Numerical analysis on loading transfer mechanism of geosynthetic-reinforced embankments over the Hong Kong marine deposits improved by deep cement mixed soil columns

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ABSTRACT: The loading transfer mechanism of geosynthetic-reinforced embankments over soft ground improved by piles or columns has been studied for many years. However, for most cases, the consolidation of the soft soil ground, such as the Hong Kong Marine Deposits (HKMD), with noticeable time-dependent stress-strain behavior, has not been considered before. In this study, a finite element analysis is utilized to study the loading transfer of geosynthetic-reinforced embankment over HKMD improved by deep cement mixed soil (DCM) columns during both construction and post-construction stages. Based on the numerical analysis, it is found that, in the stage of embankment construction, the soil arching develops with increasing the filling height and the limit height of arching is 1.67 times the spacing of the DCM columns. In the stage of the post-construction, the soil arching undergoes a further development and the stress concentration ratio between the DCM columns and surrounding soil increases exponentially with the differential settlement.

Keywords: Embankment, geosynthetic reinforcement, deep cement mixed soil columns, soil arching

1 INTRODUCTION

Embankments are usually built by compacted fill materials to construct the highways, railways, and airport runways. Due to the land limitation for infrastructures and other developments, geotechnical engineers have to face the challenge of the construction of embankments over soft soils. Inherent characteristics, such as high compressibility and low bearing capacity, of soft soils usually induce the excessive total and differential settlements or even failure of the embankments.

Various techniques, such as replacing the weak soils with proper fill materials, preloading plus vertical drains, ground improvement by installation of piles, and applying geosynthetics, have been adopted to reduce settlements for many years (Hausmann, 1990; Magnan, 1994). Among different kinds of ground improvement techniques, the combination of pile support and geosynthetic reinforcement is the most suitable technique for the embankment construction over soft soil due to its effectiveness and economic efficiency. Therefore, the so-called geosynthetic-reinforced pile-supported (GRPS) embankments have earned much attention of lots of researchers and engineers (Han and Wayne, 2000; Han and Arkins, 2002; Han and Gabr, 2002; Gangakhedkar, 2004; Liu *et al*. 2007; Rowe and Taechakumthorn, 2011; Lai *et al*. 2014.).

After Terzaghi (1943) presenting the concept of soil arcing, plenty of numerical and experimental studies have been carried out to investigate the arching effect and loading transfer mechanism of pile-supported embankments without and with geosynthetic reinforcement (Low et al. 1994; Han and Wayne, 2000; Deb *et al*. 2007; Chen et al. 2008; Kang *et al*. 2009). Although, several design methods and guidelines have been proposed and modified in the latest version of the BS 8006 (2010), there are still some modifications can be investigated (Van Eekelen *et al*. 2011).

Supports of embankments can be either achieved by installing prefabricated concrete piles or by using soils columns which are filled by aggregates or mixed with cement (Ariyarathne and Liyanapathirana, 2015). Concrete piles have well-understood performance and easily ensured quality, while soil columns such as deep cement mixed (DCM) columns have complicated behavior and the performance of the DCM columns could be largely affected by the surrounding soil conditions. Since the DCM columns are usually used for soft soil ground, the consolidation behavior and dissipation of excess pore water pressure of the surround soils are influenced by the columns. Huang and Han (2009) utilized FLAC3D to simulate the consolidation behavior of the geosynthetic-reinforced embankment DCM column-supported embankment. Yapage *et al*. (2013) simulated column-supported embankments with considering the strain-softening behavior of the DCM columns. Even though, the investigations of the loading transfer mechanism directly on DCM column-supported embankments are still limited.

In this paper, a numerical analysis was carried out to investigate the loading transfer mechanism of geosynthetic-reinforced embankments over marine clay. The plane strain finite element model was established to simulate both the stage of embankment construction and the stage of post-construction. The development of soil aching in the embankment and the consolidation behavior of the underlying marine clay were discussed. The marine clay involved in this study is the Hong Kong Marine Deposits (HKMD). HKMD are regarded as the weak soils for reclamation projects in Hong Kong due to the low shear strength, high compressibility, and obvious time-dependent behavior (Yin and Zhu, 1999).

2 FINITE ELEMENT MODEL AND PARAMETERS

PLAXIS 2D (2015 version) was adopted to simulate a geosynthetic-reinforced embankment over HKMD improved by DCM columns under the plane strain condition. The embankment is 5 m in height and 10 m in crest width. The side slopes of the embankment are 1:1.2 (vertical: horizontal). The underlying marine deposits are 15m in thickness, as shown in Figure 1. The embankment is supported by DCM columns with a diameter of 600mm and a centre to centre spacing of 900mm. Rectangular pattern arrangement of the columns was adopted. The equivalent modulus of the columns based on the area replacement ratio along the direction perpendicular to the cross section is calculated as:

$$E_{ce} = \alpha E_c + (1-\alpha)\bar{E}_s \tag{1}$$

where E_{ce} is the equivalent modulus of the DCM columns under the plane strain condition, E_c is the elastic modulus of the DCM column obtained from 28 days unconfined compression test, $\bar{E}_s$ is the simplified average modulus of the HKMD which will be discussed later, α is the area replacement ratio along the direction perpendicular to the concerned cross section.

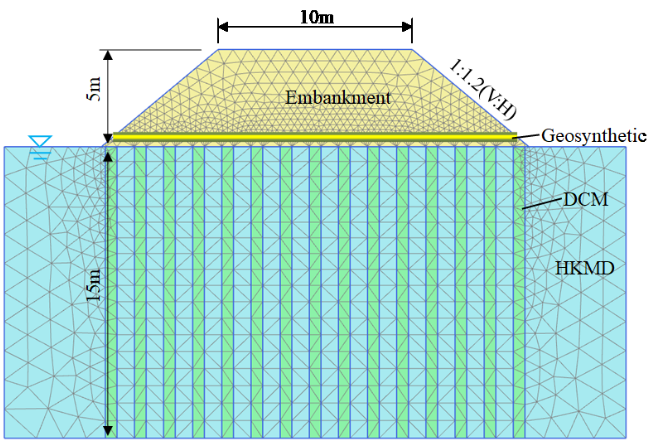

Figure 1. Finite element model

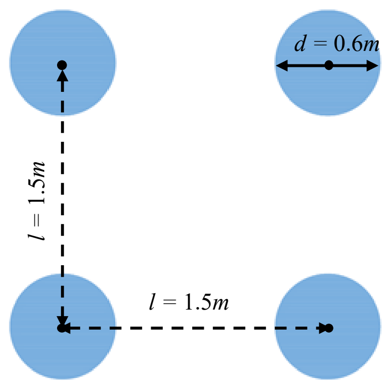

Figure 2. Arrangement of the DCM columns

The geosynthetic reinforcement layer is located at the level of 500mm from the bottom of the embankment. Two geotechnical stages which are the stage of embankment construction and the stage of the post-construction were simulated. The stage of embankment construction was divided into ten steps in order to investigate the development of the soil arching during the construction, as listed in Table 1. Minimum excess pore pressure item was selected as the loading type for calculation in the PLAXIS 2D to ensure consolidation process is fully completed.

Table 1 Steps of embankment construction

Step	1	2	3	4	5	6	7	8	9	10
Filling Height (m)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0

The HMKD was simulated by soft soil creep model, the filling materials of the embankment was simulated by Mohr-Coulomb model. The DCM columns was simplified as an elastic material and the geosynthetic reinforcement was modelled by geogrid elements. The interfacial friction between the geosynthetic reinforcement and surrounding fills was considered by using interface elements. Based on the oedometer tests conducted by Fang and Yin (2007) on cement mixed soil columns, the coefficient of permeability of the DCM columns is 2×10^{-4} m/day in this study. The involved parameters are listed in the Table 2.

Considering the compression modulus of the HKMD $E_{s,z}$ varies with depth, the average value of the modulus of the HKMD $\overline{E}_s$ used for determined the equivalent modulus of DCM columns was calculated by Eq. 2:

$$\overline{E}_s = \frac{\int_0^H E_{s,z}\,dz}{H} \tag{2}$$

where H is the thickness of the HKMD.

By considering the consolidation analysis of the HKMD, the compression modulus $E_{s,z}$ at depth z can be determined as:

$$E_{s,z} = \frac{\Delta\sigma'_z}{1.15\kappa^* \lg(\sigma'_{zp}/\sigma'_{z0}) + 2.3\lambda^* \lg(\sigma'_{z0} + \Delta\sigma'_z/\sigma'_{zp})} \tag{3}$$

where σ'_{zp} is the pre-consolidation pressure, λ^* is the modified compression index, κ^* is the modified swelling index. The same values of the modified indices as Feng and Yin (2017) used in the finite element modelling are chosen for this simulation.

Table 2 Parameters used in the numerical analysis

Material	γ kN/m^3	E MPa	J kN/m	POP kPa	κ^*	λ^*	μ^*	k_x m/day	k_y m/day	c' kPa	φ' °
HKMD	14.5	-	-	20	0.0217	0.174	0.0076	3.5×10^{-4}	1.9×10^{-4}	0.1	25
Fills	20	12	-	-	-	-	-	1.0	1.0	5	30
DCM columns	22	60	-	-	-	-	-	2×10^{-4}	2×10^{-4}	-	-
Geosynthetic	-	-	5000	-	-	-	-	-	-	-	-

3 RESULTS ANALYSIS AND DISCUSSIONS

To investigate the loading transfer mechanism in the geosynthetic-reinforced embankment over marine deposits improved by DCM columns, the stage of embankment construction and the stage of post-construction were considered in this numerical analysis. One span of reinforced embankment was focused to understand the vertical loading transferring and to neglect the influence of lateral deformation of the embankment.

3.1 *Embankment construction*

3.1.1 *Development of soil arching*

Figure 3 shows the vertical stresses distribution over the DCM columns and surrounding HKMD for different heights. The horizontal axis reflects the magnitude of the vertical stresses, the vertical axis reflects the heights of the concerned locations over the DCM columns and HKMD, and the tags in the yellow boxes are the fillings heights of the embankment with corresponding to the steps in the table 2. The distributions of vertical stress over the DCM columns are denoted by black solid lines, while the distributions of vertical stress over the HKMD are denoted by blue dotted lines.

With increasing the filling height during construction, the difference between the vertical stresses in the embankment over the DCM columns and the HKMD increases. Apparent bifurcation can be seen from the vertical stresses distributions. The point of bifurcation divides the embankment into two parts, which are the part with the soil arching effect and the part without the arcing effect. The height of the point is defined as the arching height in this study. Below the arching height, the vertical stresses over the DCM columns exceed the surcharge loading provided by completed fill layer of the embankment, while the stresses over the HKMD are less than the loading related to the self-weight of the fill layer. Beyond the arching height, there is no difference between the two vertical stresses distributions. The red line with an arrow in the Figure 3 shows the development of the arching height. It is noted that the arching height increases at the beginning with the construction of embankment, after reaching a certain height (around 1.5m), the soil arching becomes stable.

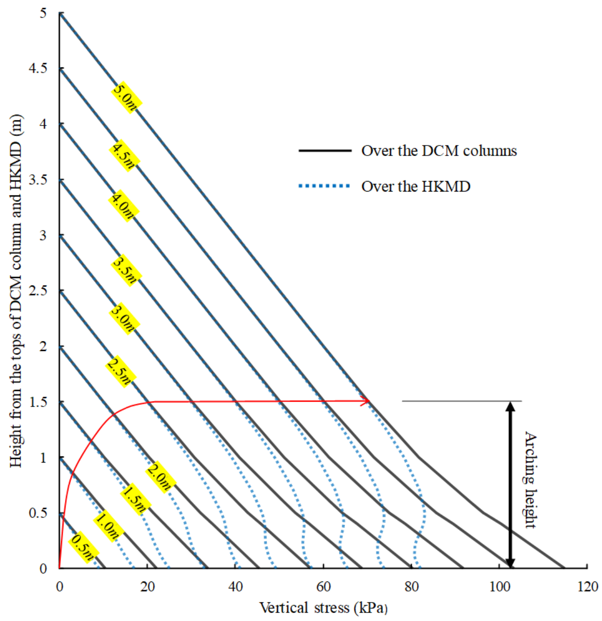

Figure 3. The distribution of the vertical stresses over the DCM columns and surrounding HKMD for different filling height.

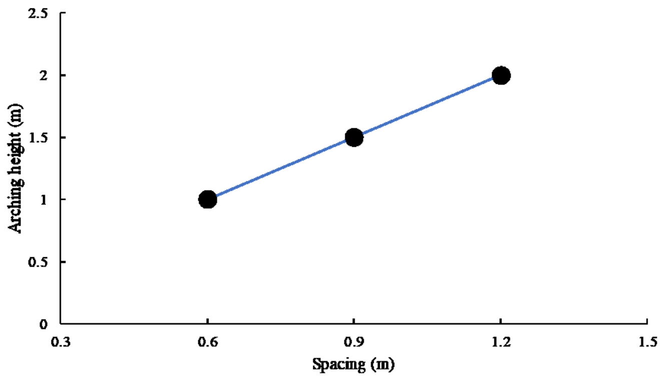

Figure 4. Arching heights for different spacings of the DCM columns

The spacing of the DCM columns is one of the most important parameters to influence the development of the soil arching. In order to investigate the relationship between the arching height and the mean spacing of the DCM columns, three different spacings of 0.6m, 0.9m, and 1.2m were selected. The stable arching heights during embankment construction are shown in the Figure 6. For different spacings, the arching heights are around 1.67 times the mean spacing of the DCM columns in this study.

3.2 *Post-construction*

3.2.1 *Consolidation behaviour*

Five points, A, B, C, D, and E were selected to simulate the dissipation of excess pore water pressure along vertical direction and horizontal direction, as shown in Figure 4 (it is normally expressed as: as shown in Figure 4, as displayed in Figure 4). It is noted that horizontal drainage mainly happens at the beginning of the consolidation by comparing the excess pore water pressures of point B to point D and the excess pore water pressures of point C to point E. After 0.1 day, the vertical drainage is dominated while the effect of the horizontal drainage is negligible.

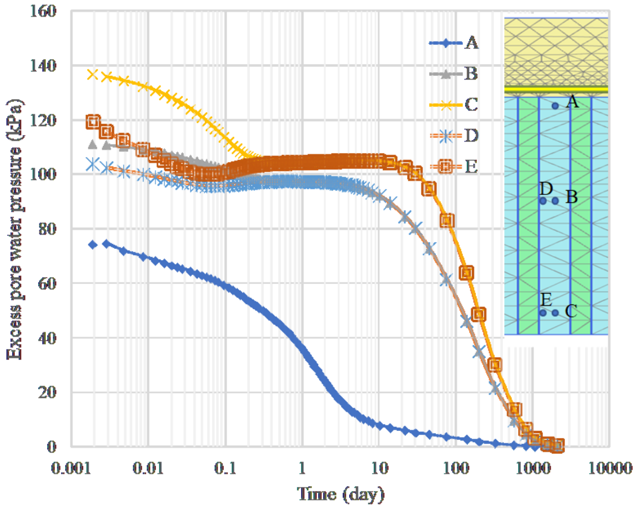

Figure 5. The dissipation of excess pore water pressure *versus* time

The average degree of consolidation *U* is defined by settlement and can be calculated as follows:

$$U = \frac{s_t}{s_f} \times 100\% \tag{4}$$

where s_t is the settlement at the corresponding time; s_f is the final settlement when the excess pore water pressure equals zero. The average degree of consolidation of HKMD and DCM columns are shown in the Figure 6. The degree of consolidation of the HKMD is larger than that of the DCM columns. Due to the difference in the consolidation process of the HKMD and the DCM columns, differential settlement between the HKMD and columns increases with time and tends to be stable, (as the Figure 7 shows). This differential settlement will influence the soil arching in the overlying geosynthetic-reinforced embankment.

3.2.2 *Development of soil arching*

It is noted that there is a further development of the arching effect within the stage of post-construction. Figure 8 compares the vertical stresses distribution in the stage of embankment construction (denoted as U=0), to the stresses distribution at the time when consolidation is completed (denoted as U=100%). The arching height increases to 2m from 1.5m which was developed in the stage of embankment construction. Figure 9 reveals that the stress concentration ratio between the DCM columns and HKMD grows with increasing the differential settlement in the stage of post-construction. The relationship between the stress concentration ratio *n* and differential settlement *s* can be fitted by an exponential function.

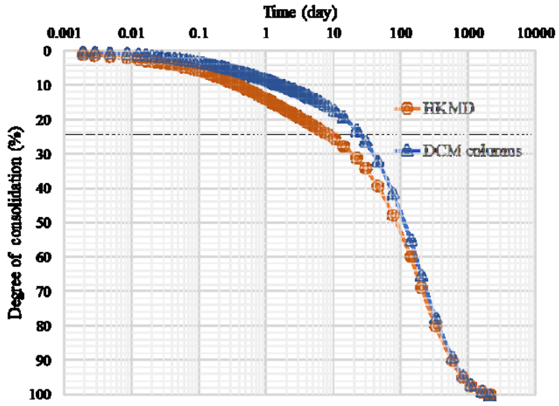

Figure 6. Average degree of consolidation of the DCM columns and HKMD *versus* time

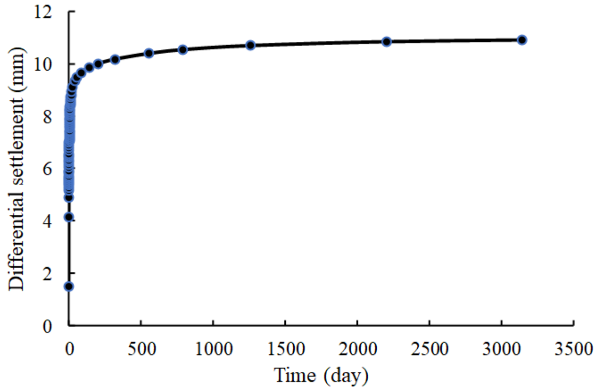

Figure 7. Differential settlement between the DCM columns and HKMD versus time

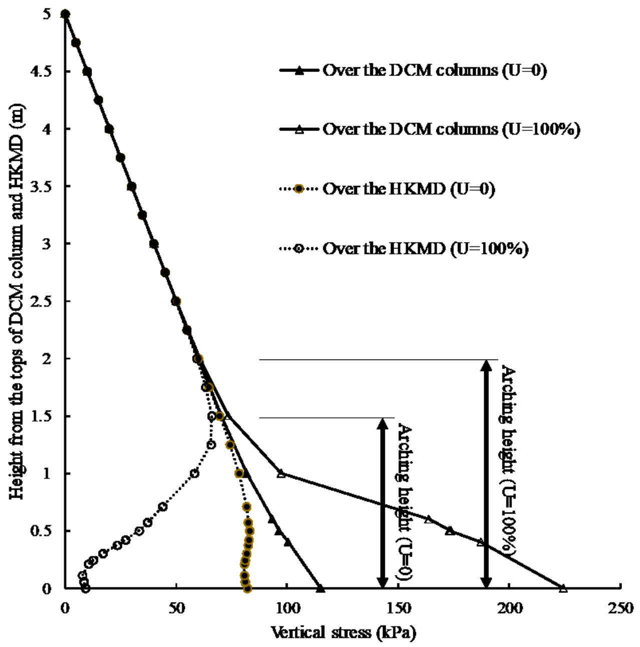

Figure 8. The distribution of the vertical stresses over the DCM columns and surrounding HKMD during the stage of post-construction.

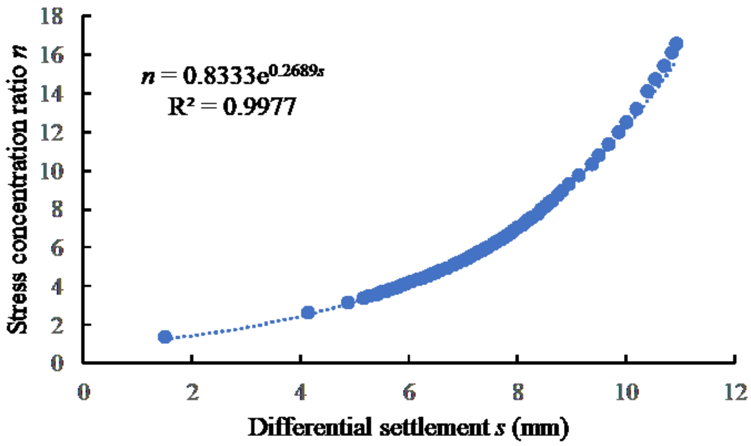

Figure 9. Stress concentration ratios of the DCM columns to the HKMD *versus* the differential settlement between the DCM columns and the HKMD.

4 CONCLUSIONS

In this study, a plane strain finite element model was established by PLAXIS 2D to simulate both the stage of embankment construction and the stage of post-construction of a geosynthetic-reinforced embankment over the HKMD improved by DCM columns. Based on the numerical analysis, the soil arching develops with increasing the filling height and the limit height of arching is 1.67 times the spacing of the DCM columns in the stage of embankment construction. In the stage of the post-construction, the soil arching undergoes a further development and the stress concentration ratio between the DCM columns and surrounding soil increases exponentially with the differential settlement.

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REFERENCES

Ariyarathne, P., & Liyanapathirana, D. S. (2015). Review of existing design methods for geosynthetic-reinforced pile-supported embankments. Soils and Foundations, 55(1), 17-34.

BS 8006. 2010. Code of Practice for Strengthened/Reinforced Soils and Other Fills. British Standard Institution, UK.

Chen, R. P., Chen, Y. M., Han, J., & Xu, Z. Z. (2008). A theoretical solution for pile-supported embankments on soft soils under one-dimensional compression. Canadian Geotechnical Journal, 45(5), 611-623.

Deb, K., Chandra, S. & Basudhar, P.K., 2007. Nonlinear analysis of multilayer extensible geosynthetic sheet-reinforced granular bed on soft soil. Geotechnical and Geological Engineering, 25(1), pp.11-23.

Fang, Z., & Yin, J. H. (2007). Responses of excess pore water pressure in soft marine clay around a soil–cement column. *International Journal of Geomechanics*, *7*(3), 167-175.

Feng, W. Q. & Yin, J. H. 2017. A new simplified Hypothesis B method for calculating consolidation settlements of double soil layers exhibiting creep. International Journal for Numerical and Analytical Methods in Geomechanics, 41, 899-917.

Gangakhedkar, R. (2004). Geosynthetic reinforced pile supported embankments (Doctoral dissertation, University of Florida).

Han, J., & Akins, K. (2002). Use of geogrid-reinforced and pile-supported earth structures. In Deep Foundations 2002: An International Perspective on Theory, Design, Construction, and Performance (pp. 668-679).

Han, J., & Gabr, M. A. (2002). Numerical analysis of geosynthetic-reinforced and pile-supported earth platforms over soft soil. Journal of geotechnical and geoenvironmental engineering, 128(1), 44-53.

Hausmann, M. R. (1990). Engineering principles of ground modification (pp. 321-335). New Han, J., & Wayne, M. H. (2000). Pile-soil-interactions in geosynthetic reinforced platform/piled embankments over soft soil. In Rep.

No. 000777, Presentation and CD-Print at 79th Annual Transportation Research Board Meeting.York: McGraw-Hill.
Huang, J., & Han, J. (2009). 3D coupled mechanical and hydraulic modeling of a geosynthetic-reinforced deep mixed column-supported embankment. Geotextiles and Geomembranes, 27(4), 272-280.
Kang, F. E. I., & Han-Long, L. (2009). Field test study and numerical analysis of a geogrid-reinforced and pile-supported embankment. Rock and Soil Mechanics, 30(4), 1004-1012 [in Chinese].
Lai, H. J., Zheng, J. J., Zhang, J., Zhang, R. J., & Cui, L. (2014). DEM analysis of "soil"-arching within geogrid-reinforced and unreinforced pile-supported embankments. Computers and Geotechnics, 61, 13-23.
Liu, H. L., Ng, C. W., & Fei, K. (2007). Performance of a geogrid-reinforced and pile-supported highway embankment over soft clay: case study. Journal of Geotechnical and Geoenvironmental Engineering, 133(12), 1483-1493.
Magnan, J. P. (1994, June). Methods to reduce the settlement of embankments on soft clay: a review. In Vertical and Horizontal Deformations of Foundations and Embankments (pp. 77-91). ASCE.
Rowe, R. K., & Taechakumthorn, C. (2011). Design of reinforced embankments on soft clay deposits considering the viscosity of both foundation and reinforcement. Geotextiles and Geomembranes, 29(5), 448-461.
Terzaghi K. (1943). Theoretical soil mechanics. New York: Wiley
Van Eekelen, S. V., Bezuijen, A., & Van Tol, A. F. (2011). Analysis and modification of the British Standard BS8006 for the design of piled embankments. Geotextiles and Geomembranes, 29(3), 345-359.
Yapage, N., Liyanapathirana, S., Leo, C. J., Poulos, H. G., & Kelly, R. B. (2013). Towards the development of a new design guideline for geosynthetic reinforced column supported embankments. *Australian Geomechanics: Journal and News of the Australian Geomechanics Society*, *48*(3), 35-49.
Yin, J. H., & Zhu, J. G. (1999). Measured and predicted time-dependent stress-strain behaviour of Hong Kong marine deposits. Canadian Geotechnical Journal, 36(4), 760-766.