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Numerical Modelling of Embankment Supported by Fibre Reinforced Load Transfer Platform and Cement Mixed Columns Reinforced Soft Soil

Modélisation numérique du remblai supporté par une plate-forme de transfert de charge renforcée par des fibres et des colonnes mixtes à base de ciment, sol mou renforcé

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ABSTRACT: This paper presents the numerical modelling of a new ground modification technique utilising fibre reinforced load transfer platform (FRLTP) and columns supported (CS) embankment constructed on top of multilayers of soft soil. To investigate the influences of thickness and tensile strength of FRLTP on the embankment behaviour, a series of finite element analyses (FEA) was conducted on the full geometry of a CS embankment reinforced without or with an FRLTP. The FRLTP thickness varied in a range of 0~3 m, and the FRLTP tensile strength ranged from 10 kPa to 240 kPa, which were considered in this numerical modelling. The numerical results reveal that an increase in the FRLTP thickness significantly improved the stress concentration ratio between columns and surrounding soil, meanwhile resulted in a considerable reduction of the lateral deformation and hence, effectively improved the stability of the embankment system. The findings of the parametric study also indicate that when the FRLTP tensile strength increased in the investigated range, the embankment lateral displacement was found to reduce to a certainly low value, and then it remained almost unchanged. It is also found that the time-dependent embankment behaviour was considerably affected by the changes in the tensile strength and the thickness of FRLTP.

RÉSUMÉ: Cet article présente la modélisation numérique d'une nouvelle technique de modification du sol utilisant une plate-forme de transfert de charge renforcée par des fibres (FRLTP) et un remblai supporté par colonnes (CS) construit au-dessus de multicouches de sols meubles. Afin d'étudier les influences de l'épaisseur et de la résistance à la traction du FRLTP sur le comportement du remblai, une série d'analyses par éléments finis (FEA) a été réalisée sur la géométrie complète d'un remblai CS renforcé sans ou avec un FRLTP. L'épaisseur du FRLTP varie entre 0 et 3 m et la résistance à la traction du FRLTP entre 10 kPa et 240 kPa, ces intervales ont étés pris en compte dans la modélisation numérique. Les résultats numériques révèlent qu'une augmentation de l'épaisseur de FRLTP améliore considérablement le rapport de concentration des contraintes entre les colonnes et le sol environnant, ce qui entraîne une réduction considérable de la déformation latérale et améliore donc efficacement la stabilité du système de remblai. Les résultats de l'étude paramétrique indiquent également que, lorsque la résistance à la traction du FRLTP augmente dans la plage étudiée, alors le déplacement latéral du remblai est réduit à une valeur pratiquement constante. On a également constaté que le comportement du remblai dépendant du temps est considérablement affecté par les modifications de la résistance à la traction et de l'épaisseur de FRLTP.

Keywords: Fibre Reinforced Materials; Columns; Embankment; Ground Improvement; FRLTP

1 INTRODUCTION

Ground improvement technique using deep cement mixing (DCM) columns and geosynthetic reinforced platform supported embankments has been widely used in construction practice because it provides an economical and fast ground improvement solution for the construction of road and highway embankments over soft soil (Dang et al. 2016a; Dang et al. 2019b; Han & Gabr 2002). However, Zhang et al. (2013) reported that the popular applications of the geosynthetic reinforced traditional angular platform (GRTAP) over columns supported embankments built on top of soft soils has come up with many geotechnical difficulties such as intolerable total and differential settlements, larger lateral earth pressure and displacement, local or global instability, and potential failures due to over-bearing or bending capacity of DCM columns. Therefore, a novel ground modification technique utilising eco-friendly, low cost and recycled materials such as lime treated soils with bagasse fibre/ash (Dang et al. 2016b; Dang et al. 2015; Dang et al. 2016c; Dang & Khabbaz 2018a, 2018b, 2019; Dang et al. 2017; Dang et al. 2018b) used as reinforced load transfer platform (Dang et al. 2019a) to replace GRTAP and DCM column-supported embankments constructed over soft soil is required to overcome those aforementioned geotechnical difficulties. Recently, Nguyen et al. (2016) conducted two-dimensional (2D) numerical study on the failure pattern of columns supported embankment with cement stabilised slab as an LTP (load transfer platform) by taking the effect of the cement stabilised slab on the failure pattern of DCM columns. Anggraini et al. (2015) studied the performance of a lime-fibre reinforced soil platform and rigid piles supported embankment over soft soil by both physical and numerical modelling using 2D axisymmetric unit cell model. Based on the numerical results, they reported that the application of the lime-fibre reinforced LTP was very effective in reducing the differential settlement, while relatively enhancing the efficacy and the bending performance of the reinforced LTP. Nonetheless, as the 2D unit cell model scaled down was adopted in their study (Anggraini et al. 2015), the influences of the reinforced LTP, the group effect of rigid pile interactions on the lateral deformation, the soil arching effect, and the variations of excess pore water pressure were essential but not taken into account in the physical and numerical modelling.

In this study, 2D numerical simulations of floating DCM columns supported embankment without or with FRLTP, using a full geometry embankment model, were carried out to investigate the influences of thickness and tensile strength of FRLTP on the time-dependent behaviour of embankment founded on top of multilayers of soft soil. Based on the results of the numerical modelling, the stress distribution mechanism and lateral displacements are evaluated and discussed to comprehend the influences of the FRTLP characteristics on the time-dependent behaviour of a CS embankment constructed over multilayered soft soils.

2 CASE STUDY

In this numerical modelling, a 6 m high embankment reinforced with FRLTP and DCM columns in soft clay layers is considered. The embankment geometry is shown in FIG. 1 representing the only right half of the domain of the embankment due to the embankment symmetry along its centreline. As can be seen from FIG. 1, the embankment is 20.8 m wide and 6 m high with a 1V:1.8H side slope. The embankment is made of good quality soil with a cohesion value of 20 kPa, a friction angle of 35° and an average unit weight of 19 kN/m^3(Chai et al. 2015). It is constructed on a 1 m thick fill material followed by as a surface layer overlaying an 11 m thick deposit of soft clay. Meanwhile, the soft clay deposit overlies a 3 m thick stiff clay stratum followed by a 15 m thick sand layer. 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. Fibre-reinforced soils as adopted in the previous study (Dang et al. 2016a) is used as an FRLTP in this study, resting on the top of DCM columns.

It is noted that DCM columns with 1.2 m diameter and 10 m length are used and arranged in a square grid pattern with a centre-to-centre distance of 1.9 m. For this FEA, the DCM column parameters were selected to represent the typical soil-cement columns properties from published data available in the literature. Therefore, the unconfined compressive strength (q_u) was assumed to be 1000 kPa (Chai et al. 2015) and the 100 MPa young modulus (E) of DCM columns was determined using the correlation $E=100q_u$ (Yapage et al. 2014). The 150 kPa tensile strength of the DCM columns was considered to $0.15q_u$ (CDIT 2002) and the undrained shear strength of 500 kPa of DCM columns was assumed to be $c_u = 1/2q_u$. The average unit weight of 15 kN/m^3 was considered to be in a range of 3-15% higher than that of soft soil (CDIT 2002) and a Poisson's ratio of 0.15 (Chai et al. 2015) was selected as of the typical properties of DCM columns. 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 (Chai et al. 2015) to a total height of 6 m including the 0.5 FRLTP height. After the embankment construction end, the consolidation period is left for 2 years.

3 NUMERICAL MODELING AND MODEL PARAMETERS

2D plane strain FEA was performed using geotechnical software PLAXIS 2D version 2015 adopting the equivalent 2D numerical analysis method proposed by previous researchers (Chai et al. 2015; Dang et al. 2018a) to simulate the performance of the FRLTP and DCM columns supported highway embankment. The equivalent 2D model was selected because of less analysis time consuming, while generating results with reasonable accuracy. The DCM columns were simulated by continuous plane strain walls of 0.6 m thickness for the entire columns length of 10 m to maintain the same area replacement ratio of a column to surrounding soil, while the equivalent normal stiffness (EA) was taken into account as implemented and recommended for numerical simulations of columns supported embankments by many researchers (Chai et al. 2015). Thus, the centre-to-centre distance between two adjacent walls in this simulation was remained the same as the 1.9 m centre-to-centre distance between two adjacent DCM columns.

For this 2D modelling, the DCM columns, FRLTP, sandy clay and embankment fill materials were modelled as a linear elastic-perfectly plastic material using the Mohr-Coulomb (MC) model. Subsequently, the surface and soft soil layers were represented by Modified Cam Clay (MCC) model. It is assumed that the values of horizontal permeability (k_h) are about 1.5 times the corresponding values of vertical permeability (k_v) of the subgrade soils, whereas the horizontal and vertical permeability of sandy clay and DCM columns are equal. A summary of the constitutive model parameters is presented in Table 1 and 2. Due to an increase in embankment load during consolidation process, the hydraulic permeability was changed attributable to the relationship between the void ratio change and the corresponding embankment load; therefore, the permeable change index $C_k = 0.5e_0$ (initial void ratio) was adopted in this investigation. The vertical and horizontal displacements, 15 node-triangular elements and their interface, mesh generation and boundary conditions (see Figure 2) are described in further detail by Dang et al. [7].

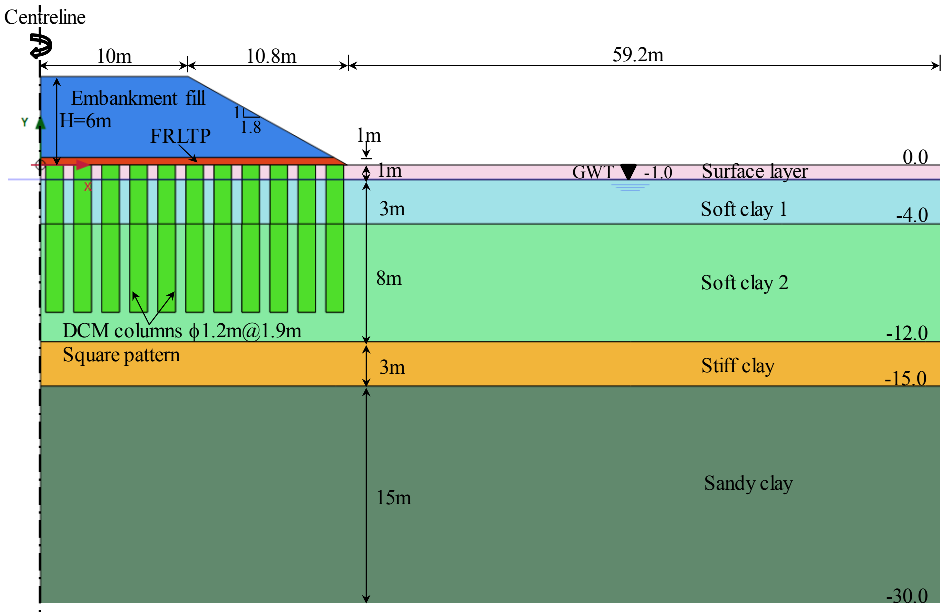

Figure 1. A typical profile of the FRLTP and DCM columns supported embankment

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

Parameters	Surface layer	Soft clay 1	Soft clay 2	Stiff clay
Depth (m)	0-1	1-4	4-12	12-15
Material model	MCC*	MCC	MCC	MCC
γ (kN/m^3)	16	13.4	14.3	18
ν	0.15	0.15	0.15	0.15
λ	0.25	0.87	0.43	0.12
κ	0.025	0.087	0.043	0.012
OCR	1.5	2.5	1.2	1.0
M	1.2	1.2	1.2	1.4
e_0	1.5	3.1	2.49	0.8
k_v (m/day)	6×10^{-4}	4.4×10^{-4}	4.6×10^{-4}	2.5×10^{-3}
k_h (m/day)	9.1×10^{-4}	6.6×10^{-4}	6.9×10^{-4}	2.5×10^{-3}
Behaviour	UD	UD	UD	UD

*MCC: Modified Cam Clay, UD: undrained

Table 2. Material properties of the embankment, FRLTP, DCM columns and sandy clay strata adopted in Mohr-Coulomb model

Parameters	Sandy clay	FRLTP	Embank-ment fill	DCM columns
Depth (m)	15-30	-	-	-
Material model	MC*	MC	MC	MC
γ (kN/m^3)	19	12.5	19	15
E (MPa)	20	125.8	1	100
ν	0.10	0.32	0.40	0.15
c′ (kPa)	20	75	20	c_u=500
φ′ (°)	35	42	35	-
e_0	0.7	-	-	-
k_v (m/day)	2.5×10^{-2}	-	-	4.6×10^{-4}
k_h (m/day)	2.5×10^{-2}	-	-	4.6×10^{-4}
Behaviour	drained	UD	UD	UD

*MC: Mohr-Coulomb model; c_u: undrained cohesion

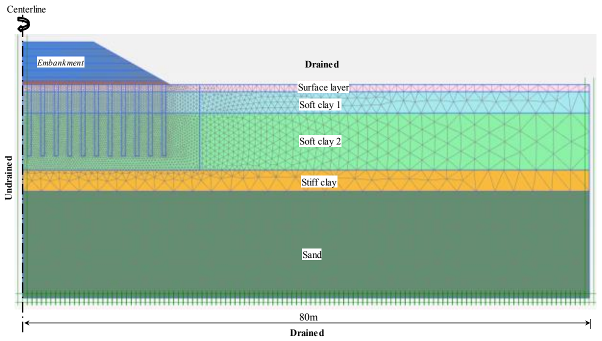

Figure 2. Mesh and boundary conditions for a 2D FEA model of embankment

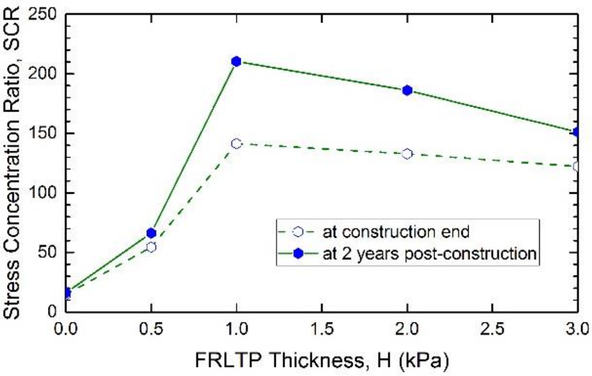

Figure 3. Influence of various FRLTP thickness on the time-dependent stress concentration ratio (SCR)

4 RESULTS AND DISCUSSION

4.1 Influence of FRLTP thickness on the stress concentration ratio and the lateral displacement

The influence of various FRLTP thickness (H) on the stress concentration ratio (SCR) at the embankment base centre at the construction end and the 2 years post-construction is illustrated in Figure 3. It can be noted that the SCR is defined as the ratio of vertical effective stress on the DCM columns head to vertical effective stress applied to foundation soil between two adjacent DCM columns. As Figure 3 shows, it could be found that the SCR significantly increased as the FRLTP thickness initially increased in a range of H=0~1 m. However, a further increase in the FRLTP thickness was observed to result in a slight decrease in the SCR. Moreover, Figure 3 exhibits that the difference in the SCR between the construction end and the 2 years post-construction cases considerably and rapidly increases as the FRLTP thickness initially increases from H=0 to H=1 m, but it becomes smaller as the H value increases further up to 3 m. It is also observed that the SCR value was higher for the embankment post-construction case. Referring to Figure 3, it can be concluded that the FRLTP thickness has a notable influence on the enhancement of the time-dependent SCR of the embankment with FRLTP.

Figure 4 presents the influence of various FRLTP thickness on the lateral displacement of the DCM column top under the embankment toe. By inspecting Figure 4, it can be seen that the lateral displacement was considerably affected by the FRLTP thickness increase. For instance, about 92% and 83% reduction of the embankment lateral displacement were observed for the cases of the construction end and the 2 years post-construction, respectively, when the FRLTP thickness increased from H=0 m to H=1 m. This finding confirms the beneficial effect of the FRLTP thickness on the resistance to the embankment lateral movement. Nevertheless, the predicted results in Figure 4 also reveal that the effect of the FRLTP in which its thickness was greater than H=1 m on the lateral deformation became lesser. This was because the lateral deformation was found to slightly increase as an additional increase in the height of the FRLTP exceeded H=1 m. As observed in Figure 4, the difference in the lateral displacement between the construction end and 2 years post-construction cases was relatively small as the FRLTP thickness increased from 0 to 1 m. On the other hand, the time-dependent lateral displacement difference became substantial as the FRLTP thickness increased further to H=3 m. This behaviour implies that the thinner FRLTP thickness (H≤1 m) was predicted to be more effective in improving the post-construction lateral displacement than the thicker FRLTP.

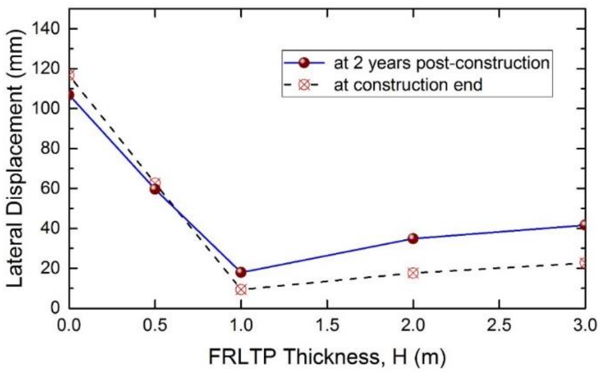

Figure 4. Influence of various FRLTP thickness on the time-dependent lateral displacement

As evident in Figure 4, it is found that as the FRLTP thickness was thin (H<0.5 m), the embankment lateral displacement was smaller for the case of the 2 years post-construction compared to the construction end case. However, the post-construction lateral displacement reversed from smaller to larger than the lateral displacement at the construction end as the additional increase in the FRLTP thickness exceeded H=0.5 m. Hence, this phenomenon reconfirms that the thicker FRLTP is not effective in mitigating the post-construction differential settlement compared to the thinner FRLTP thickness (e.g. H≤1 m). It is assumed that the dissipation of the excess pore water pressure of underlying soft soils below embankment during the consolidation process could be one of the main reasons for the changes in the post-construction lateral displacement at the embankment toe. Inspection of Figure 4 reveals that the FRLTP thickness was found to result in a less notable effect on the improvement in the lateral displacement once it exceeded a certain threshold of H=1 m. Therefore, an FRLTP with a thickness of 1 m could be required to be taken into consideration during the design stage of a CS embankment sitting on soft soil.

4.2 Influence of FRLTP tensile strength on the lateral displacement

Figure 5 illustrates that the lateral displacement of a DCM column head under the embankment toe was considerably influenced by the FRLTP tensile strength. As Figure 5 shows, a significant reduction of the lateral displacement by almost 50% was predicted for the embankment at the 2 years post-construction when the FRLTP tensile strength increased from 10 kPa to 125 kPa. However, an additional increase in the FRLTP tensile strength greater than 125 kPa resulted in a negligible reduction of the lateral deformation. It can be noted that the lateral displacement improvement of the column top under the embankment toe when the FRLTP tensile strength increased could be mainly contributed from the higher tensile strength of FRLTP in which it served as a stronger horizontal element to tie DCM columns together from the top part, facilitating the better resistance to the lateral spreading forces imposed from the embankment loading. Hence, the reduction of the embankment (lateral) deformation assists in enhancing the embankment stability against sliding, bending or tensile failures subjected to the increased embankment load.

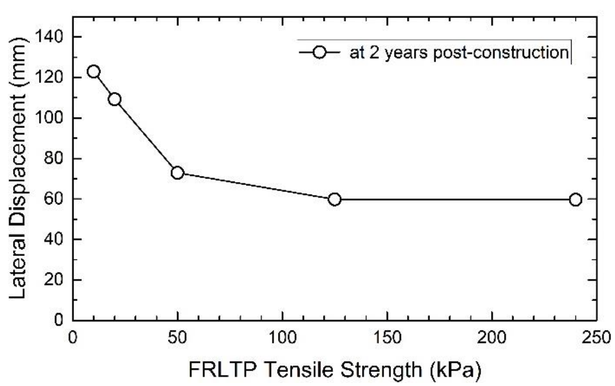

Figure 5. Influence of various FRLTP tensile strength on the lateral displacement

5 CONCLUSIONS

In this paper, an equivalent two-dimensional finite element model of a full geometry embankment was developed to examine the time-dependent behaviour of floating columns supported embankment without or with FRLTP. The effects of the FRLTP thickness and tensile strength on the embankment performance during the construction and post-construction periods were numerically investigated.

The findings of this study indicate that when compared with the CS embankment without FRLTP, the application of the FRLTP with a height of 1 m combined with DCM column supported embankment was found to significantly improve the SCR, meanwhile effectively mitigated the lateral displacements during both construction and post-construction stages. Additionally, the FRLTP tensile strength was predicted to have a significant influence on the lateral displacements of the examined embankment, which should be taken into consideration during the design stage of a CS embankment system reinforced with an FRLTP.

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