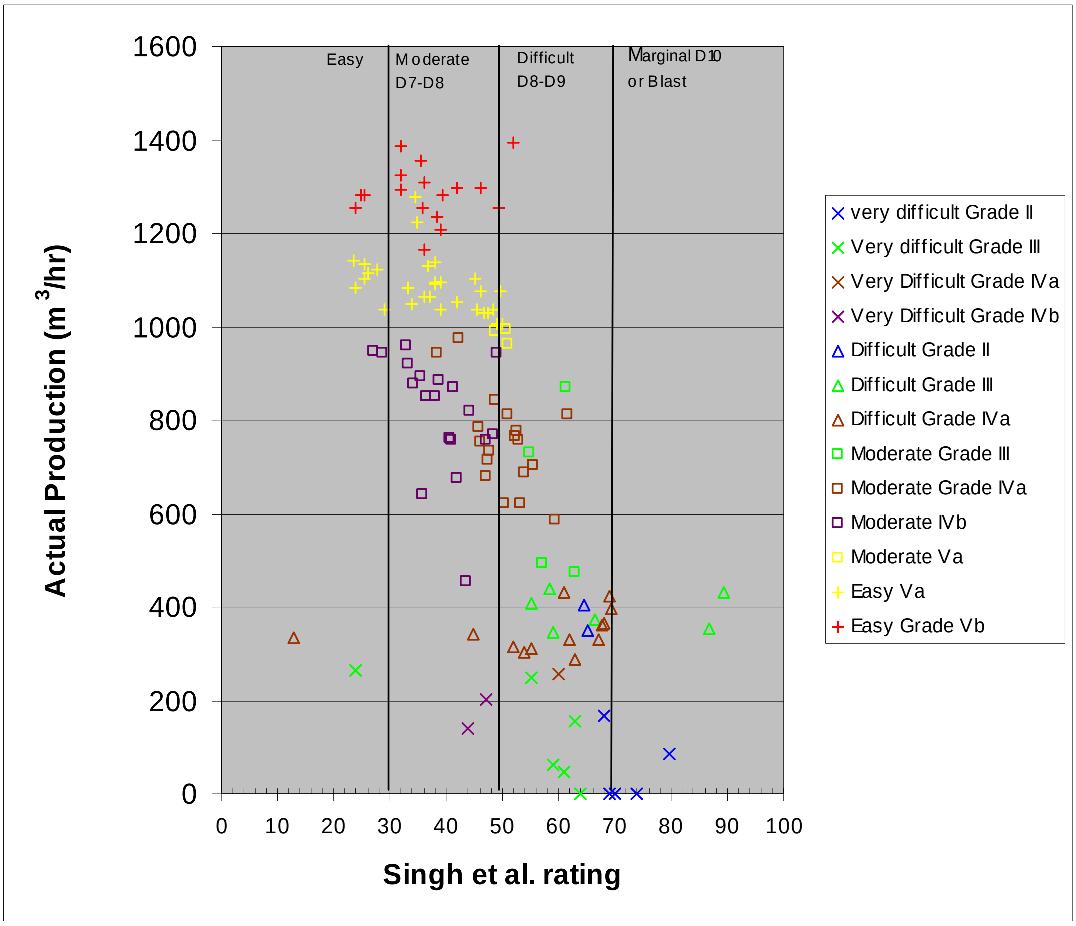


Figure 8.5 : Singh et al. Excavability Assessment.

8.4.2 MacGregor et al. Assessment

In MacGregor et al. (1994) assessment, UCS, weathering grade, grain size, sonic wave velocity, roughness, joint set, joint spacing and the structure parameters are considered. MacGregor et al. suggested that the production volume that can be expected from the equation given (Equation 3.5). By entering these parameters in the equation 3.5, predicted production rates can be plotted as in Figure 8.6. As the actual ripping results were also presented in m^3/hr, thus the same production rate should be expected. The data should fall on the line, marking that the same production rate was noted. Data for grade Va and Vb were found to be far out of the range, and were predicted to have production rates of 100 to 400 m^3/hr only but in actual fact produced more than 1000 m^3/hr. As found in this study, the weaker materials in grade V are greatly influenced by their weathering grade together with jar slaking index and not so dependant on other parameters. However, in MacGregor et al. assessment, the prediction is much more dependant on other parameters such as grain size, sonic velocity, joint set and spacing. The significance of these parameters is quite important, thus affecting the predictions for these groups of materials.

The prediction for materials in grade IVb is also underestimated. The data was predicted to have less than 400 m^3/hr but the actual ripping test showed the production of 600 to 1000 m^3/hr. The finding in this study showed that some measure on compactness (dry density), weathering grade, joint spacing, strength and ripping direction have a great influence on the productivity. Although MacGregor et al. considered most of the parameters in their equations; the ripping direction parameter was not considered. The ripping direction was found to have great influence on increasing or decreasing the productivity in these materials. In addition to that the lacking of ripping direction parameter and their rating for weathering grade are also underestimated.

MacGregor et al.'s predictions for materials in grade II and III was about 70 percent overestimated. About 25 percent of materials in grade III were predicted to produce about 500 to 800 m^3/hr , however in the actual ripping test it produced less than 200 m^3/hr . The same case also applies to grade II materials, which were predicted to produce more than 200 to 500 m^3/hr but only produced 0 to 200 m^3/hr. For these materials weathering grade, ripping direction and the joint spacing play a significant role in the prediction, which was not significantly considered by this method of assessment.

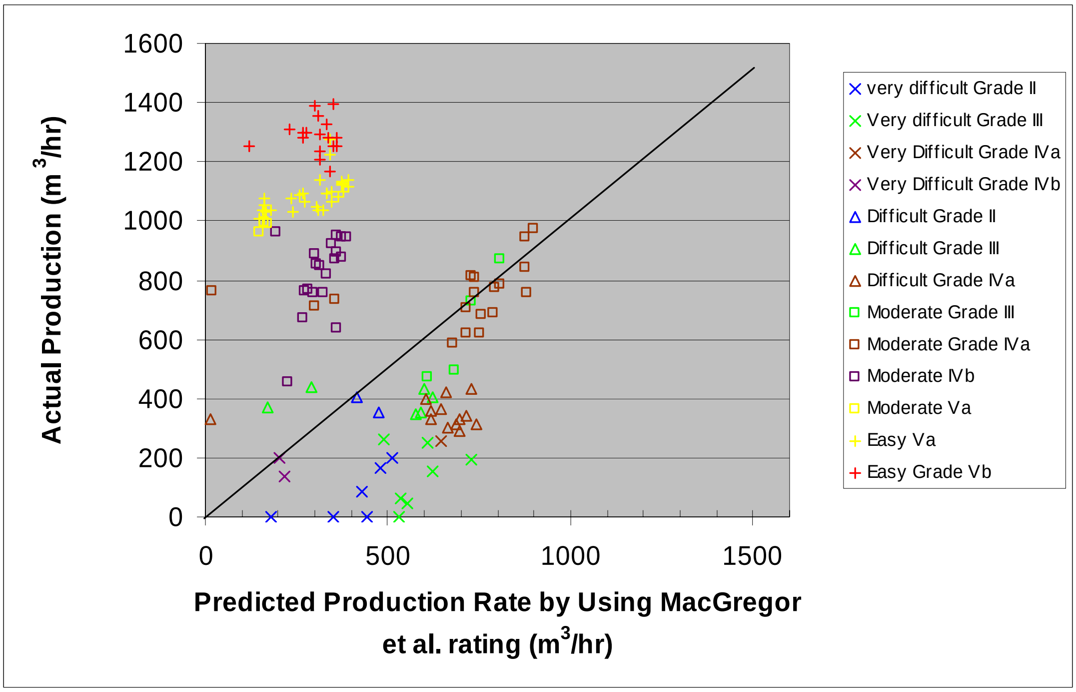


Figure 8.6 : MacGregor et al. Excavability Assessment

8.4.3 Karpuz Assessment

Karpuz's excavatability assessment looks at 5 parameters which are: strength (measured by UCS or Is_{50}), joint spacing, sonic velocity, weathering and surface hardness of materials. The rating for strength, joint spacing and sonic velocity is 25 respectively. However, the rating of only 10 for weathering is the lowest of all parameters taken into account, showing that weathering is the least important factor in assessing excavability. There is also no element of ripping direction considered in Karpuz's assessment.

The results show that grade IVb which has productivity of more than 1100 m^3/hr lies in the easy and moderate column although they produce the same amount of production. Grade Va materials which have produced production rates of 900 to 1200 m^3/hr fell into the same column. Rationally, the same ratings will produce the same production rate, however, this hypothesis does not apply to grade V, IVb and IVa materials in the easy and medium columns with this assessment. The variations for these grades are too vast from 100 to 1400 m^3/hr for materials with the same rating number in the easy column while in the medium column, the production rate varies from 200 to 1200 m ^{3}/hr. The results suggest that weathering grade should be considered more highly whereas the element for surface hardness should not be considered highly for weak rock conditions. There are also some data that fall in the easy column but in actual ripping tests the materials were found too difficult to rip and produced less than 200 m ^{3}/hr.

About 55 percent of materials in the moderate column that can be ripped by D9 ripper were found only produced 0 to 400m ^{3}/hr . This applies to stronger materials in weathering grade IVa, III and II. The underestimation of the rippability especially on these stronger materials by Karpuz was also reported by Basarir and Karpuz (2004). As found in this study, ripping direction plays a significant role in the excavatability assessment especially in these stronger rock masses and thus, must be considered.

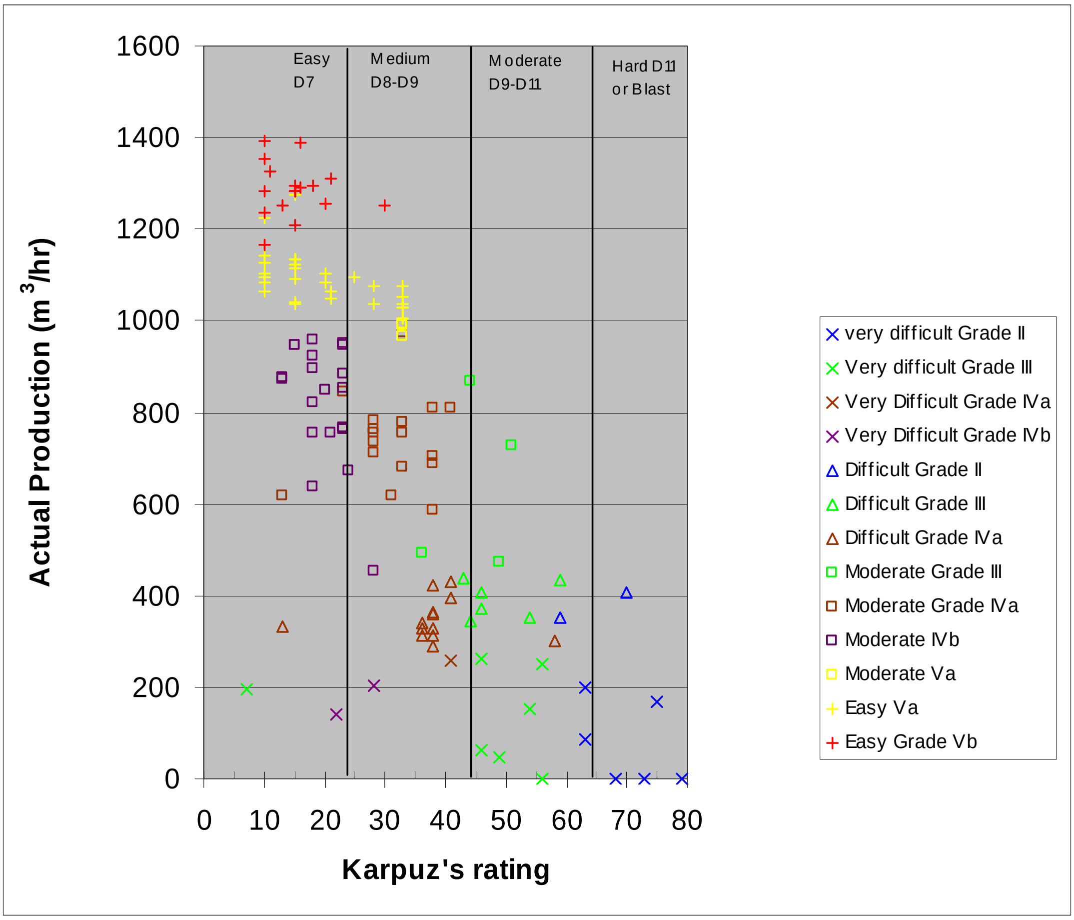


Figure 8.7 : Karpuz Excavability Assessment

8.4.4 Basarir and Karpuz Assessment

The most recent assessment was proposed by Basarir and Karpuz (2004) on the rippability of rock mass. This study will then use this assessment as a comparison. The most important factor in this rating is the strength parameter (measured by UCS or Is_{50}), followed by seismic wave velocity, discontinuity spacing and the surface hardness (Schmidt Hammer value). The ease of ripping is categorized into the following classes: very easy, easy, moderate, difficult and very difficult situations. Data from the field and laboratory were used to assess this assessment and the results are plotted in Figure 8.7 marked by their respective weathering grade.

From the results, it is noted that the assessment showed the least production rate for materials in the difficult column. The production rate in this column is from 0 to 500 m^3/hr. The variation might be due to the ripping direction that was not considered in this assessment. Grade II and III materials dominated this column. However, materials which produced less than 285 m^3/hr in this difficult column should be put in the very difficult column (0-285 m^3/hr).

In the moderate column, a wide variation of data was encountered. In this column, the productivity should be higher (450 – 1000 m^3/hr) than the materials in the difficult column. Grade III and an outlier from grade IVa fall in this category with production of about 100 to 700 m^3/hr. As discussed in Chapter 6, for materials in this zone, ripping direction and the discontinuity orientation play a significant role but are not considered in this assessment. This might be the cause of the variations.

In the easy column, there is a group of grade IVa materials that gave production of about 400 m^3/hr which were rated at the same rate as materials with production rates at about 1000 m^3/hr. This column should accommodate the data for production of 1000 to 1500 m^3/hr. These materials which produced about 400 m^3/hr were found difficult to be ripped but classified as easy in this diagram. For materials in grade IVa, the ripping direction and the spacing with their weathering grade should be highly rated. Most of grade Vb materials that produced about 1200 m ^{3}/hr fall in the very easy column. Materials in grade V supposedly to be very dependant on the weathering grade and their ratings should be highly regarded. There is also grade IVb materials that only produced about 600 to 900 m ^{3}/hr which also fell in this column. Generally, Basarir and Karpuz rating underestimated the rating for some of the parameters such as weathering grade and discontinuity spacing. In addition, ripping direction was not considered.

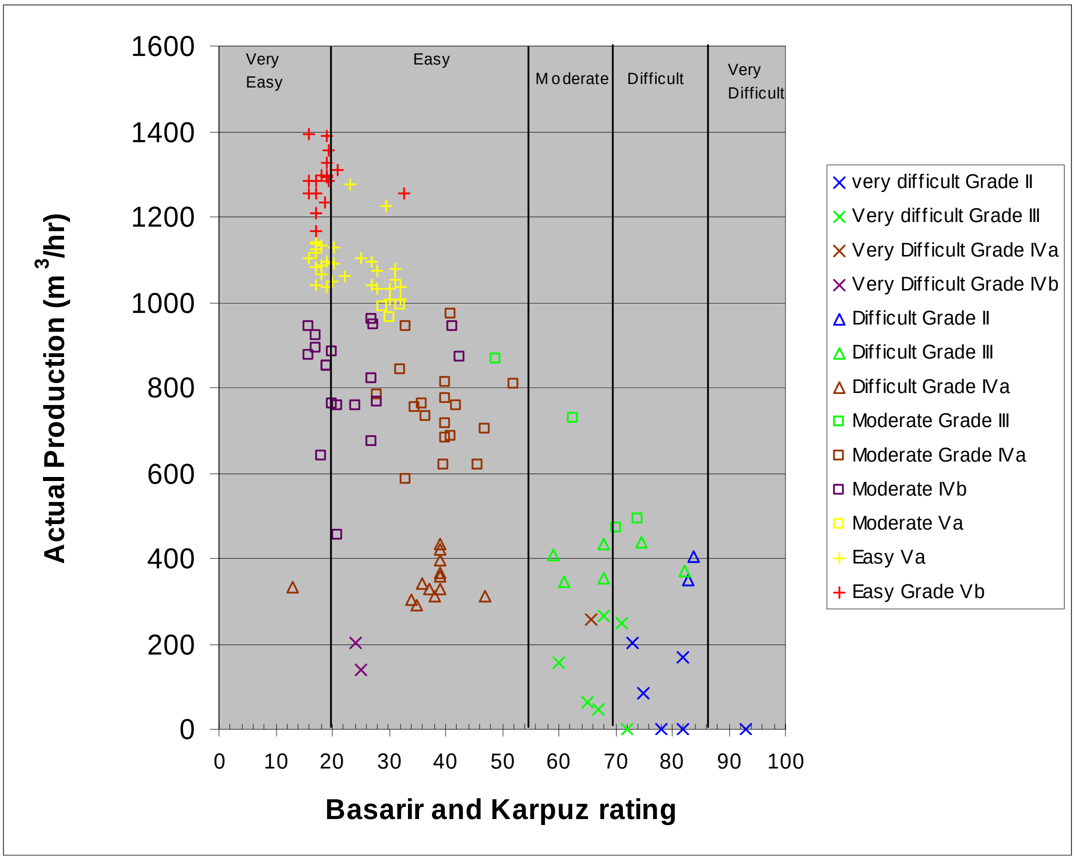


Figure 8.8 : Basarir and Karpuz Excavability Assessment

8.5 Prediction by using Seismic Refraction Method

The use of seismic refraction tests for excavation assessment at the site has been presented in Chapter 5. The results showed that the field seismic test provided poor prediction of the excavatability. Materials that were actually unrippable were predicted to be easily rippable by using this method of prediction. This situation was noted in all test lines at Bukit Indah, Mersing, Desa Tebrau and Kempas. The setback in using this method for evaluating excavatability has also been reported by previous researchers (Church, 1981; Minty and Kearns, 1983; Hadjigeogiou and Scoble, 1988). Weathering grade IV that showed a low seismic velocity in Bukit Indah, Line 1, was unrippable due to the wide joint spacing and could not be sensed by the seismic wave. It was also because of a 4 centimetre thick of iron pan that coated the surface of the grade IVb sandstone which was not detected by the seismic method. Even though seismic velocity can be a useful geophysical tool in assessing excavatability with rapid results, the results obtained should be handled with great care, recognizing the results may contain potential errors in production. Some potential errors when using seismic velocities are listed below:

i) the presence of joints in rock material is not accurately sensed by the seismic wave. The widely spaced joints in a weak material (grade IVa/IVb) might refuse ripping works because the ripper cannot break the large blocks. On the other hand, the presence of close joints in stronger material may allow ripping works

ii) the occurrence of iron pan on the rock surface, which is normally found in tropical weathered rock masses is not detected by the seismic wave. This dense and hard iron pan of only a few centimetres can resist penetration of the ripper tine

iii) the heterogeneity of rock mass with inter-bedded layers is not clearly detected. This problem may become more serious with a thin layer or when the hard layer masks the weaker layer

iv) the presence of moisture content in the rock may provide a misinterpretation as the waves travel faster in this material, even though the material is weak (Turk and Dearman, 1986)

v) the presence of boulders is difficult to detect, if present within an easily rippable material (Smith, 1986)

8.6 Prediction by Using Suggested Regression Equations

This section presents the results obtained using the previously described statistical techniques in Chapter 7. A summary of the results used in these predictions is shown in Table 7.12.

Figure 8.9 presents the plot of the estimates from regression equation 7.50 versus the actual data. The straight line indicates a 100 percent accuracy of the prediction and the actual production. The coefficient of determination for this data is 0.916, which is considered very significantly correlated. The result shows acceptable predictions where almost all the data are along the 100 percent accuracy line. A histogram of the residuals was plotted to check the assumption of normality of the error term. A residual is the difference between the observed and model-predicted values of the dependent variable. The histogram shows that the residual plot follows an acceptable distribution curve and gives a standard deviation of 0.996.

In this prediction equation, inputs of weathering grade, joint spacing, ripping direction, slaking index and slake durability index (Id_1) were entered. The weathering grade data indicates the weathering assessment of sandstone and shale that can be assessed in the field. It roughly indicates the quality of the rock mass. Joint spacing and ripping direction are also found to have a great influence on the excavatability. The measurements of these parameters can be done on site by using scan lines on the exposed rock faces. While the ripping direction indicates the direction of machine advancement relative to the joint orientation, the joint spacing indicates the block size of the ripped material. Slaking index can be a useful predictive tool for assessing the weathering grade for very weak rock and this has been discussed in Chapter 6. Slake durability index (Id_1) was found to be able to assess the quality of rock materials in weak to moderate strength classes. It is noted that there is no index of strength of material (UCS or Is_{50}) used in the equation. Therefore, it is assumed that the strength of materials can be estimated from the parameters quoted above. This finding can be said to be in contrast with the previous researchers (Pettifer and Fookes, 1994; and Basarir and Karpuz, 2004) where material strength parameter measured by Is_{50} or UCS was found to be the most important parameter to be included in their assessments. However, if Is_{50} is preferred to be included in the prediction, then equation 7.49 can be used.

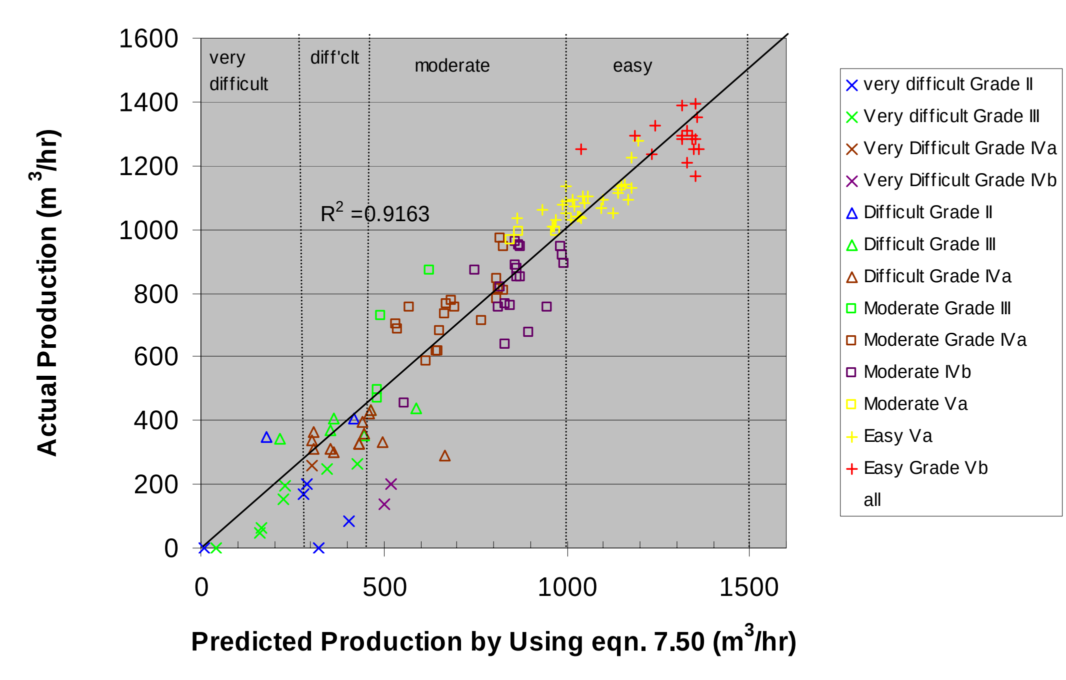


Figure 8.9: The plot of the estimates from regression equation 7.50 versus the actual production data.

Another approach to predict productivity is by assessing the respective weathering grade at the start of an assessment. By using these methods, weathering grade is pre-determined and predictions can be made by using the regression equation for the particular grade. If these predictions were employed, the result shows better coefficient of determination of 0.96 as compared to 0.92 if without specifying or classifying the weathering grades. Figure 8.10 shows the result of the actual and the predicted production rate by using equations listed in Table 7.12. The results shows an exceptionally good prediction and the histogram of the residuals shows the data as acceptable and follows the normal curve with a standard deviation of 0.996.

Equations used in these predictions are equation 7.38 for materials in grade II and III, equation 7.41 and 7.43 for sandstone and shale respectively for grade IVa and IVb and equation 7.47 for materials in grade Va and Vb. As for materials in grade II and III, predictors of Id_2, weathering grade, joint spacing, Is_{50} and ripping directions were used. Id_2 is recommended for materials with higher strength as compared to Id_2 for materials in moderate strength for the classification purposes. Joint spacing and ripping direction relative to joint orientation remain important parameters to be incorporated in the high strength material. The Is_{50} parameter acts as the measurement of the material strength.

As for grade IVa and IVb materials, joint spacing, weathering grade, ripping direction, Is_{50} or slaking index and dry density are the important predictors. As discussed before, grade IV materials are the most confusing materials for excavation assessment because of their ‘rock-soil’ characteristics. Changes of moisture content can drastically change the strength and behaviour, thus this parameter is also one of the predictors. It is noted that any strength measurements taken on these samples must be assessed with the site moisture content and adjustment must be made if there are changes of moisture content, as this would have a great affect on the strength index value (Is_{50}). Ripping direction and joint spacing indicates the discontinuity characteristic and the favourability of joint assistance on ripping works. As for sandstone, grain size parameter is another important predictor in addition to the other parameters as discussed above. Equation 7.41 and 7.43 are used for both sandstone and shale respectively.

As for grade V materials, only two predictors were chosen which are: weathering grade and slaking index as shown in Equation 7.47. Slaking index was found to be a useful predictor for these very weak rocks. However, if Is_{50} is preferred to be the predictor, Equation 7.48 can be used.

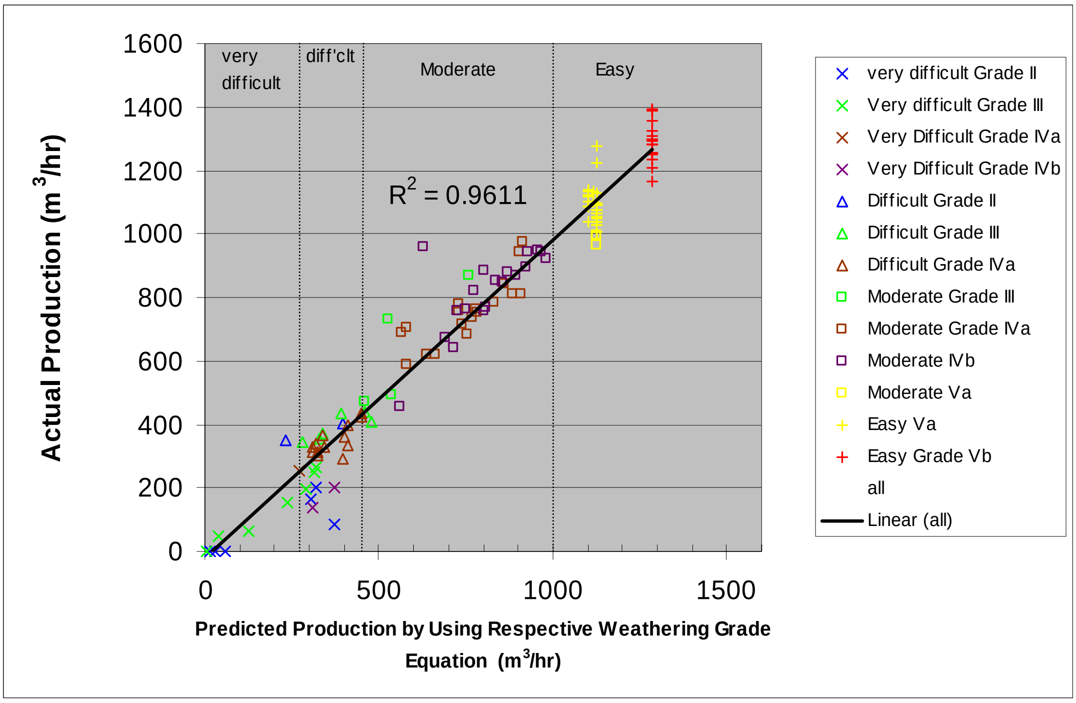


Figure 8.10: Actual production rate versus the predicted production by using the respective weathering grade equation

8.7 Suggested Approach of Assessing the Production Prediction

Production prediction equations were derived from practical performance assessment using a combination of graphs and regression equations. In order to predict the performances, some form of background and experience would be essential to gain expected results.

This section proposed the methods to be employed when dealing with weathered rock mass particularly for sandstone and shale. This proposal is presented in order to avoid unnecessary testing to be carried out on the samples and that the parameters measured have been shown to contribute the performance prediction. A summary of the proposal is shown in Figure 8.11.

When dealing with unexcavated materials (by digging), a simple evaluation needs to be made whether the rock mass is possible to be ripped or not depending on the topography. Ripping is possible on a flat ground but it is impossible to be deployed on a hill slope. For such cases, blasting should be considered.

If the topography of the unexcavated materials allowed ripping works, an evaluation of the rock masses should be done. The rock masses should be evaluated and classified based on their weathering grades. A classification of determining the weathering grades as discussed in Chapter 5 is proposed. Once the weathering grades are established, the presence of iron pan (if any) needs to be considered. Thick iron pan that caps the surface rock material can resist the penetration of ripper tine, thus production is not possible. The thickness of iron pan that can refuse penetration for each weathering grade is shown in Figure 8.11. If the thickness of iron pan exceeds a certain thickness within a particular weathering grade as shown in the flowchart, blasting works should be considered as the ripper tine is not able to penetrate the layer. However, if there is no or only a thin layer of iron pan present, further works on field and laboratory testing is proposed.

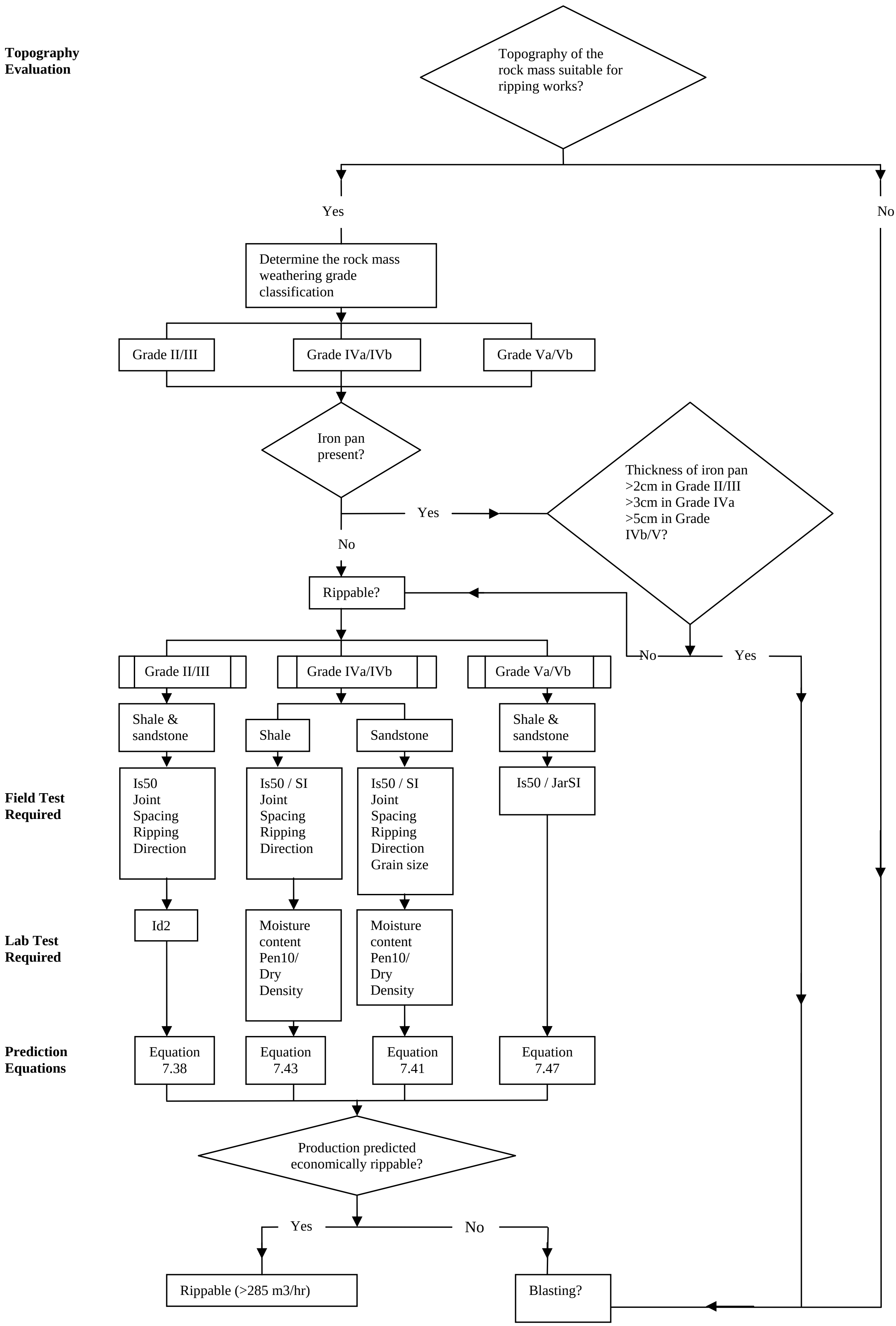

Topography Evaluation
Topography of the rock mass suitable for ripping works?
Yes
No
Determine the rock mass weathering grade classification
Grade II/III
Grade IVa/IVb
Grade Va/Vb
Iron pan present?
Yes
No
Thickness of iron pan >2cm in Grade II/III >3cm in Grade IVa >5cm in Grade IVb/V?
Rippable?
No
Yes
Grade II/III
Grade IVa/IVb
Grade Va/Vb
Shale & sandstone
Shale
Sandstone
Shale & sandstone
Field Test Required
Is50 Joint Spacing Ripping Direction
Is50 / SI Joint Spacing Ripping Direction
Is50 / SI Joint Spacing Ripping Direction Grain size
Is50 / JarSI
Lab Test Required
Id2
Moisture content Pen10/ Dry Density
Moisture content Pen10/ Dry Density
Prediction Equations
Equation 7.38
Equation 7.43
Equation 7.41
Equation 7.47
Production predicted economically rippable?
Yes
No
Rippable (>285 m3/hr)
Blasting?

Figure 8.11: Summary for Suggested Approach for Weathered Rocks

Details of the testing required in the field and laboratory is shown in Figure 8.11. In this evaluation, a more accurate result is produced by using equations designed specially for the respective weathering grade. It was found that a different set of tests is required for a particular weathering grade. Joint spacing and ripping direction which can be measured from scan lines are needed for grade II, III and IV materials. For grade IVa and IVb materials, shale and sandstone are proposed to be evaluated separately by using different equations. The difference is the grain size parameter is added to evaluate sandstone. As for grades II, III and V, sandstone and shale can be assessed together.

Materials in grade V need the least number of tests. In addition to the weathering grade classification in grades Va or Vb, only the jar slaking index is needed. Materials in grade IVa and IVb require the most number of parameters as these materials need to be thoroughly investigated due to their 'rock-soil' behaviour. In addition to the discontinuity characteristics, it needs point load index or jar slaking index to be measured to assess its strength. This testing can be done either in the field or laboratory. Sandstone requires a grain size parameter as it can significantly affect productivity. Moisture content, penetration test index and dry density will need to be conducted in the laboratory. Grade II and III material needs joint spacing and ripping direction parameters to evaluate their discontinuity characteristics. In addition, it also requires point load index and slake durability index that can be measured in the laboratory.

It is interesting to note that for all the testing proposed, no sophisticated tests are required including the UCS or ITS parameter. This enables quick and economical testing to produce satisfactory prediction for ripping works. Once the parameters needed for each weathering grade are established, production can be predicted using the respective equations as outlined in the flowchart. Alternatively, a general equation can be used with input of joint spacing, ripping direction, point load or jar slaking index and slake durability index (Id_1). Once the performance is predicted, decisions can be made on whether it is economical to rip based on the predicted production. If not, blasting should be the next option.

8.8 Summary

From the comparisons made of the proposed methods of predicting productivity, it was found that weak rock needs a special attention during the evaluation. None of the present techniques employed could satisfactorily predict the actual performance. There are different parameters that were found to influence greatly the results for materials in each weathering grade, which have not been adequately addressed before. Thus, this study was undertaken.

The proposed method of evaluating the excavatability in weak rocks is an improvement on the previous methods, and it provides a more accurate prediction of productivity for weathered rock masses. By using the equations proposed in this study, the prediction could acceptably predict the actual production. In general, the results are positive and indicate that successful performance prediction is possible by employing these suggested equations. It is important to note that the equations were derived from sandstone and shale weathered rock, thus any usage of the prediction equations on other types of rock should be verified first.

CHAPTER 9

CONCLUSION

9.1 Introduction

A method for predicting and assessing production rate by ripping works based on geotechnical properties has been developed, concentrating on weathered sedimentary rock masses. A rock's physical properties are of prime importance when deciding the use of mechanical excavation, drill or blast techniques. This conclusion was derived based on experience gained from systematic and comprehensive field and laboratory studies undertaken.

For each site, a number of site dependent relationships were investigated. Observations also enabled a number of comparisons to be made between factors, which affect the productivity. All data analyzed was obtained under actual production conditions. This gives the advantage of providing data that is able to predict the actual production performance. Statistical techniques were used to analyze the data obtained by using regression analysis. The predictions based on the specific weathering grade were also correlated.

The study shows that he use of the existing excavatability assessment methods proposed by other researchers for defining the ease with which rock can be ripped has a number of inherent flaws when considering weathered sandstone and shale. The nature of the excavation process in the different weathering grades does not lend itself to ready quantification because of the different rock material and mass properties. The differences in the rock properties produced different sets of relationships between the different weathering grades for productivity prediction. It was possible to observe how a particular geological environment influences the rippability of the rock masses. The best assessment should be able to produce a high accuracy of prediction in the simplest and most economical way. The conclusions are structured along similar lines to the presentation of this thesis, discussing the necessary indices for performance assessment, the monitoring methods and techniques for performance prediction.

9.2 Evaluation of Rock Material and Rock Mass Indices in Terms of Production Prediction

In terms of predicting the likely production rate for rock ripping work, a plethora of tests have been developed. The complex mechanism involved with rock cutting, ensures that all rock properties have to be evaluated before any conclusion on the significance of the tests can be made. The criteria used to select and rank these tests were validity, economics and universal applicability. For all these tests, the methodologies are standardised so that information can be readily communicated. The data that these tests produce vary in usefulness for the prediction of production rate.

The complex mechanism of rock cutting needs a careful selection on the rock properties that will influence significantly on their rippability. The analysis undertaken, revealed that some rock properties do not significantly affect the production prediction. As a consequence, it was felt that the test most suitable to rippability should be identified in order to provide maximum information suited to the range of materials for ripping.

9.2.1 Field Testing

Under field conditions, fast and simple in-situ testing and measurements were carried out including surface hardness, strength, durability, weathering grade classification and discontinuity characterization.

It was found that Schmidt hammer test did not provide a good result in predicting the productivity in weak rock. This is due to the presence of many joints in the rock mass that makes the blocks unstable when tested and the nature of the rock material itself that is very weak. Materials in grade IVb, Va and Vb gave no rebound reading during the test.

As for these weak rock materials, point load testing can be an alternative for measuring the strength. However, research found that the portable point load testing equipment used was not suitable to measure the strength in very weak material especially in materials in weathering grade IVb, Va and Vb. The point load test by using highly sensitive equipment such as a Universal Testing Machine (UTM) was found more suitable to measure the strength of very weak material. However, by using UTM machine means that samples will need to be brought to the laboratory to be tested.

Another significant finding is the use of jar slaking index to classify weak rock. It was discovered that the weak rock material can breakdown completely in less than 30 minutes. For instance, grade Vb material could just breakdown completely in 5 minutes thus this test was further improved from Santi (1998) and Zainab Mohamed (2004) by splitting the slaking index to every 10, 15, 30 and 60 minutes for each jar. By observing the slaking behaviour, an index will be given for each case. Subsequently, the index for all the series will be added and the total is the slaking index. A higher index indicates the greater durability of the sample when immersed in water, and relatively will produce low productivity. This method was found suitable to classify samples especially in the weak to very weak materials in a fast and simple way. Classifying materials by jar slaking index was found to be a good indicator for determining classes of very weak material (Grade IVb, Va and Vb). This method can also be carried out in the field without having the trouble to transport the material to the laboratory.

Joint spacing and ripping direction in respect to the discontinuity orientation were found significant parameters for materials in grade II, III and IV in assessing its excavatability. These discontinuity parameters affect greatly on harder material but do not affect greatly on weak materials in grade V. From a geotechnical point of view, one of the most important factors in assessing the stability of the medium to strong rock is the nature of the weakness planes in the rock mass and these have to be determined before any predictions on productivity can be made. In view of the large number of discontinuities in the mass it is a further prerequisite that these planes are systematically measured. Analysis has revealed that the ripping direction classifications that were made based from Fowell and Johnson (1994) recommendation was found very useful for the performance predictions.

9.2.2 Laboratory Testing

Under laboratory conditions it is possible to derive highly accurate indices for determining the strength, durability, density, penetration and petrography of rock materials. Not all the samples are available for testings due to the nature of weak rock that can be easily broken. Ultimately, certain tests were proposed to classify rock material depending on their weathering grade. Weak material may need different tests for classification and the stronger material was found suitable to be tested by the standard testing equipment proposed by the ISRM.

Another test that was found to correlate well with machine performance was the penetration test when using a 10 mm probe and point load bit. This test was further extended from Zainab Mohamed’s (2004) work where she used a 4.63 mm cylindrical probe. However this research found that the 4.63 mm diameter was not sufficient to withstand the forces in strong rocks (grade II and III materials) due to bending. Thus, a 10 mm diameter probe and point load bit were used. The use of the point load bit as the penetration probe is by modifying the well established point load tester for penetration whereas the 10 mm probe was used as this diameter size can sustain the load for penetrating rock material without bending and able to penetrate the sample. With this test, the force required to penetrate the confined samples were measured. By confining the samples in a container when penetrated, this simulates the field condition (without joint influence).

Penetration tests conducted on rock materials show that this test is also suitable to predict the strength properties of a weak rock. Another advantage for employing this test is that it can be done on all materials regardless of the weathering grade, even on very weak samples. Interestingly, the test results show significant inverse agreement with the penetration of ripper tine at the actual site. The penetration forces were also decreased in respective materials when it was soaked in water. This suggested that moisture content plays a significant role in reducing the material strength especially for materials in grade IV and V. Absorption of water for materials in grade II and III was minimal compared to grade IV and V materials.

This study has also found moisture content has great effect particularly for materials in grade IVa, IVb. The increase of moisture content may influence the rippability of these materials significantly. Changes of moisture content on grade II, III and V does not influence much on these materials. Grade V materials are already weak and the high moisture content, will not significantly affect the production rate compared to grade IV materials. Previous researchers did not adequately address this parameter. They assumed that the strength parameter is enough to assess the excavatability. However, the problem persists when the materials are assessed and excavation works are carried out on different moisture content. This problem always occurs in tropical countries where we can expect heavy rain. The moisture does not affect so much on stronger materials (grade II and III), however it may reduce the strength of weaker materials especially in grade IV materials significantly.

Durability testing either by using the slake durability index or the jar test was found to give valuable information on performance prediction. The tests can be done based on the strength and weathering grade of samples. If materials are in grade II or III, second cycles of slake durability are able to predict the performance. For materials in grade IVa and IVb, the first cycle of slake durability is enough to classify these materials and for the weaker materials in grade IVb, Va and Vb, the jar slaking index is considered to be a good predictor.

In terms of the grain size affecting the productivity, there was evidence found that coarse grained materials are easier to be ripped compared to the finer grained materials especially in weathering grade IVa and IVb. In weathering grade II, III and V, grain size does not affect significantly the productivity. This is because, materials are already weak in grade V, whereas in grade II and III, materials are well cemented and the interlocking between grains are intact.

The data produced many interesting and valuable correlations between the variety of indices. From the experiences of conducting the tests, it can be noted that some testing are only suitable for rock materials in particular weathering grade. Some testing such as UCS just could not be carried out on weaker samples (Grade V) because the samples break easily during preparation. Thus, the excavation assessment needs to be flexible in evaluating the excavation method. In such cases, it was not possible to perform the UCS or Brazillian indirect tensile strength tests as samples could not be prepared to the standard size for the testing. Thus, assessments made solely by UCS and indirect tensile strength, such as Singh et al. (1987) are difficult to apply on weak material.

9.2.3 Iron Pan

Occurrence of iron pan is another usual feature that can be expected in tropical weathered rock. Accumulation of iron minerals along the joints was found to be as thick as 5 cm. The iron pan was very strong and dense with a density of more than 4 t/m^3 and Is_{50} of more than 7 MPa. A 3 cm layer of iron pan is able to prevent penetration of the ripper tine in grade II and III materials. A 4 or 5 cm thick can prevent penetration in grade IVb and IVa materials respectively, thus productivity will be zero. This problem has never been addressed by previous researchers before when assessing excavatability. The presence of iron pan along the joints can enhance the material surface hardness depending on its thickness and the weathering grade of the parent rock. This case was noted at nine locations during the study, where zero production was measured.

9.3 Performance Prediction

It was found that ripping works are greatly influenced by the weathering grade, rock mass properties and the direction of the ripping relative to discontinuity orientation in addition to plant capabilities. Weathering grade was found to very significantly affecting the production rate of a ripper in weak sandstone and shale.

For each weathering grade, there are different factors that will influence the ripping works as discussed in Chapter 7. A systematic method has been suggested to derive the production prediction for a particular weathering grade. This has been established through statistical analysis used to evaluate the data. The resultant methods both adequately models and predicts performance in which a flexible approach can be easily adopted dependent on the available data. Comparisons between actual and predicted performance were generally satisfactory and have improved from previous methods proposed by other researchers.

It has been found out that different sets of factors are necessary to predict productivity for materials in their respective weathering grade. Generally, excavatability of rock masses depends on the weathering grade, joint spacing, material strength and the ripping direction. However, this research found that a different form of parameters is required in respective weathering grade to predict the productivity more accurately. Factors that have contributed to the production rate in grade Va and Vb materials are weathering grade and point load index or slaking index. Discontinuity parameters are not required in this grade as the material itself is already weak.

In weathering grade IVa and IVb, joint spacing, ripping direction, weathering grade, dry density, moisture content and point load index or jar slaking index are the factors found that contribute to the production rate. In addition to the discontinuity characteristics, joint spacing and ripping direction, the moisture content and dry density were found to influence the excavatability as well. Jar slaking index was also found to be a good predictor because materials in this grade are prone to slaking in water.

In stronger materials (grade II and III), Id_2, weathering grade classification, joint spacing, ripping direction and point load index are factors found to contribute to production rate prediction. The influence of joint spacing and ripping direction in these materials was found to be significant. Closer joint spacing and very favourable ripping direction increased the production rate. Although some researchers noted that joint spacings is one of the most important parameters, not many of them include ripping direction into their consideration except for Weaver (1975), Kirsten (1982) and Smith (1986). However employing their assessment in the productivity prediction did not give satisfactory results as little weight was given to the influence of weathering grade. The joint spacing and ripping direction parameters do not greatly influence all weathering grades but only grades II, III, IVa and IVb materials. From the comparison of productivity predictions presented in Chapter 8, none of the assessments give significant predictions for the production rate. The nearest prediction was proposed by Kirsten (1982) ‘Excavatability Index’ that gave a coefficient of determination (R^2) of 0.713 for grades IVb, IVa, III and II, showing wider scatter of data and the need for refinement.

Another valuable finding was that the performance prediction can be carried out satisfactorily with field data alone without having to bring back samples to the laboratory. From the analysis of the results, it is clear that rock properties measured in the laboratory alone will not give a reliable prediction for productivity. Most of the data required to predict productivity can be best measured on site. By employing this method, the in-situ condition can be the best to represent the actual ground condition. This includes some measure for determining the strength and weathering grade. In addition, the joint characteristic can also be measured on site. The strength measured on site will represent the actual moisture content during the operations; however this strength parameter might deteriorate or be enhanced during the actual excavation period if there are changes in the moisture content. Changes in moisture content happen regularly in tropical climates, thus consideration must be given to this factor.

This work provide a clearer understanding of the importance of weathering grade and the rock mass properties in excavation works and a guide to the most suitable methods for productivity prediction.

9.4 Comparison with Other Excavation Assessments and Performance Predictions

The field seismic velocity tests showed that the seismic test alone was unable to predict satisfactorily the productivity in these weathered rocks. Tests carried out on site showed that the rock masses were supposedly able to be ripped if it is based on the Caterpillar’s (2000) chart. However, in the actual condition, the rock masses were unable to be ripped. The accuracy of the seismic test was found to be less than 40 percent in this study. The seismic wave could not detect the very thin iron pan layer (< 5 cm) on the surface of the rock material. The thickness of iron pan will dictate whether the ripper tine is able to penetrate the surface material or not. The inter-bedding of soft and hard materials in sedimentary environments was also unable to be detected. This conclusion supports the findings of Kirsten (1982), Singh (1983) and Church (1981).

Popular methods of rock mass characterization were considered and compared with the actual ripping production. The graphical based method (Pettifer and Fookes, 1994) which is simpler and considers only two parameters, i.e. point load strength and fracture spacing indices was compared with the actual production results. However this comparison was poor as the excavatability of rock masses also depends on other factors such as joint continuity, gouge, joint set number and direction of discontinuities relative to the ripping direction.

There is evidence that using a modified Geomechanic classification (RMR) and Q-system do not give satisfactorily production predictions. This is due to the fact that these classifications were designed for tunnel support evaluation and not for the excavatability assessment. The Excavation Index (EI) proposed by Kirsten (1982) was adopted from the Q-system and gave a better relationship. Comparisons made with previous assessment methods were found to be unsatisfactory to predict the production rate. This is due to insufficient weight given to the weathering effect or there is no parameter for ripping direction included in these assessments. Some of the parameters required for the above assessments could not be incorporated as on these very weak weathered samples did not allow the preparation of suitable samples, for Brazillian indirect tensile strength testing. Another factor is that previous researchers did not include the presence of iron pan and how iron pan did not allow the penetration of the tine.

Though the grading assessment system proposed is the most comprehensive assessment method, factors such as moisture content, rock mass properties, topography, bedding thickness and infilled material are not included. Except for MacGregor et al. (1994) who addressed the influence of rock type to rippability, others grading assessments are generalised by the type of geological parameters. It should be noted that different rock types might have significant differences in their weathering profile.

Igneous rocks, for example, can have many occurrences of boulders, which may have similar parameters, but their size would be important. Normal digging could excavate small boulders easily, but the larger size would need a different technique of excavation. These boulders may cause significant problems during excavation and normally need to be blasted down to a more manageable size. MacGregor et al. (1994) found that weathering is a significant variable for igneous rocks compared to other types of rock.

By adopting the suggested prediction equations, the actual and predicted productivity are very significantly correlated with a coefficient of determination (R^2) of 0.96. This correlation was made by taking into account the weathering grade of materials, ripping direction, joint spacing, durability, density and some measure of the material's strength. The results are pleasing as they indicate that successful performance prediction on weathered rock masses is possible by using the regression equations proposed.

9.5 Recommendations for Future Research

It is apparent that cutting performance is dependant upon a number of machine parameters as well as the rock mass properties. In this respect, further work is recommended as follows:

a) The penetration tests is worth refining since this test method was found to be closely related to the production rate and can be used to measure all types of rocks from any weathering grade. It can also be used to investigate the mechanics of rock indentation and penetration of the ripper tine. In addition, it can be used to determine the effect of moisture content and in-situ stress conditions on these fracture mechanisms. It will be useful if this test can be further developed to be carried out directly on the site, hence actual data and time can be saved.

b) Another interesting test that can be further developed to classify weak material is the jar test. It is a useful test for very weak rock and can easily be carried out.

c) The point load test was found to be a good alternative to measure the strength of materials. However, the limitation of this test on very weak material was noted because the gauges are not sensitive enough in the portable point load tester. If the pressure gauge can be modified to be more sensitive, the whole range of materials from very weak to very strong can be tested in the field directly.

d) The study of wear of tools in ripping works is another area to be established. The relationship between rock material properties and wear is still ambiguous. The wear of the tools is an important aspect in terms of the economics of mechanical excavation.

e) The use of the fractal dimension in characterizing the nature of a fractured surface seems to provide a useful method of studying the process involved in rock cutting. The implication of establishing a credible relationship between fractals and the energy required to cut the rock are also worth studying.

f) If the work is extended, it is also recommended to include a wider range of rock types that are commonly ripped, such as limestone. Even though, this study also proposed the prediction for different sizes of machine, it is also recommended that a future study be carried out with different sizes of ripping machine so that the actual relationship with productivity can be established related to any rock type and machine size.

In order to increase the accuracy of predictions more field data are necessary. This may require greater monitoring activities with cooperation from industry to provide a database that is suitable for analysis. The wider range of rock types can also be evaluated. By having a larger database, it is felt that it can provide enough detail and accuracy of performance prediction.

This work has provided the necessary stimulus for further investigations which should lead to a more efficient excavatability assessment classification system for weathered rock masses. Studies made at four locations with variable weathering grades revealed that the factors affecting productivity depend strongly on the weathering grade assigned during site investigation.

This research has answered many questions but at the same time has identified areas requiring more research effort. The industry is moving fast in the direction where more powerful machines are being developed and the awareness of environmental issues demanded the use of mechanical methods instead of rock blasting in sensitive areas. It is therefore, essential that research maintain momentum in order for the industry to be seen as both innovative and informed.

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APPENDIX A
THE Q-SYSTEM AND RATINGS DESCRIPTION (AFTER BARTON ET AL., 1974).

1. Rock Quality Designation		RQD (%)
A. Very poor		0 – 25
B. Poor		25 -50
C. Fair		50 -75
D. Good		75 – 90
E. Excellent		90 – 100
2. Modified Joint Set Number		Jn
A. Massive, none or few joints		0.5 –1.0
B. One joint set		2
C. One joint set plus random		3
D. Two joint set		4
E. Two joint set plus random		6
F. Three joint set / fissure set		9
G. Three joint set plus random		12
H. Four or more joint set, random heavily jointed "sugar cube" etc.		15
J. Multiple joint /fissure set		20
3. Joint Roughness Number	Jr	
(a). Rock wall contact and		
(b). Rock wall contact and before 10-cm shear		Note :
		1. Add 1.0 if the mean
A. Discontinuous joint	4.0	spacing of the relevant
B. Rough or irregular, undulating	3.0	joint set is greater than
C. Smooth, undulating	2.0	3m.
D. Slickensided, undulating	1.5	2. Jr = 0.5 can be used
E. Rough or irregular, planar	1.5	for planar slickensided
F. Smooth, planar	1.0	joints the lineations are
G. Slickensided, planar	0.5	favorable oriented.
(c). No rock wall contact when sheared		
H. Zone containing clay material thick enough		3. Descriptions B –G
to prevent rock wall contact	1.0^b	refer to small-scale
I. Sandy, gravelly, or crushed zone thick enough		Features & intermediate
to prevent rock wall contact	1.0^b	scale features in that order
4. Joint Alteration Number		
(a) Rock wall contact		Ja
$Ø_r$(approx)		
A. Tightly healed, hard, nonsoftening, impermeable filling, i.e., quartz or epidote		0.75

B. Unaltered joint wall, surface staining only	1.0	25 – 35°
C. Slightly altered joint walls, Non- softening mineral coatings, sandy particles, clay-free disintegrated rock, etc.	2.0	25 – 30°
D. Silty or sandy clay coatings, small clay fraction (non softening)	3.0	20 – 25°
E. Softening or low-friction clay mineral coatings, i.e., kaolinite, mica. Also chlorite, talc, gypsum, and graphite, etc., and small quantities of swelling clays (discontinuous coating, 1-2mm or less in thickness	4.0	8 –16°
(b) Rock wall contact before 10-cm shear		
F. Sandy particles, clay-free disintegrate rock etc.	4.0	25 – 30°
G. Strongly over-consolidated, non-softening clay Mineral filling (continuous, < 5mm in thickness)	6.0	16 – 24°
H. Medium or low over-consolidation, softening, Clay mineral fillings (continuous, < 5mm in thickness)	8.0	12 –16°
I. Swelling clay filling, i.e., monmorilonite (continuous, < 5mm in thickness). Value of Ja depends on percentage of swelling clay sized particles, and access to water, etc.	8.0-12.0	6 – 12°
(c) No rock contact when sheared		
K. Zone or bands of disintegrated or crushed rock and Clay (see G., H., J., for description of clay condition)	6.0-8.0 or 8.0-12	16-24°
L. Zone or bands of silty or sandy clay, small clay fraction (nonsoftening)	5.0	
M. Thick , continuous zones or bands of clay (see G., H., J., for description of clay condition)	10.0 – 13 or 13-20	6-24°

Note : Value of $Ø_r$ are intended as an approximate guide to the mineralogical properties of the alteration products.

5. Stress Reduction Factor	SRF
(a) Weakness zones intersection excavation, Which may cause loosening of rock mass When tunnel is excavated	
A. Multiple occurrences of weakness zones Containing clay or chemically disintegrated rock, very loose surrounding rock (any depth)	10.0
B. Single-weakness zones containing clay or chemically disintegrated rock (depth of excavation <50 m)	5.0
C. Single-weakness zones containing clay or chemically	

disintegrated rock (depth of <50 m)	2.5
D. Multiple-shear zones in competent rock (clay-free), Loose surrounding rock (any depth)	7.5
E. Single-shear zones in competent rock (clay-free), (depth of excavation <50 m)	5.0
F. Single-shear zones in competent rock (clay-free), (depth of excavation <50 m)	2.5
G. Loose open joints, heavily jointed or "sugar cube", etc. (any depth)	5.0

(b) Competent rock, stress rock problems.

	σ_c/σ_1	σ_t/σ_1	
H. Low stress, near surface	>200	>13	2.5
I. Medium stress	200-10	13-0.66	1.0
J. High stress, very tight structure (usually favorable to stability, may be unfavorable to wall stability	10-5	0.66-0.33	0.5-2.0
K. Mild rock burst (massive rock)	<25	<0.16	10-20

(c) Squeezing rock; plastic flow of incompetent rock under the influence of high rock pressure

L. Mild squeezing rock pressure	5-10
M. Heavy squeezing rock pressure	10-20

(d) Swelling rock : chemical swelling activity depending on presence of water

N. Mild swelling rock pressure	5-10
O. Heavy swelling rock pressure	10-15

Note :

(i) Reduce the SRF value by 25-50% if the relevant shear zones only influence but do not intersect the excavation.

(ii) For strongly anisotropic stress field (if measured) : when $5< \sigma_1/\sigma_3<10$, reduce σ_c and σ_t to 0.6 σ_c and 0.6 σ_t (where σ_c = UCS and σ_t = tensile strength (point load), σ_1 and σ_3 = major and minor principal stresses).

6. Joint Water Reduction Factor

	Jw	Approximate water Pressure (kg/cm^2)
A. Dry excavation or minor inflow, i.e., 5 litre/min locally	1.0	<1
Medium inflow or pressure occasional Outwash of joint fillings	0.66	1.0-2.5
B. Large inflow or high pressure in		

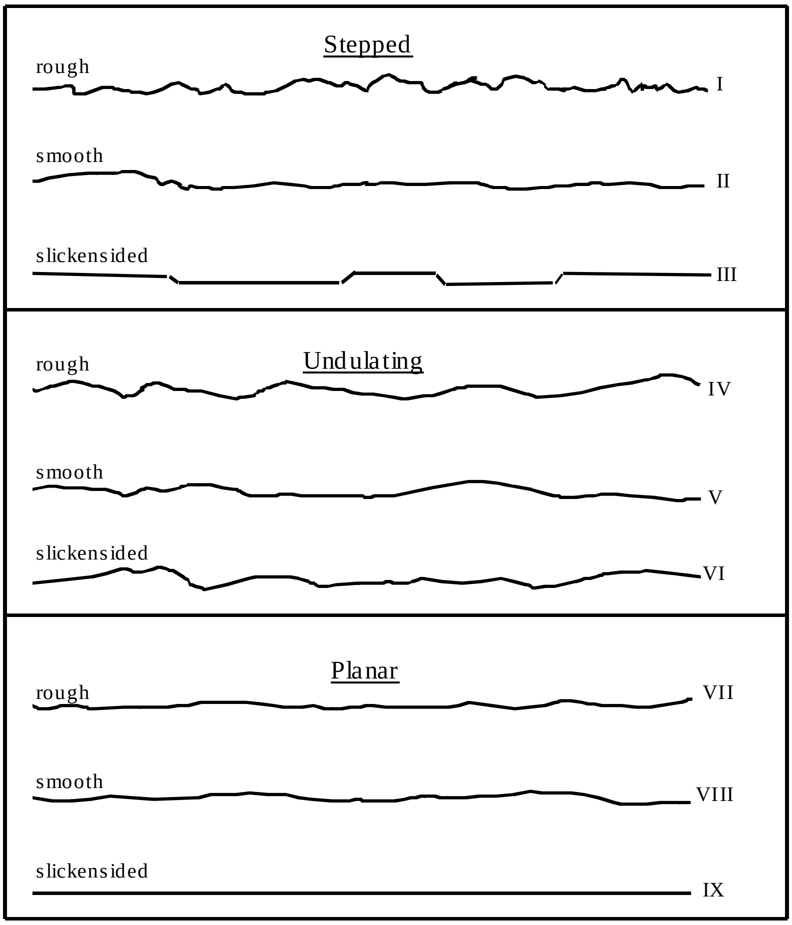
Competent rock with unfilled joints	0.5	2.5-10.0
C. Large inflow or high pressure		
considerable outwash of joint fillings	0.33	2.5-10.0
D. Exceptionally high inflow or water pressure		
At blasting , decaying with time	0.2-0.1	>10.0
E. Exceptionally high inflow or water pressure		
Continuing without noticeable decay	0.1-0.05	>10.0

Note :

Factor C-F is crude estimates. Increase JW if drainage measures are installed. Special problem caused by ice information are not considered.

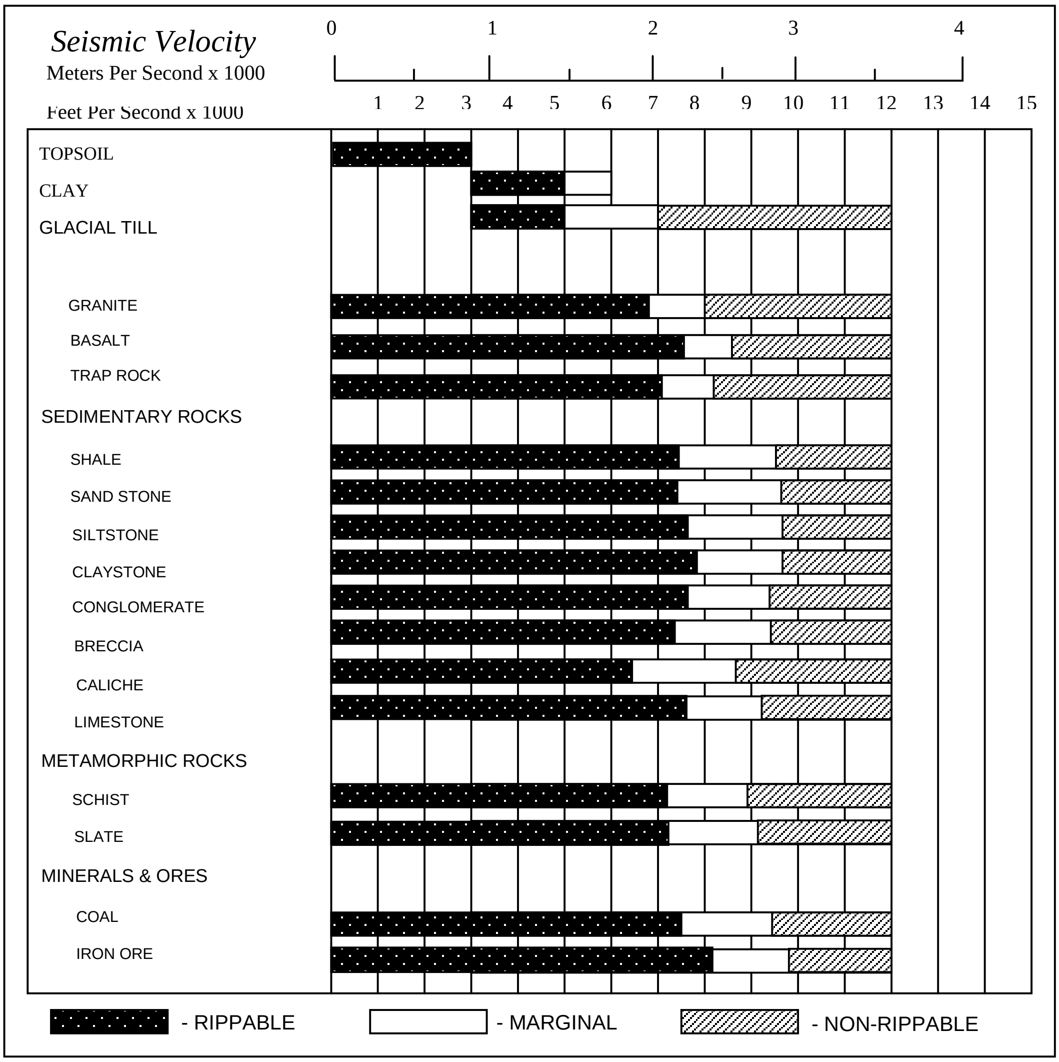
APPENDIX B

CLASSIFICATION OF THE JOINT ROUGHNESS (AFTER ISRM, 1981)



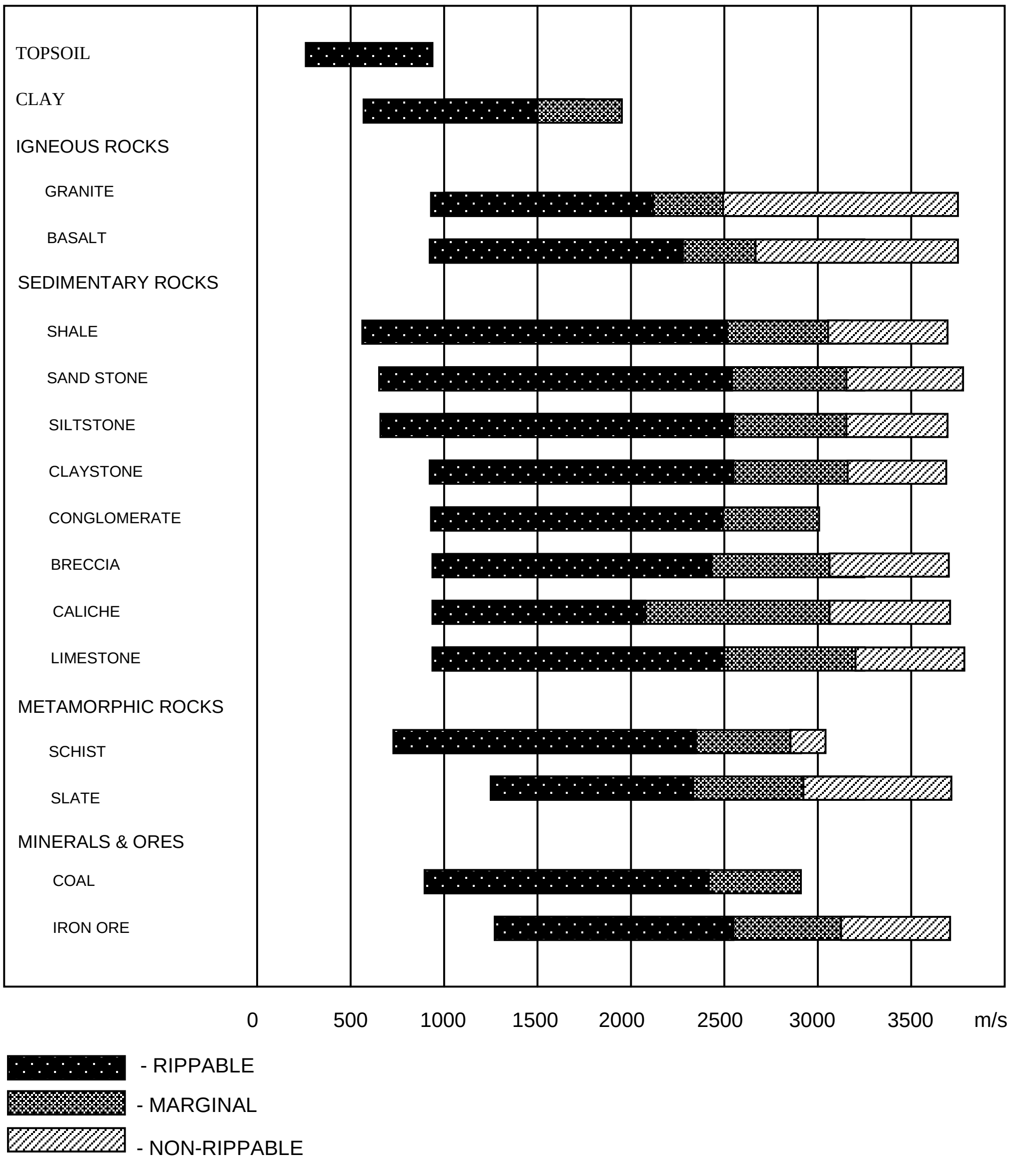
APPENDIX C

CATERPILLAR AND KOMATSU SUGGESTED CHARTS



Rippability Assessment chart recommended by Caterpillar Tractor Co. for CAT D9 type dozer (Caterpillar Performance Handbook, 2001).

D335A Giant



Rippability Assessment chart recommended by Komatsu for D355A ripper (Anon, 1987).

APPENDIX D
CLASSIFICATION PROPOSED BY KIRSTEN

Mass strength number (Ms) for rocks (Kirsten, 1982)

Hardness	**Identification in profile**	**UCS, (MPa)**	**Mass strength number, Ms**
Very soft rock	Material crumbles under firm blows with sharp end of geological pick and can be peeled of with a knife it is too hard to cut a triaxial sample by hand	1.7 1.7-3.3	0.87 1.86
Soft rock	Can just be scraped and peeled with a knife indentions 1 mm to 3 mm show in the specimen with firm blows of the pick point	3.3-3.6 6.6-13.2	3.95 8.39
Hard rock	Cannot be scraped or peeled with a knife; hand-held specimen can be broken with hammer end of a geological pick with a single firm blow	13.2-26.4	17.70
Very hard rock	Hand held specimen breaks with hammer end of pick under more than one blow	26.4-53.0 53.0-106.0	70.0 140.0
Extremely hard rock (very very hard rock)	Specimen requires many blows with geological pick to break through intact material	212.0	280

Mass strength number (Ms) for detritus, (Kirsten, 1982)

Consistency	**Identification in profile**	**In-situ deformation modulus (MPa)**	**Mass strength number (Ms)**
Very loose	Detritus very loosely packed. High percentage voids and very easily dislodged by hand. Matrix crumbles very easily when scraped with geological pack. Ravelling often occurs in excavated faces.	0-4	0.02
Loose	Detritus loosely packed some resistance to being dislodged by hand. Large number of voids. Matrix shows small resistance to penetrate by sharp end geological pack.	4-10	0.05
Medium dense	Detritus very closely packed. Difficult to dislodge individual particles by hand. Voids less apparent. Matrix has considerable resistance to penetration by sharp end of geological pack.	10-30	0.1
Dense	Detritus very closely packed and occasionally very weakly cemented. Cannot dislodge individual particles by hand. The mass has a very high resistance to penetration by sharp end of geological pack, required many blows to dislodge particles.	30-80	0.21
Very dense	Detritus very densely packed and usually cemented together. The mass has a high resistance to repeated blows of geological pick – requires power tools for excavation.	80-200	0.44

Joint roughness number (Jr), (Kirsten, 1982)

Joint separation	**Condition**	**Joint roughness number (Jr)**
Joints/fissures tight or closing during excavation	Discontinuous joint/fissures Rough or irregular, undulating Smooth undulating Slickensided undulating Rough or irregular, planar Smooth planar Slikinsided planar	4.0 3.0 2.0 1.5 1.5 1.0 0.5
Joints/fissures open and remain open during excavation	Joints/fissures either open or containing relative very soft gouge of sufficient thickness to prevent joint/fissures wall contact upon excavation. Shattered or micro-shattered clays	1.0 1.0

Joint count number (Jc), (Kirsten, 1982)

Number of joints per cubic metre, (Jc)	**Ground quality designation, (RQD)**	**Number of joints per cubic metre, (Jc)**	**Ground quality designation, (RQD)**
33	5	18	55
32	10	17	60
30	15	15	65
29	20	14	70
27	25	12	75
26	30	11	80
24	35	9	85
23	40	8	90
21	45	6	95
20	50	5	100

Joint set number (Jn), (Kirsten, 1982)

Number of joints sets	**Joint set number, Jn**
Intact no or few joint/fissures	1.00
One joint/fissure set	1.22
One joint/fissure set plus random	1.50
Two joint/fissure set	1.83
Two joint/fissure set plus random	2.24
Three joint/fissure set	2.73
Three joint/fissure set plus random	3.34
Four joint/fissure set	4.09
Four joint/fissure set plus random	5.00

Relative ground structure number (Js), (Kirsten, 1982)

Dip direction of closer spaced joint set (degree)	**Dip angle of closer spaced joint set (degree)**	**Ratio of Joint Spacing, r**			
		1 :1	**1 : 2**	**1 : 4**	**1 : 8**
180/0	90	1.00	1.00	1.00	1.00
0	85	0.72	0.67	0.62	0.56
0	80	0.63	0.57	0.50	0.45
0	70	0.52	0.45	0.41	0.38
0	60	0.49	10.44	0.41	0.37
0	50	0.49	0.46	0.43	0.40
0	40	0.53	0.49	0.46	0.44
0	30	0.63	0.59	0.55	0.53
0	20	0.84	0.77	0.71	0.68
0	10	1.22	1.10	0.99	0.93
0	5	1.33	1.20	1.09	1.03
0/180	0	1.00	1.00	1.00	1.00
180	5	0.72	0.81	0.86	0.90
180	10	0.63	0.70	0.76	0.81
180	20	0.52	0.57	0.63	0.67
180	30	0.49	0.53	0.57	0.59
180	40	0.49	0.52	0.54	0.56
180	50	0.53	0.56	0.58	0.60
180	60	0.63	0.67	0.71	0.73
180	70	0.84	0.91	0.97	1.01
180	80	1.22	1.32	1.40	1.46
180	85	1.33	1.39	1.45	1.00
180/0	90	1.00	1.00	1.00	

Joint alteration number (Ja), (Kirsten, 1982)

Description of gouge	**Joint alteration number (Ja)**		
	<1.01	**1.0 – 5.0[2]**	**1.0 – 5.03[3]**
Tightly healed, hard, non-softening impermeable filling	0.75	-	-
Unaltered joint walls, surface staining filling	1.0	-	-
Slightly altered, non-softening, non-cohesive rock mineral or crushed rock filling	2.0	4.0	6.0
Non-softening, slightly clayey non-cohesive filling	3.0	6.0	10.0
Non-softening strongly over-consolidated clay mineral filling, with or without crushed rock	3.0	6.0	10.0
Softening or low friction clay mineral coating and small quantities of swelling clays	4.0	8.0	13.0
Softening moderately over-consolidated clay minerals filling, with or without crushed rock	4.0	8.0	13.0
Shattered or micro-shattered (swelling) clay gouge, with or without crushed rock	5.0	10.0	18.0

Excavation classification system for soil, detritus, rock and boulders (Kirsten, 1982)

Class	**Excavation class boundaries**	**Description of excavatability**	**Bulldozer characteristics**					**Backhoe characteristics**			
			Type	**Operating mass (kg)**	**Flywheel Power (kW)**	**Stalling Speed**	**1.6 km/h**	**Type**	**Operating Mass (kg)**	**Flywheel Power (kW)**	**Max. Drawbar Pull (kN)**
1	<0.01	Hand spade	D3	6340	46	151	65				
2	0.01-0.0999	Hand pick and spade	D4E/D5B	8820/11700	56/78	165/202	77/110	Cat215	17282	63	132
3	0.1-0.999	Power tools	D6D	14270	104	250	147	Cat255	23405	101	163
4	1.0-9.99	Easy ripping	D7G	20230	149	376	220	Cat235	38297	145	263
5	10.0-99.9	Hard ripping	D8K	31980	224	500	323	Cat245	59330	242	472
6	100.0-999.9	Very Hard ripping	D9H	42780	306	667	445	RH 40	83200	360	-
7	100-999.9	Extremely hard ripping blasting	D10	77870	522	1230	778	-	-	-	-
8	Larger than 10000	Blasting	-	-	-	-	-	-	-	-	-

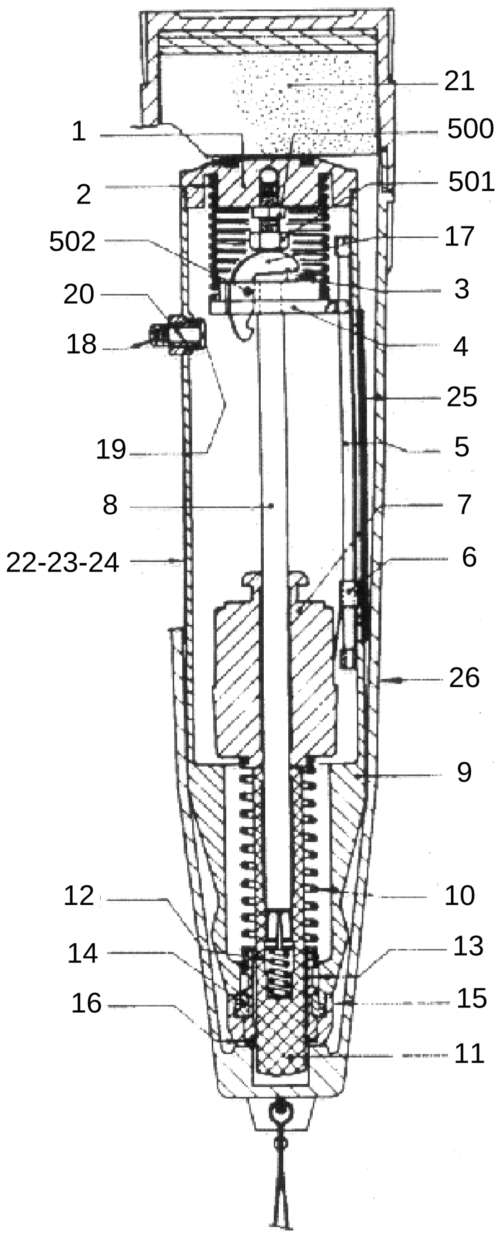
Excavation system for four classifications for soil, detritus, rock and boulders (Kirsten, 1982)

Class	**Excavation class boundaries**	**Description of excavatability**	**Bulldozer characteristics**					**Backhoe characteristics**			
			Type	**Operating mass kg**	**Flywheel Power kW**	**Stalling Speed**	**1.6 km/h**	**Type**	**Operating Mass kg**	**Flywheel Power kW**	**Max. Drawbar Pull kN**
1	<0.1	Hand pick and spade	D3/D4E/D5B	6340-11700	46-78	151-202	65-110	Cat215	17282	63	132
2	0.1-9.98	Power tools easy ripping	D6D/D7G	14270/2023	104/149	250/376	147/220	Cat225/223	23405/38297	101/145	163/263
3	10.999	Hard- very hard ripping	D8K/D9H	31960/42780	224/306						
4	>1000	Extremely hard ripping blasting									

APPENDIX E
CROSS SECTION OF SCHMIDT HAMMER

Schmidt Hammer

1 -Cap
2 -Pressure spring
3 -Pawl spring
4 -Guide flange
5 -Pointer guide rod
6 -Rebound reading pointer
7 -Hammer
8 -Guide rod
9 -Housing
10-Percussion spring
11-Plunger head
12-Shock-absorber spring
13-Spring fastening sleeve
14-Two-part pressure ring
15-Threaded ring nut
16-Dust sealing ring
17-Hook
18-Push-button
19-Push-button pin
20-Push-button spring
21-Carborundum stone
22-23-24-Self adhesive sticker
with Mpa-kg/sq.cm-P.S.I scale
25-Graduated plate
26-Complete case
500-Lock nut
501-Regulation screw
502-Pin for hook



APPENDIX F
SAMPLES OF STEREONET

SUMMARY OF SCANLINE MEASUREMENTS

KEMPAS, JOHOR

LINE 11 — **ROCK TYPE: sandstone** (OLD ALLUVIUM) Va
DATE: 15/3/2004 — **TYPE OF EXCAVATION:** RIP

No.	Distance (m)	PLT Is(50) (MPa)	UCS (MPa)	RQD (%)	Js* (m)	Remarks ond. of dis	αj	βj	Jr	Ja	Jr/Ja	Remarks
1	1,25	0,038	0,418	5	1,25	10ss	310	40	RSU1.5	2	0,75	
2	2,48	0,038	0,418	5	1,23	10ss	300	50	RSU1.5	2	0,75	
3	3,95	0,038	0,418	5	1,47	10ss	320	50	RSU1.5	2	0,75	
4	5,20	0,038	0,418	5	1,25	10ss	310	40	RSU1.5	2	0,75	
5	6,89	0,038	0,418	5	1,69	10ss	300	50	RSU1.5	2	0,75	
6	8,20	0,038	0,418	5	1,31	10ss	300	50	RSU1.5	2	0,75	
7	9,54	0,038	0,418	5	1,34	10ss	320	50	RSU1.5	2	0,75	
8	11,20	0,038	0,418	5	1,66	10ss	310	40	RSU1.5	2	0,75	
9	12,30	0,038	0,418	5	1,10	10ss	300	50	RSU1.5	2	0,75	
10	14,50	0,038	0,418	5	2,20	10ss	320	50	RSU1.5	2	0,75	
11	15,83	0,038	0,418	5	1,33	10ss	310	40	RSU1.5	2	0,75	
12	17,20	0,038	0,418	5	1,37	10ss	300	50	RSU1.5	2	0,75	
Average		0,038	0,418	5	1,43	10					0,75	
Rating{R}		0,00	0,00	1	15,48							
				λ=	0,70							

Rating for Ground water →	15	Joint Set No. (Jn) →	2	γ=	16,85 kN/m³
RMR →	**41,48**	Joint Water Reduction →	1		
Rating for orientation →	-2	Stress Reduction Facto	2,5		
Total RMR →	**39,48**	**Q** →	**0,75**		
		Excavatbility Index (E	**0,26**		

λ= 1/spacing dicontinuity = 1/1.43 = 0.70 joints/m
RQD= 5%
Js*) = Spacing discontinuity in direction of machine advance
Disc. = Discontinuity

αj = Disc. Dip direction — qtz = quartz — sft = Soft
cly = Clay — S = Smooth — chl = Chlorite
U = Undulating — car = carbonate — oa = old aluvium
SL = Slightly — P = Planar — ss = silty sand

R for PLT Is(50) } 0.038 < 1 = 0
R for RQD } 5% = 1
R for disc. Spacing (Js*) } 1.43m = (((1.43-0.6)/1.4) x (17.5-12.5)) + 12.5 = 15.48
Rating for Ground water is constant = 15 (Dry)

RMR = RUCS + RRQD + RJs*) + Cond.disc + GW
=0 + 1 + 15.48 + 10 + 15 = 41.48
Class of Rock Mass = III
The rating for Orientation(Fowell&Johnson,1991) = -2(class IV)
Total RMR = 41.48 - 2 = 39.48 (Grade IV)(Poor Rock)

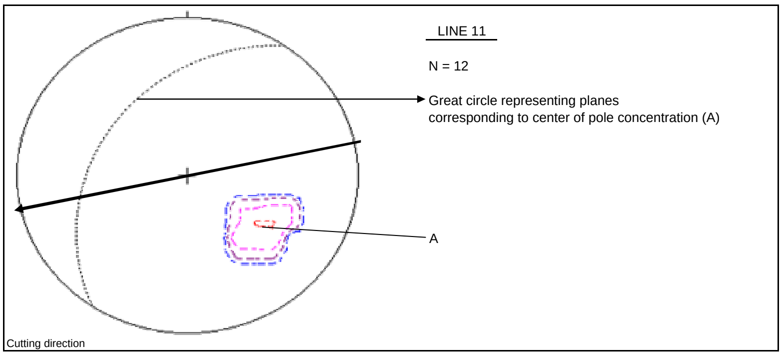
Jn = 1 joint set without Random = 2 — SRF = Near surface or low stress = 2.5 — Jw = Dry. = 1.0

Q = (RQD/Jn) x (Jr/Ja) x (Jw/SRF) = (5/2) x (0.75) x (1.0/2.5) = 0.75

Excavatability Index (EI) =Ms x (RQD/Jn) x Js x (Jr/Ja) = 0.261 x (5/2) x 0.53 x (0.75) = 0.26

Where, Ms = γ/27 x 0.418 = 16.85 /27 x 0.418 = 0.261

Js = 1 joint set, ratio (r) = 1; αj = 100-130, cutting direction SW, dip is assumed = 180 or 0; βj = 40-50 or = 40, Thus Js = 0.53



APPENDIX F
SAMPLES OF STEREONET

SUMMARY OF SCANLINE MEASUREMENTS

KEMPAS, JOHOR

LINE 11 **ROCK TYPE: sandstone** (OLD ALLUVIUM) Va
DATE: 15/3/2004 **TYPE OF EXCAVATION:** RIP

No.	Distance (m)	PLT Is(50) (MPa)	UCS (MPa)	RQD (%)	Js* (m)	Remarks ond. of dis	αj	βj	Jr	Ja	Jr/Ja	Remarks
1	1,25	0,038	0,418	5	1,25	10ss	310	40	RSU1.5	2	0,75	
2	2,48	0,038	0,418	5	1,23	10ss	300	50	RSU1.5	2	0,75	
3	3,95	0,038	0,418	5	1,47	10ss	320	50	RSU1.5	2	0,75	
4	5,20	0,038	0,418	5	1,25	10ss	310	40	RSU1.5	2	0,75	
5	6,89	0,038	0,418	5	1,69	10ss	300	50	RSU1.5	2	0,75	
6	8,20	0,038	0,418	5	1,31	10ss	300	50	RSU1.5	2	0,75	
7	9,54	0,038	0,418	5	1,34	10ss	320	50	RSU1.5	2	0,75	
8	11,20	0,038	0,418	5	1,66	10ss	310	40	RSU1.5	2	0,75	
9	12,30	0,038	0,418	5	1,10	10ss	300	50	RSU1.5	2	0,75	
10	14,50	0,038	0,418	5	2,20	10ss	320	50	RSU1.5	2	0,75	
11	15,83	0,038	0,418	5	1,33	10ss	310	40	RSU1.5	2	0,75	
12	17,20	0,038	0,418	5	1,37	10ss	300	50	RSU1.5	2	0,75	
Average		0,038	0,418	5	1,43	10					0,75	
Rating{R}		0,00	0,00	1	15,48							
				λ=	0,70							

Rating for Ground water →	15
RMR →	**41,48**
Rating for orientation →	-2
Total RMR →	**39,48**

Joint Set No. (Jn) →	2
Joint Water Reduction →	1
Stress Reduction Facto	2,5
Q →	**0,75**
Excavatbility Index (E	**0,26**

γ= 16,85 kN/m^3

λ= 1/spacing dicontinuity = 1/1.43 = 0.70 joints/m
RQD= 5%
Js*) = Spacing discontinuity in direction of machine advance
Disc. = Discontinuity

αj = Disc. Dip direction
cly = Clay
U = Undulating
SL = Slightly

qtz = quartz
S = Smooth
car = carbonate
P = Planar

sft = Soft
chl = Chlorite
oa = old aluvium
ss = silty sand

R for PLT Is(50) } 0.038 < 1 = 0
R for RQD } 5% = 1
R for disc. Spacing (Js*) } 1.43m = (((1.43-0.6)/1.4) x (17.5-12.5)) + 12.5 = 15.48
Rating for Ground water is constant = 15 (Dry)

RMR = RUCS + RRQD + RJs*) + Cond.disc + GW
=0 + 1 + 15.48 + 10 + 15 = 41.48
Class of Rock Mass = III
The rating for Orientation(Fowell&Johnson,1991) = -2(class IV)
Total RMR = 41.48 - 2 = 39.48 (Grade IV)(Poor Rock)

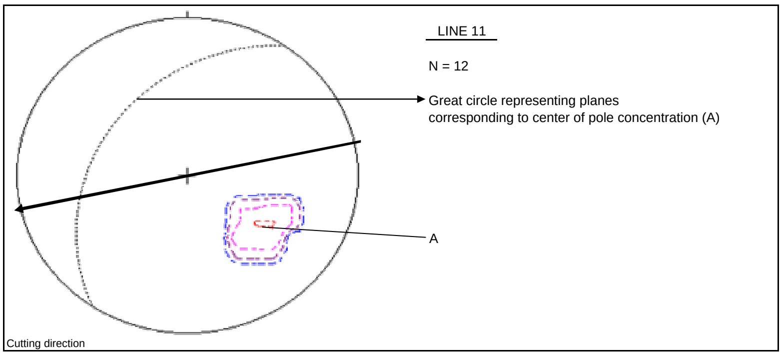
Jn = 1 joint set without Random = 2 SRF = Near surface or low stress = 2.5 Jw = Dry. = 1.0

Q = (RQD/Jn) x (Jr/Ja) x (Jw/SRF) = (5/2) x (0.75) x (1.0/2.5) = 0.75

Excavatability Index (EI) =Ms x (RQD/Jn) x Js x (Jr/Ja) = 0.261 x (5/2) x 0.53 x (0.75) = 0.26

Where, Ms = γ/27 x 0.418 = 16.85 /27 x 0.418 = 0.261

Js = 1 joint set, ratio (r) = 1; αj = 100-130, cutting direction SW, dip is assumed = 180 or 0; βj = 40-50 or = 40, Thus Js = 0.53



SUMMARY OF SCANLINE MEASUREMENTS

DESA TEBRAU, JOHOR

DT COARSE 3 **ROCK TYPE:** ALUVIUM, SANDSTONE IVa
DATE: 25-12-2004 **TYPE OF EXCAVATION: rip**

No.	Distance (m)	UCS (MPa)	RQD (%)	Js* (m)	Remarks ond. of dis	αj	βj	Jr	Ja	Jr/Ja	Remarks
1	0,00	8,489	99	0,00	25oa	140	80	RP1.5	6,0	0,25	
2	0,10	8,489	99	0,10	25oa	170	80	RP1.5	6,0	0,25	
3	0,50	8,489	99	0,40	25oa	160	70	RP1.5	6,0	0,25	
4	1,10	8,489	99	0,60	25oa	320	80	RP1.5	6,0	0,25	
5	1,46	8,489	99	0,36	25oa	340	80	RP1.5	6,0	0,25	
6	3,20	8,489	99	1,74	25oa	160	70	RP1.5	6,0	0,25	
7	4,94	8,489	99	1,74	25oa	320	70	RP1.5	6,0	0,25	
8	5,54	8,489	99	0,60	25oa	340	80	RP1.5	6,0	0,25	
9	5,90	8,489	99	0,36	25oa	140	80	RP1.5	6,0	0,25	
10	6,50	8,489	99	0,60	25oa	170	70	RP1.5	6,0	0,25	
11	6,86	8,489	99	0,36	25oa	160	80	RP1.5	6,0	0,25	
12	8,60	8,489	99	1,74	25oa	320	80	RP1.5	6,0	0,25	
13	10,34	8,489	99	1,74	25oa	340	80	RP1.5	6,0	0,25	
14	10,74	8,489	99	0,40	25oa	320	80	RP1.5	6,0	0,25	
15	12,48	8,489	99	1,74	25oa	340	80	RP1.5	6,0	0,25	
16	14,22	8,489	99	1,74	25oa	140	80	RP1.5	6,0	0,25	
17	14,62	8,489	99	0,40	25oa	170	80	RP1.5	6,0	0,25	
18	15,22	8,489	99	0,60	25oa	340	80	RP1.5	6,0	0,25	
19	15,58	8,489	99	0,36	25oa	320	70	RP1.5	6,0	0,25	
20	15,94	8,489	99	0,36	25oa	320	80	RP1.5	6,0	0,25	
21	17,68	8,489	99	1,74	25oa	340	80	RP1.5	6,0	0,25	
22	19,42	8,489	99	1,74	25oa	170	80	RP1.5	6,0	0,25	
23	21,16	8,489	99	1,74	25oa	160	70	RP1.5	6,0	0,25	
24	22,90	8,489	99	1,74	25oa	320	80	RP1.5	6,0	0,25	
25	24,64	8,489	99	1,74	25oa	340	70	RP1.5	6,0	0,25	
26	25,00	8,489	99	0,36	25oa	320	70	RP1.5	6,0	0,25	
Average		8,489	99	0,96	25					0,25	
Rating		1,76	19,85	13,79							
			λ=	1,04							

Rating for Ground water →	15	Joint Set No. (Jn) →	4	γ= 22,09	kN/m^3
RMR →	**50,40**	Joint Water reduction →	1		
Rating for orientation →	-5	Stress Reduction Facto	2,5		
Total RMR →	**45,40**	**Q** →	**2,475**		
		Excavatbility Index (E	**37**		

λ= 1/spacing dicontinuity = 1/0.96 = 1.04
RQD= 100e$^{-0.1λ}$(λ0.1+1)=99
Js*) = Spacing discontinuity in direction of machine advance
Disc. = Discontinuity Cond. = Condition
αj = Disc. Dip direction βj = Disc.dip qtz = quartz sft = Soft
cly = Clay GW = Ground water S = Smooth chl = Chlorite
U = Undulating R = Rough car = carbo oa = old aluvium
SL = Slightly cao = Caoline P = Planar

R for UCS } 8.489 Mpa = (((8.489-5)/20) x (3-1.5))+1.5 = 1.76
R for RQD } 99% = (((99-90)/10) x 1.5) + 18.5 = 19.85
R for disc. Spacing (Js*) } 0.96m = (((0.96-0.6)/1.4) x (17.5-12.5)) + 12.5 = 13.79
Rating for Ground water is constant = 15 (Dry)

RMR = RUCS + RRQD + RJs*) + Cond.disc + GW
= 1.76 + 19.85 + 13.79 + 20 + 15 = 50.40
Class of Rock Mass = III
The rating for Orientation(Fowell&Johnson,1991) = -5 (III)
Total RMR = 50.40 - 5= 45.40

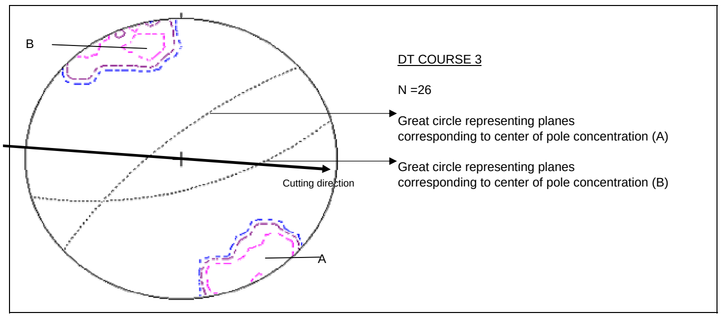
Jn = 2 joint set without Random = 4 SRF = Near surface or low stress = Jw = Dry. = 1.0

Q = (RQD/Jn) x (Jr/Ja) x (Jw/SRF) = (99/4) x (0.25) x (1.0/2.5) = 2.475

Excavatability Index (EI) = Ms x (RQD/Jn) x Js x (Jr/Ja) = 6.945 x 100/4 x 0.84 x 0.25 = 37

Where, Ms = γ/27 x 8.489 = 22.09/27 x 8.489 = 6.945

Js = 2 joint set, ratio (r) = (JaA/JaB) (r) =1.054/0.834 = 1.264 is assumed ; αjA = 320-340, cutting direction NE,
Dip direction is assumed = 180 or 0; βjB = 70-80 or =70 .Thus, Js = 0.84



SUMMARY OF SCANLINE MEASUREMENTS

DESA TEBRAU, JOHOR

DT FINE 1 — **ROCK TYPE:** ALUVIUM, sandstone, FINE, LIGHT GREY IVa

DATE: 25-12-2004 — **TYPE OF EXCAVATION: rip**

No.	Distance (m)	UCS (MPa)	RQD (%)	Js* (m)	Remarks ond. of dis	αj	βj	Jr	Ja	Jr/Ja
1	1,10	14,548	100	1,10	25oa	160	90	RP1.5	2,0	0,75
2	2,50	14,548	100	1,40	25oa	90	50	RP1.5	2,0	0,75
3	3,20	14,548	100	0,70	25oa	100	50	RP1.5	2,0	0,75
4	4,30	14,548	100	1,10	25oa	270	80	RP1.5	2,0	0,75
5	5,40	14,548	100	1,10	25oa	270	50	RP1.5	2,0	0,75
6	6,21	14,548	100	0,81	25oa	270	90	RP1.5	2,0	0,75
7	7,65	14,548	100	1,44	25oa	270	90	RP1.5	2,0	0,75
8	8,53	14,548	100	0,88	25oa	90	80	RP1.5	2,0	0,75
9	9,30	14,548	100	0,77	25oa	270	60	RP1.5	2,0	0,75
10	10,40	14,548	100	1,10	25oa	160	50	RP1.5	2,0	0,75
11	11,50	14,548	100	1,10	25oa	100	50	RP1.5	2,0	0,75
12	12,30	14,548	100	0,80	25oa	90	80	RP1.5	2,0	0,75
13	13,20	14,548	100	0,90	25oa	160	90	RP1.5	2,0	0,75
14	14,30	14,548	100	1,10	25oa	160	90	RP1.5	2,0	0,75
15	15,60	14,548	100	1,30	25oa	270	50	RP1.5	2,0	0,75
16	16,70	14,548	100	1,10	25oa	100	90	RP1.5	2,0	0,75
17	17,20	14,548	100	0,50	25oa	180	80	RP1.5	2,0	0,75
Average		14,548	100	1,01	25					0,75
Rating		2,22	20	13,97						
			λ=	0,99						

Rating for Ground water →	15
RMR →	**76,19**
Rating for orientation →	-12
Total RMR →	**64,19**

Joint Set No. (Jn) →	6
Joint Water reduction →	1,0
Stress Reduction Facto	2,5
Q →	**5**
Excavatbility Index (E	**123**

γ= 21,99 kN/m^3

Ms= **10,83**

λ= 1/spacing dicontinuity = 1/1.01 = 0.99

RQD= $100e^{-0.1\lambda}(\lambda 0.1+1)$= 100

Js*) = Spacing discontinuity in direction of machine advance

Disc. = Discontinuity	Cond. = Condition		
αj = Disc. Dip direction	βj = Disc.dip	qtz = quartz	sft = Soft
cly = Clay	GW = Ground water	S = Smooth	chl = Chlorite
U = Undulating	R = Rough	car = carbo	oa = old aluvium
SL = Slightly	cao = Caoline	P = Planar	

RMR = RUCS + RRQD + RJs*) + Cond.disc + GW

Class of Rock Mass = II

The rating for Orientation(Fowell&Johnson,1991) = -12 (class I)

Total RMR = 76.19 - 12 = 64.19

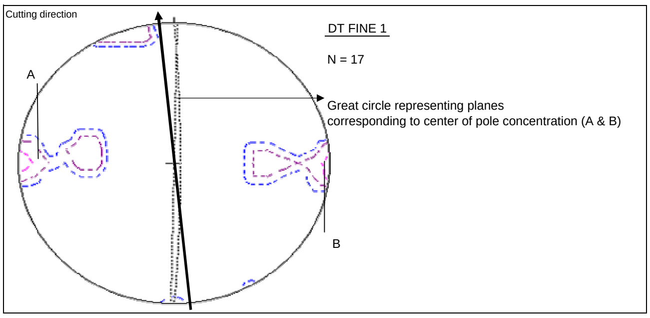
Jn = 3 joint set without Random = 6 SRF = Near surface or low stress = Jw = Dry. = 1.0

Q = (RQD/Jn) x (Jr/Ja) x (Jw/SRF) = (100/6) x (0.75) x (1.0/2.5) = 5

Excavatability Index (EI) = Ms x (RQD/Jn) x Js x (Jr/Ja) = 11.848 x 100/6 x 0.84 x 0.75 = 123

Where, Ms = γ/27 x 14.548 = 21.99/27 x 14.548 = 11.848

Js = 2 joint set, ratio (r) = (JaB/JaA) (r) = 1.086/0.970 = 1.190 is assumed ; αjB = 250-270, cutting direction N, Dip direction is assumed = 180 or 0; βjB = 50-90 assume = 70.Thus, Js = 0.84



APPENDIX G
RESULT OF THE ROCK MASS CLASSIFICATION

Sample	Colour	Location	Material	Weathering Grade	Joint Spacing (m)	Q-system	EI	RMR
R8 LN6 R2S	Yellowish Brown	Bukit Indah	sandstone	II	0.17	6.60	1165	61
R8 LN3 R4S	Reddish Brown	Bukit Indah	sandstone	II	0.54	8.78	715	62
B8 L3	Light Grey	Bukit Indah	sandstone	II	0.30	8.53	842	61
R8 LN2 UR1	Reddish Brown	Bukit Indah	sandstone	II	0.56	9.65	616	56
R3 L1 R4S	Light Brown	Bukit Indah	sandstone	III	0.31	9.40	331	50
B8 L9	Grey	Bukit Indah	sandstone	III	0.11	3.77	95	55
R8 LN2 R3S	Reddish Black	Bukit Indah	sandstone	III	0.17	9.13	385	57
R8 LN7 UR1	Reddish Brown	Bukit Indah	sandstone	III	0.34	9.09	409	57
R6 L1	Reddish	Bukit Indah	sandstone	III	0.39	9.24	433	59
LN8 UR2	Reddish Brown	Bukit Indah	sandstone	III	0.36	9.76	401	54
B2 L3	Light Grey	Bukit Indah	sandstone	IVa	0.36	13.20	91	59
R8 LN2 R1	Reddish	Bukit Indah	sandstone	IVa	0.10	5.40	18	52
LN3 R3S	Light Brown	Bukit Indah	sandstone	IVa	0.49	13.10	194	60
R7 L1	Reddish Brown	Bukit Indah	sandstone	IVa	1.09	4.90	50	60
LN8 R3	Reddish	Bukit Indah	sandstone	IVa	0.13	8.00	55	55
LN4 R4	Light Grey	Bukit Indah	sandstone	IVa	0.24	4.59	26	53
B1 L3	Reddish	Bukit Indah	sandstone	IVa	1.22	14.42	126	55
B1 L2	Light Brown	Bukit Indah	sandstone	IVa	0.41	9.11	61	62
LN4 R3S	Reddish	Bukit Indah	sandstone	IVa	0.52	7.33	75	60
R8 LN6 R1	Grey	Bukit Indah	sandstone	IVb	0.19	4.75	21	45
R8 LN8 R2	Reddish Grey	Bukit Indah	sandstone	IVb	0.25	4.68	14	44
R4 L8	Grey	Bukit Indah	sandstone	IVb	0.23	3.99	58	49
LN2 R1S	Yellowish Brown	Bukit Indah	sandstone	IVb	0.47	5.26	20	47
B4 LA	Brownish Grey	Bukit Indah	sandstone	IVb	0.55	7.78	18	49
R8 LN6 R3	Grey	Bukit Indah	sandstone	IVb	0.49	7.56	29	50
B7 L2	Reddish Grey	Bukit Indah	sandstone	IVb	0.78	4.82	14	51
R7 L2	Light Grey	Bukit Indah	sandstone	Va	0.49	0.70	0	39
R4 L7	Light Brown	Bukit Indah	sandstone	Va	0.20	0.50	0	39
B2 SH4	Light Brown	Bukit Indah	sandstone	Va	0.24	0.45	1	35
R4 L4	Yellowish Grey	Bukit Indah	sandstone	Va	0.21	0.23	0	38
R5	Light Grey	Bukit Indah	sandstone	Va	0.09	0.50	1	32
R8 LN7 UR2	Reddish	Bukit Indah	sandstone	Va	0.73	0.49	0	42
R8 LN3 R1	Reddish Brown	Bukit Indah	sandstone	Va	0.70	0.50	0	30
R4 L3	Yellowish Grey	Bukit Indah	sandstone	Va	0.53	0.51	1	41
B6 L2	Light Grey	Bukit Indah	sandstone	Vb	1.51	0.09	0	43
R8 LN1 R1	Yellowish Grey	Bukit Indah	sandstone	Vb	0.26	0.09	0	36
B7 L3	Light Grey	Bukit Indah	sandstone	Vb	0.22	0.05	3	38

Sample	Colour	Location	Material	Weathering Grade	Joint Spacing (m)	Q-system	EI	RMR
R4 L5	Reddish Brown	Bukit Indah	sandstone	Vb	0.50	0.09	0	41
LN7 R3	Light Brown	Bukit Indah	sandstone	Vb	0.40	0.03	4	41
R8 LN4 R1	Yellowish Brown	Bukit Indah	sandstone	Vb	0.31	0.09	0	40
R8 LN4 R2S	Light Grey	Bukit Indah	sandstone	Vb	0.20	0.10	0	36
R8 LN8 UR1	Grey	Bukit Indah	sandstone	Vb	0.49	0.11	0	36
RL 3 C L1	Reddish Brown	Mersing	sandstone	II	0.21	9.07	313	57
RL 1 L6	Light Brown	Mersing	sandstone	III	0.24	9.30	288	54
RL1 L5	Light Grey	Mersing	sandstone	III	0.25	9.00	274	60
RL 3 C L2	Grey	Mersing	sandstone	III	0.78	8.90	303	50
RL 3 E L1	Light Brown	Mersing	sandstone	III	0.80	8.70	148	50
RL 3 Slope Area 2 L3	Brownish Grey	Mersing	sandstone	III	0.38	6.97	86	52
RL 3 Slope Area 1 L5(a)	Reddish	Mersing	sandstone	IVa	0.41	14.00	206	59
RL 3 A L1	Reddish Brown	Mersing	sandstone	IVb	0.56	7.40	21	48
RL 1 (b) L3	Brownish Grey	Mersing	sandstone	Va	0.27	0.49	0	40
RL 3 Slope Area 1 L1	Brownish Grey	Mersing	sandstone	Va	0.33	0.50	0	38
RL 3 Slope Area 1 L5 (Zone C)	Brownish Grey	Mersing	sandstone	Vb	0.48	0.10	0	42
RL 3 Slope Area 1 L2	Brownish Grey	Mersing	sandstone	Vb	0.24	0.10	0	38
RL 3 Slope Area 2 L1	Brown	Mersing	sandstone	Vb	0.25	0.10	0	39
RL 3 A L2	Brownish Grey	Mersing	sandstone	Vb	0.39	0.20	0	40
RL 3 A L4	Light Brown	Mersing	sandstone	Vb	0.56	0.10	0	40
DT FINE 1	Light Grey	Desa Tebrau	sandstone	IVa	1.01	5.00	123	64
DT FINE 2	Light Grey	Desa Tebrau	sandstone	IVa	0.83	7.43	156	71
DT FINE 3	Light Grey	Desa Tebrau	sandstone	IVa	0.96	5.00	64	71
DT FINE 4	Light Grey	Desa Tebrau	sandstone	IVa	1.06	15.00	274	66
DT FINE 5	Light Grey	Desa Tebrau	sandstone	IVa	1.09	5.00	71	67
DT COARSE 1	Light Grey	Desa Tebrau	sandstone	IVa	0.91	2.49	29	70
DT COARSE 2	Light Grey	Desa Tebrau	sandstone	IVa	1.09	1.67	18	71
DT COARSE 3	Light Grey	Desa Tebrau	sandstone	IVa	1.00	2.48	37	45
DT COARSE 4	Light Grey	Desa Tebrau	sandstone	IVa	0.68	1.65	30	73
DT COARSE 5	Light Grey	Desa Tebrau	sandstone	IVa	1.13	3.00	30	69
Line 1	Light Grey	Kempas	sandstone	Va	1.37	0.38	0	41
Line 1a	Light Grey	Kempas	sandstone	Va	1.56	0.75	0	42
Line 2a	Light Grey	Kempas	sandstone	Va	1.42	0.38	0	41
Line 3	Light Grey	Kempas	sandstone	Va	1.14	0.75	0	40
Line 4	Light Grey	Kempas	sandstone	Va	1.53	0.75	0	42
Line 5	Light Grey	Kempas	sandstone	Va	1.45	1.00	1	41

Sample	Colour	Location	Material	Weathering Grade	Joint Spacing (m)	Q-system	EI	RMR
Line 6	Light Grey	Kempas	sandstone	Va	1.59	0.75	1	42
Line 7	Light Grey	Kempas	sandstone	Va	1.53	0.75	0	42
Line 8	Light Grey	Kempas	sandstone	Va	1.26	0.75	0	41
Line 9	Light Grey	Kempas	sandstone	Va	1.20	0.75	0	41
Line 10	Light Grey	Kempas	sandstone	Va	1.58	0.75	0	40
Line 11	Light Grey	Kempas	sandstone	Va	1.43	0.75	0	39
R4 L9	Yellow	Bukit Indah	shale	II	0.29	9.61	1189	50
C	Grey	Bukit Indah	shale	II	0.28	6.99	442	60
R8 LN1 R6	Reddish Brown	Bukit Indah	shale	III	0.22	5.97	147	57
LN4 R2	Light Brown	Bukit Indah	shale	III	0.49	9.19	387	40
LN6 R4S	Yellowish Grey	Bukit Indah	shale	III	0.60	9.01	185	60
LN7 R2	White	Bukit Indah	shale	III	0.34	8.47	386	59
LN6 R1	Grey	Bukit Indah	shale	IVa	0.26	4.55	39	59
R4 L6	Reddish Grey	Bukit Indah	shale	IVa	0.47	3.14	36	55
R8 LN1 R5	Dark Grey	Bukit Indah	shale	IVa	0.44	2.54	26	55
LN7 R1	Light Grey	Bukit Indah	shale	IVa	0.16	6.04	82	58
B2 SH1	Light Grey	Bukit Indah	shale	IVa	0.24	8.47	34	58
R8 LN1 R2	Dark Grey	Bukit Indah	shale	IVa	0.20	9.18	59	67
R8 LN4 R3	Reddish	Bukit Indah	shale	IVa	0.23	9.48	156	56
R8 LN7 R4	Grey	Bukit Indah	shale	IVa	0.24	8.99	93	56
LN8 R2	Brownish Grey	Bukit Indah	shale	IVa	0.27	6.53	74	57
R3 L6 R2	Brownish	Bukit Indah	shale	IVb	0.71	1.15	2	39
R8 LN1 R4	Dark Grey	Bukit Indah	shale	IVb	0.22	5.05	12	47
R8 LN3 R3	Light Grey	Bukit Indah	shale	IVb	0.94	5.12	22	39
R8 LN11 R5	Light Grey	Bukit Indah	shale	IVb	1.06	2.63	11	40
R8 LN12 R2	Grey	Bukit Indah	shale	IVb	0.51	2.33	10	46
B8 L5	Grey	Bukit Indah	shale	IVb	0.21	4.46	13	47
R4 L2	Brownish Grey	Bukit Indah	shale	IVb	0.17	3.29	7	45
R8 LN2 R2	Reddish Brown	Bukit Indah	shale	IVb	0.24	5.55	24	43
R8 LN14 R1	Reddish Brown	Bukit Indah	shale	IVb	0.29	4.80	9	45
LN3 R5	Light Grey	Bukit Indah	shale	IVb	0.32	4.75	18	45
R8 LN10 R4S	Grey	Bukit Indah	shale	IVb	1.10	1.15	4	50
B8 L4	Grey	Bukit Indah	shale	IVb	0.41	1.25	2	45
R8 LN5 R3	Grey	Bukit Indah	shale	IVb	0.31	0.22	5	45
R2 L2	White	Bukit Indah	shale	Va	0.37	0.75	1	40
R8 LN10 R2	Light Grey	Bukit Indah	shale	Va	0.52	0.73	1	39
LN5 R2	Reddish	Bukit Indah	shale	Va	0.22	0.23	0	37
R8 LN11 R1	Grey	Bukit Indah	shale	Va	0.29	0.25	0	37
R8 LN 11 R3	Light Grey	Bukit Indah	shale	Va	0.24	0.49	8	37
B7 L1	Light Grey	Bukit Indah	shale	Va	0.33	0.49	8	40
B7 L5	Light Grey	Bukit Indah	shale	Va	0.25	0.45	1	39
R8 LN3 R2	Dark Grey	Bukit Indah	shale	Va	0.39	0.13	0	39
R2 L1	Yellow	Bukit Indah	shale	Vb	0.20	0.10	0	40

Sample	Colour	Location	Material	Weathering Grade	Joint Spacing (m)	Q-system	EI	RMR
LN6 R5	Grey	Bukit Indah	shale	Vb	0.29	0.07	0	39
LN8 R1S	Grey	Bukit Indah	shale	Vb	0.26	0.08	0	39
B8 L1	Grey	Bukit Indah	shale	Vb	0.31	0.09	0	38
RL 1 L3	Reddish	Mersing	shale	II	0.83	9.80	407	55
RL 1 (b) L1	Reddish	Mersing	shale	III	0.44	9.70	306	53
RL 1 (a) L3	Reddish	Mersing	shale	III	0.81	9.30	378	54
RL 1 L1	Grey	Mersing	shale	IVa	0.81	3.30	70	55
RL1 L4	Reddish	Mersing	shale	IVa	0.78	9.50	94	54
RL1 L7	Reddish	Mersing	shale	IVa	0.68	9.78	171	59
along foliation	Light Grey	Mersing	shale	Va	0.57	0.50	0	40
RL 1 L2	Brownish	Mersing	shale	Va	0.20	0.49	0	41

APPENDIX H
SUMMARY OF ROCK MATERIAL TEST RESULTS

Sample No	Location	Sample	Material	Grain size	Weathering Grade	Dry Density (kg/m3)	Is50 (MPa)	Is50 (MPa) (portable)	UCS (MPa)	Brazillian (MPa)	Schmidt Hammer (MPa)	Slake Durability		Slaking Index	Sonic wave	Penetration Test (MPa)	
												Id1 (%)	Id2 (%)		velocity (m/s)	10mm probe	Point Load Bit
1	Bukit Indah	R8 LN6 R2S	sandstone	fine	II	2526	4,960	3,820	82,58	4,37	74	98,03	97,50	21	2634	1058,370	775,98
2	Bukit Indah	R8 LN3 R4S	sandstone	moderate	II	2561	4,511	4,640	NA	3,42	92	98,91	94,55	20	2861	1243,539	2139,06
3	Bukit Indah	B8 L3	sandstone	fine	II	2565	3,932	3,510	62,93	3,21	88	94,52	91,48	21	2873	977,912	2880,14
4	Bukit Indah	R8 LN2 UR1	sandstone	very fine	II	2528	3,101	3,360	55,45	2,77	43	96,77	90,27	23	2832	958,050	660,71
5	Bukit Indah	R3 L1 R4S	sandstone	very fine	III	2352	1,288	2,530	NA	2,27	55	91,53	87,42	17	2342	408,980	359,36
6	Bukit Indah	B8 L9	sandstone	very fine	III	2417	1,025	2,356	19,83	2,17	40	92,04	73,21	16	2541	375,748	321,26
7	Bukit Indah	R8 LN2 R3S	sandstone	very fine	III	2479	2,114	2,590	35,32	1,90	82	94,45	86,24	17	2232	451,940	327,44
8	Bukit Indah	R8 LN7 UR1	sandstone	fine	III	2514	2,531	2,104	NA	2,71	34	92,66	90,02	16	2960	385,998	478,27
9	Bukit Indah	R6 L1	sandstone	fine	III	2433	2,672	2,300	39,35	2,61	28	99,03	90,25	16	2438	387,015	359,70
10	Bukit Indah	LN8 UR2	sandstone	fine	III	2483	1,288	2,208	28,36	2,30	30	95,83	84,23	16	2030	502,419	499,59
11	Bukit Indah	B2 L3	sandstone	fine	IVa	2118	0,384	1,750	NA	1,25	23	75,78	52,53	9	1645	305,729	282,55
12	Bukit Indah	R8 LN2 R1	sandstone	very fine	IVa	2235	0,251	1,600	3,62	1,10	22	84,96	41,35	9	1631	273,902	302,33
13	Bukit Indah	LN3 R3S	sandstone	very fine	IVa	2196	0,794	1,650	11,18	2,16	25	87,88	70,45	9	1878	387,015	289,76
14	Bukit Indah	R7 L1	sandstone	fine	IVa	2342	0,763	1,035	10,35	2,11	17	85,32	71,14	11	1875	291,343	268,43
15	Bukit Indah	LN8 R3	sandstone	fine	IVa	2146	0,493	1,716	7,08	1,51	24	85,32	70,51	10	1620	262,381	260,91
16	Bukit Indah	LN4 R4	sandstone	fine	IVa	2158	0,384	1,160	6,12	1,14	24	83,06	48,52	9	1624	326,735	278,19
17	Bukit Indah	B1 L3	sandstone	fine	IVa	2354	0,581	1,523	7,58	1,53	18	90,44	71,63	8	1828	326,225	260,15
18	Bukit Indah	B1 L2	sandstone	fine	IVa	2346	0,407	1,920	NA	NA	21	82,02	52,36	13	1811	305,729	278,19
19	Bukit Indah	LN4 R3S	sandstone	fine	IVa	2396	0,433	1,710	6,95	1,46	10	96,03	71,59	10	1852	311,469	262,55
20	Bukit Indah	R8 LN6 R1	sandstone	fine	IVb	2148	0,278	0,285	NA	NA	NA	31,25	0,00	9	1627	193,253	233,98
21	Bukit Indah	R8 LN8 R2	sandstone	fine	IVb	2120	0,285	0,255	NA	NA	NA	25,67	0,00	8	1433	166,454	202,76
22	Bukit Indah	R4 L8	sandstone	fine	IVb	2341	0,909	0,760	NA	NA	NA	28,25	0,00	8	1572	187,715	123,93
23	Bukit Indah	LN2 R1S	sandstone	fine	IVb	2057	0,149	0,790	NA	NA	NA	32,38	0,00	8	1731	260,471	216,96
24	Bukit Indah	B4 LA	sandstone	very fine	IVb	2224	0,140	0,052	NA	NA	NA	31,22	0,00	8	1423	237,683	222,35
25	Bukit Indah	R8 LN6 R3	sandstone	moderate	IVb	2124	0,231	0,380	NA	NA	NA	32,58	0,00	8	1366	232,272	177,02
26	Bukit Indah	B7 L2	sandstone	fine	IVb	2121	0,145	0,480	NA	NA	NA	33,34	0,00	9	1438	204,201	174,22
27	Bukit Indah	R7 L2	sandstone	fine	Va	1898	0,025	0,000	NA	NA	NA	0,00	0,00	5	1247	171,600	181,77
28	Bukit Indah	R4 L7	sandstone	moderate	Va	1958	0,048	0,000	NA	NA	NA	0,00	0,00	5	1369	132,463	154,22
29	Bukit Indah	B2 SH4	sandstone	moderate	Va	1968	0,082	0,000	NA	NA	NA	0,00	0,00	5	1319	140,102	120,67
30	Bukit Indah	R4 L4	sandstone	fine	Va	1811	0,053	0,000	NA	NA	NA	0,00	0,00	5	1274	172,374	154,92
31	Bukit Indah	R5	sandstone	fine	Va	1729	0,090	0,000	NA	NA	NA	12,12	0,00	5	1645	121,642	175,05
32	Bukit Indah	R8 LN7 UR2	sandstone	fine	Va	2103	0,035	0,000	NA	NA	NA	0,00	0,00	5	1325	132,463	124,93
33	Bukit Indah	R8 LN3 R1	sandstone	fine	Va	1851	0,039	0,000	NA	NA	NA	0,00	0,00	5	1348	166,454	160,29
34	Bukit Indah	R4 L3	sandstone	fine	Va	1819	0,056	0,000	NA	NA	NA	0,00	0,00	5	1319	142,903	123,93
35	Bukit Indah	B6 L2	sandstone	moderate	Vb	2162	0,009	0,000	NA	NA	NA	0,00	0,00	4	1620	49,459	38,10
36	Bukit Indah	R8 LN1 R1	sandstone	moderate	Vb	2136	0,009	0,000	NA	NA	NA	0,00	0,00	4	1328	36,155	141,20
37	Bukit Indah	B7 L3	sandstone	fine	Vb	2193	0,007	0,000	NA	NA	NA	0,00	0,00	4	1476	37,301	52,34
38	Bukit Indah	R4 L5	sandstone	moderate	Vb	1958	0,005	0,000	NA	NA	NA	0,00	0,00	4	1251	57,925	127,21
39	Bukit Indah	LN7 R3	sandstone	fine	Vb	1711	0,014	0,000	NA	NA	NA	0,00	0,00	4	1673	60,471	37,58
40	Bukit Indah	R8 LN4 R1	sandstone	moderate	Vb	2166	0,007	0,000	NA	NA	NA	0,00	0,00	4	1366	95,226	88,97
41	Bukit Indah	R8 LN4 R2S	sandstone	fine	Vb	2030	0,014	0,000	NA	NA	NA	0,00	0,00	4	1355	99,300	96,25
42	Bukit Indah	R8 LN8 UR1	sandstone	fine	Vb	2081	0,015	0,000	NA	NA	NA	0,00	0,00	4	1247	118,969	89,66

43	Mersing	RL 3 C L1	sandstone	fine	II	2533	3,669	4,210	52,35	4,08	48	98,79	94,32	21	2857	1507,70	1865,463
44	Mersing	RL 1 L6	sandstone	very fine	III	2409	1,028	2,750	21,36	2,03	30	96,01	78,98	17	2520	549,71	446,130
45	Mersing	RL1 L5	sandstone	very fine	III	2436	2,623	2,521	38,52	3,31	34	92,04	89,55	16	2643	555,19	476,671
46	Mersing	RL 3 C L2	sandstone	fine	III	2379	1,977	3,004	31,65	2,90	28	93,09	82,16	16	2610	577,59	745,145
47	Mersing	RL 3 E L1	sandstone	very fine	III	2379	2,839	2,610	26,08	3,80	44	95,23	90,24	16	2694	687,01	655,084
48	Mersing	RL 3 Slope Area 2 L3	sandstone	fine	III	2149	2,009	3,290	20,98	2,19	37	91,63	89,47	16	2615	621,52	1376,690
49	Mersing	RL 3 Slope Area 1 L5(a)	sandstone	very fine	IVa	2243	0,491	1,320	11,18	1,44	29	61,02	49,03	11	1990	280,33	331,508
50	Mersing	RL 3 A L1	sandstone	moderate	IVb	2184	0,141	1,112	NA	NA	NA	18,29	0,00	8	1445	246,15	237,707
51	Mersing	RL 1 (b) L3	sandstone	moderate	Va	2053	0,033	0,000	NA	NA	NA	0,00	0,00	5	1395	121,64	140,117
52	Mersing	RL 3 Slope Area 1 L1	sandstone	moderate	Va	2150	0,044	0,000	NA	NA	NA	0,00	0,00	5	1366	137,30	168,553
53	Mersing	RL 3 Slope Area 1 L5 (Zone C)	sandstone	moderate	Vb	2204	0,088	0,000	NA	NA	NA	0,00	0,00	4	1345	36,16	37,576
54	Mersing	RL 3 Slope Area 1 L2	sandstone	fine	Vb	2108	0,005	0,000	NA	NA	NA	0,00	0,00	4	1225	22,98	29,181
55	Mersing	RL 3 Slope Area 2 L1	sandstone	fine	Vb	2169	0,007	0,000	NA	NA	NA	0,00	0,00	4	1295	16,87	31,606
56	Mersing	RL 3 A L2	sandstone	fine	Vb	2176	0,005	0,000	NA	NA	NA	0,00	0,00	4	1275	74,54	103,503
57	Mersing	RL 3 A L4	sandstone	fine	Vb	2120	0,006	0,000	NA	NA	NA	0,00	0,00	4	1298	33,93	38,540
58	Desa Tebrau	DT FINE 1	sandstone	fine	IVa	2199	0,242	1,850	14,55	2,70	20	74,36	43,54	15	1909	451,11	566,163
59	Desa Tebrau	DT FINE 2	sandstone	fine	IVa	2168	0,192	1,320	10,03	1,93	20	75,65	39,94	13	1988	445,00	479,201
60	Desa Tebrau	DT FINE 3	sandstone	fine	IVa	2123	0,206	1,150	12,43	1,74	21	74,33	40,34	13	1967	405,35	360,832
61	Desa Tebrau	DT FINE 4	sandstone	fine	IVa	2177	0,203	1,654	10,80	1,97	20	73,57	40,21	13	1901	395,10	302,063
62	Desa Tebrau	DT FINE 5	sandstone	fine	IVa	2218	0,244	1,400	14,17	2,35	22	74,29	42,43	13	1912	400,89	514,435
63	Desa Tebrau	DT COARSE 1	sandstone	coarse	IVa	2159	0,151	0,850	9,23	1,43	19	71,56	39,25	10	1947	301,78	282,890
64	Desa Tebrau	DT COARSE 2	sandstone	coarse	IVa	2150	0,149	0,892	9,12	1,35	19	72,44	32,47	10	2030	432,59	251,061
65	Desa Tebrau	DT COARSE 3	sandstone	coarse	IVa	2209	0,138	0,655	8,49	1,93	19	71,35	38,45	10	1928	298,47	265,332
66	Desa Tebrau	DT COARSE 4	sandstone	coarse	IVa	2209	0,165	0,741	10,70	1,04	20	72,94	38,36	10	1871	291,34	293,942
67	Desa Tebrau	DT COARSE 5	sandstone	coarse	IVa	2248	0,132	0,933	8,37	0,66	18	72,38	38,21	10	1928	312,60	262,554
68	Kempas	Line 1	sandstone	coarse	Va	1636	0,043	0,095	NA	NA	NA	0,00	0,00	5	1194	153,533	130,352
69	Kempas	Line 1a	sandstone	coarse	Va	1648	0,041	0,028	NA	NA	NA	0,00	0,00	5	1175	100,382	80,809
70	Kempas	Line 2a	sandstone	coarse	Va	1659	0,045	0,061	NA	NA	NA	0,00	0,00	5	1190	68,937	54,961
71	Kempas	Line 3	sandstone	coarse	Va	1665	0,025	0,060	NA	NA	NA	0,00	0,00	5	1172	82,304	52,961
72	Kempas	Line 4	sandstone	coarse	Va	1607	0,043	0,060	NA	NA	NA	0,00	0,00	5	1161	82,260	71,932
73	Kempas	Line 5	sandstone	coarse	Va	1695	0,057	0,079	NA	NA	NA	0,00	0,00	5	1196	95,175	73,226
74	Kempas	Line 6	sandstone	coarse	Va	1681	0,066	0,055	NA	NA	NA	0,00	0,00	5	1172	85,016	67,771
75	Kempas	Line 7	sandstone	coarse	Va	1592	0,035	0,085	NA	NA	NA	0,00	0,00	5	1143	70,764	54,123
76	Kempas	Line 8	sandstone	coarse	Va	1731	0,025	0,067	NA	NA	NA	0,00	0,00	5	1142	95,175	76,032
77	Kempas	Line 9	sandstone	coarse	Va	1709	0,032	0,075	NA	NA	NA	0,00	0,00	5	1179	76,187	65,277
78	Kempas	Line 10	sandstone	coarse	Va	1706	0,026	0,056	NA	NA	NA	0,00	0,00	5	1157	69,574	56,890
79	Kempas	Line 11	sandstone	coarse	Va	1685	0,038	0,059	NA	NA	NA	0,00	0,00	5	1133	78,020	73,032
80	Bukit Indah	R4 L9	shale	.	II	2851	3,932	2,650	55,91	3,80	35	96,31	91,57	20	2857	637,046	461,68
81	Bukit Indah	C	shale	.	II	2785	3,699	3,010	47,32	3,75	31	95,85	90,46	20	2857	555,188	461,94
82	Bukit Indah	R8 LN1 R6	shale	.	III	2486	1,015	2,520	16,37	1,69	34	97,87	80,27	18	2634	315,850	404,43
83	Bukit Indah	LN4 R2	shale	.	III	2694	2,328	1,990	34,53	3,47	35	95,66	88,98	16	2620	336,283	393,78
84	Bukit Indah	LN6 R4S	shale	.	III	2510	1,979	1,810	25,62	2,10	30	92,69	84,29	17	2994	395,990	383,17
85	Bukit Indah	LN7 R2	shale	.	III	2415	2,747	2,200	41,35	3,57	39	97,65	91,27	18	2417	305,156	386,88
86	Bukit Indah	LN6 R1	shale	.	IVa	1987	0,302	1,200	9,49	0,83	20	68,57	39,51	7	1247	199,618	274,21
87	Bukit Indah	R4 L6	shale	.	IVa	2378	0,632	1,110	9,86	1,55	26	89,59	85,46	9	2417	261,999	206,61

88	Bukit Indah	R8 LN1 R5	shale	.	IVa	2243	0,396	1,600	10,25	0,85	25	86,23	75,61	9	2196	199,760	212,42
89	Bukit Indah	LN7 R1	shale	.	IVa	2314	0,693	1,260	12,23	1,69	35	86,60	79,15	7	2634	286,442	264,66
90	Bukit Indah	B2 SH1	shale	.	IVa	2150	0,334	0,980	5,49	0,85	30	82,81	60,21	8	1897	219,987	257,80
91	Bukit Indah	R8 LN1 R2	shale	.	IVa	1987	0,450	1,350	6,75	1,27	23	97,68	48,62	9	2576	275,430	208,99
92	Bukit Indah	R8 LN4 R3	shale	.	IVa	2385	0,632	1,200	8,83	1,61	25	92,85	86,21	11	2417	199,787	302,06
93	Bukit Indah	R8 LN7 R4	shale	.	IVa	2372	0,531	1,330	9,09	1,53	27	91,35	83,44	7	2417	230,681	213,97
94	Bukit Indah	LN8 R2	shale	.	IVa	2215	0,472	1,500	9,89	1,31	29	95,30	90,99	13	2030	316,041	237,56
95	Bukit Indah	R3 L6 R2	shale	.	IVb	1855	0,108	0,570	NA	NA	NA	21,33	0,00	8	1897	145,067	176,40
96	Bukit Indah	R8 LN1 R4	shale	.	IVb	2457	0,100	0,143	NA	NA	NA	38,65	0,00	6	1645	114,067	156,30
97	Bukit Indah	R8 LN3 R3	shale	.	IVb	2166	0,247	0,309	NA	NA	NA	32,34	0,00	8	1828	117,568	142,29
98	Bukit Indah	R8 LN11 R5	shale	.	IVb	2285	0,199	0,427	NA	NA	NA	35,21	0,00	9	1476	149,841	110,58
99	Bukit Indah	R8 LN12 R2	shale	.	IVb	2302	0,145	0,233	NA	NA	NA	36,34	0,00	6	1366	116,805	100,59
100	Bukit Indah	B8 L5	shale	.	IVb	1903	0,165	0,625	NA	NA	NA	30,14	0,00	8	1645	145,321	154,22
101	Bukit Indah	R4 L2	shale	.	IVb	2087	0,128	0,183	NA	NA	NA	31,48	0,00	9	1476	159,962	102,24
102	Bukit Indah	R8 LN2 R2	shale	.	IVb	2132	0,108	0,687	NA	NA	NA	32,83	0,00	6	1828	109,484	181,11
103	Bukit Indah	R8 LN14 R1	shale	.	IVb	1947	0,149	0,405	NA	NA	NA	30,71	0,00	6	1476	127,180	136,48
104	Bukit Indah	LN3 R5	shale	.	IVb	2367	0,200	1,090	NA	NA	NA	36,24	0,00	6	1828	157,479	176,52
105	Bukit Indah	R8 LN10 R4S	shale	.	IVb	1873	0,162	0,780	NA	NA	NA	29,62	0,00	6	1628	199,618	102,82
106	Bukit Indah	B8 L4	shale	.	IVb	2284	0,100	0,352	NA	NA	NA	36,31	0,00	6	1897	100,637	191,34
107	Bukit Indah	R8 LN5 R3	shale	.	IVb	2168	0,199	0,291	NA	NA	NA	33,48	0,00	6	1795	129,281	161,13
108	Bukit Indah	R2 L2	shale	.	Va	2155	0,090	0,000	NA	NA	NA	0,00	0,00	5	1198	39,465	85,52
109	Bukit Indah	R8 LN10 R2	shale	.	Va	1961	0,093	0,000	NA	NA	NA	0,00	0,00	5	1795	87,715	75,57
110	Bukit Indah	LN5 R2	shale	.	Va	2150	0,035	0,000	NA	NA	NA	0,00	0,00	5	1366	71,674	60,86
111	Bukit Indah	R8 LN11 R1	shale	.	Va	2174	0,073	0,000	NA	NA	NA	0,00	0,00	5	1673	86,442	89,25
112	Bukit Indah	R8 LN 11 R3	shale	.	Va	2104	0,078	0,000	NA	NA	NA	0,00	0,00	5	1476	71,678	68,09
113	Bukit Indah	B7 L1	shale	.	Va	1612	0,075	0,000	NA	NA	NA	0,00	0,00	5	1198	87,715	76,06
114	Bukit Indah	B7 L5	shale	.	Va	1917	0,077	0,000	NA	NA	NA	0,00	0,00	5	1174	94,017	67,89
115	Bukit Indah	R8 LN3 R2	shale	.	Va	1628	0,009	0,000	NA	NA	NA	0,00	0,00	5	1174	85,041	67,66
116	Bukit Indah	R2 L1	shale	.	Vb	1927	0,024	0,000	NA	NA	NA	0,00	0,00	4	1247	60,471	40,76
117	Bukit Indah	LN6 R5	shale	.	Vb	2219	0,024	0,000	NA	NA	NA	0,00	0,00	4	1198	39,465	38,10
118	Bukit Indah	LN8 R1S	shale	.	Vb	2241	0,029	0,000	NA	NA	NA	0,00	0,00	4	1198	40,866	51,45
119	Bukit Indah	B8 L1	shale	.	Vb	2461	0,025	0,000	NA	NA	NA	0,00	0,00	4	1247	7,320	55,50
120	Mersing	RL 1 L3	shale	.	II	2525	3,445	3,520	52,36	3,76	31	94,58	91,57	20	2857	1248,06	476,338
121	Mersing	RL 1 (b) L1	shale	.	III	2434	1,497	2,330	28,62	1,97	19	87,44	82,47	17	2417	277,72	356,552
122	Mersing	RL 1 (a) L3	shale	.	III	2268	2,682	2,940	36,53	3,48	25	90,07	87,14	16	2576	344,43	359,129
123	Mersing	RL 1 L1	shale	.	IVa	2372	0,966	2,460	19,74	1,68	17	46,76	30,82	11	1820	257,48	260,760
124	Mersing	RL1 L4	shale	.	IVa	2433	0,402	2,190	8,35	1,66	25	75,22	62,02	10	1820	249,78	332,302
125	Mersing	RL1 L7	shale	.	IVa	2492	0,543	1,930	14,36	1,63	20	68,15	59,13	10	1852	181,80	244,446
126	Mersing	along foliation	shale	.	Va	2206	0,033	0,000	NA	NA	NA	0,00	0,00	6	1366	102,48	77,117
127	Mersing	RL 1 L2	shale	.	Va	1985	0,033	0,000	NA	NA	NA	0,00	0,00	6	1366	41,44	24,03

APPENDIX I
EFFECT OF MOISTURE CONTENT TO PENETRATION LOAD

Bukit Indah and Mersing sandstone

Grade	Sample	0 minute Initial Moisture (%)	Penetration load (MPa)	Moisture content after 15 minute soaked (%)	Penetration load (MPa)	Increase of Moisture Content(%)	Reduced Penetration (%)
II	R8 LN3 R4S	0.98	1,243.54	1.12	1168.47	0.14	6.04
	R8-LN6 R2S	0.98	280.33	1.47	258.32	0.49	7.85
	B8 L3	0.23	977.91	0.89	890.64	0.66	8.92
	RL3 CL1	0.42	1,507.702	1.10	1365.00	0.68	9.46
	R8 LN2 UR1	5.52	387.01	6.33	350.12	0.81	9.53
	LN2 UR1	5.52	714.64	6.50	623.80	0.98	12.71
III	R6 L1	1.78	621.51	2.92	523.87	1.14	15.71
	R8 LN7 UR1	0.20	237.68	1.65	200.00	1.45	15.85
	B8 L9	2.31	140.10	5.24	113.00	2.93	19.34
	B6 L1	0.42	451.11	3.56	360.12	3.14	20.17
	RL 3 C L2	0.21	577.59	3.15	464.66	2.94	19.55
	RL1 L5	1.01	555.19	3.79	450.31	2.78	18.89
	R8 LN2 R3S	3.13	305.73	5.22	255.40	2.09	16.46
	R3 L1 R4S	2.70	273.90	5.88	218.00	3.18	20.41
	RL1(b) L2	2.95	339.40	5.80	273.97	2.85	19.28
	RL 3 E L1	0.21	687.02	1.92	578.00	1.71	15.87
IV a	MG RL3 A L3	0.11	958.05	3.33	750.30	3.22	21.68
	B2 L3	0.85	305.73	4.30	230.00	3.45	24.77
	B1 L3	1.45	121.64	5.00	90.78	3.55	25.37
	LN3 UR1	2.18	312.22	5.86	230.07	3.68	26.31
	LN8 UR1	3.78	291.34	7.69	200.41	3.91	31.21
	LN4 R3S	7.91	387.01	12.12	254.31	4.21	34.29
	LN4-R4	0.98	201.53	5.46	130.24	4.48	35.37
	LN8 R3	0.84	262.38	5.63	158.68	4.79	39.52
	B1 L1	0.22	351.43	4.00	246.88	3.78	29.75
	B1 L2	5.34	132.46	10.30	78.36	4.96	40.84
	R7L1	1.01	291.34	8.9	150.03	7.89	48.50
	RL3 SlopeArea1 L5 (Zone B)	0.17	451.94	5.60	255.33	5.43	43.50
	RL3 2nd Slope L2	0.35	549.71	7.1	289.00	6.75	47.43
	R8 LN2 R1	0.83	142.90	6.43	80.00	5.60	44.02
	LN3 R3S	7.13	193.25	12.95	107.30	5.82	44.48
	RL3 SlopeArea1	0.12	408.98	7.68	210.75	7.56	48.47

	L5(a)						
IV b	R8 LN6 R3	4.32	324.19	12.33	158.42	8.01	51.13
	RL3 A L1	4.1	16.87	12.58	7.99	8.48	52.63
	R8 LN6 R1	4.7	132.46	13.20	60.35	8.50	54.44
	R8 LN8 R2	3.55	166.45	12.67	74.13	9.12	55.46
	R4 L8	6	187.71	15.32	75.35	9.32	59.86
	LN2 R1S	4.53	260.47	14.00	100.99	9.47	61.23
	B3 L1	4.44	99.30	14.78	37.65	10.34	62.08
	B4 LA	1.64	95.23	12.57	30.39	10.93	68.09
	B7 L2	1.25	37.30	13.21	11.17	11.96	70.05
V a	B2 SH4	3.19	204.20	15.22	60.78	12.03	70.24
	R4 L7	5.16	60.47	17.64	17.31	12.48	71.37
	RL3 SlopeArea1 L1	2.23	22.98	14.97	6.37	12.74	72.28
	RL1 (b) L3	2.81	246.15	15.86	66.43	13.05	73.01
	R8 LN7 UR2	4.52	386.00	18.67	100.36	14.15	74.00
	R8 LN3 R1	3.77	507.51	18.00	99.15	14.23	80.46
	R4 L4	19.99	172.37	35.34	30.25	15.35	82.45
	R7 L2	12	118.97	27.64	20.00	15.64	83.19
	R4 L3	11.59	375.75	27.96	60.35	16.37	83.94
	B2 SH4	0.88	204.20	17.69	32.45	16.81	84.11
V b	R8 LN4 R1	4.81	311.65	22.35	47.97	17.54	84.61
	R8 LN1 R1	3.51	36.16	21.35	4.73	17.84	86.92
	B6 L2	3.19	49.46	21.46	5.19	18.27	89.51
	R4 L5	12.24	57.92	31.50	4.78	19.26	91.75
	RL3 Slope Area1 L5 (Zone C)	0.27	36.16	19.70	2.90	19.43	91.97
	R8 LN4 R2S	4.61	326.23	26.19	26.10	21.58	92.00
	R8 LN8 UR1	6.01	326.73	29.87	20.56	23.86	93.71
	B7 L3	10.8	171.16	36.74	9.75	25.94	94.30
	LN7 R3	7.65	326.23	34.20	15.36	26.55	95.29
	R5	9.98	232.27	37.22	10.00	27.24	95.69
	RL3 SlopeArea1 L2	2.7	305.54	31.76	8.83	29.06	97.11
	RL3 SlopeArea2 L1	2.9	137.30	33.26	2.96	30.36	97.84
	RL3 A L2	2.41	958.05	35.55	8.43	33.14	99.12
	RL3 A L4	2.8	60.84	37.15	0.01	34.35	99.99

Bukit Indah and Mersing Shale

Grade	Sample	0 minute Initial Moisture (%)	Penetration load (MPa)	15 minute soaked (%)	Penetration Load (MPa)	Reduced Moisture (%)	Reduced Penetration (%)
II	C	4.00	230.68	5.68	200.00	1.68	13.30
	R4 L9	4.50	395.99	6.35	340.26	1.85	14.07
	RL1 L3	0.22	400.64	2.40	311.21	2.18	22.32
III	R8 LN1 R6	8.56	262.00	10.55	199.00	1.99	24.05
	LN7 R2	10.28	40.87	12.35	29.96	2.07	26.69
	LN4 R2	4.26	219.99	6.51	158.76	2.25	27.83
	LN6 R4S	0.95	352.00	2.30	268.35	1.35	23.76
	RL1(a) L3	0.52	344.43	4.23	245.00	3.71	28.87
	RL1 b L1	0.41	181.80	3.12	130.96	2.71	27.96
IV a	R8 LN1 R2	5.12	275.43	9.00	170.34	3.88	38.16
	R8 LN1 R5	2.98	100.64	6.98	60.32	4.00	40.06
	R8 LN4 R3	9.26	145.07	13.45	86.59	4.19	40.31
	B2 SH1	1.28	129.28	3.25	120.31	1.97	6.94
	LN7 R1	6.66	286.44	11.56	155.00	4.90	45.89
	LN6 R1	8.50	199.62	13.76	101.78	5.26	49.01
	LN7 R4	5.45	114.07	10.00	68.32	4.55	40.11
	R4 L6	11.62	157.48	16.20	93.44	4.58	40.67
	LN8 R2	0.90	316.04	7.37	219.99	6.47	30.39
	R8 LN11 R5	1.25	71.67	5.65	42.01	4.40	41.38
	RL1 L2	0.39	7.32	3.66	4.58	3.27	37.43
	RL1 L7	3.25	277.72	9.65	137.40	6.40	50.53
	RL1 L1	0.41	257.48	6.83	127.31	6.42	50.56
IV b	R8 LN1 R4	20.69	87.71	27.30	40.67	6.61	53.63
	R8 LN5 R3	13.09	71.67	19.66	42.01	6.57	41.38
	R8 LN10 R4S	3.97	276.00	10.25	146.72	6.28	46.84
	R8 LN3 R3	2.90	117.57	9.86	50.68	6.96	56.90
	R8 LN2 R2	5.21	219.99	11.66	107.13	6.45	51.30
	R8 LN14 R1	6.21	127.18	13.00	60.12	6.79	52.73
	B8 L4	9.32	87.71	16.00	40.33	6.68	54.02
	B8 L5	3.22	94.02	10.34	43.97	7.12	53.23
	LN3 R5	8.74	262.00	16.00	168.24	7.26	35.79
	R3 L6 R2	13.15	86.44	20.00	44.75	6.85	48.23
	R4 L2	15.57	159.96	22.66	70.68	7.09	55.81
V a	R8 LN11 R1	7.59	145.32	14.80	67.12	7.21	53.81
	R8 LN11 R3	9.19	149.84	16.87	68.53	7.68	54.26
	R8 LN10 R2	9.00	109.48	17.05	47.23	8.05	56.86

	R8 LN3 R2	4.25	85.04	11.56	39.10	7.31	54.02
	B7 L5	13.02	305.16	21.30	129.22	8.28	57.66
	B7 L1	4.32	315.85	12.68	130.78	8.36	58.59
	LN5 R2	3.45	336.28	12.10	129.54	8.65	61.48
	R2 L2	5.98	39.47	14.83	14.13	8.85	64.21
	Along Foliation	2.00	102.48	11.00	30.82	9.00	69.92
V b	R8 LN12 R2	9.92	116.80	19.03	24.96	9.11	78.63
	B8 L1	2.91	41.44	12.10	8.32	9.19	79.92
	LN8 R1S	5.15	199.62	14.55	38.03	9.40	80.95
	LN6 R5	6.21	305.16	15.93	50.70	9.72	83.39
	B1 R2 L1	7.46	60.47	18.06	3.25	10.60	94.63

Desa Tebrau

Grade	Sample	0 minute Initial Moisture (%)	Penetration	15 minute soaked (%)	Penetration	Reduced Moisture (%)	Reduced Penetration (%)
IV a	DT FINE 1	1.66	451.11	8.48	243.98	6.82	45.916
	DT FINE 2	2.61	445	8.88	276.96	6.27	37.762
	DT FINE 3	1.55	405.35	8.83	238.19	7.28	41.238
	DT FINE 4	1.55	395.1	8.83	254.3	7.28	35.637
	DT FINE 5	0.74	400.89	7.38	209.61	6.64	47.714
	DT COARSE 1	1.71	301.78	13.16	140.61	11.45	53.406
	DT COARSE 2	1.18	432.59	11.61	133.67	10.43	69.100
	DT COARSE 3	0.73	298.47	11.78	120	11.05	59.795
	DT COARSE 4	0.73	291.34	11.78	157.48	11.05	45.946
	DT COARSE 5	0.32	312.6	9.13	162.19	8.81	48.116

Kempas

Grade	Sample	0 minute Initial Moisture (%)	Penetration (MPa)	15 minute soaked (%)	Penetration (MPa)	Reduced Moisture (%)	Reduced Penetration (%)
Va	Line 1	1.38	153.53	6.23	27.99	4.85	81.77
	Line 1a	2.21	100.38	7.21	6.46	5.00	93.56
	Line 2a	2.25	68.94	8.20	5.27	5.95	92.35
	Line 3	1.63	82.30	4.21	14.96	2.58	81.82
	Line 4	1.87	82.26	5.23	18.70	3.36	77.27
	Line 5	1.12	95.18	5.21	26.35	4.09	72.31
	Line 6	1.86	85.02	5.54	24.19	3.68	71.55
	Line 7	1.20	70.76	6.10	9.64	4.90	86.38
	Line 8	1.40	95.18	5.30	10.36	3.90	89.11
	Line 9	1.25	76.19	5.10	7.96	3.85	89.55
	Line 10	1.20	69.57	7.10	5.89	5.90	91.54
	Line 11	1.35	78.02	6.50	14.41	5.15	81.53

Monitored Ripping Bukit Indah (Shale)

Panel Name	Weathering grade	Location	Rock Type	Dozer Type	Ripping Time (s)	Ripping Depth (m)	Ripping Penetration %	Ripping Width (m)	Ripping Length (m)	Cross Section Area (m2)	Production per run (m3)
R4 L9	II	Bukit Indah	Shale	CAT D9	8	0,4	33	0,4	3,15	0,08	0,252
C	II		Shale	CAT D9	12	0,5	42	0,5	7,12	0,125	0,89
R8 LN1 R6	III		Shale	CAT D9	10	0,8	67	1	4,58	0,4	1,832
LN4 R2	III		Shale	CAT D9	30	0,8	67	1	9,81	0,4	3,924
LN6 R4S	III		Shale	CAT D9	30	0,7	58	1	8,37	0,35	2,9295
LN7 R2	III		Shale	CAT D9	18	0,8	67	1,1	6,55	0,44	2,882
LN6 R1	IV a		Shale	CAT D9	12	1	83	1,5	5	0,75	3,75
R4 L6	IV a		Shale	CAT D9	15	1	83	1,5	5,22	0,75	3,915
R8 LN1 R5	IV a		Shale	CAT D9	30	1	83	1,4	10,9	0,7	7,63
LN7 R1	IV a		Shale	CAT D9	6	1	83	1,5	2,4	0,75	1,8
B2 SH1	IV a		Shale	CAT D9	8	0,9	75	1,2	4,3	0,54	2,322
R8 LN1 R2	IV a		Shale	CAT D9	9	0,9	75	1,2	5,01	0,54	2,7054
R8 LN4 R3	IV a		Shale	CAT D9	11	1	83	1,4	4,52	0,7	3,164
R8 LN7 R4	IV a		Shale	CAT D9	10	0,9	75	1,2	5,19	0,54	2,8026
LN8 R2	IV a		Shale	CAT D9	18	1	83	1,5	6,79	0,75	5,0925
R3 L6 R2	IV b		Shale	CAT D9	70	1	83	1,5	15,68	0,75	11,76
R8 LN1 R4	IV b		Shale	CAT D9	6	1,1	92	1,5	2,41	0,825	1,98825
R8 LN3 R3	IV b		Shale	CAT D9	100	0,8	67	1	18,71	0,4	7,484
R8 LN11 R5	IV b		Shale	CAT D9	190	0,8	67	1	24,45	0,4	9,78
R8 LN12 R2	IV b		Shale	CAT D9	25	1,1	92	1,5	7,17	0,825	5,91525
B8 L5	IV b		Shale	CAT D9	8	1	83	1,4	3,9	0,7	2,73
R4 L2	IV b		Shale	CAT D9	8	1	83	1,4	4	0,7	2,8
R8 LN2 R2	IV b		Shale	CAT D9	12	1,1	92	1,5	4,58	0,825	3,7785
R8 LN14 R1	IV b		Shale	CAT D9	8	1,1	92	1,5	3,15	0,825	2,59875
LN3 R5	IV b		Shale	CAT D9	16	1,1	92	1,5	6,36	0,825	5,247
R8 LN10 R4S	IV b		Shale	CAT D9	50	1	83	1,4	25,4	0,7	17,78
B8 L4	IV b		Shale	CAT D9	25	1,2	100	1,6	7,35	0,96	7,056
R8 LN5 R3	IV b		Shale	CAT D9	20	1,1	92	1,5	7,65	0,825	6,31125
R2 L2	V a		Shale	CAT D9	18	1,2	100	1,6	7,8	0,96	7,488
R8 LN10 R2	V a		Shale	CAT D9	20	1,1	92	1,4	10,44	0,77	8,0388
LN5 R2	V a		Shale	CAT D9	10	1,2	100	1,6	4,18	0,96	4,0128
R8 LN11 R1	V a		Shale	CAT D9	13	1,2	100	1,6	5,21	0,96	5,0016
R8 LN 11 R3	V a		Shale	CAT D9	10	1,2	100	1,6	4,25	0,96	4,08
B7 L1	V a		Shale	CAT D9	15	1,2	100	1,6	6,56	0,96	6,2976
B7 L5	V a		Shale	CAT D9	11	1,2	100	1,6	4,84	0,96	4,6464
R8 LN3 R2	V a		Shale	CAT D9	18	1,2	100	1,6	7,75	0,96	7,44
R2 L1	V b		Shale	CAT D9	8	1,2	100	1,6	3,87	0,96	3,7152
LN6 R5	V b		Shale	CAT D9	14	1,2	100	1,6	6,77	0,96	6,4992
LN8 R1S	V b		Shale	CAT D9	10	1,2	100	1,6	4,95	0,96	4,752
B8 L1	V b		Shale	CAT D9	12	1,2	100	1,6	5,94	0,96	5,7024

Prod m3/hr
85
200
495
353
264
432
844
705
687
810
784
812
777
757
764
454
895
202
139
639
921
945
850
877
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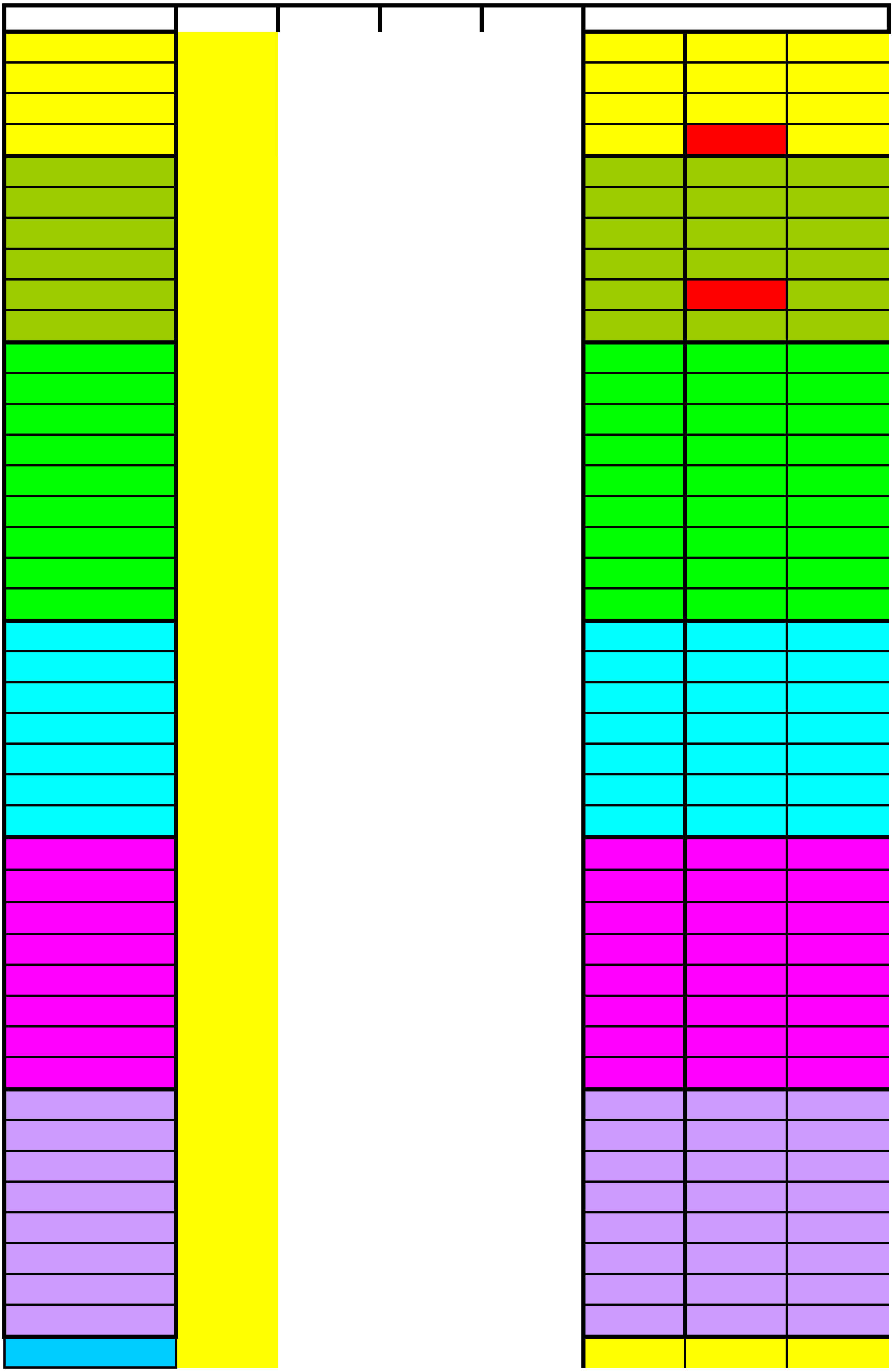

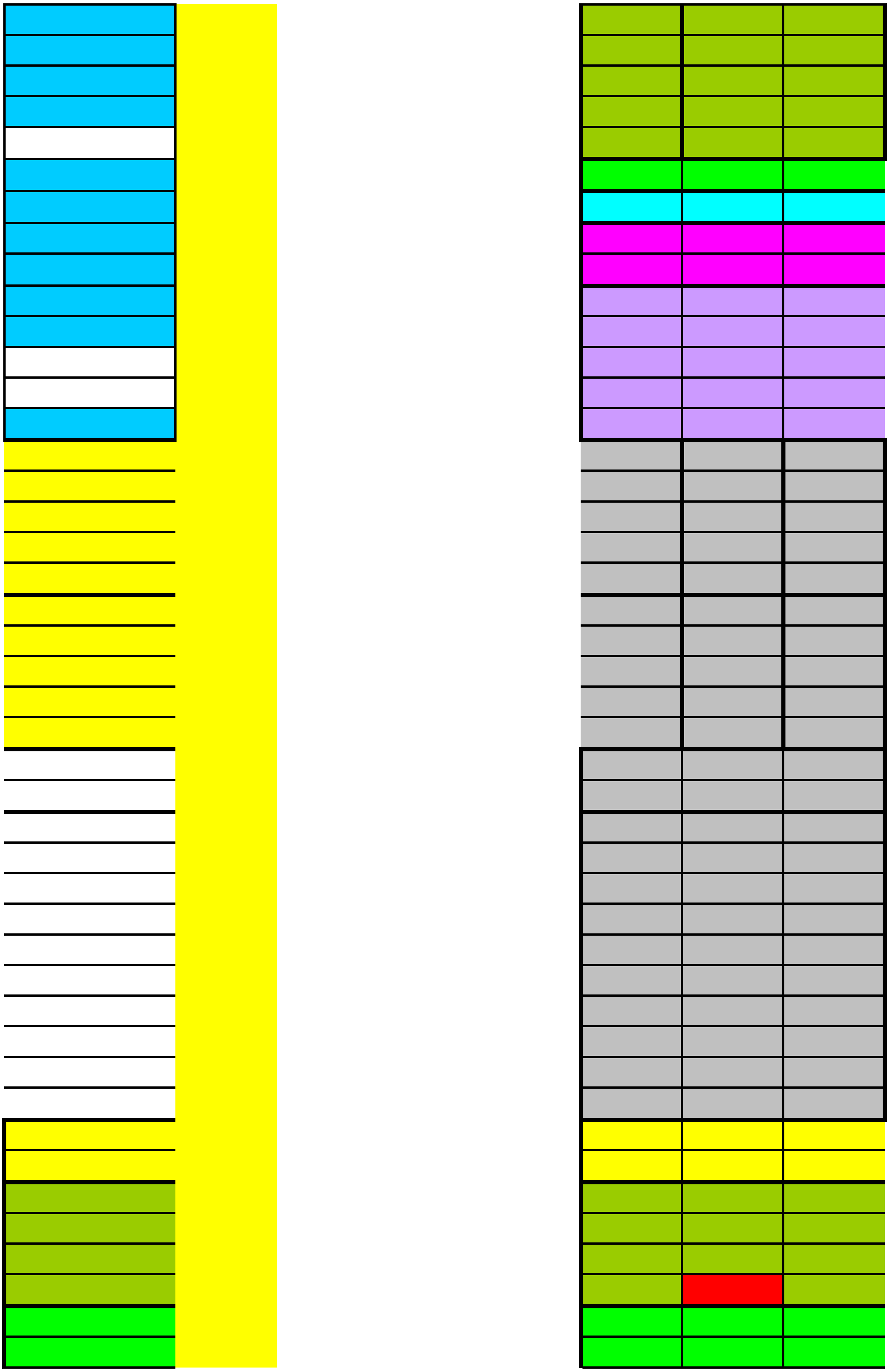

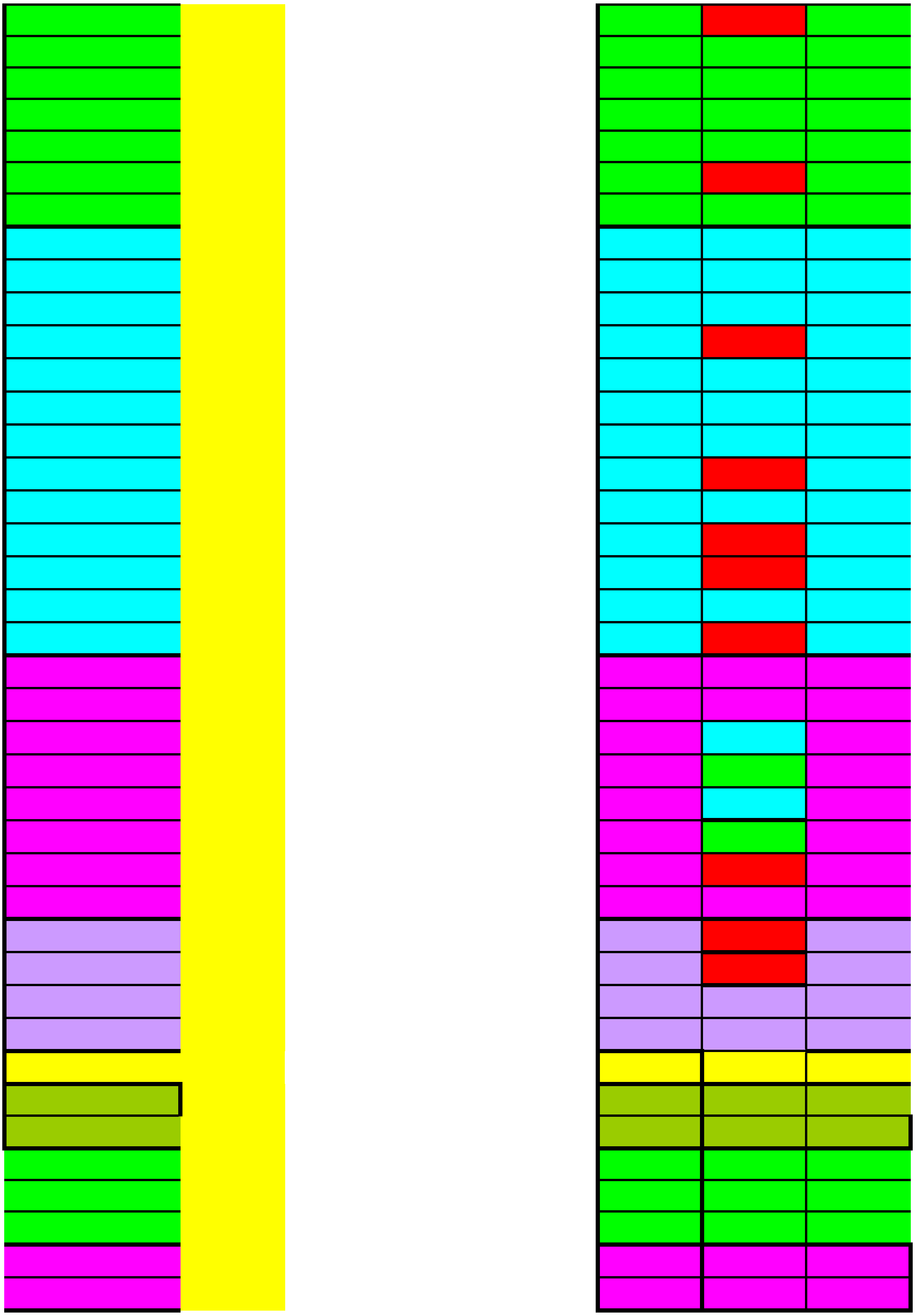

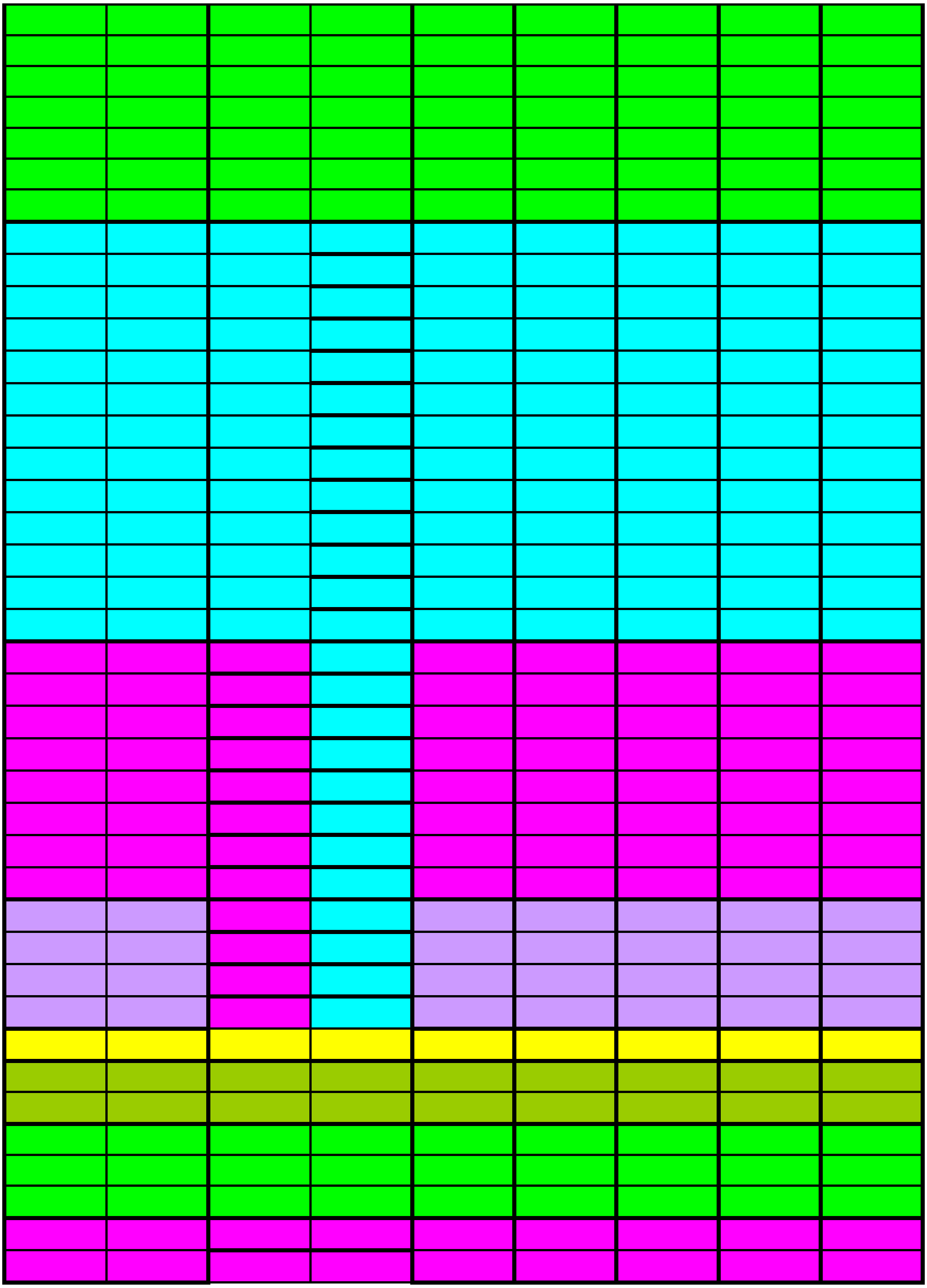

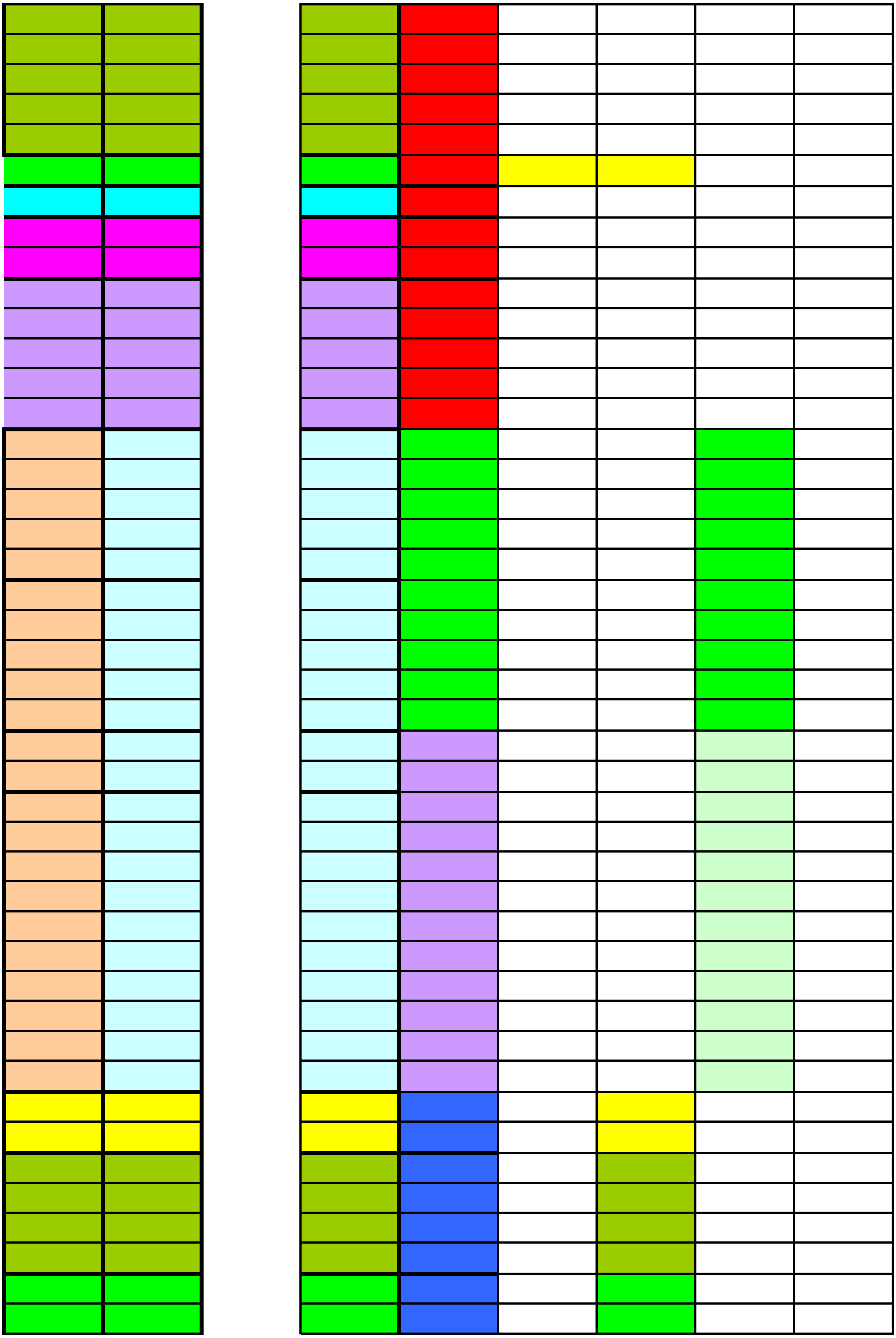

APPENDIX 7.2
SUMMARY OF RIPPING DIRECTION IN RELATION TO THE DISCONTINUITIES MEASUREMENTS

Sample	Material	Location	Weathering Grade	Discontinuity set	Notes	Ripping Direction
R8 LN6 R2S	sandstone	Bukit Indah	II	J2, J5	Both major joints 80/100, 70/300, tight with some clay	Very favourable
R8 LN3 R4S	sandstone	Bukit Indah	II	J2, J4	J2 50/85 is major joint set while J4 70/150 is minor, rough, tight	Unfavourable
B8 L3	sandstone	Bukit Indah	II	J1,J2	Both major joint sets, rough, undulating with same clay	Favourable
R8 LN2 UR1	sandstone	Bukit Indah	II	J1, J3	J3 80/200 is major set, surface is rough and undulating	Unfavourable
R3 L1 R4S	sandstone	Bukit Indah	III	J2	Major joints 70/90, tight aperture, undulating surfaces	Very favourable
B8 L9	sandstone	Bukit Indah	III	J3, J5	Major joints 60/220, 80/340, rough undulating	Very favourable
R8 LN2 R3S	sandstone	Bukit Indah	III	J2, J5, J3	J5 is major joint set, rough undulating	Favourable
R8 LN7 UR1	sandstone	Bukit Indah	III	J2	Major joints, rough undulating , tight with discolouration	Fair
R6 L1	sandstone	Bukit Indah	III	J3, J4, J5	J3 50/210 is major joint set, rough, undulating, tight	Fair
LN8 UR2	sandstone	Bukit Indah	III	J2, J4, J5	J2 30/110, J5 50/310 are major are major joint sets, rough undulating	Unfavourable
B2 L3	sandstone	Bukit Indah	IVa	J3	Major joints 50/210, smooth undulating	Favourable
R8 LN2 R1	sandstone	Bukit Indah	IVa	J2, J3	Major joint J2, rough, undulating	Very favourable
LN3 R3S	sandstone	Bukit Indah	IVa	J3	Major joints 220/40, slightly rough, undulating	Favourable
R7 L1	sandstone	Bukit Indah	IVa	J4, J5	Both sets are major joints with 30/160 and 60/310	Fair
LN8 R3	sandstone	Bukit Indah	IVa	J1, J2	J1 is major joints 80/280, tight and slightly rough	Very favourable
LN4 R4	sandstone	Bukit Indah	IVa	J4, J5	Major joint sets 40/180, 80/340, rough undulating	Fair
B1 L3	sandstone	Bukit Indah	IVa	J3	J3 60/210 is major joint set, rough, undulating	Unfavourable
B1 L2	sandstone	Bukit Indah	IVa	J2, J4	J2 is major joint set, rough, undulating with some clay	Very favourable
LN4 R3S	sandstone	Bukit Indah	IVa	J1, J2	Both are major joint sets, rough, undulating	Favourable
R8 LN6 R1	sandstone	Bukit Indah	IVb	J3, J5	J3 is major joints, slightly rough, undulating	Favourable
R8 LN8 R2	sandstone	Bukit Indah	IVb	J2, J3, J5	J5 is major joint set, rough undulating	Very favourable
R4 L8	sandstone	Bukit Indah	IVb	J3, J5	Major joints, rough undulating , tight with discolouration	Fair
LN2 R1S	sandstone	Bukit Indah	IVb	J2, J3	J2 60/90 is major joint, rough, undulating	Favourable
B4 LA	sandstone	Bukit Indah	IVb	J3	J3 50/200 is major joint set, rough, undulating	Favourable
R8 LN6 R3	sandstone	Bukit Indah	IVb	J1, J2	Both sets are major joints with 70/110 and 60/280	Very favourable
B7 L2	sandstone	Bukit Indah	IVb	J2, J5	J5 is major joint set, rough undulating	Very favourable
R7 L2	sandstone	Bukit Indah	Va	J4	Major joints 40/80, rough undulating	Favourable
R4 L7	sandstone	Bukit Indah	Va	J2, J3	J2 is major joints 60/70	Very favourable
B2 SH4	sandstone	Bukit Indah	Va	J2, J3	Both major joint sets 70/30, 80/200, smooth undulating	Fair
R4 L4	sandstone	Bukit Indah	Va	J2, J3	Major joint sets, tight, clay	Very favourable
R5	sandstone	Bukit Indah	Va	J2, J4	J2 is major joint set, tight with clay	Very favourable
R8 LN7 UR2	sandstone	Bukit Indah	Va	J4, J5	J4 80/140 is major joint set, rough, undulating	Very favourable
R8 LN3 R1	sandstone	Bukit Indah	Va	J1, J2	J1 is major joints 80/280, tight and slightly rough	Very favourable
R4 L3	sandstone	Bukit Indah	Va	J2, J5	J5 80/320 is major joint set, rough undulating	Very favourable
B6 L2	sandstone	Bukit Indah	Vb	J2	Major joints 80/100, tight	Favourable
R8 LN1 R1	sandstone	Bukit Indah	Vb	J2	Major joints 40/50, tight	Favourable
B7 L3	sandstone	Bukit Indah	Vb		Major joints 60/200, slight undulating with clay	Very favourable
R4 L5	sandstone	Bukit Indah	Vb	J1, J3	Both are major joint sets, rough, undulating	Very favourable
LN7 R3	sandstone	Bukit Indah	Vb	J4	J4 60/160 is major joint set, rough, undulating with some clay	Very favourable
R8 LN4 R1	sandstone	Bukit Indah	Vb	J3, J4	J3 and J4 are major joint sets, clay at surface	Very favourable
R8 LN4 R2S	sandstone	Bukit Indah	Vb	J3, J5	J3 70/210 is major joint set, J5 minor, rough, undulating	Favourable
R8 LN8 UR1	sandstone	Bukit Indah	Vb	J2, J3, J4	J2 50/80 is major joint set, rough, undulating	Very favourable
RL 3 C L1	sandstone	Mersing	II	J1, J4, J6	J4 is major joint set, J1,J6 are minor, rough, undulating	Fair
RL 1 L6	sandstone	Mersing	III	J4	J4 70/160 is major joint set, rough, undulating with some iron stain	Fair
RL1 L5	sandstone	Mersing	III	J4, J6	J4 is major joint set, rough, undulating	Favourable
RL 3 C L2	sandstone	Mersing	III	J4, J6	60/170 is major joint set, J6 minor	Unfavourable
RL 3 E L1	sandstone	Mersing	III	J4, J6	J6 80/340 is major joint set, rough, undulating	Unfavourable
RL 3 Slope Area 2 L3	sandstone	Mersing	III	J5, J6	Both major joint sets J5 70/210 J6 80/320, rough, undulating	Unfavourable
RL 3 Slope Area 1 L5(a)	sandstone	Mersing	IVa	J2, J3, J4	J3 60/100 is major joint set, rough, undulating	Favourable
RL 3 A L1	sandstone	Mersing	IVb	J2	J2 40/60 is major joint set, rough and undulating	Favourable
RL 1 (b) L3	sandstone	Mersing	Va	J1, J4, J5	J1 60/40 is major joint set, joints are rough and undulating	Very favourable
RL 3 Slope Area 1 L1	sandstone	Mersing	Va	J3, J4	J3 80/100 is major joint set, tight aperture	Favourable
RL 3 Slope Area 1 L5 (Zone C)	sandstone	Mersing	Vb	J1, J2, J4, J5	J2 is major joint set, rough, undulating with some clay	Very favourable
RL 3 Slope Area 1 L2	sandstone	Mersing	Vb	J4	J4 80/160 is major joint set, surface is undulating	Very favourable
RL 3 Slope Area 2 L1	sandstone	Mersing	Vb	J4	J4 70/150 is major joint set, rough, undulating	Very favourable
RL 3 A L2	sandstone	Mersing	Vb	J4	J4 major joint set, some clay observed on surface	Very favourable
RL 3 A L4	sandstone	Mersing	Vb	J3	J3 60/110 is major joint set, rough, undulating	Favourable
DT FINE 1	old alluvium	Desa Tebrau	IVa	J1, J2, J6	J1 50/160, J2 80/90, J6 50/270. J2 and J6 are major joint sets	Very unfavourable
DT FINE 2	old alluvium	Desa Tebrau	IVa	J2	J2 80/100, major joint set, rough, planar	Fair
DT FINE 3	old alluvium	Desa Tebrau	IVa	J2, J3, J5	J5 50/200 is major joint set, rough, planar	Fair
DT FINE 4	old alluvium	Desa Tebrau	IVa	J3	J3 80/170 major joint set, rough, planar	Unfavourable
DT FINE 5	old alluvium	Desa Tebrau	IVa	J3, J5	Both are major joint sets, tight, planar and rough	Unfavourable
DT COARSE 1	old alluvium	Desa Tebrau	IVa	J1, J3	Major joint sets, tight, rough, planar	Fair
DT COARSE 2	old alluvium	Desa Tebrau	IVa	J3	J3 80/170 major joint set, rough, planar	Fair
DT COARSE 3	old alluvium	Desa Tebrau	IVa	J3, J4	J3 80/170, J4 70/320 are major joint sets, rough, planar	Fair
DT COARSE 4	old alluvium	Desa Tebrau	IVa	J2, J6	J2 80/80, J6 50/260 are major joint sets, rough, planar	Favourable
DT COARSE 5	old alluvium	Desa Tebrau	IVa	J2, J5	Both are major joint sets, rough, planar	Unfavourable
Line 1	old alluvium	Kempas	Va	J1, J2	J1 50/300, J2 40/140 are major joint sets, rough, slightly undulating	Very favourable
Line 1a	old alluvium	Kempas	Va	J3	Major joint set, slightly undulating and rough	Very favourable
Line 2a	old alluvium	Kempas	Va	J1, J3	J1 50/300, J3 50/210 are major joint sets, rough, slightly undulating	Very favourable
Line 3	old alluvium	Kempas	Va	J1	J1 50/300 is major joint set, tight, rough but quite soft	Very favourable
Line 4	old alluvium	Kempas	Va	J1	J1 50/310 is major joint set, rough, slightlt undulating	Very favourable
Line 5	old alluvium	Kempas	Va	J1	J1 is major joints set, tight and slightly rough, undulating	Favourable

Line 6	old alluvium	Kempas	Va	J1	J1 50/310 is major joint set, rough, slightly undulating	Very favourable
Line 7	old alluvium	Kempas	Va	J1	J1 50/310 is major joint set, rough, slightly undulating	Very favourable
Line 8	old alluvium	Kempas	Va	J1	J1 is major joint set, tight, slight iron stain	Very favourable
Line 9	old alluvium	Kempas	Va	J1	Major joint set, slightly undulating and rough	Very favourable
Line 10	old alluvium	Kempas	Va	J1	Major joint set, slightly undulating and rough	Favourable
Line 11	old alluvium	Kempas	Va	J1	J1 40/310 is major joint set, slightly undulating and rough	Favourable
R4 L9	shale	Bukit Indah	II	J2, J3	J2 is major joint set, rough, undulating with some clay	Very unfavourable
C	shale	Bukit Indah	II	J2, J3	Both major joint sets, tight, rough and undulating	Favourable
R8 LN1 R6	shale	Bukit Indah	III	J1, J3	Major joint sets, rough, undulating	Favourable
LN4 R2	shale	Bukit Indah	III	J2, J3	J3 is major joint set. Surface is rough	Favourable
LN6 R4S	shale	Bukit Indah	III	J2, J4	J2 is major joint set, surface is undulating	Favourable
LN7 R2	shale	Bukit Indah	III	J2, J3	Both major joint sets, rough	Favourable
LN6 R1	shale	Bukit Indah	IVa	J2, J4	J2 60/80, J4 60/160 are major joint sets, rough, undulating	Very favourable
R4 L6	shale	Bukit Indah	IVa	J2	Rough, undulating joint, some iron stain	Fair
R8 LN1 R5	shale	Bukit Indah	IVa	J2, J3, J4	Major joint sets, tight, rough, undulating	Fair
LN7 R1	shale	Bukit Indah	IVa	J4, J5	J5 70/330 is major joint set. Rough, undulating	Very favourable
B2 SH1	shale	Bukit Indah	IVa	J4, J5	J4 70/150 is major joint set, rough, undulating	Very favourable
R8 LN1 R2	shale	Bukit Indah	IVa	J1, J3, J5	J5 is major joint set, rough undulating	Very favourable
R8 LN4 R3	shale	Bukit Indah	IVa	J1, J2, J3	J1 is major joint set, tight, slight iron stain	Favourable
R8 LN7 R4	shale	Bukit Indah	IVa	J2	J2 70/90 is major joint set	Favourable
LN8 R2	shale	Bukit Indah	IVa	J3, J4	Both major joint set, rough and undulating	Favourable
R3 L6 R2	shale	Bukit Indah	IVb	J2, J5	J2 40/90, J5 80/340 are major joint sets, rough, undulating	Unfavourable
R8 LN1 R4	shale	Bukit Indah	IVb	J2	J2 is major joint set, rough, undulating	Very favourable
R8 LN3 R3	shale	Bukit Indah	IVb	J2, J3	Major joint sets, dipping 20-80. Rough, undulating	Unfavourable
R8 LN11 R5	shale	Bukit Indah	IVb	J4, J5	Both major joint sets. Rough, undulating	Unfavourable
R8 LN12 R2	shale	Bukit Indah	IVb	J2, J3	Both major joint sets, rough, undulating with some clay	Favourable
B8 L5	shale	Bukit Indah	IVb	J2, J3	J3 is major joint set. Rough and undulating	Very favourable
R4 L2	shale	Bukit Indah	IVb	J3, J5	Both are major joint sets. Rough and undulating	Favourable
R8 LN2 R2	shale	Bukit Indah	IVb	J2, J3	J3 is major joint set. Rough and undulating	Favourable
R8 LN14 R1	shale	Bukit Indah	IVb	J2	Major joint set, some clay on surface	Favourable
LN3 R5	shale	Bukit Indah	IVb	J2, J3	J3 is major joint set. Rough and undulating with clay	Favourable
R8 LN10 R4S	shale	Bukit Indah	IVb	J3, J4, J5	All major joint sets, surface is rough	Very favourable
B8 L4	shale	Bukit Indah	IVb	J2, J4, J5	All major joint sets, surface is rough	Favourable
R8 LN5 R3	shale	Bukit Indah	IVb	J1, J2, J4	All major joint sets, surface is rough, undulating	Favourable
R2 L2	shale	Bukit Indah	Va	J4	Major joint set, undulating and rough	Very favourable
R8 LN10 R2	shale	Bukit Indah	Va	J3	Major joint set, rough, undulating with some clay	Favourable
LN5 R2	shale	Bukit Indah	Va	J3	Major joint set. Dip from 15 - 80.	Favourable
R8 LN11 R1	shale	Bukit Indah	Va	J2, J3	J3 is major joint set. Rough and undulating	Favourable
R8 LN 11 R3	shale	Bukit Indah	Va	J2, J3	Both major joint sets, rough and undulating	Favourable
B7 L1	shale	Bukit Indah	Va	J2, J4	J2 is major joint set, rough, undulating with some clay	Very favourable
B7 L5	shale	Bukit Indah	Va	J4	J4 is major joint set 40/180. Surface is rough and undulating	Very favourable
R8 LN3 R2	shale	Bukit Indah	Va	J3, J4	Both major joint sets, some iron stain	Very favourable
R2 L1	shale	Bukit Indah	Vb	J3, J4	Major joint sets, rough, undulating	Very favourable
LN6 R5	shale	Bukit Indah	Vb	J2, J3	Both major joint sets, surface is undulating	Very favourable
LN8 R1S	shale	Bukit Indah	Vb	J3	Major joint set, dip 15-80. Surface is rough	Very favourable
B8 L1	shale	Bukit Indah	Vb	J2, J3	J2 70/90 is major joint set, rough and undulating	Very favourable
RL 1 L3	shale	Mersing	II	J3, J4	J3 60/100 is major joint set, rough, undulating	Very unfavourable
RL 1 (b) L1	shale	Mersing	III	J3, J4	J3 is major joints, slightly rough, undulating	Unfavourable
RL 1 (a) L3	shale	Mersing	III	J3, J4	J3 is major joints, slightly rough, undulating	Very unfavourable
RL 1 L1	shale	Mersing	IVa	J2, J3, J4	3 major joints, rough and undulating	Unfavourable
RL1 L4	shale	Mersing	IVa	J3, J4	J3 20/110 is major joint set, surface is rough	Unfavourable
RL1 L7	shale	Mersing	IVa	J3	J3 is major joints, slightly rough, undulating	Fair
along foliation	shale	Mersing	Va	J4	J4 80/150 is major joint, rough and undulating	Favourable
RL 1 L2	shale	Mersing	Va	J3	J3 is major joints, dipping 20 - 70	Favourable

APPENDIX K
SUMMARY OF RIPPING DIRECTION AND DISCONTINUITIES MEASUREMENTS

Sample	Material	Location	Weathering Grade	Discontinuity set	Notes	Ripping Direction
R8 LN6 R2S	sandstone	Bukit Indah	II	J2, J5	Both major joints 80/100, 70/300, tight with some clay	Very favourable
R8 LN3 R4S	sandstone	Bukit Indah	II	J2, J4	J2 50/85 is major joint set while J4 70/150 is minor, rough, tight	Unfavourable
B8 L3	sandstone	Bukit Indah	II	J1,J2	Both major joint sets, rough, undulating with same clay	Favourable
R8 LN2 UR1	sandstone	Bukit Indah	II	J1, J3	J3 80/200 is major set, surface is rough and undulating	Unfavourable
R3 L1 R4S	sandstone	Bukit Indah	III	J2	Major joints 70/90, tight aperture, undulating surfaces	Very favourable
B8 L9	sandstone	Bukit Indah	III	J3, J5	Major joints 60/220, 80/340, rough undulating	Very favourable
R8 LN2 R3S	sandstone	Bukit Indah	III	J2, J5, J3	J5 is major joint set, rough undulating	Favourable
R8 LN7 UR1	sandstone	Bukit Indah	III	J2	Major joints, rough undulating , tight with discolouration	Fair
R6 L1	sandstone	Bukit Indah	III	J3, J4, J5	J3 50/210 is major joint set, rough, undulating, tight	Fair
LN8 UR2	sandstone	Bukit Indah	III	J2, J4, J5	J2 30/110, J5 50/310 are major are major joint sets, rough undulating	Unfavourable
B2 L3	sandstone	Bukit Indah	IVa	J3	Major joints 50/210, smooth undulating	Favourable
R8 LN2 R1	sandstone	Bukit Indah	IVa	J2, J3	Major joint J2, rough, undulating	Very favourable
LN3 R3S	sandstone	Bukit Indah	IVa	J3	Major joints 220/40, slightly rough, undulating	Favourable
R7 L1	sandstone	Bukit Indah	IVa	J4, J5	Both sets are major joints with 30/160 and 60/310	Fair
LN8 R3	sandstone	Bukit Indah	IVa	J1, J2	J1 is major joints 80/280, tight and slightly rough	Very favourable
LN4 R4	sandstone	Bukit Indah	IVa	J4, J5	Major joint sets 40/180, 80/340, rough undulating	Fair
B1 L3	sandstone	Bukit Indah	IVa	J3	J3 60/210 is major joint set, rough, undulating	Unfavourable
B1 L2	sandstone	Bukit Indah	IVa	J2, J4	J2 is major joint set, rough, undulating with some clay	Very favourable

LN4 R3S	sandstone	Bukit Indah	IVa	J1, J2	Both are major joint sets, rough, undulating	Favourable
R8 LN6 R1	sandstone	Bukit Indah	IVb	J3, J5	J3 is major joints, slightly rough, undulating	Favourable
R8 LN8 R2	sandstone	Bukit Indah	IVb	J2, J3, J5	J5 is major joint set, rough undulating	Very favourable
R4 L8	sandstone	Bukit Indah	IVb	J3, J5	Major joints, rough undulating , tight with discolouration	Fair
LN2 R1S	sandstone	Bukit Indah	IVb	J2, J3	J2 60/90 is major joint, rough, undulating	Favourable
B4 LA	sandstone	Bukit Indah	IVb	J3	J3 50/200 is major joint set, rough, undulating	Favourable
R8 LN6 R3	sandstone	Bukit Indah	IVb	J1, J2	Both sets are major joints with 70/110 and 60/280	Very favourable
B7 L2	sandstone	Bukit Indah	IVb	J2, J5	J5 is major joint set, rough undulating	Very favourable
R7 L2	sandstone	Bukit Indah	Va	J4	Major joints 40/80, rough undulating	Favourable
R4 L7	sandstone	Bukit Indah	Va	J2, J3	J2 is major joints 60/70	Very favourable
B2 SH4	sandstone	Bukit Indah	Va	J2, J3	Both major joint sets 70/30, 80/200, smooth undulating	Fair
R4 L4	sandstone	Bukit Indah	Va	J2, J3	Major joint sets, tight, clay	Very favourable
R5	sandstone	Bukit Indah	Va	J2, J4	J2 is major joint set, tight with clay	Very favourable
R8 LN7 UR2	sandstone	Bukit Indah	Va	J4, J5	J4 80/140 is major joint set, rough, undulating	Very favourable
R8 LN3 R1	sandstone	Bukit Indah	Va	J1, J2	J1 is major joints 80/280, tight and slightly rough	Very favourable
R4 L3	sandstone	Bukit Indah	Va	J2, J5	J5 80/320 is major joint set, rough undulating	Very favourable
B6 L2	sandstone	Bukit Indah	Vb	J2	Major joints 80/100, tight	Favourable
R8 LN1 R1	sandstone	Bukit Indah	Vb	J2	Major joints 40/50, tight	Favourable
B7 L3	sandstone	Bukit Indah	Vb		Major joints 60/200, slight undulating with clay	Very favourable
R4 L5	sandstone	Bukit Indah	Vb	J1, J3	Both are major joint sets, rough, undulating	Very favourable
LN7 R3	sandstone	Bukit Indah	Vb	J4	J4 60/160 is major joint set, rough, undulating with some clay	Very favourable
R8 LN4 R1	sandstone	Bukit Indah	Vb	J3, J4	J3 and J4 are major joint sets, clay at surface	Very favourable

R8 LN4 R2S	sandstone	Bukit Indah	Vb	J3, J5	J3 70/210 is major joint set, J5 minor, rough, undulating	Favourable
R8 LN8 UR1	sandstone	Bukit Indah	Vb	J2, J3, J4	J2 50/80 is major joint set, rough, undulating	Very favourable
RL 3 C L1	sandstone	Mersing	II	J1, J4, J6	J4 is major joint set, J1,J6 are minor, rough, undulating	Fair
RL 1 L6	sandstone	Mersing	III	J4	J4 70/160 is major joint set, rough, undulating with some iron stain	Fair
RL1 L5	sandstone	Mersing	III	J4, J6	J4 is major joint set, rough, undulating	Favourable
RL 3 C L2	sandstone	Mersing	III	J4, J6	60/170 is major joint set, J6 minor	Unfavourable
RL 3 E L1	sandstone	Mersing	III	J4, J6	J6 80/340 is major joint set, rough, undulating	Unfavourable
RL 3 Slope Area 2 L3	sandstone	Mersing	III	J5, J6	Both major joint sets J5 70/210 J6 80/320, rough, undulating	Unfavourable
RL 3 Slope Area 1 L5(a)	sandstone	Mersing	IVa	J2, J3, J4	J3 60/100 is major joint set, rough, undulating	Favourable
RL 3 A L1	sandstone	Mersing	IVb	J2	J2 40/60 is major joint set, rough and undulating	Favourable
RL 1 (b) L3	sandstone	Mersing	Va	J1, J4, J5	J1 60/40 is major joint set, joints are rough and undulating	Very favourable
RL 3 Slope Area 1 L1	sandstone	Mersing	Va	J3, J4	J3 80/100 is major joint set, tight aperture	Favourable
RL 3 Slope Area 1 L5 (Zone C)	sandstone	Mersing	Vb	J1, J2, J4, J5	J2 is major joint set, rough, undulating with some clay	Very favourable
RL 3 Slope Area 1 L2	sandstone	Mersing	Vb	J4	J4 80/160 is major joint set, surface is undulating	Very favourable
RL 3 Slope Area 2 L1	sandstone	Mersing	Vb	J4	J4 70/150 is major joint set, rough, undulating	Very favourable
RL 3 A L2	sandstone	Mersing	Vb	J4	J4 major joint set, some clay observed on surface	Very favourable
RL 3 A L4	sandstone	Mersing	Vb	J3	J3 60/110 is major joint set, rough, undulating	Favourable
DT FINE 1	old alluvium	Desa Tebrau	IVa	J1, J2, J6	J1 50/160, J2 80/90, J6 50/270. J2 and J6 are major joint sets	Very unfavourable
DT FINE 2	old alluvium	Desa Tebrau	IVa	J2	J2 80/100, major joint set, rough, planar	Fair
DT FINE 3	old alluvium	Desa Tebrau	IVa	J2, J3, J5	J5 50/200 is major joint set, rough, planar	Fair
DT FINE 4	old alluvium	Desa Tebrau	IVa	J3	J3 80/170 major joint set, rough, planar	Unfavourable
DT FINE 5	old alluvium	Desa Tebrau	IVa	J3, J5	Both are major joint sets, tight, planar and rough	Unfavourable
DT COARSE 1	old alluvium	Desa Tebrau	IVa	J1, J3	Major joint sets, tight, rough, planar	Fair

DT COARSE 2	old alluvium	Desa Tebrau	IVa	J3	J3 80/170 major joint set, rough, planar	Fair
DT COARSE 3	old alluvium	Desa Tebrau	IVa	J3, J4	J3 80/170, J4 70/320 are major joint sets, rough, planar	Fair
DT COARSE 4	old alluvium	Desa Tebrau	IVa	J2, J6	J2 80/80, J6 50/260 are major joint sets, rough, planar	Favourable
DT COARSE 5	old alluvium	Desa Tebrau	IVa	J2, J5	Both are major joint sets, rough, planar	Unfavourable
Line 1	old alluvium	Kempas	Va	J1, J2	J1 50/300, J2 40/140 are major joint sets, rough, slightly undulating	Very favourable
Line 1a	old alluvium	Kempas	Va	J3	Major joint set, slightly undulating and rough	Very favourable
Line 2a	old alluvium	Kempas	Va	J1, J3	J1 50/300, J3 50/210 are major joint sets, rough, slightly undulating	Very favourable
Line 3	old alluvium	Kempas	Va	J1	J1 50/300 is major joint set, tight, rough but quite soft	Very favourable
Line 4	old alluvium	Kempas	Va	J1	J1 50/310 is major joint set, rough, slightlt undulating	Very favourable
Line 5	old alluvium	Kempas	Va	J1	J1 is major joints set, tight and slightly rough, undulating	Favourable
Line 6	old alluvium	Kempas	Va	J1	J1 50/310 is major joint set, rough, slightly undulating	Very favourable
Line 7	old alluvium	Kempas	Va	J1	J1 50/310 is major joint set, rough, slightly undulating	Very favourable
Line 8	old alluvium	Kempas	Va	J1	J1 is major joint set, tight, slight iron stain	Very favourable
Line 9	old alluvium	Kempas	Va	J1	Major joint set, slightly undulating and rough	Very favourable
Line 10	old alluvium	Kempas	Va	J1	Major joint set, slightly undulating and rough	Favourable
Line 11	old alluvium	Kempas	Va	J1	J1 40/310 is major joint set, slightly undulating and rough	Favourable
R4 L9	shale	Bukit Indah	II	J2, J3	J2 is major joint set, rough, undulating with some clay	Very unfavourable
C	shale	Bukit Indah	II	J2, J3	Both major joint sets, tight, rough and undulating	Favourable
R8 LN1 R6	shale	Bukit Indah	III	J1, J3	Major joint sets, rough, undulating	Favourable
LN4 R2	shale	Bukit Indah	III	J2, J3	J3 is major joint set. Surface is rough	Favourable
LN6 R4S	shale	Bukit Indah	III	J2, J4	J2 is major joint set, surface is undulating	Favourable
LN7 R2	shale	Bukit Indah	III	J2, J3	Both major joint sets, rough	Favourable

LN6 R1	shale	Bukit Indah	IVa	J2, J4	J2 60/80, J4 60/160 are major joint sets, rough, undulating	Very favourable
R4 L6	shale	Bukit Indah	IVa	J2	Rough, undulating joint, some iron stain	Fair
R8 LN1 R5	shale	Bukit Indah	IVa	J2, J3, J4	Major joint sets, tight, rough, undulating	Fair
LN7 R1	shale	Bukit Indah	IVa	J4, J5	J5 70/330 is major joint set. Rough, undulating	Very favourable
B2 SH1	shale	Bukit Indah	IVa	J4, J5	J4 70/150 is major joint set, rough, undulating	Very favourable
R8 LN1 R2	shale	Bukit Indah	IVa	J1, J3, J5	J5 is major joint set, rough undulating	Very favourable
R8 LN4 R3	shale	Bukit Indah	IVa	J1, J2, J3	J1 is major joint set, tight, slight iron stain	Favourable
R8 LN7 R4	shale	Bukit Indah	IVa	J2	J2 70/90 is major joint set	Favourable
LN8 R2	shale	Bukit Indah	IVa	J3, J4	Both major joint set, rough and undulating	Favourable
R3 L6 R2	shale	Bukit Indah	IVb	J2, J5	J2 40/90, J5 80/340 are major joint sets, rough, undulating	Unfavourable
R8 LN1 R4	shale	Bukit Indah	IVb	J2	J2 is major joint set, rough, undulating	Very favourable
R8 LN3 R3	shale	Bukit Indah	IVb	J2, J3	Major joint sets, dipping 20-80. Rough, undulating	Unfavourable
R8 LN11 R5	shale	Bukit Indah	IVb	J4, J5	Both major joint sets. Rough, undulating	Unfavourable
R8 LN12 R2	shale	Bukit Indah	IVb	J2, J3	Both major joint sets, rough, undulating with some clay	Favourable
B8 L5	shale	Bukit Indah	IVb	J2, J3	J3 is major joint set. Rough and undulating	Very favourable
R4 L2	shale	Bukit Indah	IVb	J3, J5	Both are major joint sets. Rough and undulating	Favourable
R8 LN2 R2	shale	Bukit Indah	IVb	J2, J3	J3 is major joint set. Rough and undulating	Favourable
R8 LN14 R1	shale	Bukit Indah	IVb	J2	Major joint set, some clay on surface	Favourable
LN3 R5	shale	Bukit Indah	IVb	J2, J3	J3 is major joint set. Rough and undulating with clay	Favourable
R8 LN10 R4S	shale	Bukit Indah	IVb	J3, J4, J5	All major joint sets, surface is rough	Very favourable
B8 L4	shale	Bukit Indah	IVb	J2, J4, J5	All major joint sets, surface is rough	Favourable
R8 LN5 R3	shale	Bukit Indah	IVb	J1, J2, J4	All major joint sets, surface is rough, undulating	Favourable

R2 L2	shale	Bukit Indah	Va	J4	Major joint set, undulating and rough	Very favourable
R8 LN10 R2	shale	Bukit Indah	Va	J3	Major joint set, rough, undulating with some clay	Favourable
LN5 R2	shale	Bukit Indah	Va	J3	Major joint set. Dip from 15 - 80.	Favourable
R8 LN11 R1	shale	Bukit Indah	Va	J2, J3	J3 is major joint set. Rough and undulating	Favourable
R8 LN 11 R3	shale	Bukit Indah	Va	J2, J3	Both major joint sets, rough and undulating	Favourable
B7 L1	shale	Bukit Indah	Va	J2, J4	J2 is major joint set, rough, undulating with some clay	Very favourable
B7 L5	shale	Bukit Indah	Va	J4	J4 is major joint set 40/180. Surface is rough and undulating	Very favourable
R8 LN3 R2	shale	Bukit Indah	Va	J3, J4	Both major joint sets, some iron stain	Very favourable
R2 L1	shale	Bukit Indah	Vb	J3, J4	Major joint sets, rough, undulating	Very favourable
LN6 R5	shale	Bukit Indah	Vb	J2, J3	Both major joint sets, surface is undulating	Very favourable
LN8 R1S	shale	Bukit Indah	Vb	J3	Major joint set, dip 15-80. Surface is rough	Very favourable
B8 L1	shale	Bukit Indah	Vb	J2, J3	J2 70/90 is major joint set, rough and undulating	Very favourable
RL 1 L3	shale	Mersing	II	J3, J4	J3 60/100 is major joint set, rough, undulating	Very unfavourable
RL 1 (b) L1	shale	Mersing	III	J3, J4	J3 is major joints, slightly rough, undulating	Unfavourable
RL 1 (a) L3	shale	Mersing	III	J3, J4	J3 is major joints, slightly rough, undulating	Very unfavourable
RL 1 L1	shale	Mersing	IVa	J2, J3, J4	3 major joints, rough and undulating	Unfavourable
RL1 L4	shale	Mersing	IVa	J3, J4	J3 20/110 is major joint set, surface is rough	Unfavourable
RL1 L7	shale	Mersing	IVa	J3	J3 is major joints, slightly rough, undulating	Fair
along foliation	shale	Mersing	Va	J4	J4 80/150 is major joint, rough and undulating	Favourable
RL 1 L2	shale	Mersing	Va	J3	J3 is major joints, dipping 20 - 70	Favourable

APPENDIX L

INDEX VALUE USED FOR MACHINE PERFORMANCE (PRODUCTION) PREDICTION

Index value	Ripping Direction
1	Very Unfavourable
2	Unfavourable
3	Fair
4	Favourable
5	Very Favourable

Index value	Weathering Grade
1	II- Slightly Weathered
2	III- Moderately Weathered
3	IVa- Highly Weathered
4	IVb- Highly Weathered
5	Va- Completely Weathered
6	Vb- Completely Weathered

Index value	Grain Size
1	Very fine
2	Fine
3	Medium
4	Coarse

For the other parameters, the actual value to be entered as shown in Appendix G and H.