ISSN 2278-3091
Volume 8, No.1.6, 2019
International Journal of Advanced Trends in Computer Science and Engineering
Available Online at http://www.warse.org/IJATCSE/static/pdf/file/ijatcse6481.62019.pdf
https://doi.org/10.30534/ijatcse/2019/6481.62019

Stability Assessment of Embankment on Soft Soil Improved with Prefabricated Vertical Drains Using Empirical and Limit Equilibrium Approaches

Rufaizal Che Mamat[1,2], Azuin Ramli[3], Abd Manan Samad[4], Anuar Kasa[5], Siti Fatin Mohd Razali[6], Mohd Badrul Hafiz Che Omar[7]

[1]PhD candidate,Centre of Engineering and Built Environment Education Research (PeKA),Universiti Kebangsaan Malaysia, Malaysia, rufaizal.cm@gmail.com
[2]Senior lecturer, Department of Civil Engineering, Politeknik Ungku Omar, Malaysia, rufaizal@puo.edu.my
[3]Senior lecturer, Department of Civil Engineering, Politeknik Ungku Omar, Malaysia, azuin.ramli@puo.edu.my
[4]Professor, Faculty of Architecture, Planning & Surveying, Universiti Teknologi MARA, 40450 Shah Alam, Selangor,Malaysia, dr_abdmanansamad@ieee.org
[5]Senior lecturer, Centre of Engineering and Built Environment Education Research (PeKA), Universiti Kebangsaan Malaysia, Malaysia, anuar@eng.ukm.my
[6]Senior lecturer, Smart and Sustainable Township Research Centre (SUTRA), Universiti Kebangsaan Malaysia, Malaysia, fatinrazali@ukm.edu.my
[7]PhD candidate, Faculty of Architecture, Planning & Surveying, Universiti Teknologi MARA, 40450 Shah Alam, Selangor,Malaysia, 2019563007@siswa.uitm.edu.my

ABSTRACT

This article provides an assessment study of the embankment stability on soft soil improved with prefabricated vertical drains (PVDs). An empirical approach based on Barron theory is used to predict settlement grounds with PVDs and compared to measured. This comparative study is essential to validate the soil parameters in analyzing the stability of the embankment with a limit equilibrium method (LEM). The effectiveness of PVDs and geotextiles installations has also been investigated in stabilizing the soft soil beneath the embankment. This study reveals that the ground improvement by PVDs has an effect on reducing the vertical displacements of subsoil. The geotextiles installed under the embankment provides higher stability to the surface soil, and the maximum settlement can be reduced in the long term period.

Key words : Soft soil; Prefabricated vertical drains; Settlement; Slope stability; Limit Equilibrium method.

1. INTRODUCTION

Precisely predicting the behaviour of embankments constructed on soft soil stabilized with vertical drains remained a challenging issue, although tremendous progress has been made via rigorous numerical model over the past few years [1]. Reducing long-term infrastructure settlement and ensuring cost-effective foundations with sufficient load-bearing capacity are strategic priorities in most countries for infrastructure development. Poor soil characteristic can cause excessive settlement, causing undrained infrastructure failure if proper soil improvement is not performed [2]. Hence it is important to apply appropriate ground improvement techniques to existing soft soils prior to construction in order to avoid inappropriate excessive and unequal settling along with improving the bearing capacity of the foundations [3]. One of the effective soil improvement techniques practised worldwide is the installation of prefabricated vertical drains (PVD).

The primary concern of the embankment design is the stability and settlement of the ground foundation. Construction on soft soil leads to major problems such as the high magnitude of settlement [4]. In order to improve the workability of the embankment on soft soil, ground improvement should be performed. There are several commonly used improvement methods such as the installation of PVDs [5], piles [6], geotextiles [7] and stone column [8]. However, the installation of PVDs and geotextiles can reduce construction costs [9].

In recent years, there has been an increasing interest among researchers in settlement predicting [10], simulating the behaviour [11] and developing analytical solutions [12] of the embankment with PVDs. Factors found to be influencing embankment stability with PVDs have been explored in several studies [13]–[15]. However, a major problem with this kind of application is that its effect on stability is limited in the existing literature.

Thus, the performance of PVDs and geotextiles installed under the embankment was assessed to investigate its effectiveness in this study. The settlement of soft soils under the embankment was predicted by empirical methods and compared with measured. The slope stability analysis of the embankment was performed using the LEM.

2. CONSOLIDATION OF SOFT SOIL

Soft soil consolidation is an important aspect that needs to be considered for large construction projects in or near coastal areas. The main purpose of soft soil consolidation with PVDs is to achieve the required degree of consolidation within a specified period of time. In the classical one-dimensional consolidation Terzaghi's theory [16], consolidation due to vertical drainage is considered only for natural drainage boundaries [17]. In 1948, Barron [18] summarized the one-dimensional reinforcement theory presented a comprehensive solution to the problem of reinforcement for cylindrical-shaped soil with sand drainage in the middle. The method allows the issue of settlement to be solved into two conditions, namely independent vertical deformation and equivalent vertical deformation. Both of these conditions provide an almost uniform settlement. Several assumptions have been made to develop solutions for horizontal reinforcement using a ground cylinder with vertical drainage. Some of the assumptions made are:

(i) Soil is homogeneous and isotropic and saturated.
(ii)The compression of details and water is negligible.
(iii) The burden used is uniformly distributed.
(iv) The average reinforcement is calculated based on pore pressure.
(v) The stress that occurs is in the vertical direction only.
(vi) The legality of Darcy's law.
(vii) The drainage effect zone is round and axisymmetric.

In multi-stage construction, the estimation of the degree of consolidation or ultimate settlement of soft clay is significant. This can be evaluated by field instrumentation using settlement gages and piezometers. The field settlement can be measured using different methods to determine the final soft soil settlement from the time of initial installation. In 1978, Asaoka [19] proposed a revised method of using Barron solution [18] for pure radial drainage to solved consolidation problems with vertical drains [4]. The prediction of the ultimate settlement is affected by the period after the placement of the surcharge as well as the time interval used for the assessment [11]. It is difficult to assess the best fit line through the data points at small intervals. In order to assess the best-fit line through the data points, a longer time interval may require a long-term instrumentation monitoring program.

3. LIMIT EQUILIBRIUM METHOD

In slope stability measurement, limit equilibrium method (LEM) is widely used by researchers and engineers for many years [20]–[22]. Due to the rapid growth of software technology and the increasing popularity of the limit equilibrium method in geotechnical engineering, it is now practicable to perform a comprehensive numerical study of the soft soil behaviour stabilized with multiple vertical drains. Two-dimensional plane strain analysis is widely used for simplicity in the field of slope stability [3], [17], [23]. The two-dimensional slope stability analysis of LEM is considered to be a statically indeterminate problem, and an evaluation of the safety factor (FOS) involves assumptions on the internal force distribution [24]. The factor of safety (FOS) defines the structural strength of an embankment or slope beyond the anticipated or actual loads, whether natural or excavated. The surface of the critical slip is the surface that corresponds to the minimum FOS value. In the problem of plane strain, in many existing LEM, the slip surface is assumed to be a circular arc and could be a combination of a straight line and a circular arc, or a combination of a straight line and a logarithmic spiral.

4. METHODOLOGY

The site under study is located at Ujung Pasir, Melaka. The area surrounding the project was known located over soft soil deposit of soft clay, silt and sand. Thus, relevant data such as the properties of soil both before and after ground improvement work was collected from the results of soil investigation performed prior to ground improvement and after the ground improvement. The pre-compression and vertical drain method was implemented as ground improvement of the project.

The field monitoring was performed to observe the settlements obtained from rod settlement gauges. In addition, the achievement of ground improvement criteria can be evaluated by observing the time required to reach the predetermined criteria of the ground improvement project through settlement monitoring. Settlement analysis was performed for backfilling on original soil without and with surcharge preloading and vertical drain following the method suggested in the Barron solution [18]. This solution was used to predict the settlement rate based on the data obtained from the laboratory.

4.1 Field works

The soil conditions are determined from a geotechnical site investigation comprised of field and laboratory studies. A site investigation was conducted, which included drilling ten (10) boreholes from which samples were extracted using 3-inch diameter Shelby tubes for laboratory testing. In addition, four (4) Standard Penetration test (SPT) were conducted and also obtained a disturbed soil sample for the visual examination and laboratory testing. Standard Penetration Test (SPT) was carried in accordance with Test No. 19 BS 1377:1975.

The foundation layer consists of four layers; starting from the bottom, it consists of 10m soft clay layer, 9m very soft clay layer, 1.0m suitable fill and 1.5m sand blanket. After obtaining the soil properties of the test area, the topsoil was removed before the tests. The construction procedures are summarized as follows:

(i) Install geotextiles after 7 days.
(ii) The existing ground level is on average at reference level (RL) 2.2m and finish platform level is at RL 3.7m thus required approximately 1.7m fill.
(iii) The geotechnical instrument was installed and summarised in Table 1.
(iv) The PVDs were installed at a spacing of 1.2 m c/c

arranged in a triangle along the embankment. The PVDs have penetrated a depth of about 18m into the subsoil.

(v) Placing embankment surcharge using homogeneous soil with 2H: 1V side slope and compacted.

(vi) 20 kPa traffic loads is applied. In order accelerated consolidation surcharge of 1.5m adopted with a rest period of 6 months.

(vii) The embankment is allowed to be consolidated for a six month, and the settlement measurement is performed.

A field monitoring program has been established to monitor surface and underground settlements, excessive pore pressure and lateral movements. A total of 5 settlement plates, 4 inclinometers and 3 piezometers were installed in each test embankment. Near the center of the test embankment, the surface and subsurface settlement gauge are installed. At a vertical interval of 3 m, sub-surface settlement gauges and piezometers were installed. The plan and details of the embankment instrumentation are given in Table 1.

Table 1: Summary of instrumentations

Instruments Type	Numbers	Location
Standpipe Piezometer	1	Located at least 10m away from embankment
Vibration Wire Piezometer	3	Depth 6m, 9m, 12m below ground in one borehole located 10m from embankment edge
Inclinometer Casing	4	Depth 33m located 1.0m from embankment toe
Settlement Plate / Gauge	5	Placed below sand blanket located at edge of embankment and centre
Settlement Marker	9	Placed on top of surcharge, located at embankment edge and centre

The data will be summarized and interpreted in accordance with the parameters required for the settlement evaluation of empirical analysis. The subsoil properties were calculated on the basis of the site investigation report being modelled in the LEM. The soil properties used to represent the stress-strain behaviour and strength of the soft clay, and very soft clay are shown in Table 2.

Table 2: Soil parameters for stability analysis

Soil	Thick (m)	Unit Weight (kN/m^3)	Soil Cohesion (kN/m^2)	Friction angle
Very Soft Clay	9.0	15.0	15.0	0.0
Soft Clay	10.0	16.0	25.0	0.0
Suitable Fill	1.0	19.0	5.0	28.0
Sand Blanket	1.5	18.0	0.0	30.0

4.2 Subsoil condition

The basic properties of average SPT-N values, initial void ratio (e_0), specific gravity (G_s) and compression index (c_c) are summarized together in Table 3. Subsoil profile consists of very soft clay at 9m thickness. It is underlain with soft clay at 10m thickness and follows by a sand blanket at 1.5m thickness. It is then underlain by homogenous soil as a suitable fill at 1m thickness.

Table 3: Summary of the soft ground properties

BH	Depth (m)	Sample No	P_c (kN/m^2)	C_c	e_o	C_v (m^2/yr)
BH 1	4.5	UD1	30	0.69	1.56	0.66
BH 1	10.5	UD2	75	0.25	0.83	1.03
BH 2	4.5	UDI	45	1.39	3.57	1.35
BH 2	7.5	UD2	34	0.40	1.35	0.93
Average			46	0.68	1.83	0.99

Consolidation parameters have been adopted using the average values. It is shown that the anticipated geotechnical problem is related to the strength and settlement of the embankment. Hence, PVD with surcharge was implemented as a ground treatment for accelerated settlement. In addition, strengthening the stability of the embankment using PEC-150 was used to increase the stability of the embankment.

5. SETTLEMENT ANALYSIS

The one-dimensional (1D) consolidation theory of Terzaghi [16] was used to estimate the settlements of the 1D primary consolidation. Settlement analysis was made for the anticipated settlement under backfilling to the design platform and compensation fill. The settlement under backfill and surcharge fill of 1.5 m was evaluated to observe the effect of pre-compression. Effect of the vertical drain in speeding up the consolidation process was also evaluated.

The performance of ground improvement can be identified by the achievement of the prescribed performance criteria and the improvement in terms of engineering properties. In order to verify the design analysis, an instrumented embankment was constructed prior to the commencement of earthwork. The achievement of the performance criteria was evaluated by settlement measurement and the achievement of the predicted settlement in terms of time. Due to vertical drainage U_v and radial drainage U_r is provided by Asaoka, considering the effect of smear and well resistance factors on the combined degree of consolidation U given by equation (1).

$$U = 1 - (1 - U_v)(1 - U_r) \tag{1}$$

Different types of treatment include, vertical drains treatment and surcharge treatment were used to treat the soft clays to minimize the differential settlement and to avoid costly maintenance of projects. The control situation embankment without treatment also used to assess the performance of soil settlement. About 1.5m surcharge was used for consolidation of soft subsoil.

Table 4: Summary of the settlement at the 90% of consolidation

Treatment	Settlement (m)	Time (month)
Without Treatment	1.03	1087
PVD & surcharge	1.03	7
Surcharge	1.03	1087

The settlement measurement in Table 4 indicates that in general, the embankment had reached the targeted 90% consolidation in less than 7 months after the construction. Resting period of about 6 months was required to reach the prescribed consolidation settlement before the surcharge could be removed. The results also show that the embankment without treatment and with surcharge treatment had reached the targeted 90% consolidation in a long period of time. The estimation of the final settlement by the Barron method is influenced by the evaluation period after the placement of the surcharge as well as the time interval used for the analysis.

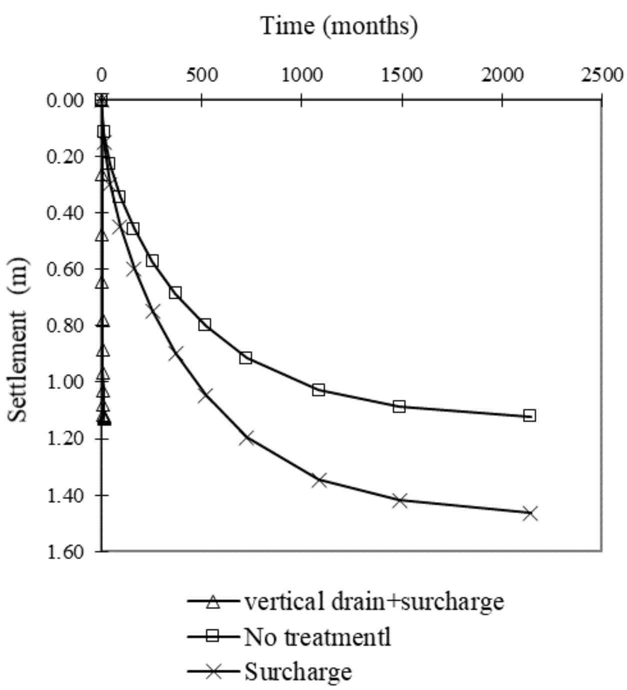

Figure 1: Time – settlement curve for different embankment treatment.

Figure 1 shows the graph of field time (t) –settlement (S_t) curve from settlement monitoring. From the data in these figures, it is apparent that the consolidation settlement process is faster during the initial stage of embankment filling, which shows a significant difference in magnitude of settlement. The differences in cumulative settlement term, however, are decreasing and attempting to converge for a long-term consolidated period. A possible explanation for these results may be due to the compaction energy that during the first stage of sand cushion filling imposed on the upper layer of soft clay resulting in a higher settlement rate that cannot be modelled. This finding is in agreement with Mamat et al., [17] results that after the consolidation of 70% to 90%, the consolidation rate decreases to a minimum value and enabling second-stage loading is economically and technically feasible. At this point, the additional load will increase the shear strength of the subsoil.

6. SLOPE STABILITY

Stress based stability analysis was performed for the models to check the variation of the FOS with the different rates of construction. The LEM defines the FOS as follows:

$$FOS = \frac{\text{Shear strength of soil}}{\text{Shear stress required for equilibrium}} \tag{2}$$

Figures 2 and 3 show the stability values for two different cases; without and with the installation of geotextile reinforcements. The internal slope stability analyses were done with high strength geotextile reinforcements. The ultimate tensile capacity of the geotextile reinforcements consisted of PEC-150 was 150 kN/m and vertical spacing of 0.5m. Slope stability analyses are performed using the industry-recognized SLOPE/W perimeter bund software developed by Geoslope. The software program implements several methods for analyses of random circular, non-circular slip and sliding failure surfaces. The Morgenstern-Price Method is used to calculate the factor of safety. In the Morgenstern-Price Method, compatibility of both moment and force equilibrium is enforced; this provides a higher level of reliability than methods that compute moment or force equilibrium alone [25].

Table 5: Computed FOS for embankment stability

Treatment	FOS	Remarks
Without treatment	1.23	< 1.3
Embankment stability reinforcement PEC 150 kN/m	1.41	> 1.3

Stability analysis was performed for the models to check the variation of the FOS with the different method of ground treatment. The factor of safety values for two different cases; without treatment and embankment with the installation of reinforcement has been shown in Table 5. Furthermore, as shown in Figure 2, the simulation of LEM analysis for embankment without treatment and Figure 3 showed the simulation of LEM analysis for embankment treatment with reinforcement. The results FOS indicate that the embankment without treatment and embankment stability using reinforcement 150kN/m (PEC 150) was 1.234 and 1.405, respectively.

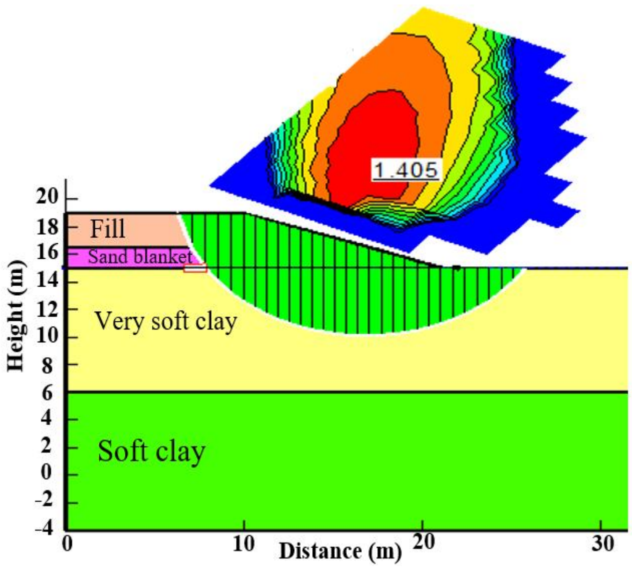

Figure 2: FOS value identified from the LEM analysis for embankment with reinforcement.

This finding suggested that the installation of the geotextiles results in higher stability values. The finding is consistent with findings of past studies [15], [20], [26] which found that the factor of safety of the embankment decreases in the loading stage and increases during each consolidation stage. The use of reinforcement produces a marginal increase in the overall factor of safety compared to that without reinforcement.

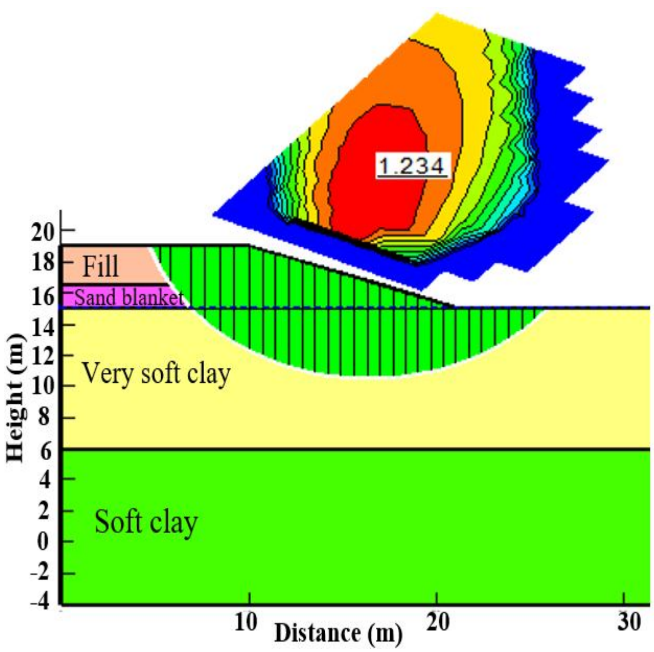

Figure 3: FOS value identified from the LEM analysis for embankment without treatment.

7. CONCLUSION

The present study was designed to compare the performances of settlement on a soft soil deposit stabilized with different embankment treatment. The method of assessment is essential during stage construction of embankment on thick deposits of soft soil for determination of the degree of consolidation of instrumented sections. In addition, from this method, the waiting period for each stage corresponding to the degree of consolidation can be estimated. Theoretical graphs have been prepared, which can estimate the settlement and time at ultimate consolidation for different treatment of embankment. The degree of consolidation at 90% is estimated to be in the range of 7 to 8 months for embankment treated with PVDs and surcharge. This study has found that PVDs stabilize the embankment produces higher stability compared to the soft soil without improvement. Further emperical study using different subsoil thickness, drain spacing ratios and c_r/c_v ratio is strongly recommended.

The second major finding was that determination of the factor of safety using LEM calculation methods, to allow for an expedite assessment of the stability of soft soil slopes, for different ground improvement method. The use of reinforcement 150kN/m (PEC 150) in soil embankment, and according to the LEM approach, appears to be the most effective way of enhancing its FOS, especially when in soft soil condition. The results of this study show that the used of geotextile (PEC150) under the embankment provides a reinforcement effect to the surface soil, and the maximum settlement can been reduced compared to that without reinforcement.

ACKNOWLEDGEMENT

This project is financially supported by the Fundamental Research Grant Scheme [Ref: FRGS/1/2018/TK06/UITM/ 01/1] Ministry of Education Malaysia (MOE), Malaysia. UiTM Research Management Centre (UiTM-RMC), Universiti Tekonologi MARA (UiTM), Politeknik Ungku Omar (PUO) and Universiti Kebangsaan Malaysia (UKM) are also acknowledged.

REFERENCES

1. A. Zakaria and M. S. N. Ibrahim. **Numerical Performance Evaluation of Savonius Rotors by Flow-driven and Sliding-mesh**, *Int. J. Adv. Trends Comput. Sci. Eng.*, vol. 8, no. 1, pp. 57–61, 2019. https://doi.org/10.30534/ijatcse/2019/10812019
2. A. Krishnamoorthy and S. Kamal. **Stability of an Embankment on Soft Consolidating Soil with Vertical Drains**, *Geotech. Geol. Eng.*, vol. 34, no. 2, pp. 657–669, 2016.
3. R. C. Mamat, A. Kasa, and S. F. M. Razali. **Comparative Analysis of Settlement and Pore Water Pressure of Road Embankment on Yan soft soil Treated with**

PVDs, *Civ. Eng. J.*, vol. 5, no. 7, pp. 1609–1618, 2019.
4. R. C. Mamat. **Engineering properties of Batu Pahat soft clay stabilized with lime, cement and bentonite for subgrade in road construction**, MS Thesis, Faculty of Civil and Environmental Engineering, Universiti Tun Hussien Onn Malaysia, 2013.
5. G.-B. Ye, Z. Zhang, J. Han, H.-F. Xing, M.-S. Huang, and P.-L. Xiang. **Performance Evaluation of an Embankment on Soft Soil Improved by Deep Mixed Columns and Prefabricated Vertical Drains**, *J. Perform. Constr. Facil.*, vol. 27, no. 5, pp. 614–623, 2013.
6. M. A. Nunez, L. Briançon, and D. Dias. **Analyses of a pile-supported embankment over soft clay: Full-scale experiment, analytical and numerical approaches**, *Eng. Geol.*, vol. 153, pp. 53–67, 2013. https://doi.org/10.1016/j.enggeo.2012.11.006
7. I. Hosseinpour, M. S. S. Almeida, and M. Riccio. **Ground improvement of soft soil by geotextile-encased columns**, *Proc. Inst. Civ. Eng. - Gr. Improv.*, vol. 169, no. GI4, pp. 1–9, 2016.
8. Q. A. Aljanabi, Z. Chik, and A. Kasa. **Construction of a New Highway Embankment on the Soft Clay Soil Treatment By Stone Columns in Malaysia**, *J. Eng. Sci. Technol.*, vol. 8, no. 4, pp. 448–456, 2013.
9. B. Indraratna, I. Sathananthan, C. Bamunawita, and A. S. Balasubramaniam. **Theoretical and Numerical Perspectives and Field Observations for the Design and Performance Evaluation of Embankments Constructed on Soft Marine Clay**. Elsevier Ltd., 2015.
10. C. Li. **A simplified method for prediction of embankment settlement in clays**, *J. Rock Mech. Geotech. Eng.*, vol. 6, no. 1, pp. 61–66, 2014.
11. L. G. Lam, D. T. Bergado, and T. Hino. **PVD improvement of soft Bangkok clay with and without vacuum preloading using analytical and numerical analyses**, *Geotext. Geomembranes*, vol. 43, no. 6, pp. 547–557, 2015.
12. Z. Zhang, G. Ye, and H. Xing. **Consolidation analysis of soft soil improved with short deep mixed columns and long prefabricated vertical drains (PVDs)**, *Geosynth. Int.*, vol. 22, no. 5, pp. 366–379, 2015. https://doi.org/10.1680/jgein.15.00018
13. B. Indraratna, D. Perera, C. Rujikiatkamjorn, and R. Kelly. **Soil disturbance analysis due to vertical drain installation**, *Proc. Inst. Civ. Eng. - Geotech. Eng.*, vol. 168, no. 3, pp. 236–246, 2015.
14. K. F. Chan, B. M. Poon, and D. Perera. **Prediction of embankment performance using numerical analyses – Practitioner’s approach**, *Comput. Geotech.*, vol. 93, pp. 163–177, 2018.
15. E. M. Da Silva, J. L. Justo, P. Durand, E. Justo, and M. Vázquez-Boza. **The effect of geotextile reinforcement and prefabricated vertical drains on the stability and settlement of embankments**, *Geotext. Geomembranes*, vol. 45, 2017. https://doi.org/10.1016/j.geotexmem.2017.07.001
16. K. Terzaghi. **Theoretical Soil Mechanics**. New York, USA: John Wiley & Sons, 1943.
17. R. C. Mamat, A. Kasa, and S. F. M. Razali. **Performance Prediction of Road Embankment on Soft Soil Stabilized with Prefabricated Vertical Drains Using Numerical Method**, *Int. J. Adv. Trends Comput. Sci. Eng.*, vol. 8, no. 4, pp. 1601–1608, 2019. https://doi.org/10.30534/ijatcse/2019/85842019
18. R. A. Barron. **Consolidation of fine-grained soils by drain wells**, *Trans. ASCE*, vol. 113, no. 2346, pp. 718–724, 1948.
19. A. Asaoka. **Observational procedure of settlement prediction**, *Soils Found.*, vol. 18, no. 4, pp. 87–101, 1978.
20. J. L. Borges and A. S. Cardoso. **Overall stability of geosynthetic-reinforced embankments on soft soils**, *Geotext. Geomembranes*, vol. 20, no. 6, pp. 395–421, 2002. https://doi.org/10.1016/S0266-1144(02)00014-6
21. N. Luo, R. J. Bathurst, and S. Javankhoshdel. **Probabilistic stability analysis of simple reinforced slopes by finite element method**, *Comput. Geotech.*, vol. 77, pp. 45–55, 2016.
22. L. Li and X. Chu. **Locating the Multiple Failure Surfaces for Slope Stability Using Monte Carlo Technique**, *Geotech. Geol. Eng.*, vol. 34, no. 5, pp. 1475–1486, 2016.
23. A. Burman, S. P. Acharya, R. R. Sahay, and D. Maity. **A Comparative Study of Slope Stability Analysis Using Traditional Limit Equilibrium Method And Finite Element Method**, *Asian J. Civ. Eng.*, vol. 16, no. 4, pp. 467–492, 2015.
24. S. Artidteang, S. Chaiyaput, D. T. Bergado, and T. Tanchaisawat. **Embankment reinforced with limited life geotextiles on soft clay**, *Gr. Improv.*, vol. 168, no. 2, pp. 130–143, 2015.
25. S. Y. Liu, L. T. Shao, and H. J. Li. **Slope stability analysis using the limit equilibrium method and two finite element methods**, *Comput. Geotech.*, vol. 63, pp. 291–298, 2015.
26. Y. H. Huang. **Slope stability anlysis by the limit equilibrium method**. Virginia, United States: ASCE, 2014. https://doi.org/10.1061/9780784412886