Evaluation of Stability of Embankment Constructed on Soft Consolidating Soil with Lime–CFG Composite Column System

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Abstract

Effectiveness of providing lime and CFG composite column system on the safety factor of embankment constructed on consolidating soil is studied at different time intervals during consolidation of foundation soil. The effectiveness of providing composite column system is compared with the effectiveness of providing only lime or CFG columns. In addition, the effectiveness of composite column system on settlement of foundation soil and consolidation process is also investigated. Embankment, foundation soil and columns are modeled using finite element method. Numbers of trial surfaces with different center and radius are generated at each time interval and the critical surface is selected to calculate the safety factor using the effective stresses obtained by finite element analysis. From the study, it is concluded that provision of lime or CFG columns, either individually or in combination, reduces the settlement and improves the safety factor. However, the most effective type of columns and their arrangement to reduce the settlement may not be the most effective to enhance the safety factor and hence, the type of columns and their arrangements has considerable influence on the purpose for which columns are provided.

Keywords Embankment · Safety factor · Lime–CFG composite column · Soft consolidating soil · Finite element method

Introduction

Construction of embankments on sites once considered as unsuitable is becoming greatly inevitable nowadays due to limited availability of appropriate sites and fast-increasing urbanisation. The rapid growth of infrastructure facilities has necessitated the expansion of construction activities in areas with poor subsoil conditions [1]. Due to the presence of various problematic soils, embankments constructed on these type of soils show large settlement and excessive pore water pressure. The low shear strength and low permeability of soft soils often reduce the stability of embankment constructed on these soils after the construction and limit the embankment height. Hence, embankments constructed on such soils need improvement to resolve these problems by implementing different cost-effective techniques. The various techniques suggested in the past to improve soft soils include the use of materials having lightweight for

embankment, preloading, reducing the slope of the embankment, stage-wise construction of embankment, excavating and replacing the existing ground with appropriate material, providing vertical drains and by providing columns. Among the various techniques available for ground improvement, inclusion of columns is considered as the most common and cost-effective technique. It is the most efficient and appropriate method with various advantages, such as to reduce the vertical and lateral settlements after the construction of embankment, to improve the slope stability and consolidation and to increase the bearing capacity. The high column stiffness reduces foundation load or vertical stress on the soil body and decreases the generation of excess pore water pressure [2]. Various types of materials, such as lime, sand, stone, soil–cement (SC), cement–fly ash–gravel (CFG), are suggested in the past for the columns. According to Zhang et al. [3], the columns may be grouped as granular piles (sand and stone columns), flexible piles (cement–soil piles) and rigid piles (CFG columns).

In thick soft soil, if only one ground improvement technique cannot meet the requirement of safety and low cost, then several ground improvement techniques can be combined to deal with the problem comprehensively [4]. Composite column system generally consists of combination of

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columns of shorter length to mobilise the strength at shallow depth and longer columns to transfer the load to the deeper hard strata. It has larger equivalent stiffness and hence reduces the vertical stresses in the soft soil. Combinations of lime and CFG [4–6], lime and cement [7, 8], lime and fly ash [9], soil and cement [10–12], lime, soil and cement [5] are few of the composite materials suggested for columns. One such technique of composite system consists of lime column and CFG column. This technique has been validated in practice and can achieve good technical effectiveness and significant economic benefits. The provision of lime columns improves the bearing capacity and the settlement of the composite ground. Lime columns are similar to stone columns but they are formed by mixing lime with soft soil. In addition, lime columns are stiffer than stone columns [13]. Due to numerous advantages, such as improvement in strength and reduction in settlement of weak subsoil, CFG columns are also widely applied in ground treatment due to its simplicity in construction and reliable quality. CFG columns have large bond strength due to combination of fly ash, cement, aggregate chips, gravel, sand and water along with soil. CFG columns are used similar to conventional piles rather than lime columns to mobilise bearing capacity from the deeper soil strata, because, CFG columns are stiffer compared to lime columns. Zheng et al. [4] investigated the effectiveness of multi-pile ground formed by the CFG and lime columns on bearing capacity and settlement. Zheng et al. [6] also studied the behaviour of CFG and lime composite pile foundations for various distribution of loads. Abusharar et al. [5] investigated the effectiveness of composite foundation system consisting of CFG–lime or SC–lime columns for embankment constructed on the soft soil.

Thus, it may be noted that there is a significant investigation to assess the effectiveness of CFG and lime composite column system to improve the thick soft soil. However, all these studies are limited to investigate the effectiveness of the composite system to improve the settlement and consolidation behaviour of soft soil. In addition to settlement and consolidation behaviour, the major parameter to measure the overall stability of embankment is safety factor. Safety factor and critical slip surface are the basic results for the stability analysis of slopes [14]. The safety factor based on an appropriate geotechnical model as an index of stability, is required to evaluate slope stability [15]. Moreover, the safety factor of embankment on soft soil varies with time due to the consolidation of foundation soil. Hence, to check the stability, the safety factor after construction of embankment till the end of consolidation of foundation soil is also required in addition to settlement. Hence, in the proposed study, the effectiveness of providing lime and CFG composite system on stability of embankment is investigated in terms of safety factor at different time intervals during the consolidation of soft soil. Besides, the effect of providing

lime–CFG composite column system on other parameters that contribute to the stability of embankment, such as the settlement and rate of dissipation of excess pore water pressure, in foundation soil is also studied.

Finite element method is the most potent numerical technique for analysing the problem consisting of embankment constructed on soil with CFG–lime composite column system. The finite element method is adopted widely to model the soil improved using various types of columns [16–24]. When the soil improved with columns is modeled using finite element method, the actual three-dimensional problem consisting of soil and columns is converted into a two-dimensional problem with plane strain condition to minimise the computational time. In this case, various matching procedures are used to convert the actual three-dimensional distribution of columns into equivalent columns for plane strain condition. The two commonly used matching procedures to convert the columns in actual three-dimensional problem to equivalent two-dimensional plane strain model are the equivalent area method and column wall method proposed by Abusharar and Han [25]. In the proposed study, two-dimensional plane-strain finite element method is used to model the soft soil improved with lime–CFG column system. The columns are modeled as line elements with three degrees of freedom and soil is modeled using plane strain element as reported by Abusharar et al. [5] and Borges et al. [26].

Method of Analysis

The actual problem consisting of columns embedded in soil is three-dimensional. However, due to the complexity of a three-dimensional arrangement of multiple columns, a three-dimensional problem has been commonly converted into a two-dimensional model which has equivalent properties and dimensions [25, 28]. Generally, engineers prefer to perform a two-dimensional analysis for the assessment of the slope's behaviour and stability because of its simplicity and ease of understanding [22]. For the proposed study, embankment on the consolidating soil improved by columns is modeled using finite element method. The actual three-dimensional problem is modeled as equivalent plane strain two-dimensional problem. The detailed procedure adopted for the analysis is as follows:

Modeling of Consolidating Soil

A procedure proposed by Zienkiewicz [27] is used to formulate the coupled system of simultaneous equations. In this procedure, the displacement u , pore pressure p and forces f in soil during consolidation is expressed as,

$$\begin{bmatrix} k_s & L \\ 0 & H \end{bmatrix} \begin{Bmatrix} u \\ p \end{Bmatrix} + \begin{bmatrix} 0 & 0 \\ L^T & 0 \end{bmatrix} \begin{Bmatrix} \dot{u} \\ \dot{p} \end{Bmatrix} = \begin{Bmatrix} f \\ 0 \end{Bmatrix} \quad (1)$$

where K_s , H and L are, respectively, the stiffness matrix, flow matrix and coupling matrix. The coupling matrix L can be obtained using the equation.

$$L = \int_s N_u^T \left\{ \frac{\partial}{\partial x} \right\} N_p ds \quad (2)$$

where N_p and N_u are the shape functions used to relate the pore pressure and displacement at any point to the pore pressure at nodes and displacements at nodes, respectively. In incremental form, the variation of u and p from time t to $t + \Delta t$ can be expressed as

$$\begin{bmatrix} k_s & L \\ 0 & H \end{bmatrix} \begin{Bmatrix} \Delta u \\ \Delta p \end{Bmatrix} + \begin{bmatrix} 0 & 0 \\ L^T & 0 \end{bmatrix} \begin{Bmatrix} \dot{\Delta u} \\ \dot{\Delta p} \end{Bmatrix} = \begin{Bmatrix} \Delta f \\ 0 \end{Bmatrix} \quad (3)$$

Finite Element Discretisation of Embankment Soil, Foundation Soil and Columns

The various types of elements used to model the soil and columns are shown in Fig. 1a, b. To obtain the stiffness matrix K_s , in Eq. (3), two-noded line elements with two translational and one rotational degree of freedom are used to model the circular columns, and soil is modeled using four-noded quadrilateral elements having two translational degrees of freedom. Similarly, the fluid in the soil and columns is also modeled using four-noded quadrilateral elements and two-noded line elements with one pressure degree of freedom at each node, respectively, to obtain the matrix H in Eq. (3). The soil element has unit thickness, whereas, the column element has only circular c/s area and length and will not extend throughout the thickness of soil.

Fig. 1 **a** Four-noded quadrilateral element to discretise soil. **b** Two-noded line element to discretise columns

Determination of Safety Factor

Number of circular slip surfaces of varying radius and centre are generated for each time interval during the consolidation of foundation soil and the surface with minimum safety factor is considered to obtain the safety factor. The safety factor is determined from the equation,

$$F.S. = \frac{\sum \tau_{fi} \cdot \Delta L_i}{\sum \tau_i \cdot \Delta L_i} \quad (4)$$

where ΔL_i , τ_i and τ_{fi} are the length, shear stress and shear strength of the soil for i th segment, respectively. τ_i and τ_{fi} for a particular segment are obtained as,

$$\begin{aligned} \tau_{fi} &= c' + \sigma'_{ni} \tan \phi' \\ \tau_i &= 0.5(\sigma'_{yi} - \sigma'_{xi}) \sin 2\alpha_i + \tau'_{xyi} \cos 2\alpha_i \\ \sigma'_{ni} &= 0.5(\sigma'_{yi} + \sigma'_{xi}) + 0.5(\sigma'_{yi} - \sigma'_{xi}) \cos 2\alpha_i - \tau'_{xyi} \sin 2\alpha_i \end{aligned} \quad (5)$$

where c' is effective cohesion and ϕ' is effective angle of internal friction. σ'_{ni} is effective normal stress and σ'_{xi} , σ'_{yi} and τ'_{xyi} are the effective stresses on each of the segment. α_i is angle between each segment with horizontal.

The safety factor during various time intervals for a particular slip surface is determined using the stresses obtained by finite element analysis and using the equivalent values of c' and ϕ' representing cohesion and angle of internal friction of foundation soil, lime columns and CFG columns. Equivalent values of c' and ϕ' are determined using equivalent area matching procedure as proposed by Abusharar and Han [25].

Comparison of the Results Obtained From the Proposed Analysis with the Results Available in the Literature

Comparison of the results available in the literature and determined from the present analysis is made in this section. As per the best knowledge of authors, studies for obtaining both safety factor of embankment and settlement of foundation soil with columns, at various time intervals is not reported. However, there are investigations to study the effectiveness of columns on safety factor of embankment constructed on non-consolidating soil, and there are also studies to investigate the effectiveness of columns on settlement and on excess pore water pressure during the consolidation of foundation soil. Hence, the results obtained by the present analysis and available in literature is compared in two parts. In the first part, the settlement of soil beneath the centre of embankment at various time intervals during consolidation determined from the

proposed analysis and the results reported by Zhang et al. [3] are compared. Zhang et al. [3] analysed the embankment supported by granular piles (GP) and pervious concrete pile (PCP). The problem considered for the study consists of embankment of height 6 m with a pavement of 0.7 m thick. The foundation soil is of depth 24 m. Both the GP and PCP columns are of length 10 m. The embankment of 6 m height is built in 70 days and the pavement of thickness 0.7 m is constructed after six months. The variations of settlement at surface with time beneath the centre of the embankment reported by Zhang et al. [3] and obtained by the present analysis for the similar problem when GP and PCP columns are used to improve the consolidating soil is shown in Fig. 2a, b. The settlement at various time intervals reported by Zhang et al. [3] and obtained by present analysis are almost similar for GP columns, whereas, the settlement obtained by present analysis is slightly larger than that presented by Zhang et al. [3] for PCP columns. The difference in settlement for PCP columns may be due to the difference in type of elements used in the analysis reported by Zhang et al. [3] and in the proposed analysis to model the columns. In addition, it can also be observed in both the Fig. 2a, b that the time versus settlement curve is nearly constant with time after 400 days. This is because,

since both the GP and PCP columns have considerably large permeability, the consolidation is almost complete before the construction of pavement layer and hence, the consolidation settlement after 250 days is only due to the load on foundation soil due to pavement construction. The settlement due to this load is significantly lesser than that of the load due to embankment of 6 m height.

Zhang et al. [28] investigated the effectiveness of columns on safety factor for the embankment of height 5 m and side slopes 2:1 constructed on soil of height 12 m consisting of two layers of soil, top 10 m clay and 2 m thick sand beneath the clay stratum. The properties of embankment and foundation soils are as shown in Table 1. The properties of column are also shown in Table 1. In the study, the safety factor for the embankment is determined when the columns are modeled either using column wall method or using equivalent area method. In addition, the safety factor of embankment is also reported for short-term and for long-term conditions. The safety factor obtained by the proposed analysis, modeling the columns as line elements as explained above, and that reported by Zhang et al. [28] is shown in Table 2 for similar values of c' and ϕ' . As observed from the table, the safety factor obtained by the present analysis is almost similar to the safety factor obtained by Zhang et al. [28] by

Fig. 2 **a** Time v/s settlement reported by Zhang et al. [3]. **b** Time v/s settlement obtained by the present analysis

Table 1 Properties of embankment soil, foundation soils and the columns considered by Zhang et al. [28]

Material	d (m)	$\gamma(\text{kN/m}^3)$	E (MPa)	μ	c (MPa)	ϕ (°)
Embankment		18	30	0.3	10	32
Clay (short-term)		16	4	0.45	20	0
Clay (long-term)		16	4	0.45	0	20
Sand		18	100	0.3	0	30
Column	0.5	17	40	0.3	0	38

Table 2 Comparison of safety factors reported by Zhang et al. [28] and obtained by present analysis

Type	Reported by Zhang et al. [28]		Obtained by present analysis
	Column wall method	Equivalent area method	
Short-term	1.69	1.86	1.88
Long-term	1.68	1.70	1.61

equivalent area method for short-term condition, whereas for long-term condition, the safety factor obtained by the present analysis is slightly lesser than that obtained by Zhang et al. [28] by column wall and equivalent area methods.

Problem Considered for the Numerical Study

Figure 3a shows the embankment constructed on consolidating soil with columns considered for the present study. The embankment of height 5 m, width 14 m and side slopes 1:1 is constructed on soil of thickness 10 m as shown in the figure. The position of water table is also shown in figure and is at the ground surface. The material properties of foundation soil and embankment soil are as shown in the Table 3. The properties of lime and CFG columns are shown in the Table 4. The problem considered for the analysis is not an actual site, but the properties of foundation and embankment soils are similar to the soils reported in literature as referred in the Table 3. The construction of embankment is in five stages and completed in eighteen days, each stage being of height 1 m, constructed in two days with a gap of two days each. Figure 4 shows the finite element model representing the embankment, foundation soil and columns

for the problem shown in Fig. 3a. It is a two-dimensional model considering only one half of the problem due to symmetry. The behavior of embankment and foundation soils is modeled using a Mohr–Coulomb constitutive model which requires four material properties, such as Young's modulus E , Poisson's ratio μ , effective angle of internal friction ϕ' and effective cohesion c' . The behaviors of columns are assumed as linearly elastic and its stress–strain behavior is modeled using Young's modulus E and Poisson's ratio μ . The relative slip between columns and surrounding soil is neglected and perfect bond is assumed between soil and columns. Since hard rock is situated at a depth of 10 m from the ground level, a hinge support to restrain both the vertical and horizontal displacements is provided along the boundary

Table 4 Properties of lime columns and CFG columns [5, 13, 19]

	E (kN/m ²)	μ	γ (kN/m ³)	c' (kN/m ²)	ϕ' (degree)
Lime column	20,000	0.25	20	200	0
CFG column	25,000,000	0.2	20	900	35

Fig. 4 Finite element discretisation of foundation soil, embankment soil and columns **Fig. 3** **a** Embankment constructed on consolidating soil with columns considered for the study. **b** Figure showing salient points considered for studying displacement, pore pressure and forces**Table 3** Properties of embankment soil and foundation soil

	E (kN/m ²)	μ	γ (kN/m ³)	c' (kN/m ²)	ϕ' (degree)	k (m/day)	References
Embankment soil	20,000	0.4	18.7	29.3	36.5	—	[3]
Foundation soil	2300	0.3	17	2.5	23	9×10^{-4}	[5]

BC. The extent of soil from the toe of the embankment is fixed by trial and error and the horizontal displacement is restrained at all the nodes at a distance of 20 m from toe. The horizontal displacement at all the nodes along the side CD is also restrained to represent symmetry. The embankment soil is considered as dry and the pore water is assumed to drain along the horizontal ground surface AF and through embankment soil.

Results and Discussion

The effectiveness of providing lime and CFG composite column system on the safety factor of embankment on consolidating soil at various time intervals is investigated. The effectiveness of the composite column system is also compared with the effectiveness of providing only lime columns or CFG columns. Further, the effect of arrangement of lime and CFG columns on safety factor of embankment is also studied. For this, both the lime and CFG columns of equal length are provided alternatively in one case, whereas in the other case, the CFG columns are comparatively longer than

lime columns. Thus, the various cases considered for the study are as follows:

- (1) Only short lime columns (SL)
- (2) Only short CFG columns (SCFG)
- (3) Combination of short lime and short CFG columns (SL + SCFG)
- (4) Combination of short lime and long CFG columns (SL + LCFG)

Similar diameter and spacing of columns are considered for all the cases. The schematic sketch showing the plans and elevations for all the above composition of lime and CFG columns are shown in Fig. 5a, b. As shown in the figures, the short columns are of length 6 m and long columns are of length 10 m. In addition to safety factor of the embankment, the effectiveness of providing lime–CFG column system on the settlement of soil, distribution of excess pore water pressure and forces in columns are also investigated. The various points in the soil considered to study the settlement, excess pore water pressure and forces in columns are shown in Fig. 3b.

Fig. 5 **a** Plan showing various column combinations considered for study. **b** Elevation showing various column combinations considered for study

Effect of Composite Column System on Settlement

The settlement profiles of soil at the ground surface at the end of construction of embankment and at the end of consolidation of foundation soil improved with various combinations of lime and CFG columns are shown in Fig. 6a, b. The settlement profile of soil at the ground surface without columns is also shown in figure for comparison. Reduction in settlement of foundation soil beneath the embankment due to the provision of various combinations of lime and CFG columns can be clearly observed from these figures. However, among the various cases, SL + LCFG are the most effective to reduce the settlement at the base of embankment, followed by SCFG and then by SL + SCFG, and finally SL are the least effective to reduce the settlement beneath the embankment. The maximum settlement of soil (at point S) at the end of consolidation is equal to 0.387 m for SL and it reduces to 0.06 m for SL + LCFG. This clearly shows the advantages of providing short lime and long CFG columns alternatively instead of providing only short lime columns. Compared to SCFG, the SL + LCFG not only reduces the settlement, but SL + LCFG are also more economical compared to SCFG due to lesser cost of lime columns compared to CFG columns. The other observation from the Fig. 6a, b is that, the relative slip between the columns and surrounding soil at the interface (the difference in settlement between column and surrounding soil) is largest for SL + LCFG and SL + SCFG, the relative slip is lesser for SCFG, followed by SL. The settlement at different interval of time below the center of embankment at the ground surface (point S) is shown in Fig. 7. The figure indicates that among various cases, the SL + LCFG are the most effective to reduce

Fig. 7 Variation of settlement with time at point S for the soil with and without columns

the settlement both during the construction of embankment and after the construction of embankment till the end of consolidation of foundation soil. The settlement and lateral deformation at various depths in soil beneath the three points T, M and C at the end of consolidation for various combinations of lime and CFG columns are shown in Fig. 8a, b. As marked in the Fig. 3b, points C and T are at the ground level near to the center and toe of the embankment, respectively, whereas point M is in between C and T. As expected, for all the cases considered, the settlement at all the depths is largest beneath point C, followed by point M and then at point T. In contrast, the lateral deformations along the depth are largest beneath point T, followed by point M

Fig. 6 **a** Settlement at the base of embankment for the soil with and without columns at the end of construction. **b** Settlement at the base of embankment for the soil with and without columns at the end of consolidation

Fig. 8 **a** Variation of settlement with depth below points T, M and C for the soil with and without columns at the end of consolidation. **b** Variation of lateral displacement with depth below the points T, M and C for the soil with and without columns at the end of consolidation

and then point C. Further, similar to the effectiveness to reduce settlement along the ground surface, the SL + LCFG are also more effective to reduce both the settlement and lateral deformation along the depth of the soil, and compared to SL + LCFG, the effectiveness to reduce both lateral displacement and settlement along the depth decreases for SCFG, followed by SL + SCFG and finally for SL, which is the least effective to reduce both the settlement and lateral displacement along the depth of the soil. Thus, from the above observations, it may be said that, among the four cases, the SL + LCFG are the most effective, followed by

SCFG and then by SL + SCFG, and finally the SL to reduce the settlement.

Effect of Composite Column System on Excess Pore Water Pressure

The distribution of excess pore water pressure in foundation soil without columns 200 days after the construction of embankment and for the soil improved using various arrangements of columns is shown in Fig. 9a–e. As observed from the figures, the excess pore water pressure at all the

Fig. 9 **a** Distribution of excess pore water pressure (kN/m^2) at 200 days for the soil without columns. **b** Distribution of excess pore water pressure (kN/m^2) at 200 days for the soil with short Lime columns (SL). **c** Distribution of excess pore water pressure (kN/m^2) at 200 days for the soil with short CFG columns (SCFG). **d** Distribu-

tion of excess pore water pressure (kN/m^2) at 200 days for the soil with short Lime + short CFG columns (SL + SCFG). **e** Distribution of excess pore water pressure (kN/m^2) at 200 days for the soil with short lime + Long CFG columns (SL + LCFG)

points in the foundation soil with columns is lesser compared to the excess pore water pressure in the soil without columns. In addition, it can also be observed that, the excess pore water pressure after 200 days is considerably lesser for SL + LCFG compared to all other cases. This again shows that SL + LCFG are the most effective to dissipate excess pore water pressure and to accelerate consolidation process.

The next effective case to accelerate consolidation process is the SCFG and then the SL + SCFG and the least effective case to dissipate excess pore water pressure is SL. The excess pore water pressure at different time intervals during the construction of embankment and during the consolidation of foundation soil shown in Fig. 10 at points X, Y and Z also indicates the effectiveness of SL + LCFG, compared

Fig. 10 Variation of excess pore water pressure with time at points X, Y and Z for the soil with and without columns

to other cases, to dissipate the excess pore water pressure during consolidation. In this case, the excess pore water pressure at all the three points is less than 5 kN/m^2 immediately after construction and the pressure dissipates within 500 days after the construction of the embankment, whereas, for SL which is least effective, the excess pore water pressure is larger than 70 kN/m^2 at points Y and Z immediately after construction and requires more than 1000 days for complete dissipation of excess pore water pressure. The other important observation from this study is when the excess pore water pressures are compared for the two cases of SCFG and SL + LCFG. In this case, even though CFG columns are considerably stiffer than that of lime columns, the long CFG columns placed at comparatively larger spacing along with short lime columns are more effective than that of short CFG columns placed at closer spacing to accelerate consolidation process. This again shows the effectiveness of SL + LCFG compared to SCFG. This is because, the soil and SL + LCFG composite system are more stiffer than that of the soil and SCFG composite system as evident from settlement profiles shown in Fig. 6a, b.

Effect of Composite Column System on Forces in Columns

Axial forces and bending moments in columns below the points nearer to TF, MF and CF for various cases at the end of construction of embankment and at the end of consolidation of foundation soil are shown in Figs. 11 and 12, respectively. The forces shown in these figures for the cases of SL + SCFG and SL + LCFG are the forces in CFG columns. As observed from these figures, the axial forces in columns beneath all the three points at the end

of construction of embankment and at the end of consolidation of foundation soil are largest for SL + LCFG. When compared to the axial forces of SL + LCFG, the axial forces decrease for SL + SCFG and SCFG followed by SL. Again, the axial forces do not vary much with depth in case of SL, whereas, it increases with depth for the cases of SL + SCFG and SCFG, reaches a maximum value near the center of the columns and then decreases beyond this depth. In the case of SL + LCFG, the axial force increases with depth up to the center of the column and then do not vary much with depth. This may be because, the soil near the ground surface settles more than that of the columns up to a certain depth and beyond this depth, the settlement of columns is larger than that of the surrounding soil. Abusharar et al. [5] states that this is because, the displacements of subsoil are larger than those of the columns in a range of depth along the shaft and additionally, the negative friction is generated by the relatively larger settlement of shallow subsoil; however, below the neutral plane, the displacements of the columns are larger than that of the subsoil and positive skin friction is generated. Thus, the variation of axial forces with depth is strongly influenced by the type of columns and their arrangement. Also, as expected, the axial forces are lesser for the columns beneath the point TF compared to the axial forces beneath the points MF and CF. The axial forces on columns beneath the points MF and CF are almost similar.

The bending moments in columns below the points TF, MF and CF shown in Fig. 12 indicate that the bending moments are negligible for short lime columns, whereas, the CFG columns are subjected to comparatively larger bending moments at the end of construction of embankment and at the end of consolidation. Among all the cases, the bending moments in CFG columns are largest for SL + LCFG. Also,

Fig. 11 **a** Variation of axial forces with depth in columns below the points TF, MF and CF at the end of construction. **b** Variation of axial forces with depth in columns below the points TF, MF and CF at the end of consolidation

Fig. 12 **a** Variation of bending moment with depth in columns below the points TF, MF and CF at the end of construction. **b** Variation of bending moment with depth in columns below the points TF, MF and CF at the end of consolidation

the maximum bending moment in CFG columns beneath the point TF is almost similar for both the cases of SL + SCFG and SCFG, whereas, at other points, the maximum bending moment in CFG columns is larger in the case of SL + SCFG compared to the bending moment in CFG columns in the case of SCFG. Again, as expected, the bending moment is largest in columns beneath the point TF, followed by point MF and then point CF.

Effect of Composite Column System on Safety Factor

The safety factor at various time after the construction of embankment until the end of consolidation of foundation soil for the various arrangement of lime and CFG columns is shown in Fig. 13. The safety factor at various times for the embankment constructed on soil when columns are not provided is also shown in the similar figure for comparison. As observed from the figure, the safety factor at the end of construction of embankment is equal to 1.38 when the columns are not provided, whereas, the safety factor increases to 2.34, 2.96, 3.03 and 3.33, respectively, for SL, SL + SCFG, SL + LCFG and SCFG. Similarly, the safety factor at the end of consolidation is equal to 2.04 without columns and is equal to 2.58, 3.10, 3.08 and 3.42, respectively, for the embankment on soil with SL, SL + SCFG, SL + LCFG and SCFG. These observations indicate that the safety factor at the end of construction of embankment as well as at the end of consolidation increases due to the provision of columns. However, compared to all the other cases, the effectiveness to improve the safety factor is largest for SCFG, and SL + LCFG or SL + SCFG is only the next effective case to improve the safety factor followed

by SL. Also, the effectiveness to improve the safety factor is almost similar when short lime columns are provided either with short CFG columns or with long CFG columns. These observations are interesting, because, among the various cases studied, the most effective case is SL + LCFG to reduce the settlement of foundation soil and to accelerate the dissipation of excess pore water pressure, whereas, SCFGs are observed to be the most effective to improve the safety factor. Since, both the angle of internal friction and cohesion are larger for CFG columns compared to lime columns, the effectiveness to improve the safety factor is also larger when only CFG columns are provided rather than providing lime and CFG columns alternatively. Thus, comparing the effectiveness of SCFG and SL + LCFG, it can be said that, comparatively stiffer SL + LCFG and soil composite system contribute more towards achieving reduction in settlement, whereas, lesser shear strength of lime columns in the case of SL + LCFG, limits its applicability to improve the safety factor. In contrast, larger shear strength of CFG columns contribute more towards achieving larger safety factor in the case of SCFG, rather than to reduce the settlement due to the lesser stiffness of soil and SCFG composite system. These observations are important because, the similar type of columns and their arrangements may not show the similar effectiveness to reduce the settlement and safety factor. The most effective arrangement of columns to reduce the settlement may not be the most effective arrangement to enhance the safety factor. Hence, the type of columns and their arrangements have considerable influence on the purpose for which columns are provided. In addition, the safety factor increases from 1.38 at the end of construction to 2.04 at the end of consolidation when columns are not provided, whereas, it increases only from 2.34 to 2.58 for SL, 2.96 to 3.10 for SL + SCFG, 3.03 to 3.08 for SL + LCFG and 3.33 to 3.42 for SCFG as observed from Fig. 13. These observations indicate that the consolidation of soil has considerable influence on safety factor of the embankment when columns are not provided, whereas, the effect of consolidation reduces due to the provision of columns. Again, among the four cases, the effect of consolidation is largest for SL and reduces for all other cases. These results are significant, because the safety factor corresponding to the end of consolidation is achieved immediately after the end of construction of embankment when CFG columns are provided.

The slip surfaces shown in Fig. 14 for the various arrangement of columns indicate that the slip surface is larger in size and passes deeper into the foundation soil when columns are not provided. Compared to the slip surface for the case of embankment on soil without columns, the slip surface reduces in size and passes relatively at shallow depth for SL. The slip surface further decreases in size for SL + SCFG and finally it starts at the toe of the embankment and passes only through the embankment soil for both the cases of SCFG

Fig. 13 Variation of safety factor with time for the embankment constructed on the soil with and without columns

Fig. 14 **a** Critical slip surfaces for the embankment on soil with and without columns, at the end of construction of embankment. **b** Critical slip surfaces for the embankment on soil with and without columns, at the end of consolidation

and SL+LCFG. Since the slip surface in foundation soil, passes close to the ground surface, where, pore pressures do not vary much with time, the safety factor also does not vary much during the consolidation process when columns are provided.

Thus, the major factors to be considered when embankments are constructed on consolidation soil, are the variation of settlement, dissipation of excess pore water pressure and variation of safety factor with time during consolidation. Through this study, it is shown that the type of columns and their arrangement most effective to reduce the settlement and to dissipate excess pore water pressure, may not be the most effective to improve the safety factor.

Comparison of Line Elements and Plane Strain Elements for Modeling the Columns

As explained in section, Finite element discretization of embankment soil, foundation soil and columns, the columns are modeled using line elements in the proposed analysis. The other approach generally used to model the columns is using the elements similar to the elements used to model the soil (plane strain elements). In this section, to compare the two types of elements to model the columns, the settlement and safety factor obtained by modeling the columns using line elements are compared with the settlement and safety factor obtained by modeling the columns using plane strain elements. Figure 15 shows the finite element discretisation of the problem considered for the study using four-noded plane strain quadrilateral elements. As shown in the figure, the columns are also discretised using four-noded quadrilateral elements. The analysis is similar to the analysis explained under the section “[Finite element discretisation of embankment soil, foundation soil and columns](#)” other than using quadrilateral elements to

Fig. 15 Finite element discretisation of foundation soil, embankment soil and columns when columns are modeled using plane strain elements

Table 5 Comparison of settlements obtained by modeling the columns using line and plane strain elements

Column combinations	Line element		Plane strain element	
	End of construction	End of consolidation	End of construction	End of consolidation
SL	0.197	0.387	0.195	0.378
SCFG	0.098	0.180	0.077	0.165
SL+SCFG	0.120	0.228	0.113	0.205
SL+LCFG	0.0565	0.060	0.052	0.055

model the columns instead of line elements. The safety factor of the embankment is obtained using column wall method in this analysis. Table 5 compares the settlements obtained at the ground level below the centre of the embankment (point S, refers to settlement at the centre of embankment as shown in Fig. 3b) at the end of construction of embankment and at the end of consolidation

Table 6 Comparison of safety factors obtained by modeling the columns using line and plane strain elements

Column combinations	Line element/ Equivalent area method		Plane strain element/column wall method	
	End of construction	End of consolidation	End of construction	End of consolidation
SL	2.34	2.58	2.10	2.43
SCFG	3.33	3.42	3.36	3.44
SL+SCFG	2.96	3.10	2.72	2.87
SL+LCFG	3.03	3.08	2.74	2.77

of foundation soil when columns are modeled using two types of elements. Table 6 shows the safety factor at the end of construction of embankment and at the end of consolidation of foundation soil obtained when columns are modeled using plane strain and line elements. From the Table 5, it can be observed that, the settlement obtained by modeling the columns using plane strain elements is marginally lesser than that obtained when line elements are used to model the columns. This difference may be partly due to the difference in degrees of freedom considered for the elements. The rotational degrees of freedom are considered for line elements, whereas neglected for plane strain elements. Comparison of safety factor obtained by modeling the columns using two types of elements, shown in Table 6 indicates that the safety factor obtained when the columns are modeled using plane strain elements are lesser than that obtained, when line elements are used to model the columns. This is mainly because, when line elements are used to model the columns, the safety factor is obtained using equivalent area method, whereas, when the columns are modeled using plane strain elements, column wall method is used to obtain the safety factor. The differences between the safety factor obtained using two types of elements are in the range of about 8% to 12%. Similar observations of lesser safety factor obtained by column wall method compared to the safety factor obtained by equivalent area method have also been reported by Abusharar and Han [25] and Zhang et al. [28]. Abusharar and Han [25] proposed a factor of 0.9 to convert the safety factor from equivalent area method to column wall method. Zhang et al. [28] also recommended a factor 0.9 or 1.0 depending upon the properties of foundation soil to convert the safety factor from equivalent area method to column wall method. However, in the case of SCFG columns, since, the slip circle passes only through embankment soil, the safety factor obtained by modeling the columns using line elements is similar to that of the safety factor obtained by modeling the columns using plane strain elements.

Summary and Conclusion

Effectiveness of providing lime and CFG composite column system on the safety factor of embankment constructed on consolidating soil is studied numerically. The effectiveness of composite system is also compared with the effectiveness of providing only lime and CFG columns. The effective stress in soil is determined by finite element analysis and the safety factor is determined for a critical slip surface chosen from the number of trial circular slip surfaces. The effectiveness of providing composite column system on settlement and dissipation of excess pore water pressure is also investigated. From the study, the following conclusions are drawn:

- (1) The safety factor of the embankment increases due to the provision of lime and CFG columns, provided either separately or in combination. However, the effectiveness to improve the safety factor is influenced not only by the type of columns, but also by their arrangements.
- (2) The provision of columns are also effective to improve the settlement of the foundation soil and to accelerate the consolidation process. However, as in the case of effectiveness to improve the safety factor, the effectiveness of columns to improve the settlement and to accelerate the consolidation process is also influenced considerably by the arrangement of columns.
- (3) The arrangement of columns that is most effective to improve the settlement and to accelerate the consolidation process during consolidation may not be the most effective to improve the safety factor. This indicates that the similar arrangements of columns may not show the similar effectiveness to improve both the settlement and safety factor. The arrangement of columns has considerable influence on the purpose for which columns are provided.
- (4) In the case of embankment constructed on soil without columns, the safety factor increases with time and requires longer duration to achieve the final safety factor corresponding to the end of consolidation, whereas, when CFG columns are provided individually or in combination with lime columns, the final safety factor corresponding to the end of consolidation may be achieved immediately after the end of construction, indicating that the consolidation of soil has no much influence on safety factor. This is because, when the CFG columns are provided, the slip surface in foundation soil, passes very close to the ground surface throughout the consolidation process.
- (5) The large axial forces in CFG columns may not be a major limitation for these columns, considering the

larger compressive strength of CFG columns compared to lime columns. However, CFG columns may require reinforcements to resist the bending moments.

- (6) The settlement of foundation soil and safety factor of embankment when columns are modeled using plane strain elements are lesser than that obtained using line elements to model the columns.

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