Jurnal
Teknologi

Full Paper

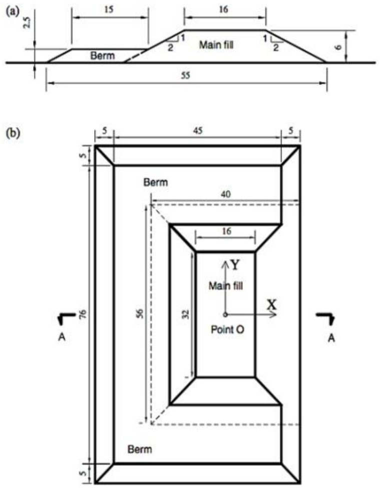
EFFECT OF WEATHERED SURFACE CRUST LAYER ON STABILITY OF MUAR TRIAL EMBANKMENT

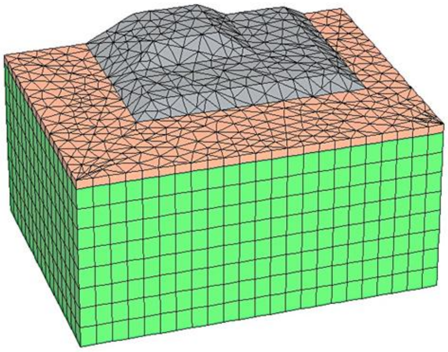
Ali Sobhanmanesh[a*], Ramli Nazir[a], Nader Saadatkhah[b]

[a]Ground Improvement Research Group, Department of Geotechnics and Transportation, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[b]Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

Article history
Received
6 July 2015
Received in revised form
26 July 2015
Accepted
30 July 2015

*Corresponding author
ali.sobhanmanesh@gmail.com





Abstract

This paper attempts to evaluate the effect of surface crust layer on the stability and deformation behavior of embankment. A full-scale case history trial embankment constructed on Muar flat in the valley of the Muar River in Malaysia was modeled and analyzed. The Muar trial embankment was simulated in two- and three-dimension (2-D and 3-D) utilizing finite element programs PLAXIS 2-D AND PLAXIS 3-D FOUNDATION, using staged-construction procedure. Sensitivity analysis was performed by varying the thickness of weathered crust layer beneath the embankment fill, i.e., three models of embankment with no surface crust, 1 m surface crust and 2 m surface crust layer. Predictions were made for the vertical and the horizontal displacements of the embankment. Factor of safety for each meter increase in the embankment height was defined until the failure is reached. It is concluded that the bearing capacity of the ground and the deformation behavior of the embankment were sensitive to the thickness of the weathered crust layer. The surface crust layer has a positive effect on the stability of the embankment and consequently reduces the settlement and increases the failure height of the embankment fill up to 37%.

Keywords: Muar trial embankment; surface crust layer; finite element analysis; stability analysis; safety factor

Abstrak

Kertas kerja ini cuba menilai kesan lapisan kerak permukaan terhadap kestabilan dan kelakuan deformasi tambakan. Kajian skala penuh terhadap tambakan cubaan yang di bina di atas dataran Muar di kawasan lembangan Sungai Muar di Malaysia telah dimodel dan analisa. Tambakan percubaan Muar disimulasikan dalam dua dan tiga dimensa (2-D dan 3-D) menggunakan program unsur terhingga PLAXIS 2-D dan PLAXIS 3-D FOUNDATION, melalui prosidur peringkat pembinaan. Analisis kepekaan telah dijalankan dengan mengubahsuai ketebalan lapisan kerak dibawah tambakan, iaitu tiga model tambakan, tanpa tambakan, 1 m kerak permukaan dan 2 m kerak permukaan. Ramalan di buat pada anjakan tegak dan mengufuk. Faktor keselamatan untuk setiap meter kedalaman ditentukan sehingga gagal. Boleh dirumuskan bahawa keupayaan galas dan sifat deformasi tambakan adalah peka terhadap ketebalan lapisan kerak permukaan. Kerak permukaan mempunyai kesan positif terhadap kestabilan dan seterusnya mengurangkan enapan dan meningkatkan ketinggian kegagalan tambakan sehingga 37%.

Kata Kunci : Tambakan percubaan Muar; lapisan kerak permukaan; analisis unsur terhingga; analisis kestabilan; faktor keselamatan

1.0 INTRODUCTION

Construction of embankments on soft ground raises several concerns due to inappropriate and weak properties of the subsoil. Low shear strength and high compressibility have led to continuing settlement of highway embankments and hence to considerable maintenance expense [1].

A significant extent of the North-South Expressway, from Bukit Kayu Hitam at the Malaysia-Thai border to Johor Bahru at the southernmost location, traverses soft marine or coastal alluvium. The coastal deposits of Peninsular Malaysia are Quaternary deposits of the Cenozoic era. The deposits are geologically unsedimented and constitute a complex inter-bedding of marine and non-marine strata with usually a few meters natural hard weathered surface crust layer above it [2].

Surface crust layer usually can be observed in many soil profiles of typical soft clay because of the factors such as weathering, desiccation from evaporation and other chemical-physical effects. This crust layer has a higher strength and stiffness compared to the underlying clay.

There is a difference between the failure mode of a soft foundation with upper crust and a homogeneous soft foundation. Meyerhof and Hanna [3],[4] proposed empirical solutions with wide range of applicability in practice.

Merifield *et al*. [5] believed that there are different failure mechanisms that are functions of both the crust thickness and its strength relative to the underlying looser layer.

Zhang *et. al.* [6] utilized a centrifugal model test to investigate the failure mode of a soft foundation with a hard clay crust and to analyze the effects of the crust on the horizontal and vertical additional stress distribution inside of the soft soil stratum.

Wen and Cai [7] studied the change law of horizontal stress on the surface of the soft substratum using laboratory tests. Researches showed that, due to the closure effect of the hard crust, an excess pore pressure was produced when the stiff crust layer is under loading and the horizontal additional pressure can be spread more widely [8]. It causes more strengthening of the bearing capacity of the soft foundation with an upper crust layer [6].

Therefore, as the surface crust layer may improve the bearing capacity and shear strength of the ground, consequently it can increase the failure height of the embankment. Hence, it is important to evaluate the effect of crust layer on the failure mechanism and define to what extent it can improve the stability and increase the critical (failure) height of the embankment.

The critical (failure) height of embankment is defined as the embankment loading caused by the shear stress of undrained shear strength of foundation soil [9].

Leroueil and Tavernas [10] and Leroueil *et al.* [11] proposed practical and simple method for calculation of the critical height of embankment. Wang [12] has simplified embankment loading for strip uniform loading. Wen *et al.* [13] has carried out the analysis of the closure effect and stress dispersion of crust.

Zhu *et. al.* [9] utilized analytical approach to study the effect of the crust layer on critical embankment height. They considered both stress dispersion effect and shear strength of crust layer, based on Flamant formula of polar coordinates representation and Mohr-Coulomb strength criterion. They deduced a new formula of critical edge pressure of natural soft foundation considering the realistic coefficient of lateral earth pressure.

In this study, numerical approach by using finite element analysis was carried out to evaluate the effect of the surface crust layer on the behavior and failure height of the Muar trial embankment constructed on Malaysian soft marine coastal alluvium.

2.0 MATERIALS AND METHODOLOGY

To evaluate the influence of weathered surface crust layer on the stability of Muar trial embankment, sensitivity analyses performed by 2-D and 3-D finite element modeling using Plaxis 2D and 3D Foundation programs respectively. In order to assess the effect of crust layer, numerical modeling of Muar trial embankment constructed on different depths of surface crust layer was carried out. The comparison of these models (with and without the surface crust) makes it possible to evaluate the effect of surface crust on the whole behavior of embankment e.g. change in the deformation pattern of the ground and increasing the bearing capacity of soft soil and consequently the failure height of embankment due to the existence of surface crust.

2.1 Muar Trial Embankment

The Muar trial embankments were constructed on Muar flat in the valley of the Muar River. Figures 1 (a) and 1 (b) show the plan view and cross section of the Muar trial embankment respectively. The main fill has a design height of 6 m with slope of 1V:2H and was surrounded with 2.5 m high berm at three-sides [1].2-D and 3-D models of Muar embankment were simulated in PLAXIS. The generated mesh for 2-D and 3-D finite element models are shown in Figures 2 (a) and 2 (b), respectively. The 2-D mesh consisted of 558 element and 4621 nodes. The 3-D mesh consisted of 9893 element and 27804 nodes.

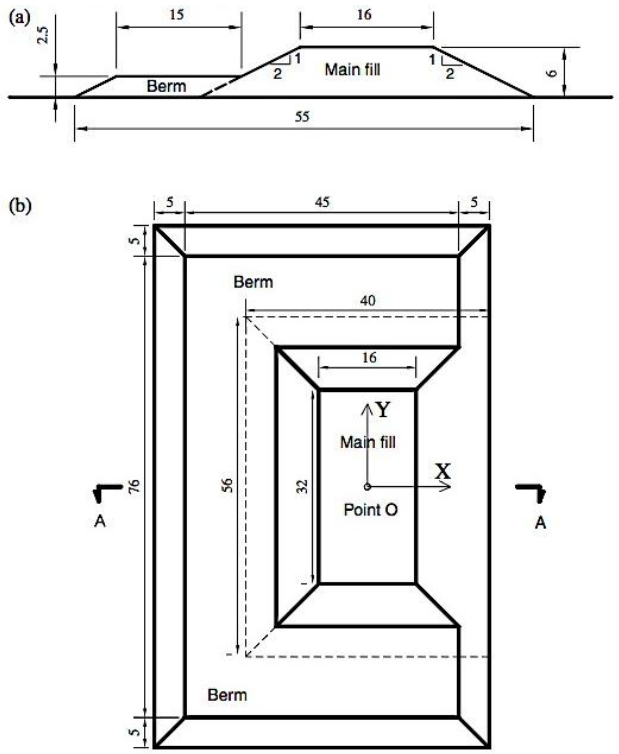
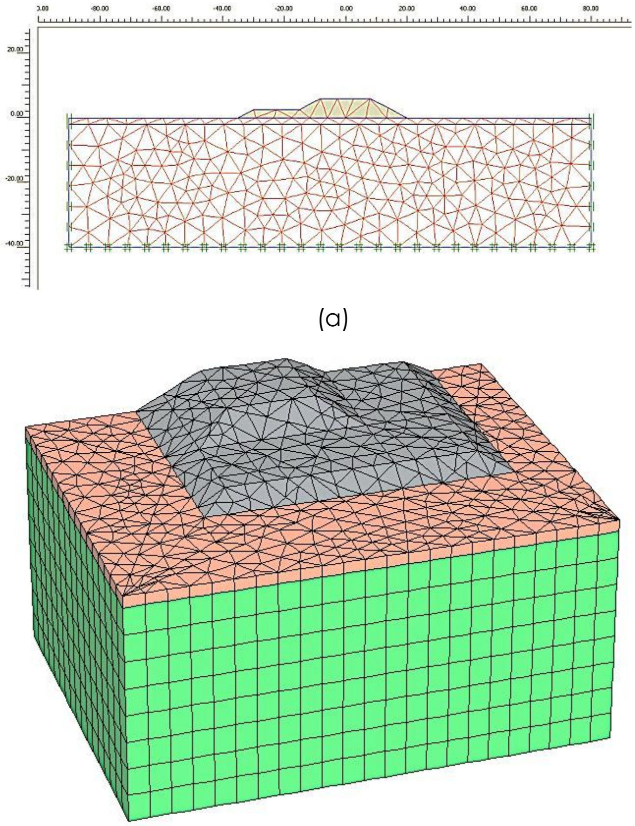


Figure 1 Muar Trial Embankment (a) cross-section, (b) plan view of

As shown in Figure 2, a 40-meter deep foundation layer is considered sufficient because of the existence of a layer of firm and dense sand below this depth. The subsoil model was assumed to be fixed at this depth, because the deformation of the below firm layer is small enough to be assumed to be zero. The horizontal boundaries should also be considered sufficiently far from the embankment centerline, so that it does not influence the stress-strain field around the model. According to Balasubramaniam *et al.* [3], the lateral boundaries of the sub-soils can be considered three times of the depth of clay layer, from the toe of the embankment. Therefore, the horizontal boundaries were extended and restrained at a distance of about 80 m from the centerline to assure that the lateral movement is small enough to be ignored at the end of this boundary.



(a)

(b)

Figure 2 FE mesh of Muar trial embankment (a) 2-D mesh (b) 3-D mesh

2.2 Soil Conditions

According to the Malaysian Highway Authority (MHA 1989), the subsoil comprises a weathered crust of 2-m thick, underlain by deposit of very soft silty clay soil with height of 6 m; and a 10 m layer of soft to firm silty clay soil. These clayey deposits overlie a 0.5 m layer of peat, 3.5 m sandy clay, and finally a layer of dense sand. Figure 3 describes the stratum and the shear strength profile of the subsoil layers. The assumed green line of Figure 3 shows the undrained shear strength has a linear incremental trend as depth beneath the weathered crust increases. As Lo and Hinchberger [4] recommended, the undrained shear strength of the crust was considered one-third of the field vane strength to account for the probable existence of fissures.

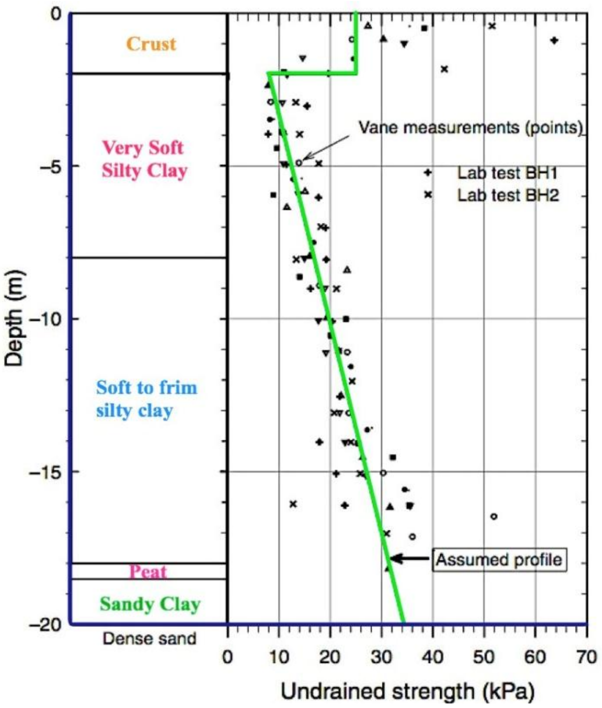


Figure 3 Soil strata and strength profile of the Muar trial embankment (data from MHA 1989)

In the FE analysis of the Muar trial embankment, the clay soil was considered to have an undrained behavior and fill material considered to have a drained behavior. Mohr-coulomb criterion was utilized for both fill and foundation soils. Parameters of the fill and the foundation subsoil used in the FE analyses are presented in Tables 1 and 2.

Table 1 Properties of fill embankment soil

Soil layer	Fill Material
Model	Mohr-Coulomb
Material Type	Drained
γ_{unsat} (kN/m^3)	20.5
γ_{sat} (kN/m^3)	22
c'(kN/m^2)	14
ϕ	31°
E (kN/m^2)	5100
Poisson ratio, ν	0.3

Table 2 Properties of foundation layers

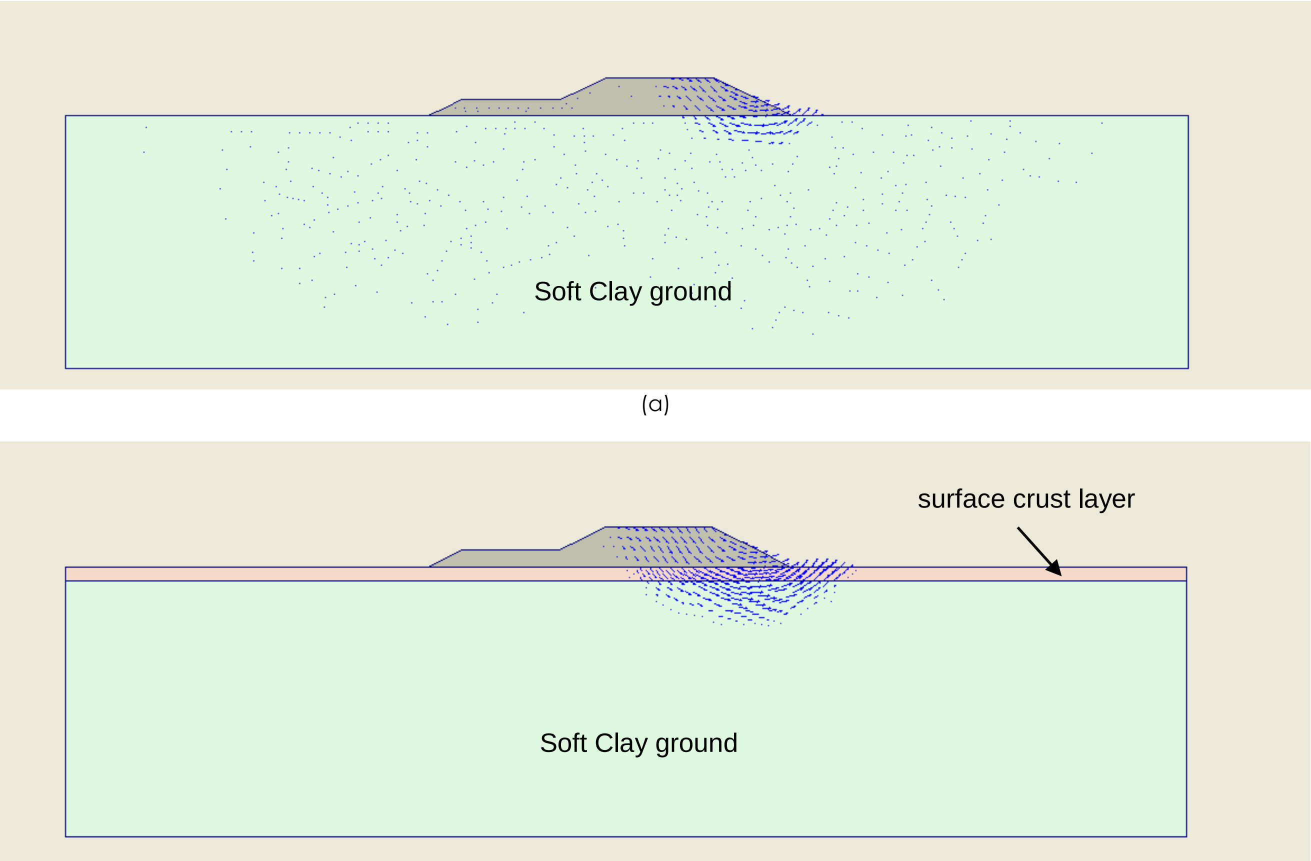
Soil layer	Surface Crust layer	Underlying soft clay layer
Depth	0-2	2-40
Model	Mohr-Coulomb	Mohr-Coulomb
Type	undrained	undrained
γ (kN/m^3)	17	16
$C_{u\ ref}$	25	8
$C_{u\ increment}$	0	1.48
E_u (kN/m^2)	25000	8000
Poisson Ratio,ν	0.33	0.33
K_0	1	0.9

3.0 RESULTS AND DISCUSSIONS

Velocity field of displacements developed by construction of embankment on grounds with and without surface crust layer is shown in Figures 4 (a) and 4 (b).

Figure 4 show that deformation pattern is somewhat different for the models with and without surface crust layer. For model without surface crust, a shallow slip is observed to take place around the embankment toe. For the model with surface crust, deformations develop over wider range and failure slip is observed below the lower end of the crust, where the shear strength is minimum in the ground.

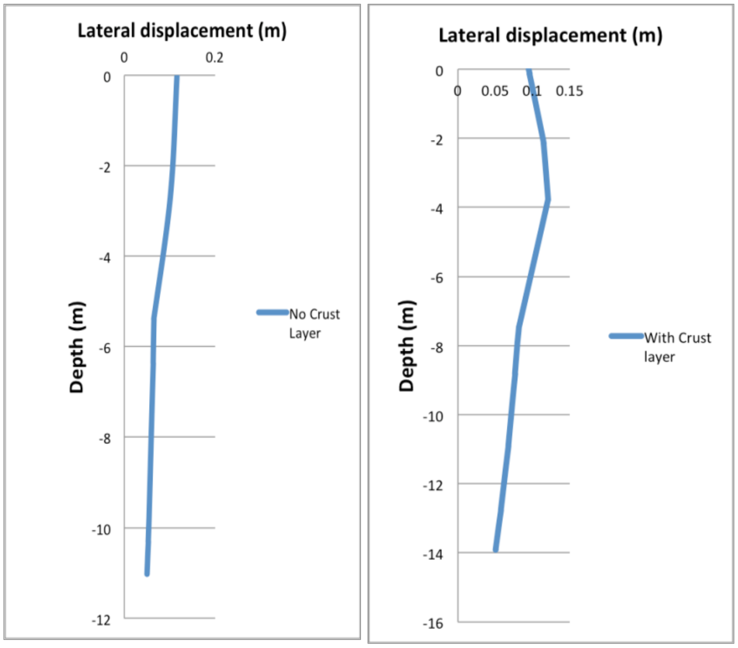
This demonstrates a horizontal sliding takes place below the lower boundary of the surface crust. The graph of lateral movement along the depth of ground beneath the embankment fill is shown in Figure 5 (a) and 5 (b) for the models with and without surface crust, respectively. The 3-D deformed mesh and contour shading of lateral movements for a section below the embankment toe are shown in Figures 6 and 7 for the models with and without crest layer, respectively. Based on these figures it is clear that for the case with crust layer, the maximum lateral displacements developed beneath the embankment toe below the lower boundary of the surface crust in the soft clay deposit where the soil rigidity is minimum. While for the case without crust layer the maximum lateral displacement developed below the embankment toe at the higher boundary of the soft clay deposit.



(a)

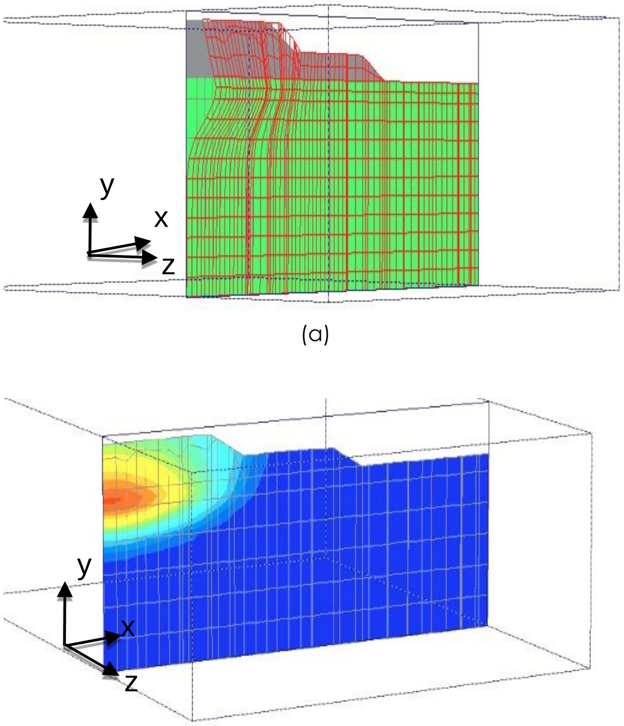
(b)

Figure 4 Deformation velocity field (a) without crust layer (b) with crust layer



(a) (b)

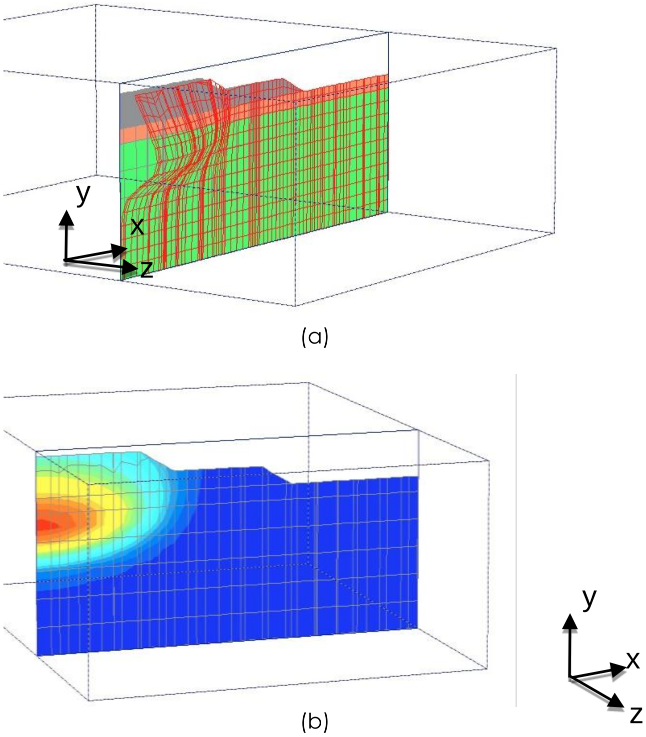
Figure 5 Lateral displacement of ground for 2-D model: (a) with crust layer and (b) without crust layer



(a)

(b)

Figure 6 Lateral displacement of 3-D model without crust layer: (a) deformed mesh (b) shading contour



(a)

(b)

Figure 7 Lateral displacement of 3-D model with crust layer: (a) deformed mesh (b) shading contour

3.1 Stability Analysis And Evaluation Of Safety Factor

The global safety factors can be computed in PLAXIS by means of *Phi-C* reduction method by using the *Safety* calculation type. In this method the strength parameters tan φ and c of the soil are continuously reduced until failure of the embankment occurs. The total multiplier Σ*Msf* is used to define the value of the soil strength parameters at a given stage in the analysis.

In structural engineering, the safety factor is usually defined as the ratio of the collapse load to the working load. For soil structures, however, this definition is not always useful. For embankments, for example, most of the loading is caused by soil weight and an increase in soil weight would not necessarily lead to collapse. Indeed, a slope of purely frictional soil will not fail in a test in which the self-weight of the soil is increased as in a centrifuge test [3]. A more appropriate definition of the factor of safety is therefore:

$$\text{Safety factor} = \frac{S_{\text{maximum available}}}{S_{\text{needed for equilibrium}}} \qquad (1)$$

Where *S* represents the shear strength. The ratio of the true strength to the computed minimum strength required for equilibrium is the safety factor that is conventionally used in soil mechanics. By introducing the standard Coulomb condition, the safety factor is obtained:

$$\text{Safety factor} = \frac{c - \sigma_n \tan\varphi}{c_r - \sigma_n \tan\varphi_r} \qquad (2)$$

Where c and φ are the input strength parameters and σ_n is the actual normal stress component. The parameters c_r and φ_r are reduced strength parameters that are just large enough to maintain equilibrium. The principle described above is the basis of the method of *Safety* that can be used in PLAXIS to calculate a global safety factor. In this approach the cohesion and the tangent of the friction angle are reduced in the same proportion:

$$\frac{c}{c_r} = \frac{\tan\varphi}{\tan\varphi_r} = \sum Msf \qquad (3)$$

The reduction of strength parameters is controlled by the total multiplier Σ*Msf*. This parameter is increased in a step-by-step procedure until failure occurs. The safety factor is then defined as the value of Σ*Msf* at failure, provided that at failure a more or less constant value is obtained for a number of successive load steps (Brinkgreve, 2010). Figure 8 shows the evaluation of safety factor for two stage of construction process in which the parameter Σ*Msf* is plotted against the displacements of node O at center of the Muar trial embankment with crust layer of 2 m depth.

In this research, to show the effect of crust layer on the stability and failure height of embankment, graph of embankment height to the safety factor for models with different thickness of crust layer was plotted and illustrated in Figure 9.

It is seen that the failure height of embankment had a direct relation with the depth of crust layer, i.e., the ground with thicker surface crust layer is able to support higher embankment fill. The computed failures heights of Muar embankment for various depths of crust layer regards to the safety factor of 1.0 and 1.5 are shown in Table 3.

Based on Table 3, it is shown that a 2.0 m surface crust layer could increase the failure height of Muar trial embankment up to 37% compared to the models without any surface crust layer.

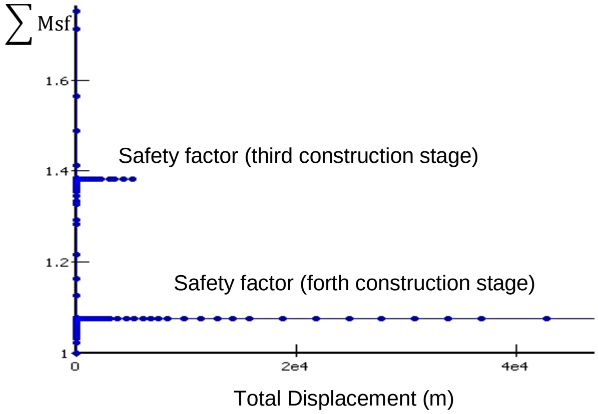


Figure 8 Evaluation of safety factor for third and fourth stages of construction process

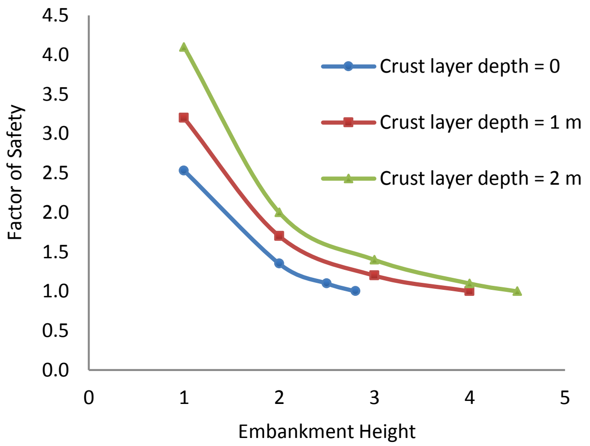


Figure 9 Effect of surface crust layer on the stability of Muar trial embankment

Table 3 Failure height of embankment for various depths of crust layers

Thickness of crust layer (m)	Failure Height of Embankment (m)	
	F.S ≅ 1.0	F.S ≅ 1.5
2	4.5	2.8
1	4.0	2.4
0	2.8	1.8

4.0 CONCLUSION

The behavior of a surface crust layer on a soft foundation was investigated using the numerical modeling by means of finite element simulations. Particular attention was given to the deformation behavior and failure height of the embankment. The following conclusions were drawn from the study:

1. For the soft foundations with upper crust layer, the movement flow of the soft soil is more constraint from the embankment toes due to the closure of the stiff surface crust layer, unlike the homogeneous soft ground. The vertical stresses of the soft foundation are disseminated as the hard crust can spread the stresses to a larger range, hence it can be effective to decrease the settlement of the foundation.
2. The sensitivity analysis of Muar trial embankment verified that the surface crust layer above the soft clay deposit has a positive effect on stability of embankment by increasing the bearing capacity and the shear strength of the soft foundation ground. The results show that for embankment on Muar clay, a 2.5-meter crust layer increases the failure height of embankment up to 37%.
3. It is shown that, the failure height of embankment had a direct relation with the depth of crust layer, i.e., the ground with deeper crust layer is able to support higher embankment fill.
4. It has also effect on the lateral movements of the embankment. For the case with crust layer, the maximum lateral displacements develop beneath the embankment toe below the lower boundary of the surface crust in the soft clay deposit where the soil rigidity is minimum, while for the case without crust layer the maximum lateral displacement develops below the embankment toe at the higher boundary of the soft clay deposit.
5. As the soft foundation with surface crust layer, can improve the bearing capacity, it is useful to utilize this closure effect for cost and time

period reduction of foundation treatments in practices.

Acknowledgement

The authors would like to thank the Faculty of Civil Engineering, Universiti Teknologi Malaysia (UTM) and Ministry of Science, Technology and Innovation (MOSTI) for providing financial support for this research through research vote: #4S077.

References

[1] Koerner, R. M. 2005. *Designing with Geosynthetics*. 5th ed. Prentice Hall.

[2] Hudson, R. R., Toh, C. T. and Chan, S. F. 1989. The embankment built to failure. In: (eds.), *The International Symposium on Trial Embankments on Malaysian Marine Clay*. Kuala Lumpur: Malaysian Highway Authority.

[3] Meyerhof, G. G. and Hanna, A. M. 1978. Ultimate bearing capacity of foundations on layered soils under inclined load. *Canadian Geotechnical Journal.* 15(4): 565-572.

[4] Meyerhof, G. G. 1974. Ultimate bearing capacity of footing on sand layer overlying clay. *Canadian Geotechnical Journal*. 11(2): 223-229.

[5] Merifield, R. S. Sloan, S. W. and Yu, H. S. 1999. Rigorous plasticity solutions for the bearing capacity of two-layered". *Geotechnique*. 49(4): 471-490.

[6] Zhang, J. Yao, Y. Zheng, J. Zhou, C. 2014. Centrifugal Model Test of Failure Mode and Addition Stress Distribution of a Soft Foundation with an Upper Crust. *Electronic Journal of Geotechnical Engineering (EJGE).* 19: 9309-9322.

[7] Yan-xu, W. Xia, C. 2009. Mechanism analysis of abutment pile foundation on soft ground affected by closure effect. *Soil Engineering and Foundation*. 23(5): 43-46.

[8] Xizhao, W. Yongcheng, X. 1996. A Study of the Horizontal Stress in Mucky Layer under Surface Loads. *Journal of Shijiazhuang Railway Institute*. 9(4): 11-16.

[9] Zhu, F. Zhan, G. Nie, L. 2012. Study on a Calculation Method of Critical Embankment Height on Natural Soft Foundation Considering the Effect of Crust Layer. *Applied Mechanics and Materials.* 208: 202-209.

[10] Leroueil, S. Tavenas, F. Roy, M. 1978. Construction pore pressures in clay foundations under embankments. Part I: the Saint-Alban test fills. *Canadian Geotechnical Engineering*. 15: 54-65.

[11] Leroueil, S. Tavenas, F. 1978. Construction pore pressures in clay foundations under embankments. Part II: generalized behaviour. *Canadian Geotechnical Engineering*. 15: 66-82.

[12] Xiaomou Wang. 2002. Calculation of proportional limit load for soft clay foundation involving the effect of dry crust. *Chinese Journal of Geotechnical Engineering*. 24(6): 720-723.

[13] Wen, Y. Zhou, J. Jia, M. 2007. Critical edge pressure of soft clay foundation considering closure effect and stress dispersion of crust. *Rock and Soil Mechanics*. 28(8): 1715-1718.

[14] Balasubramaniam, A. S. Phien-WEJ, N. Indraratna, B Bergado, D. T. 1989. Predicted behavior of a test embankment on a Malaysian marine clay. In: *International Symposium On Trial Embankments On Malaysian Marin Clays.* Kuala lumpur: The Malaysian highway authority. 1–8.

[15] Lo, K. Y. Hinchberger, S. D. 2006. Stability analysis accounting for macroscopic and microscopic structures in clays. *Proceedings of the 4th International Conference on Soft Soil Engineering*, 2006, Vancouver, B.C.: Taylor and Francis, London, 3–34.

[16] Brinkgreve, R. B. J. 2010. *PLAXIS 2D Reference Manual*. The Netherlands: Delft University of Technology & Plaxis B. V.