

STABILITY AND DEFORMATION ANALYSIS OF FAILED EMBANKMENTS FOUNDED ON SOFT CLAYS

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Abstract: This paper presents results of stability and deformation analysis of several failed embankment case histories founded on soft clay. Different methods of limit equilibrium analysis (Fellenius, Bishop, Janbu and Spencer) adopted in computer program SLOPE/W were used to calculate the Factor of Safety of each embankment. A continuum approach utilising a finite difference computer program FLAC was also used to calculate the Factor of Safety and study the deformation behaviour of the embankment. The results obtained using both methods were compared with observations. The effect of analysis methods, variation of shear strength parameters of both fill and foundation soils on the Factor of Safety were also discussed. The variation of soil strength is a dominant factor in the slope stability analysis. The limit equilibrium method which satisfies both force and moment equilibrium give better prediction on the stability of the slope.

Keywords: *Soft Clay, Slope Stability, Embankment Deformations.*

Abstrak: Kertas kerja ini membincangkan kajian kestabilan cerun dan kajian ubahbentuk daripada beberapa tambakan yang telah gagal dibina di atas lempung lembut. Simulasi dilaksanakan menggunakan perisian computer SLOPE/W yang berasaskan kaedah keseimbangan batas yang berlainan (Fellenius, Bishop, Janbu dan Spencer) dan FLAC yang berasaskan kaedah perbezaan terhingga. Hasil kajian menggunakan kedua-dua kaedah ini juga dibandingkan dengan hasil pengamatan di tapak. Kesan kaedah kajian, nilai-nilai kekuatan ricih tanah asas dan bahan tambakan terhadap hasil kajian juga dibincangkan. Hasil kajian menunjukkan bahwa nilai kekuatan tanah lebih berpengaruh terhadap faktor keselamatan cerun dibandingkan dengan kaedah yang digunakan. Kaedah yang memenuhi keseimbangan momen dan daya memberi ramalan kestabilan cerun yang lebih baik.

Katakunci: *Lempung Lembut, Kestabilan Cerun, Ubahbentuk Tambakan.*

1. Introduction

Assessment of stability of slopes is one of the earliest problems faced by geotechnical engineers. The stability of slopes is generally assessed using limit equilibrium method where Factor of Safety is estimated as the ratio of the soil strength and driving stress acting along the potential failure surface. Limit equilibrium method is widely used in practice due to its reliability for most practical cases. Duncan (1996) presented a summary of several limit equilibrium methods used in practice. Simplified approach can be used in the preliminary assessment only while more complex analyses that give more accurate results can be carried out with the help of computer programs.

A basic assumption inherent in the limit equilibrium analysis is that the method treats the soils as rigid plastic materials. The soils do not deform as long as the driving stress is less than the soil strength. Once the driving shear stress exceeds the soil strength, the soil will deform excessively and reach failure. The method assumes that the shear stresses along the potential failure surface are mobilised simultaneously, which is not true for most cases (Duncan, 1996). This assumption tends to underestimate the stability of slopes founded on material exhibiting strain-hardening behaviour such as soft clay.

Another limitation of the limit equilibrium method is that it does not take into account the possible decrease in the driving stress when the slopes deform and flatten. This is particularly important for an embankment on soft ground, which may experience excessive undrained deformations during construction. As consequences, the Factor of Safety is overestimated.

In addition, the limit equilibrium method usually assumes circular failure surface. Some of the methods which consider the noncircular failure plane, such as Morgenstein and Price, and Spencer's methods, were actually based on circular plane. The assumed failure surface does not necessarily give the weakest failure zone and this will affect the calculated Factor of Safety. Trial and error process is involved in the search of the most critical failure surface. Many computer programs for slope stability analysis were developed based on limit equilibrium approach and are available in the market such as SLOPE/W (Geoslope, 2002).

The preceding discussion suggested that deformations are often required to assess the stability of slopes, particularly when the slopes are located adjacent to structures. The deformations of slopes are estimated using a continuum mechanics approach such as finite element or finite difference methods. With the advance of computer technology, the slope stability calculation using a continuum mechanic approach is now becoming more popular (Matsui and San, 1992; Dawson and Roth, 1999). Several commercial computer programs utilising finite element and finite difference methods e.g. PLAXIS (finite element method) and FLAC (finite difference method) can be used for deformation analysis of slope.

Since a continuum mechanics approach calculates mass deformation and does not directly result in a Factor of Safety, a "strength reduction technique" (Matsui and San, 1992) is used to obtain the Factor of Safety of slopes. By using this approach, the soil strength is gradually reduced by a "factor" to bring a slope to a state of limiting equilibrium. The "factor" that brings the slope into incipient failure is defined as the Factor of Safety of the slope.

The strength reduction technique has a number of advantages over the method of slices in the limit equilibrium analysis. The most important advantage is that the critical failure surface can be found without having to perform trial and error assuming a certain shape of failure surface. In this case, the failure mechanism involving deformation of wedges can be analysed. This has a practical significance for rotational failure of retaining walls, sheet-pile walls, and for 3-D slope stability problems (Dawson and Roth, 1999). Additionally, this approach is able to consider the reduction of shear stress due to slope flattening or large deformations and appropriate stress-strain relationship of soil can be used to predict a progressive failure of the embankment.

Extensive studies have been carried out by researchers to investigate the behaviour of some instrumented trial embankment founded on soft clay (e.g. Indraratna et al., 1992; Crawford et al., 1995) utilizing the continuum approach. They compared the predicted results with the behaviour of the embankment and soft clay foundation observed through field monitoring during and after construction. While there have been some successes in predicting some of the behaviour of soft clay embankment, there are still many uncertainties controlling the behaviour of the embankment.

2. Objectives and Scope of the Study

The main objective of this study is to compare the performance of several methods of slope stability analysis derived from limit equilibrium concept with continuum mechanics approach in predicting the behaviour of embankment. The study used secondary data from well documented case histories of trial or real embankment studied and published by previous researchers. Field observation data were used to calibrate the methods against real case histories of failed embankment.

Furthermore, stability and sensitivity analyses were conducted to investigate the relative importance of several factors affecting the stability of slopes founded on soft clay such as method of analysis and the variation of shear strength parameters.

3. Case Study

3.1 Stability Analysis

In this study, the slope stability analyses were carried out based on the data presented in studies published by the previous researchers using limit equilibrium based program SLOPE/W (Geoslope, 2002) and finite different program FLAC (Itasca, 2000). Four methods of limit equilibrium analysis adopted in SLOPE/W were selected in this study i.e., Fellenius, Bishop Modified, Janbu Simplified, and Spencer. The summary of the geometry and soil data for the case study is presented in Table 1. The results of stability analysis using the limit equilibrium method and FLAC are presented in Table 2. Typical result of slope stability analysis is presented in Figure 1.

3.2. Sensitivity Analysis

Sensitivity analysis was also carried out to check the effect of varying shear strength parameters of fill, crust and clay foundation. The analysis was carried out for New Liskeard embankment test only. The results of sensitivity analysis are presented in Table 4.

4. Discussion

The effects of the method and the adopted shear strength parameters on the stability analysis are discussed based on the results of stability and sensitivity analyses of embankment founded on soft clay shown in Tables 2 and 3.

4.1 Effect of Analysis Method

It can be seen from Tables 2 and 3 that the calculated factors of safety obtained from Fellenius, Bishop, Janbu and Spencer's method are generally similar with only about $\pm 5\%$ differences. In most cases, Spencer's method yields higher Factor of Safety than Fellenius and Janbu methods. Interestingly enough, the Factor of Safety calculated using Bishop's modified method, which only satisfies the moment equilibrium, consistently similar to those computed using Spencer's method that satisfies both moment and force equilibriums. The Fellenius and Janbu methods generally result in lower Factor of Safety than Bishop and Spencer methods.

Table 1: Summary of case histories considered in the analysis

No	Case history	Failure height	Crust Thickness	Crust properties	Fill properties	Soft clay properties	References
1	New Liskeard Case 1	5.65 m	3 m	$\gamma=18.4$ kN/m ³ c=38 kPa	$\gamma=20.4$ kN/m ³ c=0; $\phi=35$	$\gamma=16.8$ kN/m ³ C=15 kPa	Lo and Stermac (1965)
2	I-95	1.7 m	6.5 m	$\gamma=18.9$ kN/m ³ c=50 kPa	$\gamma=18.4$ kN/m ³ c=0; $\phi=41^\circ$	$\gamma=17.5$ kN/m ³ c=10+2.4 Δz kPa	Ladd (1972)
3	Narbonne	9.6 m	3 m	$\gamma=15$ kN/m ³ c=50 kPa	$\gamma=20$ kN/m ³ c=53kPa; $\phi=26^\circ$	$\gamma=13$ kN/m ³ c=25 kPa	Pilot et al. (1972)
4	Pornic	4 m	2 m	$\gamma=15$ kN/m ³ c=20 kPa	$\gamma=20$ kN/m ³ c=10kPa; $\phi=40^\circ$	$\gamma=15$ kN/m ³ c=10+3.8 Δz kPa	Pilot et al. (1972)
5	NBR-James Bay	4 m	1.5 m	$\gamma=15$ kN/m ³ c=40 kPa	$\gamma=20.3$ kN/m ³ c=0kPa; $\phi=35^\circ$	$\gamma=15$ kN/m ³ c=20 kPa	Dascal et al. (1972)
6	Rio	2.8 m	2.4 m	$\gamma=13.2$ kN/m ³ c=8 kPa	$\gamma=18.4$ kN/m ³ c=10kPa; $\phi=40^\circ$	$\gamma=13.2$ kN/m ³ c=8+1.4 Δz kPa	Ramalho-Ortogao et al. (1983)
7	Muar-F	5.4 m	2 m	$\gamma=16.5$ kN/m ³ c=10-40 kPa	$\gamma=20.4$ kN/m ³ c=19kPa; $\phi=26^\circ$	$\gamma=15.5$ kN/m ³ c=10+2.3 Δz kPa	Indraratna et al. (1992)
8	Vernon	9.9 m	4 m	$\gamma=17$ kN/m ³ c=30 kPa	$\gamma=20.3$ kN/m ³ c=30kPa; $\phi=10^\circ$	$\gamma=15$ kN/m ³ c=35 kPa	Crawford et al. (1995)

Table 2. Summary of calculated Factor of Safety

No	Case history	Fellenius	Bishop Modified	Janbu Simplified	Spencer	FLAC
1	New Liskeard (Case 1)	0.82	0.89	0.83	0.89	NA
2	I-95	1.15	1.25	1.08	1.25	NA
3	Narbonne	1.03	0.95	1.01	0.95	NA
4	Pornic	1.18	1.20	1.15	1.20	NA
5	NBR-James Bay	1.50	1.59	1.47	1.59	1.49
6	Rio de Janeiro	1.07	1.02	0.99	1.03	NA
7	Muar-F	1.00	0.98	0.97	0.98	0.99
8	Vernon	1.08	1.09	1.07	1.09	1.04

NA – Not analysed

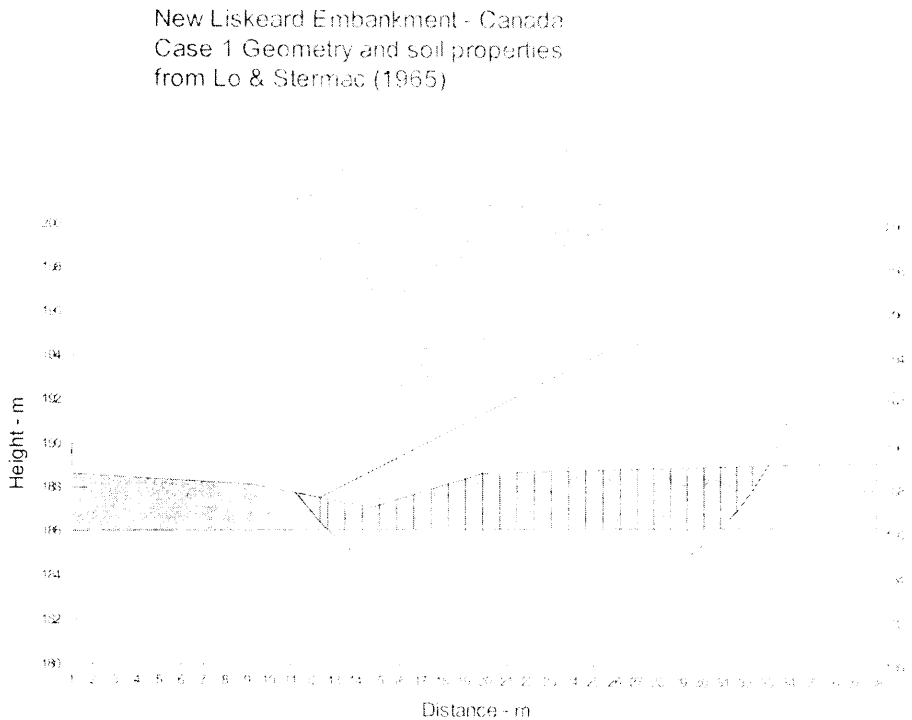


Figure 1. Typical results of slope stability analysis using SLOPE/W for New Liskeard embankment (data from Lo and Stermac, 1995)

Table 3: A summary of sensitivity analysis for New Liskeard Embankment

Case history	Crust strength c_u (kPa)	Fill strength $c=0$ kPa; $\phi=35^\circ$	Clay strength c_u (kPa)	Fellenius	Bishop Modified	Janbu Simplified	Spencer	FLAC
New Liskeard (Case-1)	38	$c=0$ kPa; $\phi=35^\circ$	15	0.82	0.89	0.83	0.89	NA
New Liskeard (Case-2)	48	$c=0$ kPa; $\phi=35^\circ$	15	0.91	0.99	0.93	0.99	NA
New Liskeard (Case 3)	38	$c=0$ kPa; $\phi=0^\circ$	15	0.77	0.77	0.63	0.77	NA
New Liskeard (Case 4)	38	$c=0$ kPa; $\phi=40^\circ$	15	0.83	0.90	0.83	0.90	NA
New Liskeard (Case 5)	38	$c=0$ kPa; $\phi=35^\circ$	$c=15+1.87 \Delta z$ kPa	0.94	1.03	0.92	1.02	NA
New Liskeard (Case 6)	38	$c=0$ kPa; $\phi=35^\circ$	$c=15$ kPa	0.70	0.77	0.72	0.77	NA

Note: geometry and soil properties from Lo and Stermac (1965)
 Variation on shear strength of Clay from Lacasse et al (1977)

It is important to note that all embankments considered in this analysis failed or experienced large deformations. Therefore the expected calculated Factor of Safety for all slopes is about 1.00. The calculated Factor of Safety for each embankment generally close to unity, except I-95, Pornic and NBR James Bay embankments. These embankments are founded on very sensitive clay with potential strength reduction with increasing strains. The discrepancy between the calculated Factor of Safety and the actual slope behaviour was attributed to strain rate effect during vane shear test, anisotropy and progressive failure (Bjerrum, 1972).

Three of the slopes were analysed using FLAC finite difference program, i.e. James Bay, Muar-F and Vernon. The calculated Factor of Safety agree quite well with the Factor of Safety from limit equilibrium analysis. However, as can be seen later, the failure surface obtained from FLAC is more realistic as it shows better agreement with the inclinometer data.

4.2 *Effect of Crust Strength*

The results of sensitivity analysis (Table 3) demonstrate the effect of crust strength on the calculated Factor of Safety. The increase of crust strength from 38 kPa to 48 kPa increases the Factor of Safety calculated using Spencer's method from 0.89 to 0.99. That is an increase of about 10%. Lo and Stermac (1965) and Lacasse et.al. (1977) showed that the undrained strength of the crust varies from 30 kPa to 65 kPa. Thus, the selection of realistic crust strength is very important to obtain realistic results of stability analysis.

4.3 *Effect of Fill Strength*

Cases 3 and 4 in Table 3 clarify the role of fill strength in the stability analysis. Omission of fill strength in the stability analysis can significantly underestimate the stability of a slope. The omission of fill strength decreases the Factor of Safety of New Liskeard embankment from 0.89 to 0.77, which is about 15% reduction. As also reported by Brand and Premchitt (1989) in the Muar Test embankment prediction, neglecting fill strength can considerably underestimate the failure height of the embankment. However, increasing the internal friction angle of the fill soil from 35 degrees friction angle to 40 degrees does not significantly affect the calculated Factor of Safety (cases 1 and 4).

4.4 *Effect of Soft Clay Parameters*

Similar to the selection of crust strength, selection of soft clay strength is not always straightforward. Different person may adopt different clay strength for their analysis based on similar set of data. For example, Lo and Stermac (1965) assumes that the clay strength is uniform with increasing thickness, even-though the actual data show that the strength increases with depth. Lacasse et al (1977) undertook the strength increase with depth by modelling the clay layer as many thin layers with increasing strength parameters. The increase in strength with depth can be modelled quite easily using computer program such as SLOPE/W.

The result of stability analysis using more realistic clay strength parameters as adopted by Lacasse et al, (1977) is shown in Table 3 - Case 5. The result indicates that the assumption of constant strength with depth tends to underestimate the calculated Factor of Safety for about 10%, thus results in uneconomical design. It is thus important to model the increase of strength with depth in this case to obtain more realistic results.

4.5 Failure Surface

The observed failure surface of Muar-F embankment is shown in Figure 2. Inclinometer data provided by Indraratna et al. (1992) as given in Figure 3 showed that the actual failure surface is not abrupt (see Figure 2). Instead, the failure occurred gradually with maximum lateral deformation at about 5m from the ground surface.

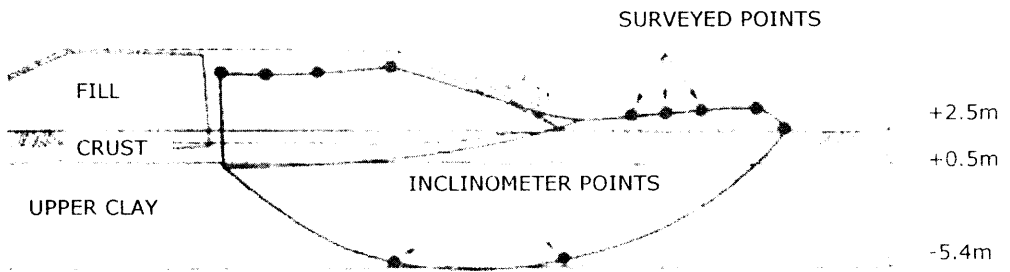


Figure 2. Muar-F failure plane at 5.4m high (Brand and Premchitt, 1989)

The failure surface obtained from limit equilibrium analysis (SLOPE/W) and FLAC are shown in Figures 4 and 5. Comparison between Figure 4 and Figure 5 reveals that the failure surfaces from limit equilibrium analysis and FLAC are in good agreement with the observed failure mode (Figure 2). The depth of failure surface is about 5.5m from the ground surface.

The deformation pattern of the embankment can closely be computed using FLAC as shown in Figure 3. The calculated movement at Inclinometer-3 (which is located underneath the downstream crest of the embankment) is larger in magnitude than the measured displacement. However, the pattern of deformation is similar. Thus, in addition to the calculated Factor of Safety of unity at failure height, a continuum mechanics approach utilising FLAC can predict realistic deformation pattern as well. Refinement on the soil stiffness for analysis can potentially increase the accuracy of the calculated deformations.

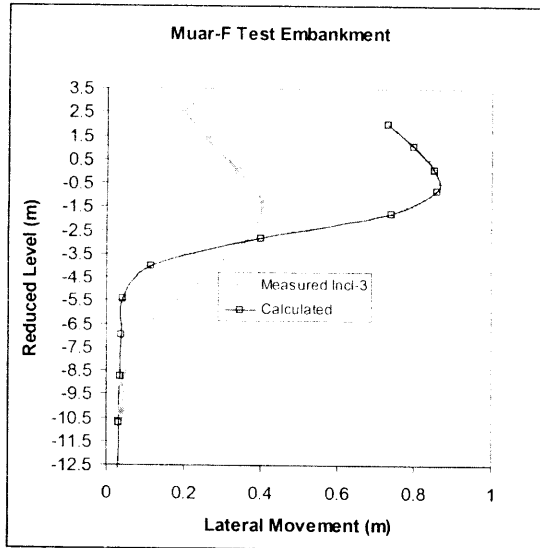


Figure 3. Calculated and measured lateral movement at Inclinometer 3 (beneath upstream embankment crest) using secondary data from Indraratna et al. (1992).

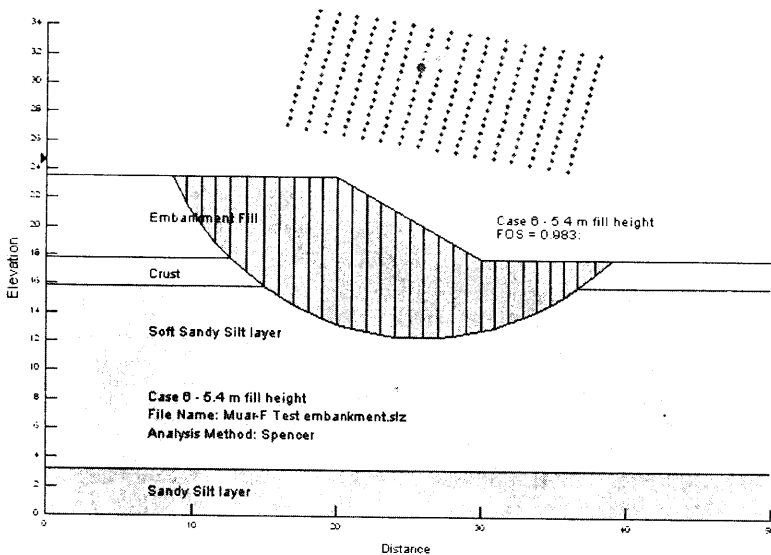


Figure 4. Failure surface from SLOPE/W. Geometry and soil properties from Indraratna et al. (1992).

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 FLAC (Version 4.00)

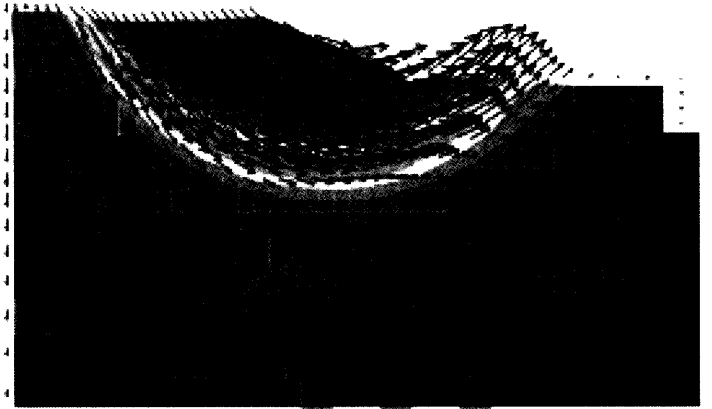


Figure 5. Failure surface from FLAC.
 Geometry and soil properties from Indraratna et al. (1992).

5. Summary and Conclusion

Several case histories of failed embankment have been analysed using limit equilibrium method and a continuum mechanic approach and the following conclusions can be drawn:

1. The error attributed to different methods of limit equilibrium analysis for the cases considered seems to be relatively less important than the error due to other factors such as assumption of soil strength, inclusion of fill strength in the analysis, and crust thickness and strength. However, in addition to proper judgment in determining soil design parameters and slope geometry, it is recommended to use methods that satisfy both force and moment equilibrium to minimise the error in calculating the Factor of Safety of slope.
2. Limit equilibrium analysis is reliable to predict the failure height of trial embankment as long as the embankment foundation does not comprise very sensitive soil exhibiting a soil softening behaviour.
3. A continuum mechanic approach provides “accurate” assessment of slope stability without having to assume any shape of failure surface. The method is superior to limit equilibrium analysis as it can also be used to predict the pattern of deformation. However, proper engineering judgment must be exercised in determining the soil stiffness.

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