Evaluation of the At-Rest Lateral Earth Pressure Coefficient of Fibre Reinforced Load Transfer Platform and Columns Supported Embankments

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Abstract. The at-rest lateral earth pressure coefficient (K_0) is an essential soil property in design of geotechnical problems, but investigating its influence on behaviour of embankments supported by load transfer platform and columns improved soft soils has remained very limited. In this study, numerical modelling of a novel ground improvement technique utilising fibre reinforced load transfer platform (FRLTP) and columns supported embankment founded on top of multilayers of soft soils is proposed and investigated by finite element analysis (FEA). This research aims to assess the influence of a new ground improvement technique using FRLTP on the embankment behaviour supported by columns in soft soils. Moreover, a numerical assessment by varying the K_0 value of FRLTP is performed through an extensive parametric study to investigate the K_0 influence on the behaviour of FRLTP and column-supported embankments over soft soils. Results of the numerical modelling show that the final settlement, the difference in settlement between columns and foundation soil, the lateral deformation can significantly be reduced by the insertion of FRLTP into a column-supported embankment system. The predicted results also indicate that the changes in the K_0 value were found to have no notable effects on the embankment behaviour.

1 Introduction

The at-rest lateral earth pressure coefficient is an important soil property in practical designs of many geotechnical problems. K_0 representing the anisotropic geostatic stress state is defined as the ratio of the horizontal effective stress to the vertical effective stress. K_0 is actually of essential input parameters for design and assessment of earth retaining structures, calculations of friction between piles/columns and surrounding soil, excavation supported systems as well as numerical simulations of boundary effects of a number of geotechnical problems. Thus, determining a proper value of K_0 is particularly important to accurately generate initial stress conditions in numerical modelling of geotechnical problems. Having several experimental and theoretical methods has been proposed to calculate the K_0 value in soils. However, the estimation method

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defined in the following equation proposed by Jaky [1] has widely been accepted for normally consolidated soft soils.

$$K_0 = 1 - \sin\phi' \quad (1)$$

where ϕ' is effective internal friction angle of shear resistance of soils. Meanwhile, the lateral earth pressure coefficient (K_0^{OC}) at rest for overconsolidated soils is expressed by a function of OCR (overconsolidation ratio) in Eq. (2) presented by Schmidt [2] that has commonly been used for estimating the K_0 value for overconsolidated soils.

$$K_0^{OC} = K_0 OCR^{\sin\phi} \quad (2)$$

It can be noted that although K_0 value was selected in a wide range of 0.5~1 for simulations of soil-cement columns supported embankments in those previous investigations [3, 4], the K_0 influence of reinforced lime-soil materials to be used as load transfer platform on the overall behaviour of embankments over soft soils has not been investigated thoroughly. In this study, a numerical assessment is undertaken on the full geometry of FRLTP and column-supported embankment over soft soils to study the effect of the FRLTP K_0 value varying in a range of 0.5~1 on the overall embankment behaviour. The calculated results of the numerical assessment consisting of final settlement, difference in settlement between columns and surrounding soil, lateral deformation during the embankment construction and long-term service are presented and thoroughly compared. The finding of this research is about to provide a better understanding of the behaviour of columns supported embankment with FRLTP while K_0 value of FRLTP varies. Comprehensive comparisons between column-supported embankment with FRLTP and without FRLTP are also made to comprehend the benefits of a column-supported embankment system with FRLTP.

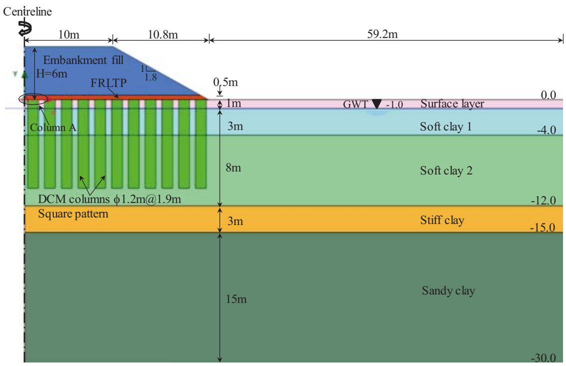

Fig. 1. A typical profile of embankment supported by FRLTP and DCM columns in soft soils

2 Description of Case Investigation

In this numerical simulation, a 6 m high embankment supported by an FRLTP with 0.5 m height and DCM columns improved layered soft soils is considered (see Fig. 1). As shown in Fig. 1, only the right half of the embankment domain is presented because of the embankment symmetry around its centreline. The embankment is constructed on a 1 m thick fill material as a surface layer overlaying an 11 m thick deposit of soft clay.

Stiff and sandy clay layers are assumed below the soft clay deposit. The ground-water table is located at a depth of 1 m below the ground surface. Details of these soil layers are summarised in Table 1 and 2. It is noted that a layer of lime-fibre reinforced soil layer with a thickness of 0.5 m as adopted in the previous study by Dang et al. [5] is used in this numerical simulation and serves as an FRLTP placed on the top of DCM columns improved soft soils. DCM columns with 1.2 m diameter and 10 m length are arranged in a square grid pattern with a centre-to-centre spacing of 1.9 m, which are used to improve the thick soft soil strata of 12 m. The construction sequence of the embankment is assumed to be in 0.5-1 m lifts at an average filling rate of 0.06 m/day [3] to a total height of 6 m including the 0.5 m FRLTP height. The completion of embankment construction is followed by a consolidation period of 2 years.

Table 1. Material properties of subgrade soil layers used in Modified Cam Clay model

Parameters	Surface	Soft clay 1	Soft clay 2	Stiff clay
Depth (m)	0-1	1-4	4-12	12-15
Material model	MCC	MCC	MCC	MCC
Unit weight, γ (kN/m^3)	16	13.4	14.3	18
Poisson's ratio, ν	0.15	0.15	0.15	0.15
Compression index, λ	0.25	0.87	0.43	0.12
Swelling index, κ	0.025	0.087	0.043	0.012
Over consolidation ratio, OCR	1.5	2.5	1.2	1.0
Slope of the critical state line, M	1.2	1.2	1.2	1.4
Initial void ratio, e_0	1.5	3.1	2.49	0.8
Vertical permeability coefficient, k_v (m/day)	6×10^{-4}	4.4×10^{-4}	4.6×10^{-4}	2.5×10^{-3}
Horizontal permeability coefficient, k_h (m/day)	9.1×10^{-4}	6.6×10^{-4}	6.9×10^{-4}	2.5×10^{-3}
K_0	0.6	0.6	0.5	0.5
Material behaviour	undrained	undrained	undrained	undrained

3 Numerical Modeling and Soil Parameters

For this study, 2D plane strain modelling was performed using geotechnical software Plaxis 2D (2017) adopting the equivalent 2D numerical analysis method proposed by previous researchers [3, 5, 6]. The DCM columns were simulated by continuous plane strain walls of 0.6 m thickness for the entire columns length of 10 m and the centre-to-centre spacing between two adjacent walls was remained the same as the 1.9 m centre-to-centre spacing between two adjacent DCM columns; meanwhile, the equivalent normal stiffness (EA) was taken into account. For this 2D simulation, a half-fine mesh was used because of geometrical symmetry of the embankment system. The foundation soil was taken to 30 m depth from the ground surface to sandy clay stratum. Meanwhile, the horizontal length of the FEA model was taken to be 80 m, which was almost three times the half width of the embankment base in order to eliminate the boundary influence. In addition, the DCM columns, FRLTP, embankment and fill materials were simulated as a linear elastic-perfectly plastic material using Mohr-Coulomb (MC) model

[5]. Whereas, the surface, soft soil and stiff clay layers were assumed to follow Modified Cam Clay (MCC) model. A summary of the constitutive model parameters is presented in Table 1 and 2. The vertical and horizontal boundary conditions are described in further detail in Dang et al. [5].

Table 2. Material properties adopted in Mohr-Coulomb model

Parameters	Sandy clay	FRLTP	Embankment fill	DCM columns
Depth (m)	15-30	-	-	-
Material model	MC	MC	MC	MC
Unit weight, γ (kN/m^3)	19	12.5	19	15
Young's modulus, E (MPa)	20	125.8	3	100
Poisson's ratio, ν	0.10	0.32	0.40	0.15
Effective cohesion, c' (kPa)	20	75	20	c_u=500
Effective friction angle, φ' (°)	35	42	35	-
Initial void ratio, e_0	0.7	-	-	-
Vertical permeability coefficient, k_v (m/day)	2.5×10^{-2}	-	-	4.6×10^{-4}
Horizontal permeability coefficient, k_h (m/day)	2.5×10^{-2}	-	-	4.6×10^{-4}
K_0	0.5	0.5	0.5	0.5
Material behaviour	drained	undrained	undrained	undrained

4 Analysis Results and Discussion

4.1 Effect of K_0 value of FRLTP on the total and differential settlements

Fig. 2a shows the effect of K_0 value of FRLTP ranging from 0.5 to 1 on the total settlement at the centre of the embankment base during construction in stages. It should be noted that a higher K_0 value of FRLTP as compared with that for a reference case presented in Table 2 was selected for this simulation. This is because previous investigations by researchers [7-10] reported that chemically treated soils using cement, lime without or with fibre reinforcement were found to have higher effective yield stress (preconsolidation pressure) due to cementation bond when compared to untreated soils. Since OCR for a soil defined in Eq. (2) is a relationship between preconsolidation pressure and present effective vertical pressure, the K_0 value has an increasing tendency as OCR increases. As Fig. 2a illustrates, the changes in K_0 value are observed to have a negligible effect on the total settlement when the embankment height increases from 0 m to 6 m. This is because a similar pattern and almost a same value of total settlement can be observed in Fig. 2a as the height of the embankment fill increases in the investigated range. Moreover, observation of the predicted results of the total settlement notes that the column-supported embankment with FRLTP was found to have about 20% reduction of the total settlement as compared with that without FRLTP reinforcement. This finding indicates that although the vertical settlement on the ground surface of the embankment with FRLTP was unnoticeably influenced by the changes in K_0 value of FRLTP, introducing FRLTP into the embankment compared with the embankment without FRLTP was predicted to have an effective influence on the improved total settlement. Additionally, the effect of K_0 value of FRLTP on the differential settlement on the ground surface under the embankment base centre is presented in Fig. 2b. It should be noted that the differential settlement is defined as the maximum settlement difference between the DCM column top and its surrounding soil at the embankment base centre. As plotted in Fig. 2b, when the K_0 value of FRLTP increased in a range of 0.5~1, no significant difference in the settlement between the column and the foundation soil was observed for the embankment with FRLTP. However, as Fig. 2b shows, the differential settlement of the embankment reinforced with an FRLTP was approximately 75% less than the corresponding value for the embankment without FRLTP reinforcement when the embankment fill increased from 0.5 m to its final height of 6 m. The significant reduction of the differential settlement observed for the embankment with FRLTP indicates that the FRLTP introduction could be an effective solution to minimising the embankment settlement difference. From the calculated result presented in Fig. 2b, it is possible to conclude that the effect of K_0 value of FRLTP in the examined range on the embankment differential settlement can be insignificant.

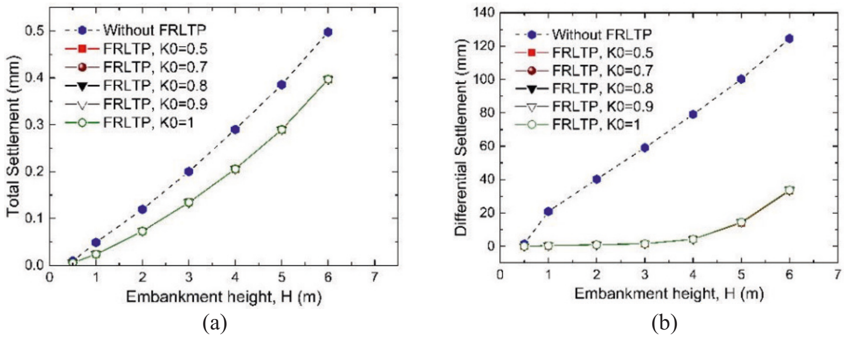

Fig. 2 Variation of (a) the total settlement and (b) the differential settlement on the ground surface under the embankment base centre

4.2 Effect of K_0 value of FRLTP on the lateral displacement

Fig. 3 presents the 2 years post-construction lateral settlement along a DCM column under the embankment toe with various K_0 values of FRLTP ranging from 0.5 to 1. It is observed that similar to the trend of the total and differential settlements plotted in Fig. 2, the lateral displacement of the embankment with FRLTP was calculated to be seemly independent of an increase in the K_0 value of FRLTP in a range of 0.5~1. Nevertheless, it is important to note that when compared with the embankment without FRLTP, the lateral displacement of the embankment with FRLTP was found to result in a considerable reduction by approximately 45% as observed in Fig. 3 for the top of the DCM column. Moreover, the introduction of FRLTP into the column-supported embankment was predicted to have a strong effect on the reduced lateral displacement of the embankment to a shallow depth. For example, the difference in the lateral deformation from the embankment with FRLTP to the embankment without FRLTP were observed to be significant for the column top, but it became smaller as the column length increased to about 5 m depth below the ground surface. In view of the authors, the significant improvement in the total and differential settlements, and the lateral displacement of the column-supported embankment with FRLTP could be attributed to the enhanced engineering properties (e.g., the high shear strength, tensile strength and stiffness) of fibre reinforced materials, used as a load transfer platform.

5 Conclusions

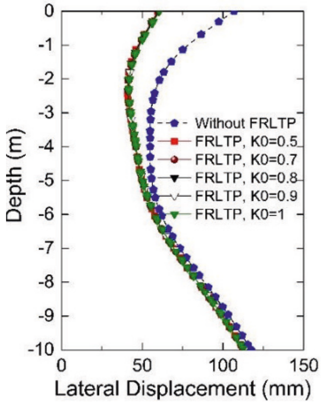

Fig. 3 Lateral settlement with various K_0 values of FRLTP under the embankment toe

This paper presents numerically investigating the deformation behaviour of an embankment built on FRLTP and floating DCM columns improved soft soils. The findings of the 2D finite element analysis indicate that the at-rest lateral earth pressure coefficient (K_0) of FRLTP changing in a range of 0.5~1 was numerically predicted to have insignificant effects on the embankment behaviour in terms of the total and differential settlements during the construction in stages, and the 2 years post-construction lateral displacement with depth. However, it is of interest to note that by comparing with the column-supported embankment without FRLTP, the column-supported embankment reinforced with a 0.5 m thick FRLTP was found to significantly decrease the total and differential settlement by 20% and 75%, and cut down 45% of the lateral displacement, respectively. The findings of this research work show that the FRLTP and DCM columns supported embankment placed on soft soils could be an effective and practical solution to ensure the embankment stability during the staged construction and services.

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