Influence of Fibre-Reinforced Load Transfer Platform Supported Embankment on Floating Columns Improved Soft Soils

Cong Chi Dang and Liet Chi Dang

Abstract Fibre reinforcement has been proved to be effective in improving geotechnical characteristics of both untreated and cemented soils, such as shear and compressive strength, bearing capacity, ductility and load-settlement behaviour. The application of fibre-reinforced soils could be beneficial to construction of embankments over soft soils because it can maintain its proper strength and bearing capacity when suffering from large total and differential settlements. In this study, fibre-reinforced cemented soil foundation is proposed to be used as a fibre-reinforced load transfer platform (FRLTP) combined with columns supported (CS) embankment constructed on multilayers of soft soils. To investigate the effect of addition of FRLTP into the CS embankment system, a numerical investigation based on the finite element analysis (FEA) using PLAXIS 2D was conducted. Moreover, a parametric analysis was carried out to evaluate the influence of the FRLTP thickness on the performance of the CS embankment when considering the vertical and differential settlements during the embankment construction and post-construction stages. The predicted results indicate that the vertical settlement and the lateral deformation considerably reduce with the insertion of FRLTP into the CS embankment system. Meanwhile, the outcomes of the parametric study reveal that the FRLTP thickness has a significant influence on the enhancement in the time-dependent differential settlement. Although the vertical settlement significantly decreases with increasing the FRLTP thickness, the post-construction vertical settlement was predicted to be most likely independent of the FRLTP thickness. The findings of this study could enable geotechnical engineers and designers to design a time-dependent performance-based FRLTP for a CS embankment over soft soils and aim to enhance the related design codes.

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1 Introduction

Fibre reinforcement has been proved to be effective in improving geotechnical characteristics of both untreated and cemented soils, such as shear and compressive strength, bearing capacity, ductility and load-settlement behaviour. The application of fibre-reinforced soils could be beneficial to construction of embankments over soft soils because it can maintain its proper strength and bearing capacity when suffering from larger total and differential settlements. In recent years, a number of researchers [1–5] conducted physical and numerical investigations on the potential use of lime/cement-treated soils [1, 3] or industrial waste materials, recycled fibre-reinforced cemented soils [2] to be adopted as an alternative load transfer platform (LTP) positioned on top of columns/piles supported embankments. It can be noted the applications of ground improvement technique using industrial waste materials such as fly ash [6, 7], bagasse ash [8–10] and recycled fibre-reinforced cemented soils [11–14] in construction of embankment foundation could be considered as an eco-friendly, low-cost and green solution for sustainable civil infrastructure development. This is because it enables to mitigate the harmful effects of waste materials on the environment.

Okyay and Dias [1] investigated the mechanical characteristics of lime/cement-stabilised soils used as an LTP using numerical analysis of a unit cell model. Anggraini et al. [2] studied the performance of a platform made of lime-fibre-reinforced soil and rigid piles supported embankment over soft soil by both physical and numerical modelling using a two-dimensional (2D) axisymmetric unit cell model. However, as a 2D unit cell model scaled down was adopted in their study, the influences of the lime-fibre reinforced LTP and the group effect of rigid pile interactions on the lateral deformation, the soil arching effect and the variations of excess pore water pressure were critically important but not taken into account in the physical and numerical modelling.

Jamsawang et al. [15] analysed the influence of deep cement mixing (DCM) columns and cement-stabilised soil mat supported embankment system on the lateral movement of precast reinforced concrete (PFRC) wall induced by an adjacent deep excavation based on three-dimensional numerical simulations. The results of the numerical analysis indicated that a stabilised mat with a thickness of 0.5 m had a considerable influence on the lateral movement of the PFRC wall, because it tied DCM columns together and behaved as a stiffer unit in resisting lateral earth pressure and displacement. Nguyen et al. [3] conducted 2D numerical investigations on the failure pattern of column-supported embankment with cement-stabilised slab (LTP) by taking the effect of the cement-stabilised slab on the failure pattern of DCM columns into account. The results of FEA revealed that the stabilised LTP thickness and compressive strength exhibited notable influences on the embankment horizontal displacement. Nguyen et al. [3] reported that the influences of the stabilised LTP on the yield stress of columns subjected to the embankment loading were greater for the higher LTP thickness regardless of the compressive strength. Dang et al. [4] conducted a 2D numerical assessment of fibre inclusion in LTP as a likely replacement of geosynthetics reinforced traditional angular LTP and piles to support high embankments founded on soft clay. By comparing the predicted result of numerical simulations with both the measured and predicted results, available in the literature, they concluded that the combined use of FRLTP and piles supported embankments experienced similar engineering characteristics when compared to the geosynthetics reinforced traditional angular LTP to support embankments with piles. Numerical studies performed by Dang et al. [16, 17] using a full geometry embankment model emphasised the effects of the mechanical properties of FRLTP on the overall behaviour of a CS embankment. The results of their numerical analysis showed that the FRLTP shear strength properties tend to be the most influential factors and need to be considered in the design stages of a target CS-FRLTP-embankment system. However, none of these investigations fully focused on investigating the influence of the FRLTP thickness on the deformation behaviour of a CS embankment during construction and post-construction periods.

In this paper, a 2D numerical simulation of floating DCM columns supported embankment without or with FRLTP, using a full geometry embankment model, was proposed and conducted to model mechanical behaviour of embankments over multilayers of soft soils during construction and post-construction periods. A parametric study on the influences of the FRLTP thickness was also performed to provide a comprehensive understanding of the deformation behaviour of the floating columns supported embankment with a varied FRLTP thickness. Some key parameters to design a CS embankment consisting of the vertical and differential settlements are evaluated and compared to comprehend the influences of adding FRTLP with a varied thickness on the time-dependent behaviour of embankments over multilayered soft soils. The FEA findings will enable geotechnical engineers and designers to select an appropriate FRLTP thickness based on the time-dependent performance for a CS embankment reinforced with an FRLTP as well as aim to enhance the associated design standards and guidelines.

2 Description of Case Study

In this numerical analysis, a 6 m high embankment reinforced with FRLTP and DCM columns in soft clay layers is considered [16]. The embankment geometry is shown in Fig. 1, representing only the right half of the domain of the embankment since the embankment is symmetrical along its centreline. The embankment is 20.8 m wide and 6 m high with a 1V:1.8H side slope. It is made of good quality soil with cohesion of 20 kPa, a friction angle of 35° and an average unit weight of 19 kN/m^3. The embankment is constructed on a 1 m thick fill material as a surface

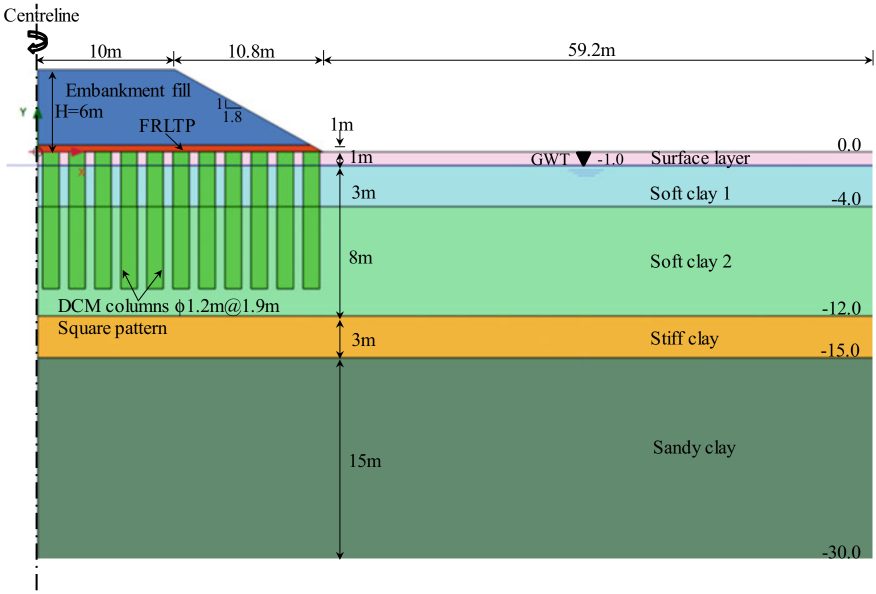


Fig. 1 Schematic representation of a highway embankment supported by FRLTP and DCM columns in soft soils (not to scale)

layer overlaying an 11 m thick deposit of soft clay. This deposit of soft clay 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 Tables 1 and 2. A fibre-lime-soil layer [2, 4, 16] is used in this numerical study and serves as an FRLTP of 1 m that is placed on the top of DCM columns. The DCM columns with 1.2 m diameter and 10 m length are introduced to improve soft soils. The columns are arranged in a square grid pattern with a centre-to-centre distance of 1.9 m. Furthermore, 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 [17, 18] to a total height of 6 m including the FRLTP with a height of 1 m. Following the completion of embankment construction, the investigated embankment is left for two years to simulate the consolidation progress.

3 Numerical Modelling

3.1 Finite Element Models and Parameters

A 2D plane strain FEA model incorporated in finite element software PLAXIS 2D (2017) and the equivalent 2D numerical analysis method proposed by previous researchers [1, 4, 19, 20] were adopted to model overall behaviour of

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[a]	MCC	MCC	MCC
Unit weight, γ (kN/m^3)	16	13.4	14.3	18
Poisson's ratio, v	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}
Material behaviour	Undrained	Undrained	Undrained	Undrained

[a]*MCC* modified Cam-clay

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

Parameters	Sandy clay	FRLTP	Embankment fill	Column
Depth (m)	15–30	–	–	–
Material model	MC[b]	MC	MC	MC
Unit weight γ (kN/m^3)	19	12.5	19	15
Young's modulus, E (MPa)	20	125.8	1	100
Poisson's ratio, v	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}
Material behaviour	Drained	Undrained	Drained	Undrained

[b]*MC* Mohr-Coulomb model, c_u undrained cohesion

FRLTP-supported highway embankment with DCM columns. The equivalent 2D FEA model was selected because of less analysis time consuming, while generating results with reasonable accuracy. The DCM columns were modelled by continuous plane strain walls of 0.6 m thickness for the entire columns length of 10 m to maintain the same area of replacement ratio of columns to surrounding soil, taking into account the equivalent normal stiffness (EA) as implemented by many researchers [21–23] for numerical simulations of column-supported embankments. Meanwhile, the centre-to-centre spacing between two adjacent walls in this numerical simulation was remained the same as the 1.9 m centre-to-centre spacing between two adjacent DCM columns.

In this modelling, the DCM columns, FRLTP, embankment fill and sandy clay were modelled as a linear elastic-perfectly plastic material using the Mohr-Coulomb (MC) model [24, 25]. Meanwhile, the surface, soft soil and stiff clay layers were represented by modified Cam-clay (MCC) model. The required parameters for the MC and MCC material models are presented in Tables 1 and 2. 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 DCM columns and sandy clay are equal. Due to an increase in embankment load during construction in stages, the hydraulic permeability was changed owing to the relationship between the void ratio change and the corresponding embankment load. Hence, the permeable change index $C_k = 0.5e_0$ was adopted in this investigation.

For this 2D simulation, a half-fine mesh was used because of geometrical symmetry of the embankment system as presented in Fig. 2. 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 made to be 80 m, which was almost three times the half-width of the embankment base in order to eliminate the boundary influence. A detailed description of the vertical and horizontal boundary conditions can be found in the numerical modelling by Dang et al. [16]. It should be noted that as the results presented in this paper are part of an ongoing research project of modelling behaviour of FRLTP and columns supported embankments over soft soils, the proposed FEA model for a CS embankment was properly validated. The predicted results showed a good agreement with the field measurement data reported in the literature. Hence, the proposed FEA model is suitable for modelling behaviour of CS embankments built on multilayers of soft soils. Further evaluation of the proposed model validation could be found in the previous investigation by Dang et al. [16].

4 Analysis Results and Discussion

4.1 Influence of FRLTP Addition on the Maximum Settlement and the Lateral Displacement

Figure 3 displays the influence of FRLTP addition on the behaviour of columns supported embankment by comparing the maximum vertical settlement at the embankment base centre. As illustrated in Fig. 3, when the embankment load increased, the addition of FRLTP with a height of 1 m combined with CS embankment was generally found to result in a noticeable reduction of the maximum vertical

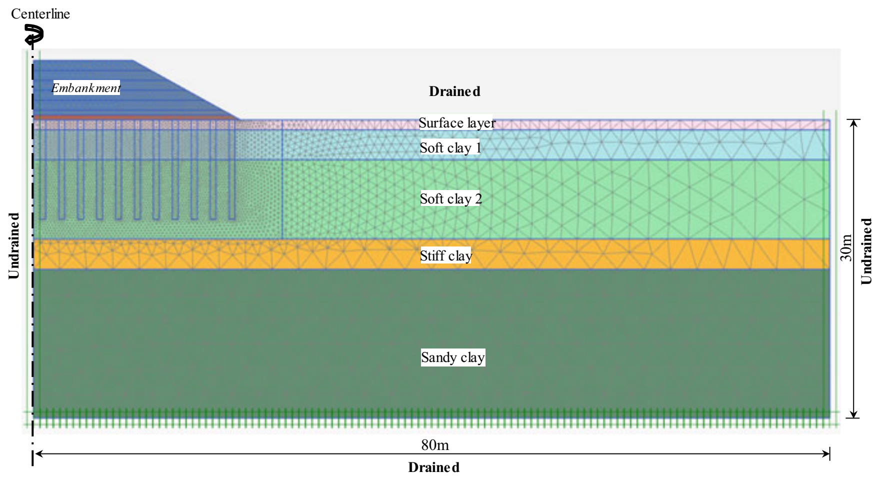
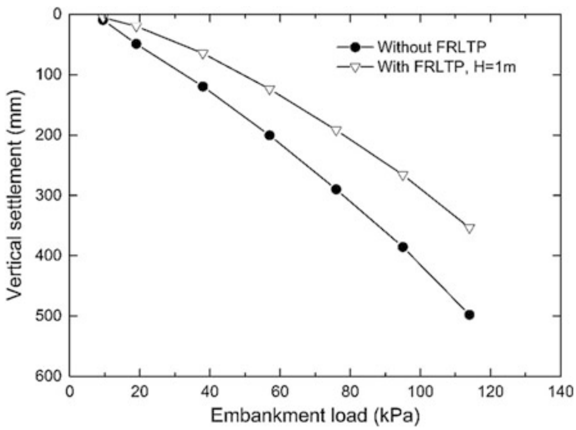


Fig. 2 Mesh and boundary conditions for a 2D FEM analysis of embankment

settlement as compared to embankment without FRLTP. Inspection of Fig. 3 also notes that a nonlinear increase in the maximum vertical settlement of the ground surface was observed for both the embankment without or with FRLTP as the embankment load increased. However, the maximum vertical settlement was calculated to be larger for the embankment without FRLTP as compared to the embankment reinforced with an FRLTP with a height of $H = 1$ m. Moreover, the maximum settlement difference from embankment without FRLTP to embankment with FRLTP was found to steadily increase when the load associated with the embankment fill increased, as shown in Fig. 3. For example, about 30% difference in the maximum settlement between the embankment without FRLTP and with FRLTP were calculated at the completion of the embankment construction as evident in Fig. 3. In other words, by comparing with the embankment without FRLTP, the introduction of an FRLTP with a thickness of 1 m into the DCM columns supported embankment system corresponded to a considerable reduction of approximately 30% of the maximum vertical settlement during the embankment construction stage. The improvement in the maximum vertical settlement corroborates the effectiveness of adding FRLTP into the CS embankment system. According to Dang et al. [22], the maximum vertical settlement was greatly improved with an FRLTP inclusion because of the enhanced stiffness and the arching effect of the entire embankment system contributed from the FRLTP insertion. This phenomenon could enable more of the embankment load to be transferred from soft foundation soil to DCM columns and consequently reduce the vertical ground surface settlement.

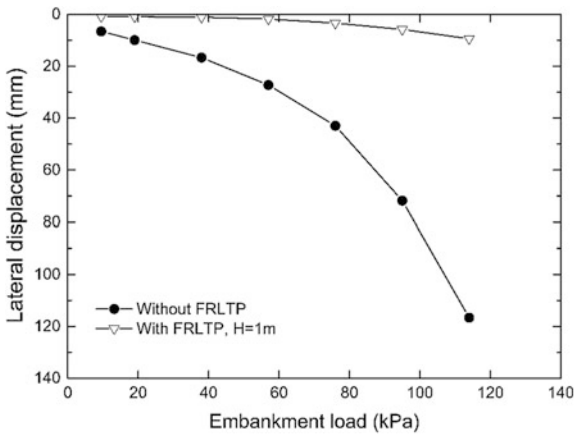
Figure 4 presents the changes of lateral displacement at the column head under the embankment toe with an increase in the embankment load from 10 kPa to around 120 kPa. By examining Fig. 4, it is noteworthy to state that a nonlinear relationship between the lateral displacement and the embankment load was visibly observed to

Fig. 3 Influence of adding FRLTP on the maximum settlement at the ground surface under the embankment base centre



be a predominant mechanism for the CS embankment with or without FRLTP ($H = 1$ m). Moreover, as Fig. 4 indicates, the addition of FRLTP into the CS embankment was found to have a significant influence on the changes of the lateral displacement. For example, by comparing with the embankment without FRLTP, the embankment with an FRLTP thickness of $H = 1$ m was calculated to reduce approximately 90% of the lateral displacement at the embankment construction end. Therefore, this finding reveals that the introduction of the FRLTP and DCM columns supported embankment can be very effective in controlling the embankment lateral displacement and hence, increase the stability of the entire embankment system placed on top of multilayers of soft soils. The improvement in the lateral displacement observed for the embankment with FRLTP could have resulted from the insertion of fibre-reinforced cemented soil to be used as FRLTP. Referring to Jamsawang et al. [15], the insertion of a stabilised soil mat (e.g. FRTLP) links DCM columns together from the top part and tends to act as a stiffer unit resulting in the better resistance to the lateral earth pressure and displacement.

Fig. 4 Influence of adding FRLTP on the lateral displacement at the embankment toe



4.2 Influence of FRLTP Thickness (H) on the Vertical Settlement

Figure 5 illustrates the results of the parametric study on the influences of various FRLTP thickness (height) on the vertical settlement of the floating DCM columns supported embankment at the construction end and the two years post-construction. It can be noted that the FRLTP thickness was varied from $H = 0$ m representing the embankment without FRLTP to $H = 3$ m showing the embankment reinforced with an FRLPT thickness of 3 m. Figure 5 shows that the vertical settlement at the base of the embankment centre was significantly influenced by the FRLTP thickness. However, the FRLTP thickness was found to have an insignificant effect on the changes of the vertical settlement from the construction end to the two years post-construction cases. To be more specific, as presented in Fig. 5, the vertical settlements at the construction end were observed to gradually reduce by approximately 40% when the FRLTP thickness increased from 0 to 3 m. Inspection of Fig. 5 also notes that when the FRLTP thickness increased, a similar pattern of the vertical settlement reduction was found in both the cases of the construction end and the two years post-construction. This pattern implies that effect of the FRLTP thickness on the long-term vertical settlement was negligible. Nonetheless, the higher settlement was observed in Fig. 5 for the case of the two years post-construction. The consolidation of the underlying unimproved soil layers could be mainly responsible for the increased post-construction settlement of the examined embankment. It is of interest to note that as the greater reduction of the vertical settlement was predicted for the thicker FRLTP, this finding corroborates that the thickness of the FRLTP plays a key role in controlling the vertical settlement of the CS embankment reinforced with an FRLTP. It can also be noted that the thicker FRLTP assists in alleviating the possibility of the FRLTP punching failure induced by penetration of column heads.

4.3 Influence of FRLTP Thickness (H) on the Differential Settlement

Figure 6 shows the variation of the construction end and two years post-construction differential settlements at the embankment base centre in conjunction with an increase in the FRLTP thickness in a typical range of 0-3 m. It can be noted that in this numerical simulation, the differential settlement is defined as the maximum difference in the vertical settlement between the column top and ground surface in the middle of two adjacent columns. As expected, the differential settlement was found to significantly decrease as the thickness of FRLTP increased. For example, when increasing the FRLTP thickness ranging from 0 to 1 m, a significant reduction of approximately 100% of the differential settlement (almost zero differential settlement) was observed for both the construction end and the

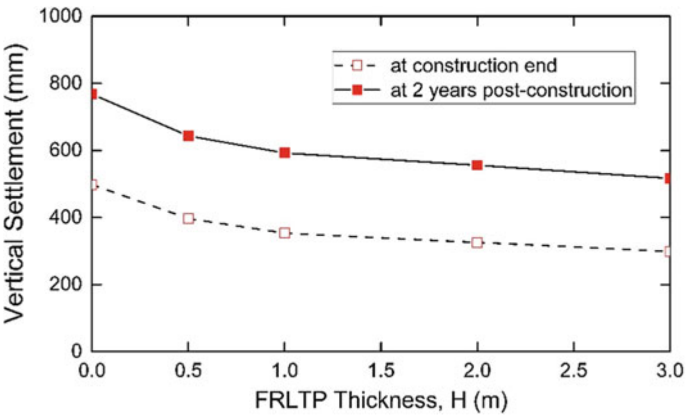


Fig. 5 Variations of vertical settlement for different FRLTP thickness at the construction end and two years post-construction

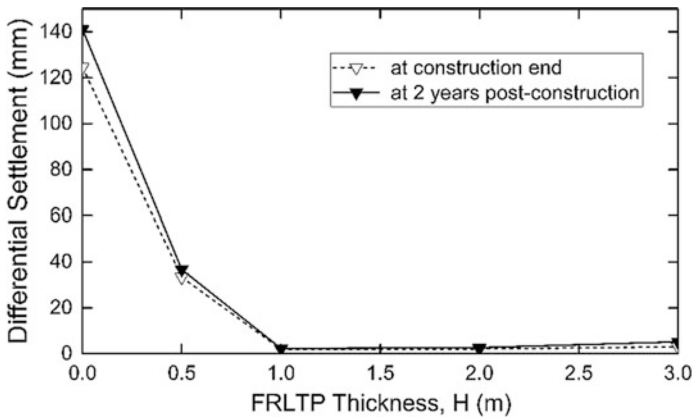


Fig. 6 Variations of differential settlement for various FRLTP thickness at the construction end and two years post-construction

two years post-construction cases. Further increase in the height of FRLTP was noted to cause the differential settlement to remain zero. Moreover, as Fig. 6 indicates, the difference in the embankment differential settlement from the case of construction completion to the post-construction case was predicted to be considerable when the embankment was not reinforced with an FRLTP ($H = 0$ m). Subsequently, the difference in the time-dependent differential settlements became negligible and converted to almost the same value as the FRLTP thickness increased further to $H = 3$ m. Therefore, it is possible to conclude that the FRLTP thickness was found to have a substantial influence on the time-dependent differential settlement of the investigated embankment. The application of FRLTP with a height of $H = 1$ m could control the insignificant (almost zero) differential settlement occurring at the ground surface under the embankment base.

5 Conclusions

An equivalent 2D 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 effect of the FRLTP thickness on the embankment performance during the construction and post-construction periods was numerically investigated by a parametric study. The main findings of this study can be summarised as follows:

- The application of the FRLTP with a height of 1 m combined with DCM columns supported embankment reduced a great amount of approximately 30% of the maximum vertical settlement, 90% of the lateral displacement and 100% of the differential settlement during the construction stage when comparing with the CS embankment without FRLTP.
- The FRLTP thickness was found to have significant influences on the time-dependent differential settlements of the investigated embankment. Whereas its influence on the post-construction vertical settlement was predicted to be negligible.
- The findings of this simulation indicate that the thickness of the FRLTP plays a vital role in improving the vertical and differential settlements of the CS embankment by effectively enhancing the vertical and horizontal stiffness on the entire embankment system as well as the load transfer mechanism between DCM columns and surrounding soft soils.
- Finally, it is important to note that this numerical study has provided a deeper insight into making use of agricultural waste materials (e.g. jute fibre, bagasse fibre [12–14, 26–28], coir fibre) as reinforcing components of fill materials for sustainable civil infrastructure construction development.

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