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AN OVERVIEW OF EXISTING ROCK EXCAVATABILITY ASSESSMENT TECHNIQUES

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Abstract: Surface excavation work is one of the most common problems that may cause dispute between contractors and clients when they do not reach mutual agreement regarding the price of excavating rock and soil. This is because the terms "rock" and "soil" are loosely defined in the contract document. Normally, blasting method would only be considered necessary if the physical limit of ripping is reached or when the cost of ripping is uneconomical. Similarly, the term "weathered rock" and its excavating method have been subjectively and differently defined. Further complication may arise in sedimentary rock masses where different layers of rock are interbedding, thus might be misjudged during the early excavation assessment. Different nature of rock indicates different weathering profile. Most of the existing rippability assessment methods are less accurate because they do not consider the weathering state at various rock mass layers. A more appropriate and practical rippability assessment method is required to economically assess the site during the preliminary stage. This paper evaluates the current surface excavation assessment techniques and their limitations especially in dealing with different nature of rock type.

Keywords: *Rock mass excavation; rippability; excavatability and excavation methods.*

Abstrak: Kerja pengorekan permukaan merupakan salah satu masalah lazim yang boleh menyebabkan perbalahan antara kontraktor dan klien apabila tidak bersetuju dengan harga pengorekan batuan dan tanah. Ini disebabkan kekaburan istilah bahan perantara "tanah" dan "batu" dalam kebanyakan dokumen kontrak. Kebiasaannya, kaedah letupan akan hanya dipertimbangkan sekiranya had fizikal perobekan dilepasi atau kos perobekan sudah tidak ekonomikal. Bahan perantara atau batuan luluhawa ini mempunyai kaedah pengorekan yang subjektif dan pengkelasannya adalah berbeza bagi kawasan yang berlainan. Isu ini lebih ketara di kawasan batuan sedimen yang terdiri daripada selang lapis unit-unit batuan yang berbeza sifatnya. Kesalahan dalam pentafsiran mungkin berlaku apabila penilaian hanya melibatkan bahan tertentu sahaja tanpa merujuk kepada sifat jasad batuan keseluruhan. Kaedah penilaian sedia ada tidak dapat menilai keseluruhan kebolehrobekan jasad batuan yang berbeza gred luluhawanya di peringkat awal perancangan. Kertas kerja ini menilai kaedah penilaian sedia ada dan kekangan yang biasa dihadapi apabila berhadapan dengan jenis batuan berbeza.

Katakunci: *Pengorekan batuan; kebolehrobekan; pengorekan dan kaedah pengorekan*

1.0 Introduction

Direct digging, ripping, and blasting are the three main methods used for breaking or loosening ground in surface excavation work. The term "excavatability" refers to the ability of any chosen method to break the ground in a more manageable size to be loaded and transported to other places. In principal, there are two main types of ground loosening mechanism in surface excavation, i.e. mechanical and blasting methods. Direct digging and ripping refer to mechanical excavation methods, where digging is defined by the process of cutting and displacement by a blade or bucket (Hadjigeorgiou and Poulin, 1998) that is usually done by excavator on softer ground. On the other hand, ripping is a process of breaking the harder ground by dragging tynes attached to a bull dozer. Ripping is the limit for mechanical method before resorting to blasting. In mechanical excavation, energy generated by machines will be transmitted to ground by means of tynes, i.e. breaking or ripping. In blasting, explosive energy in the forms of heat and gaseous is the main mechanisms for fragmenting the ground. There are many factors in deciding the most suitable method to be employed, namely type of project, rock mass, properties of 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 work, the major objective is to break the rock so that it can be economically removed (Atkinson, 1971). It has been a long notion that ripping might be cheaper than blasting. However, the advent of inexpensive explosives such as ammonium nitrate (AnFo) and metallised slurries has considerably reduced the blasting cost. In Malaysia, cost of blasting depends on volume of rock to be excavated, sensitive area surrounding, location and method of blast to be employed. Typically, price of drilling and blasting is in the range of RM2 to RM10 per ton compared to RM3 per ton for ripping (Muhibbah Engineering, 2002). Thus with this wide range of drilling and blasting cost, blasting can be cheaper than ripping in some situations.

Unclear and subjective classification of weathered rock for surface excavation purposes could lead to different interpretation on the mode of excavating this material. 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 multi-strata environment, i.e. sites which constituted of sedimentary rocks. Shale, for example, has lower strength and may be interbedded with stronger material such as sandstone. Higher moisture content may further deteriorate the shale strength to behave like soil, but in dry condition it might be difficult to rip. The weathering grades on the sedimentary rocks may not be as uniform as in igneous rocks. International Society of Rock Mechanics (ISRM, 1988) classified rock mass weathering by

6 zones, where zone I indicates fresh state and become more weathered as the grade increase with zone VI being residual soil. Weathering grades III (moderately weathered) to V (completely weathered) are always a grey area in ripping assessment. The presence of isolated rock or boulders and iron pan are other significant issues in tropical region. Currently, evaluations of excavation method in Malaysia are based on Pettifer and Fookes (1994) classification (e.g. Tajul Anuar and Sundaram, 2000; Mohd For and Edy Tonnizam, 2003; Tajul Anuar and Ismail, 2003). However, these evaluation criteria do not adequately address the weathering profile and nature of rock in the tropics.

Site experiences show that the majority of the existing rippability assessment methods do not give reliable results (Hakan, 2004). A more objective and practical rock excavation assessment method is essential to effectively assess the site during the preliminary stage. This paper reviews and evaluates the development of the surface excavation assessment methods that are being used to estimate excavatability of rock.

2.0 Rock Mass and Machine Parameters

In rock engineering, the determination of physical and mechanical properties of rock is essential to predict the behaviour of the rock mass. The selection process of the ground preparation technique is important because such activities as excavating, hauling and backfilling could be influenced by the decisions made. The two main factors involved in determining machine performance are rock and machine parameters (Fowell, 1993). Rippability can be influenced by rock type, strength, degree of weathering, rock structure, rock fabric, seismic velocity and discontinuities behaviour (Smith, 1986).

Proper selection of ripping equipment could ensure optimum production and efficient excavation operation. The principle factors for selecting appropriate ripping equipment are:

a) <u>Tractor weight</u>: this factor determines whether the tractor has sufficient penetration and the horizontal force.
b) <u>Tractor power</u>: this factor determines whether a tractor can transmit the necessary force to advance the tip. A larger horse power bulldozer will have greater drawbar pull and can easily rips harder rock material compared to a smaller bulldozer.
c) <u>Down pressure on the tip</u>: this factor determines whether penetration can be initiated and then maintained throughout the ripping works.

A balance of these three factors is essential to assure a successful and economical ripping. The size of equipment defined by its weight and power has been used for the selection of an optimum tractor-ripper for a given ripping operation (Church, 1981).

3.0 Existing Excavatability Assessment Methods

Methods that are being used for assessing surface excavation techniques can be grouped into three categories as follows:

a) seismic velocity based approximation
b) graphical method
c) grading method

Some of the assessments are based purely on the primary *(P)* wave seismic velocity of rock mass and material properties (Caterpillar Tractor Company, 2001). However, due to interacting effects between rock mass and material parameters, the assessment becomes more complex.

Generally in the early years, the excavation assessment focused on type of excavation needed and later extended to machinery type and production. The development of these assessments could be traced back in 1958, when Caterpillar Company used the seismic velocity as predictive tools for excavatability (Church, 1981). This assessment was widely used in 1960s (Pettifer and Fookes, 1994) in assessing rock excavatability.

3.1 *Seismic velocity based methods*

Seismic velocity method is the most popular and useful for rock mass characterisation in surface mining, which can facilitate the selection of excavation method (Atkinson, 1971). This method can represent various intrinsic rock properties like porosity, density and degree of cementation of the rock material (Bradybrooke, 1988). Between 1920 and 1930, seismic methods were used in oil exploration and later they were applied to earth and rock excavation. Rippability assessment using seismic velocity was developed by Caterpillar Tractor Company in 1958 and the company keeps updating the assessment procedure along with the development of their tractors (Figure 1).

Although it is one of the most popular tools in assessing rippability, seismic method alone does not give perfect assessment. According to Singh et al (1987), abrasive material, which affects the excavatability, is not detected by seismic velocity. Similarly, fresh boulders and rock columns in a matrix of completely weathered material, which are normally found in granite, gabbro, basalt and sandstones are not clearly sensed by seismic velocity. In this regard, depending on survey data alone may mislead the excavatability assessment (Pettifer and Fookes, 1994). In addition, if the thickness of high velocity layer is less than 1/3 of the overlying layer, seismic velocity may not be able to detect the layer (Bradybrooke, 1988). This is because the properties of the upper layer tend to mask the lower layer.

Seismic velocity is also unable to differentiate materials of different nature of rock (Hadjigeorgiou and Poulin, 1998). For example, seismic velocity in sandstone tends to be similar as in granite; however sandstone might be classified as rippable rock whereas granite is non-rippable. Similarly, the seismic velocity travels faster in saturated material compared to dry material as the water helps to transmit the wave through the rock body. As a result, the porous rock with higher moisture content would display a higher velocity compared to dry rocks. Thus, the seismic velocity alone does not represent the actual strength of the rock. Due to difficulties in interpreting the seismic velocity, deviations up to ± 1000m/s can be observed for the same material with accuracies ±20% (Bilgin,1989).

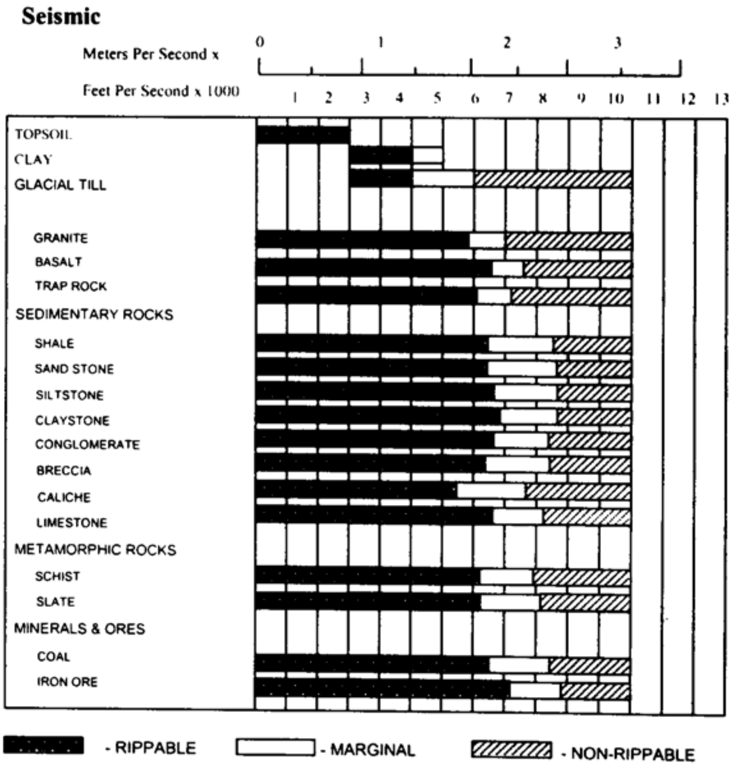

Figure 1: Rippability assessment chart recommended by Caterpillar Tractor Co. for CAT D9 type dozer (Caterpillar Tractor Company, 2001).

Atkinson (1971) and Bailey (1975) proposed excavatability assessment of rock mass without specifying the rock type and degree of weathering. Subsequently, Church (1981) proposed a graphical representation on the degree of weathering and nature of rock based on 509 excavation works and 6100 seismic studies in western America (Figure 2). Church (1981) also introduced the seismic velocity parameter and the depth of material from the ground surface to be excavated. The depth from the ground surface is based on the typical weathering profile. In addition, methods of excavation are proposed for various rock types.

Although many excavatability assessment methods are based on seismic velocity as an indicator, the results are often less reliable (Kramadibrata, 1998; Rucker, 1999; Hakan 2004). This is because the basic material properties such as strength and abrasivity that affect rippability are not detected by seismic velocity. Dozer's manufacturer. Komatsu does not define the terms 'rippable', 'marginal' and 'non-rippable' in their assessment, making it difficult for practical purposes (Anon, 1987). It is also noted that Komatsu evaluates rippability more optimistically than Caterpillar although with the same size of machines (Hakan, 2004). Dozers manufacturer charts tend to be over optimistic when predicting excavatability by classifying unrippable rocks as easily rippable (MacGregor et al, 1994). In this regard, Edy Tonnizam et al (2005) provide a good case study. They found that the recommended CAT D9 for ripping upper soil having Grade IV sandstone (composed 30% of the rock mass) and seismic velocity < 2000 m s (Caterpillar Tractor Co., 2001) was not able rip the whole part of the rock mass in the direct ripping.

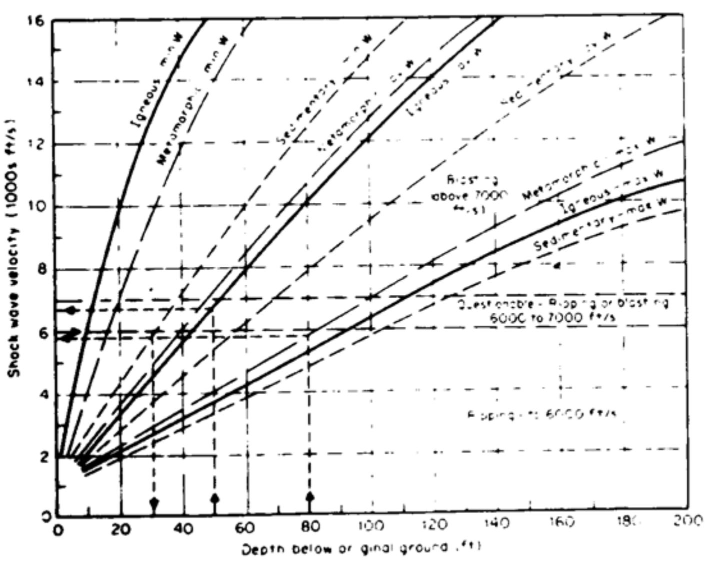

Figure 2: Relationship between seismic velocities and depth below ground surface (Church, 1981)

3.2 *Graphical based method*

Graphical methods are designed for quick and simple evaluation without supported by detailed laboratory tests. This method was introduced by Franklin et al (1971) to simplify the excavation assessment. The parameters being considered are restricted to strength and discontinuities spacing (Franklin et al, 1971; Bozdag, 1988; Pettifer and Fookes, 1994). The earlier assessment method by Franklin et al (1971) was extended by incorporating different sizes of tractors in the graph (Bozdag, 1988; Pettifer and Fookes, 1994). All these assessments use discontinuity spacing parameter and point load value to estimate excavation method without focusing on any specific rock type.

In the Graphical Method, Franklin et al (1971) subdivided the graph into the field of 'digging', 'scraping', 'ripping', 'blasting to loosen' and 'blasting to fracture'. Bozdag (1988) modified the chart and the graph boundaries into four fields and suggested types of equipment to be used. This graph was further revised by Pettifer and Fookes (1994) based on case studies in Africa, Hong Kong, United Kingdom. Discontinuity spacing and strength of intact rock are regarded the most important parameters that influent the excavatability of rock mass. In the graph, excavatability of rock mass is categorized into 'easy', 'hard', 'very hard', 'extremely hard' and 'blasting' through the point load index value (Is50) which represents the strength of rock mass and the discontinuity spacing.

3.3 *Grading based method*

In this method, rock mass and rock material properties are graded according to their importance in excavatability. The excavatability of rock mass depends on a number of geomechanical properties such as discontinuities, weathering grade and strength. Basically, no single test can uniquely defined rock material properties (Singh et al, 1986; Hakan, 2004). Instead, there are numerous tests giving either direct or indirect value to each property. While grading systems were developed to overcome the limitations of both graphical and seismic velocity methods, they are not giving desirable results (Hakan, 2004). Local conditions and rock nature are also important factors to be addressed.

Rock mass properties are usually associated with uniaxial compressive strength (UCS), degree of weathering, orientation and frequency of joints. It is also noted that favourable discontinuity orientation in medium hard ground may improve the performance of excavating equipments (Roxborough et al, 1981). Since various parameters would influence the excavatability, some researchers proposed grading system (Hadjigeorgiou and Poulin, 1998; Hakan, 2004). These systems have been used directly or indirectly in selecting excavation method in mining or civil works.

Weaver (1975) proposed rippability rating chart adopted from the Rock Mass Rating (RMR) system that was initially used for assessing tunnel support system. He replaced the Rock Quality Designation (RQD) with seismic velocity and introduced weathering parameter and discontinuity orientation (dip angle and dip direction) in his assessment. However, ground water condition was ignored and seismic velocity was used instead of RQD. By assigning scoring marks for each situation, a total index number can be calculated and the excavation method is proposed. Types of appropriate tractor for Caterpillar's machines are also proposed. Weaver (1975) however, did not mention one of the most important parameters, that is orientation dip and strike of the discontinuities in his classification.

Kirsten (1982) proposed an excavatability index based on studies from South Africa. He suggested adjustments for discontinuity orientation and omit the seismic velocity parameter. He also proposed basic and standard parameters based on Q-system (Barton et al.1974). An Excavatability Index, N was proposed as follows

$$N = Ms \frac{(RQD)}{(Jn)} Js \frac{(Jr)}{(Ja)} \quad (1)$$

where Ms is mass strength number (by multiplying the average value of UCS with coefficient of relative density), 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 (as in Q system), Ja is joint alteration number (as in Q system) and (Jr/Ja) is reducing effect on deformability and weakness of joints.

Muftuoglu (1983) devised a diggability index for sandstone and mudstone based on discontinuity spacing, rock strength and weathering of open coal mines in Britain. Abdul Latif et al (1983) studied intact rock strength and discontinuity characteristics 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 (RMR) system (Bieniawski, 1989)

Abdul Latif et al (1983) found that RQD value can be estimated from scan lines by using the equation derived by Priest et al. 1976:

$$RQD = 100e^{-0.1\lambda}(0.1\lambda + 1) \quad (2)$$

where, RQD is rock quality designation and λ is mean discontinuity frequency per metre. In addition, they found that Q-system that was introduced for tunnelling can be used as a guide in surface excavation. Abdul Latif et al (1983) also proposed that digging a rock mass is possible up to RMR 30 while ripping up to RMR 60. Above RMR 60, the rock mass must be drilled and blasted.

Smith (1986) proposed a systematic means with 6 rock parameters, i.e. rock hardness, rock weathering, joint spacing, joint continuity, joint gauge and joint orientation as a modification to the Weaver's system. There is no field verification available. He recommended a method of correlating the rating with seismic and tractor horsepower.

Singh et al (1987) introduced parameter of abrasiveness and expressed rock strength in term of uniaxial tensile strength. Based on six roadways construction works on coal rock type, Singh et al (1987) used abrasiveness of rock, discontinuity spacing, seismic velocity, weathering and indirect tensile strength to study the rock excavatability. They claimed that the current rippability indices fail to account for fracture strength of rock mass. They also noted that rock mass is rippable if shank can penetrate more than 0.6 m with min forward speed 2.5 km/h. In Turky, Karpuz (1990) proposed a diggability classification based on UCS, Schmidt hardness value, discontinuity spacing, seismic velocity and weathering index value. He also proposed type of machine to be used for different class of excavation. MacGregor et al (1994) recognized the degree of weathering is a subjective matter and need to be quantified in the excavatability assessment.

Kramadibrata (1998) studied excavatability of continuously mined limestone quarry in Austria, open gold mines in Meekatharra and Mt Gibson of Western Australia and open coal mine in Air Laya, Indonesia. Geomechanical investigations were conducted which involved scanline mapping of rock faces and various laboratory testings. He used RMR (Bienawinski, 1989) and Q-system (Barton et al, 1974) to evaluate the rock properties. From the data gathered, Kramadibrata (1998) proposed a relationship between Rock Mass Rating (RMR) versus Excavatability Index and the Q-system versus Excavatability Index. The Excavatability Index used by Kramadibrata (1998) was the one proposed by Kirsten (1982). Kramadibrata (1998) found that Q-system which was originally developed for assessing stabilisation measures of underground opening is also acceptable for surface excavation.

Hadjigeorgiou et al (1998) studied on empirical ground classification system which was divided into primary and secondary ground properties. The primary properties are parameters which are critical in dictating the ease of excavating the rock mass, i.e. point load strength and structurally defined block size. The secondary ground properties are weathering, orientation of discontinuities and ripping directions. They then established the following Excavation Index *(EI)*:

$$EI = (Is + Bs) \times W \times Js \qquad (3)$$

where, *Is* is point load strength index; *Bs* is block size index; *W* is weathering index and *Js* is relative ground structure index. Equation (3), however, does not consider interactions between type and size of machine required.

Rucker (1999) studied rippability of decomposed and slightly weathered medium-coarse granite in Arizona for a highway project. He found that RQD is the best indirect indicator of block size in rock mass for fractal geometry. Ripping causes the fractal structure of the fractured rock mass to self organizes into a critical system to resist ripping forces.

More recently, Hakan (2004) conducted a study on surface coal mine in Turkey. He used five parameters, i.e. uniaxial compressive strength (UCS), point load index, seismic velocity, Schmidt hammer value and average discontinuity spacing to assess the excavatability. He also proposed the use of specific energy (energy to remove unit volume of material) for the assessments. These parameters are then divided into five main classes with respect to their rippability classification. In addition, Hakan (2004) proposed correlation between specific energy and ripper production, thus allowing this system to predict the production rate with the different dozer sizes.

4.0 Conclusions

Even though many excavatability assessments use seismic velocity as an indicator, this method may not provide satisfactory estimates for excavation. These are attributed to geological features, which require different field procedures to be identified. Furthermore the basic material characteristics such as rock type and abrasiveness that affect rippability performance are not represented in seismic velocity. In general, seismic velocity cannot be determined to an accuracy better than 20% or variance of 1000 m/s for similar materials (Kirsten, 1982).

The graphical based method which is simpler and considers only two parameters, i.e. point load strength and fracture spacing indices was then developed. The excavatability of rock mass also depends on factors such as joint continuity, gouge, joint set number and direction of discontinuities.

Although the grading system 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 being generalised by type of geological parameters. It should be noted that each rock type displays significant differences in the structural and mode of existence. Igneous rocks, for example, can have many occurrences of boulders, which may have similar parameters, but the size would matter. Normal digging could excavate small boulders easily, but the bigger size would need 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 type of rocks. Table 1 summarises the parameters being used by various researchers. Even though uniaxial compressive strength (UCS) is the most popular parameter, the need for employing simple and practical *in-situ* testing such as point load test and Schmidt hammer are vital. With practical *in-situ* testing, logistic and sampling problems can be minimised.

In sedimentary rocks, the occurrences of bedding, folding, foliation and the multi layer of rock types are few distinctive differences compared to igneous rocks. Shale, which is interbedded with sandstone, would have lower mass strength compared to the sandstone layers. Thus, shale can be excavated by different kind of excavation techniques. However, as the rock mass is always interbedded with low and high strength rocks, the appropriate excavation method could differ 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 could significantly influent the ease of excavation. Therefore, consideration on the local inhomogeneity of rocks in the assessment is also important.

The mode of occurrence of rock mass is another important factor in deciding the excavation method. The material might be rippable but the topography would not allow such method to be effective. For the same lithology, the ease of excavating a highly moisturised rock could be easier compared to dried ones.

Despite the number of excavation assessments, they are not designed to deal with tropical weathered rock where inhomogeneity of lithology, moisture content, penetration and the topography make excavatability assessment more complicated. Thus, research effort must be directed to improve the assessment of ripping performance especially for sedimentary rock mass in tropical climate.

Table 1: Summary of parameters considered for excavation assessment

Parameters/References			Strength							Joint/Discontinuity								
	SV	GS	UCS	PLT	SH	TS	ROQ	NJS	VJC	JR	JA	JO	JS	JC	JG	BS	A	W
Caterpillar Tractor Company (2001)	X																	
Atkinson (1971)	X																	
Franklin et al (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 et al (1987)	X			X		X							X				X	X
Bozdag (1988)				X									X					
Karpuz (1990)	X		X		X								X					X
MacGregor et al (1994)	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
Rucker (1999)			X				X											
Hakan (2004)	X		X	X	X								X					

Note SV=seismic velocity ; UCS uniaxial compressive strength; GS= Grain size; PLT point load test; SH= schmidt hammer; TS= tensile strength; RQD= rock quality designation.; A- abrasiveness; W- weathering; NJS= no. of joint sets; VJC= volumetric joint count; JR= joint roughness; JA - joint alteration; JS= joint spacing; JC joint continuity; JG= joint gouge; BS= bedding spacing

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