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TECHNICAL PAPER

Stability of Embankment Constructed on Soft Soil Treated with Soil–Cement Columns

K. G. Prakash[1] · A. Krishnamoorthy[1]

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Abstract
The objective of this study was to investigate the effectiveness of soil–cement (SC) columns, provided either individually or in combination with lime columns, on the stability of embankment constructed on soft consolidating soil. The stability of the embankment was evaluated in terms of both the settlement and factor of safety at various time intervals during the consolidation. The effectiveness of columns was studied numerically using the two-dimensional plane strain finite element method. Settlement, excess pore water pressure and factor of safety were obtained at various time intervals. From the study, it was concluded that SC columns were effective in improving both the settlement and factor of safety of embankment throughout the consolidation of foundation soil. Provision of SC columns with lime columns was also effective in improving the stability of embankment. In addition, the stability of the embankment was affected by the arrangement of columns in the lime and SC composite system. The arrangement most effective to improve the settlement need not be the most effective system to improve the factor of safety after the construction of the embankment.

Keywords Embankment · Factor of safety · Soft consolidating soil · Soil–cement columns · Finite element method

1 Introduction

The rapid urbanisation, infrastructure development and industrialisation have necessitated the construction of embankments even on soft soil, which was discarded as inappropriate in earlier days. Construction of embankment on soft soil is also essential nowadays, due to the necessity of additional development to fulfil the need of the fast-growing population, scarcity of suitable land and increasing value of the land.

✉ K. G. Prakash
prakash.kg@learner.manipal.edu; prak.kg@gmail.com

1 Department of Civil Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal-576104 Udupi Taluk and District, Karnataka, India

The unfavourable geotechnical condition may pose many challenges to the embankment construction over soft soil, such as low bearing capacity, excessive settlement and slope instability (Ye et al. 2017). This may need more cost in maintenance and repair in later stages. Many techniques can be used to improve the strength of soil and its compressibility, but geotechnical engineers have two choices: deep improvement, either using deep foundations such as piles that are costly and noisy or using soil improvement (Karkush and Jabbar 2022). Improvement of soil using various techniques has a long history and is developed continuously with the innovation of new materials.

Filling of lightweight materials, preloading or surcharging, provision of vertical drains, excavation and replacing the existing soil, provision of columns, provision of reinforcements in foundation soil, stage-wise embankment construction, use of in-situ admixture in foundation soil and/or in embankment construction and many types of ground improvement techniques have been proposed to improve the ground, based on cost, time and in-situ requirements. Among these, columnar inclusion is one of the effective and widely used methods for improving the engineering properties of soft clay ground (Horpibulsuk et al. 2012). The primary function of such columns in soft soil is to transmit loads into deep stratum or deep hard soil while limiting ground level settlement. Simultaneously, these columns minimise excess pore water pressure and lateral movement of foundation soil while increasing embankment stability. For the columns, different materials such as lime, sand, stone, cement-fly ash-gravel, soil–cement and lime-cement have been proposed in the past. Among these, the inclusion of stone and lime columns in soft soil is one of the effective techniques of ground improvement. Because the stone columns are highly permeable, they act as vertical drains, allowing the soft clay around them to consolidate and improve the foundation's long-term performance (Karkush et al. 2021). For deep improvement of soft soil, the floating stone columns are considered the best and effective economically which provide lateral confinement and drainage and longitudinal skin friction (Karkush and Jabbar 2019). Lime columns also act as vertical drains and increase the rate of consolidation. Compared to stone columns, lime columns are stiffer to some extent and likely to behave linearly elastic during the loading (Poorooshasb and Meyerhof 1997). Shear strength of lime columns is also larger compared to stone columns. The other commonly used approach to improve the ground is using soil–cement (SC) columns. The inclusion of SC columns using the deep soil mixing method is one of the stabilising techniques that have been applied successfully worldwide (Farouk and Shahien 2013). Soil–cement is a mixture of cementitious chemical material (usually referred to as cement) and natural material (usually referred to as soils) (Fan et al. 2018). The most common way for constructing SC columns is to mix cement powder or slurry into soft ground. The inclusion of soil–cement columns in soft soil is a ground improvement technique that is used to reduce the settlement and improve the bearing capacity of the soft soil ground (Mohanty and Shahu 2021). The effectiveness of using SC columns to improve the soft ground has been investigated extensively (Fang and Yin 2007; Liu et al. 2012; Ye et al. 2012; Horpibulsuk et al. 2012; Farouk and Shahien 2013; Chai et al. 2015; Yi et al. 2017; Rashid et al. 2018; Jamsawang et al. 2019). From these studies, it has been reported that the SC columns are effective to improve the bearing capacity and accelerate the consolidation process. Also, when one type of column cannot satisfy both the economy and stability, then it is a common practice to combine different types of columns. The multi-pile composite ground is not only economical but can improve the strength of the soft soil till the deeper stratum. The effectiveness of the combination of lime and CFG columns, lime and SC columns to improve the settlement has been investigated by Abusharar et al. (2009).

However, all these studies are primarily concerned with improving soil settlement, lateral displacement and consolidation behaviour. But, for the embankment, the factor of safety is one of the other major parameters to be considered while assessing the stability of the embankment. The performance of an embankment and its susceptibility to failure is usually measured by its factor of safety (Abdalla et al. 2015). Moreover, the consolidating soil improved with SC columns dissipates the excess pore water pressure from the beginning of construction till the completion of the consolidation, causing the soft soil to harden continuously. The change in effective stresses causes variation in the factor of safety from embankment construction till the completion of consolidation in soft soil. As a result, assessing the stability of the embankment supported by SC columns both in terms of settlement and factor of safety is essential from the beginning of construction till the end of consolidation.

Hence, the main objective of the present study is to investigate the stability of embankment constructed on soft consolidating soil improved with SC columns in terms of both settlement and factor of safety, at various time intervals during the consolidation of soft soil. In addition, the effectiveness of providing a combination of lime and SC composite system on the stability of embankment is also investigated. It may be noted that the lime columns are much flexible and have less shear strength, but are economical compared to SC columns. As already discussed above, the effectiveness of lime and SC composite column system on settlement and excess pore water pressure has been investigated (Abusharar et al. 2009; Asakereh et al. 2018), but the effectiveness of the composite system on both settlement and factor of safety is not yet investigated. Hence, the objective of the study is also to investigate the stability of embankment constructed on soft consolidating soil improved with lime and SC composite column system both in terms of settlement and factor of safety at various time intervals during the consolidation. In addition, various combinations of lime and SC columns in a lime and SC column composite system are also investigated to assess the more effective combination of lime and SC columns.

Computing the factor of safety of an embankment on consolidating soil is a lengthy and time-consuming process that involves iterative calculations and requires computer tools. For complex geotechnical engineering problems, numerical analysis is becoming a standard and powerful tool, since it not only reduces the complication in analysis but also reduces the significant computational time required for analysis. Two-dimensional plane strain finite element method has been used to model the consolidation problem. Hence, for the proposed study, the embankment constructed on consolidating soil is analysed using two-dimensional plane strain finite element method. A computer program for plane strain finite element analysis using C language is developed to obtain settlement of foundation soil and factor of safety of embankment at various time intervals during the consolidation.

2 Method of Analysis

The embankment built on the soft consolidating soil and improved with columns is analysed using finite element method. The variation of displacement, u, and excess pore water pressure, p, due to the forces, f, in the soil at each time interval during the consolidation of foundation soil is obtained using the coupled consolidation equation proposed by Zienkiewicz (1977) as,

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

In this equation, H, L and k_s are the flow matrix, coupling matrix and stiffness matrix, respectively. Δ denotes the variations of each parameter from time t to time $t+\Delta t$. To obtain stiffness matrix k_s, both the soil and columns are discretised using four-noded plane strain elements with two displacement degrees of freedom at each node. Similarly, four-noded quadrilateral element with one pressure degree of freedom is also used to obtain the flow matrix H. The behaviour of columns is modelled as elastic using two material properties young's modulus E and Poisson's ratio μ. The behaviour of soil is modelled using a Mohr–Coulomb model. The material parameters for the model are modulus of elasticity E, Poisson's ratio μ, effective cohesion $c^{'}$ and effective angle of internal friction $\phi^{'}$. Since, at the locations of columns, along the length of the embankment, the circular columns are distributed in the soil at spacing, "s", as shown in Fig. 2c, the elastic stiffness matrix is calculated separately for the columns and the non-linear stiffness matrix is calculated separately for soil. The stiffness matrix of columns is then added to the stiffness matrix of soil as per the areas contributed by columns and soil in unit length, to obtain equivalent stiffness matrix at the locations of column element. The stiffness matrix, flow matrix and coupling matrix are calculated for each of the finite elements and assembled to obtain the overall stiffness matrix, ks, flow matrix H and coupling L in Eq.(1). To obtain the displacement and excess pore water pressure at each time interval Δt, Eq.(1)is solved in the incremental form using Newmark's method. To obtain the factor of safety, slip circles having different diameters and different centres are generated at each time interval and the factor of safety is calculated for each of these slip circles. A circle that yields a minimum factor of safety is considered a critical slip circle. The factor of safety for each slip surface is obtained using the equation,

$$F.S. = \frac{\sum \tau_f \bullet \Delta L_i}{\sum \tau_i \bullet \Delta L_i} \tag{2}$$

where ΔL_i is the length of the i^{th} segment, τ_f is the shear strength of the material and τ_i is the mobilised shear stress. At each time interval, the effective stress is obtained using the finite element method and effective cohesion $c^{'}$ and effective angle of internal friction $\phi^{'}$ is used to obtain the mobilised shear stress and shear strength along each of the generated slip surfaces. At the locations of columns, the equivalent values of $c^{'}$ and $\phi^{'}$ obtained using $c^{'}$ and $\phi^{'}$ of soil and columns based on weighted average areas of column and soil in unit length are used to calculate the factor of safety along the critical slip surface.

2.1 Validation of the Proposed Method of Analysis

The proposed method of analysis to determine the settlement and factor of safety is validated by comparing the results obtained from the proposed analysis with the results reported in the literature. Since to predict both the settlement and factor of safety is not reported, the validation is carried out in two parts. In the first part, the settlement at various time intervals during the consolidation of the foundation soil obtained from the proposed analysis is compared with the settlement reported by Abusharar et al. (2009). In the second part, the factor of safety obtained from the present analysis is compared with the factor of safety reported by Zhang et al. (2014).

Abusharar et al. (2009) reported the settlement obtained from the plane strain finite element analysis for the embankment of height 2 m and side slopes 1:1 constructed on consolidating soil consisting of three layers and improved with short lime columns and long SC columns. The diameter and length of short columns are 0.4 m and 8 m, respectively, whereas, the diameter and length of long columns are 0.4 m and 16 m, respectively. The c/c spacing of columns is equal to 1.3 m. Figure 1a shows the settlement at the ground surface below the centre of the embankment for the soils with and without columns reported by Abusharar et al. (2009) at various time intervals up to 200 days. The settlement obtained from the proposed analysis for a similar problem at various time intervals up to 200 days is shown in

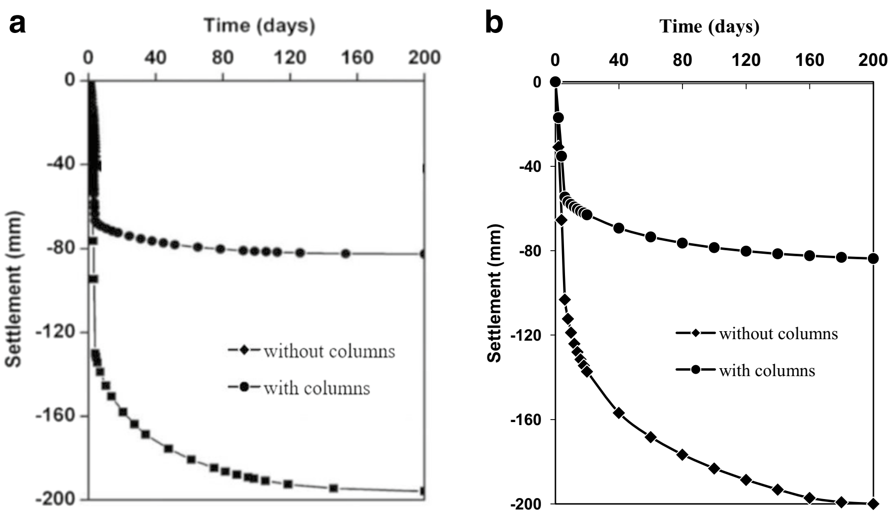


Fig. 1 **a** Settlement at the ground surface below the centre of the embankment for the soils with and without columns reported by Abusharar et al. (2009). **b** Settlement at the ground surface below the centre of the embankment for the soils with and without columns obtained from proposed analysis

Fig. 1b. From these figures, it can be observed that the settlement obtained from the proposed analysis is compared closely with the settlement reported by Abusharar et al. (2009) for the soils without columns and provided with short lime and long SC columns.

Zhang et al. (2014) reported the factor of safety of embankment of height 5 m, crest width 20 m and side slopes 2H:1V constructed on soil improved with columns, 0.5 m in diameter, 10 m long placed at a spacing of 1 m c/c. The foundation soil consists of a layer of clay up to 10 m depth and a layer of sand 2 m thick below the clay stratum. The properties of embankment soil and foundation soil are shown in Table 1. The factor of safety of the embankment reported by Zhang et al. (2014) for the problem is 1.68. The factor of safety obtained from the proposed analysis for a similar problem is equal to 1.71. The factor of safety obtained from the proposed analysis matches closely with the factor of safety reported by Zhang et al. (2014).

The above observations show that the settlement and factor of safety obtained from the proposed method of analysis is almost similar to the settlement and factor of safety reported in the literature and validates the proposed method of analysis.

3 Results and Discussions

The problem considered to study the effectiveness of SC columns on the stability of embankment constructed on consolidating soil is shown in Fig. 2a. As shown in the figure, a 5 m height embankment with side slopes 1:1 is constructed on consolidating soil of depth 10 m. The foundation soil is provided with short columns (floating columns) of length 6 m and diameter 0.5 m placed in square pattern at c/c spacing of 1.5 m as shown in Fig. 2c. A preliminary analysis is carried out to study the effect of the length of columns on a factor of safety. It was observed that as the length of the column increases, the factor of safety increases up to a length of the column is about 6 m and beyond this length, the factor of safety does not vary much. Hence, floating columns of length 6 m are considered for the proposed study. The construction sequence of embankment and method of loading is shown in Fig. 2d. As shown in the figure, the total embankment of height five m is constructed in eighteen days. Each height of one m is constructed in two days with a pause period of two days after the construction of each one m height as shown in the figure.

The material properties of the foundation soil, embankment soil and columns considered for the study are tabulated as shown in Table 2 and Table 3, respectively. The permeability of columns considered for the analysis is similar to the foundation

Table 1 Material properties considered by Zhang et al. (2014)

	γ (kN/m^3)	E (MPa)	μ	c' (kPa)	ϕ' (degree)
Embankment	18	30	0.3	10	32
Clay	16	4	0.45	0	20
Sand	18	100	0.3	0	30
Column	17	40	0.3	0	38

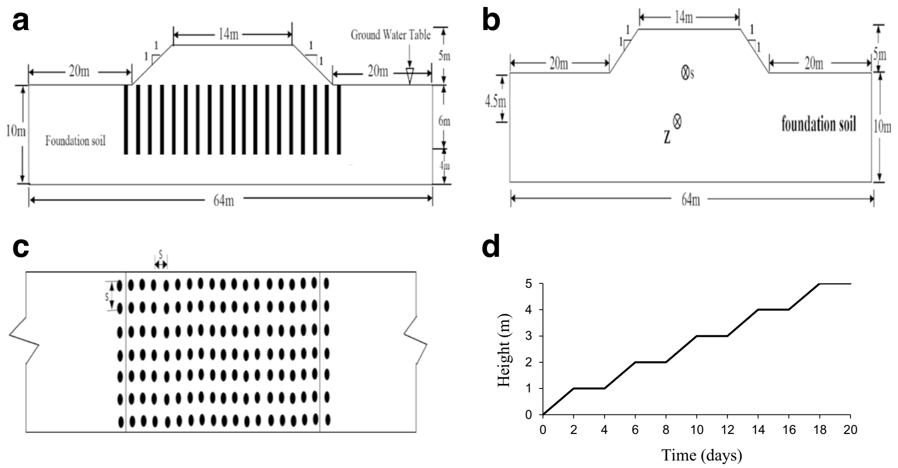


Fig. 2 **a** Embankment constructed on consolidating soil with columns considered for the study. **b** The salient points considered for studying displacement and pore pressure. **c** Plan showing position of columns in foundation soil. **d** Construction sequence of embankment and method of loading

Table 2 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	——	Zhang et al. (2016)
Foundation soil	2300	0.3	17	2.5	23	9×10^{-4}	Abusharar et al. (2009)

Table 3 Properties of lime columns and SC columns. (Abusharar et al. 2009; Poorooshasb and Meyerhof 1997; Horpibulsuk et al. 2012)

	E (kN/m^2)	μ	γ (kN/m^3)	c' (kN/m^2)	ϕ' (degree)
Lime column	20,000	0.25	20	200	0
SC column	120,000	0.3	14	600	25

soil. The finite element modelling of the problem is shown in Fig. 3a. As shown in the figure, the embankment soil, foundation soil and SC columns are discretised using four-noded quadrilateral elements. Triangular elements with three nodes at the corner are also used for discretisation near the toe of the embankment. Both the quadrilateral element and triangular element have two degrees of freedom (horizontal displacement u and vertical displacement v) at each node as shown in Fig. 3b. Because of symmetry, only half of the problem is studied. The foundation soil is assumed to be resting on a hard stratum. The water table is at the ground surface and the embankment is considered dry. Horizontal displacements, u, are restrained

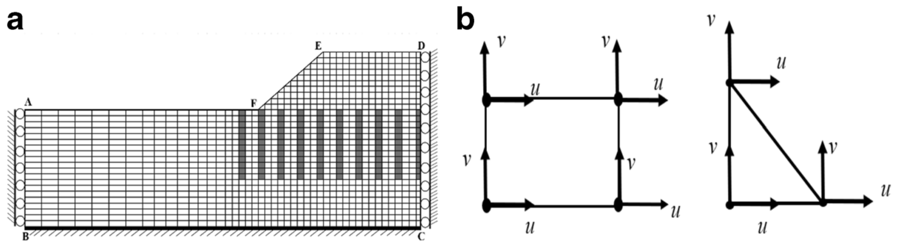
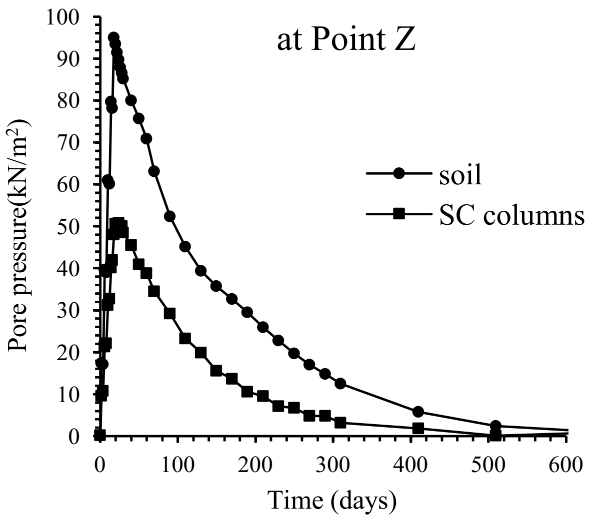


Fig. 3 **a** Finite element discretisation of foundation soil, embankment soil and columns. **b** Quadrilateral and triangular elements with two degrees of freedom at each node considered to model the soil and columns

at a distance of 20 m, from the embankment toe and roller support that prevents horizontal displacement, *u*, and permits only vertical displacement, *v*, is provided along the surface AB as shown in Fig. 3a. Similarly, roller support to prevent horizontal displacement, *u*, and to permit only vertical displacement, *v*, is also provided along the surface CD to represent symmetry. Since the base of the foundation soil is resting on a rigid base, a fixed support is provided at the base to prevent both the horizontal displacement *u* and vertical displacement *v*. Also, since the water table is at the surface of the ground and the embankment is dry, the excess pore water pressure is assigned as zero at all the nodes corresponding to the ground surface and embankment.

Variation of excess pore water pressure with time during and after the construction of embankment at point *Z*, situated at a depth 4.5 m from the ground surface below the centre of the embankment (as shown in Fig. 2b) for the foundation soils with and without columns, is shown in Fig. 4. From the figure, it can be observed that, as expected, the pore water pressure in foundation soil builds up as construction

Fig. 4 Variation of excess pore water pressure with time at point Z for the soil with and without columns



progresses and reaches the maximum at the end of construction for both the soils with and without columns. However, the maximum excess pore water pressure for the soil without columns is equal to 95 kN/m^2, whereas it is about 50 kN/m^2 for the soil with columns. Also, the total time required for complete dissipation of excess pore water pressure for the soil with columns is about 600 days and it reduces to about 300 days when columns are provided, i.e., the excess pore water pressure in soil reduces to 47% and the total time required for complete dissipation of excess pore water pressure reduces to 50% due to the provision of columns. The above observations indicate that provision of columns prevents the building up of pore water pressure during construction and rapid dissipation of excess pore water pressure after construction of the embankment.

Variation of settlement of foundation soil without columns at ground level beneath the centre of the embankment (point S as shown in Fig. 2b) at various time intervals from the beginning of construction of embankment till the end of consolidation of foundation soil is shown in Fig. 5. Variation of settlement of foundation soil with SC columns at a similar point is also shown in Fig. 5 for comparison. From the figure, it can be observed that the settlement at point S during the construction of embankment and after the construction of embankment reduces considerably due to the provision of columns. Also, the settlement at the end of consolidation without columns is equal to 0.59 m, whereas it reduces to 0.22 m when SC columns are provided, or the reduction in the settlement at point S due to the provision of columns is about 63%. This clearly shows the effectiveness of providing SC columns to reduce the settlement of foundation soil. Moreover, due to the rapid dissipation of excess pore water pressure, the final settlement corresponding to the end of consolidation can be achieved faster when columns are provided. Due to this, the post-construction settlement (settlement after construction of embankment) of foundation soil as shown in Fig. 6 is considerably lesser for the soil with columns when compared to the soil without columns. The settlement at various points at ground level immediately after the construction of embankment (18 days) and at the end of consolidation (600 days) of the foundation soil, shown in Fig. 7a and b, indicates that the

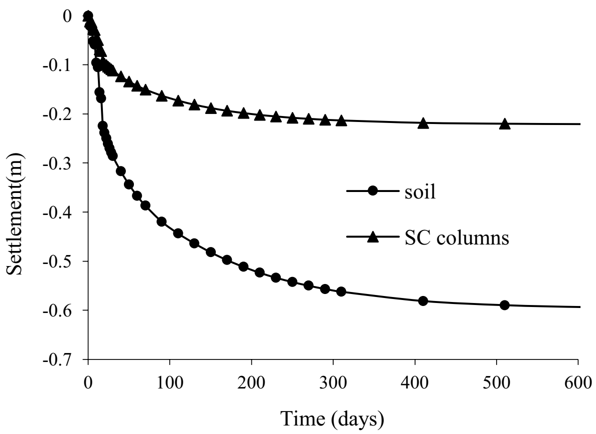


Fig. 5 Variation of settlement with time at point S for the soil with and without columns

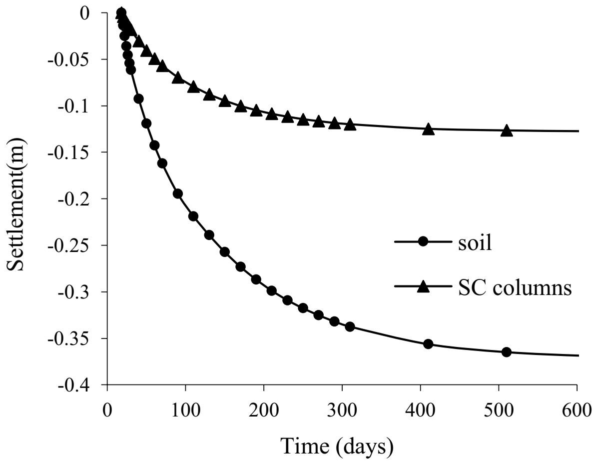


Fig. 6 Variation of post-construction settlement with time at point S for the soil with and without columns

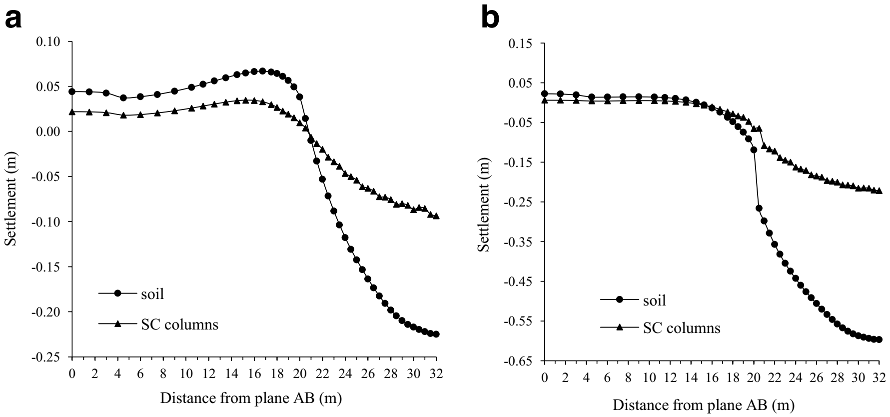


Fig. 7 **a** Settlement at the base of the embankment for the soil with and without columns at the end of construction. **b** Settlement at the base of the embankment for the soil with and without columns at the end of consolidation

settlement at all the points below the embankment as well as heave of the foundation soil beyond the embankment is lesser for the soil with columns compared to the soil without columns. This shows that the soil settles more uniformly when columns are provided compared to that of the soil without columns.

The other important parameter to assess the stability of embankment constructed on consolidating soil is to evaluate the factor of safety from the end of construction of embankment till the end of consolidation of foundation soil. The variation of a factor of safety of the embankment with time after the construction of the embankment on foundation soils with and without columns is shown in Fig. 8. From the figure, it can be observed that the factor of safety of the embankment on soil with SC columns is larger than that of the soil without columns at all the time intervals after

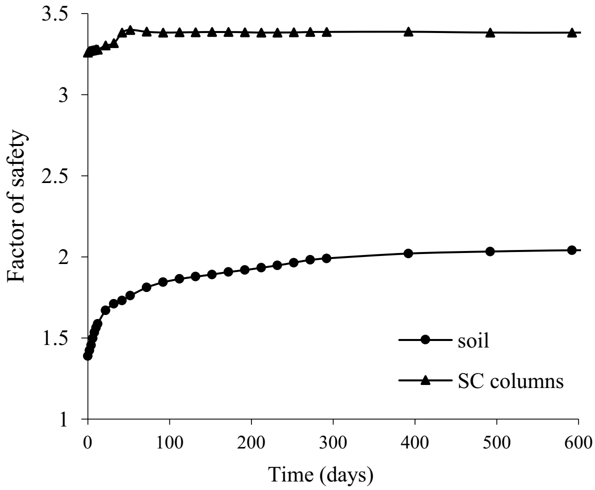


Fig. 8 Variation of factor of safety with time for the embankment constructed on the soil with and without columns

the construction of the embankment. Due to the provision of columns, the factor of safety at the end of construction improves from 1.38 to 3.25. Whereas, the improvement is from 2.04 to 3.38 at the end of consolidation, i.e., when the columns are provided, the factor of safety at the end of construction and at the end of consolidation improves to about 57% and 40%, respectively. The significant increase in the factor of safety clearly indicates the effectiveness of SC columns to enhance the factor of safety of embankment throughout the consolidation process. The other observation from Fig. 8 is that the final factor of safety corresponding to the end of consolidation is achieved within 100 days for the soil with columns. Whereas, the time required for the soil without columns is more than 600 days to achieve the final factor of safety. This shows that the provision of columns reduces the time required to achieve the final factor of safety significantly and the reduction in time required to achieve the final factor of safety is about 83%. This is one of the important advantages of providing SC columns, because the final factor of safety can be achieved within a few days after the construction of the embankment and the highways constructed on these embankments can be opened to traffic earlier, unlike, the soil without columns that requires longer duration to achieve the desired stability.

The effectiveness of using long SC columns, that extend to the base of soft soil, instead of using short columns, on the stability of embankment is also studied. The variation of settlement, excess pore water pressure and factor of safety with time for the embankment on foundation soil improved with long columns and improved with short columns are compared in Fig. 9a, b and c. From the figures, it can be observed that the long columns are more effective compared to short columns to improve the settlement throughout the consolidation process. The long columns are also effective to reduce the excess pore water pressure both during and after the construction of the embankment. However, when short columns are replaced with long columns, the factor of safety of embankment does not vary much indicating that increasing the length of columns does not have much effect on the factor of safety. This is because, increasing the length of columns till the base of soft soil, increases the stiffness of

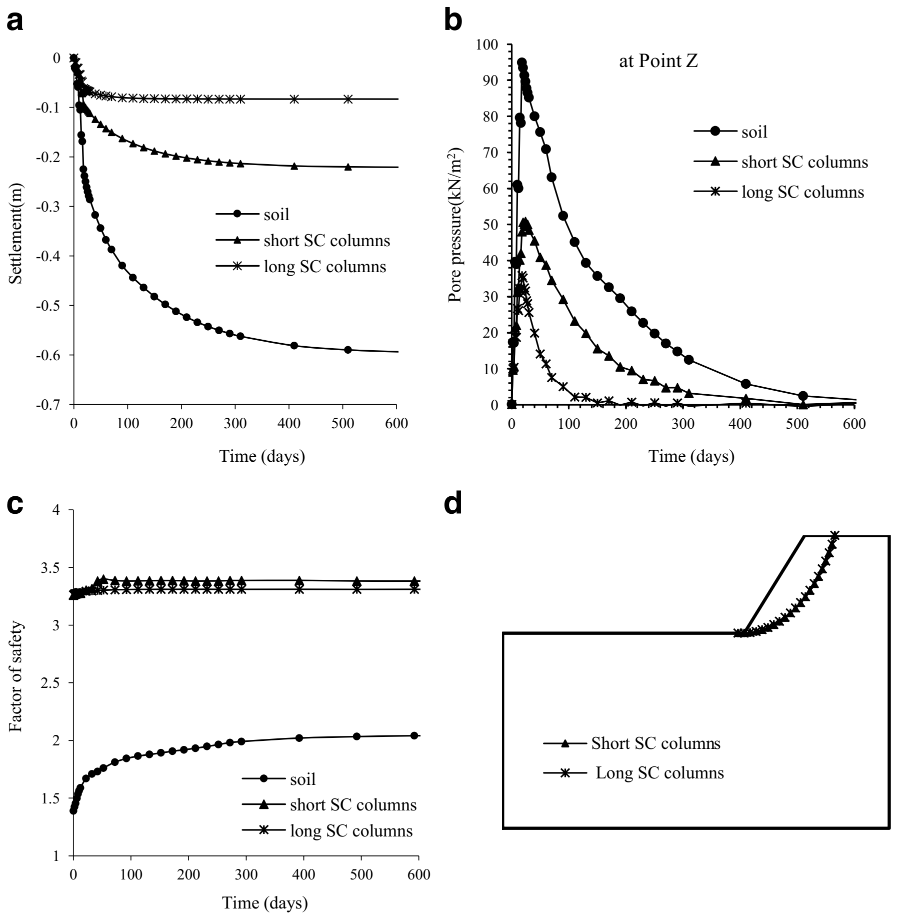


Fig. 9 **a** Variation of settlement with time at point S for the soil with and without columns. **b** Variation of excess pore water pressure with time at point *Z* for the soil with and without columns. **c** Variation of factor of safety with time for the embankment constructed on the soil with and without columns. **d** Critical slip surfaces for the soil with short SC columns and with long SC columns

soil and column composite system till the base, unlike short columns, where the stiffness of soil and column composite system improves only up to 6 m from the ground level. Since the stiffness of the soil and column composite system increases to a larger depth, the settlement decreases due to the provision of long columns. Although increasing the length of columns increases the shear strength of soil and column composite system till the base of soft soil, since the critical slip surface does not extend till the base of soft soil, the length of columns provided beyond the critical slip surface does not affect the factor of safety.

Also, from Fig. 9c, it can be observed that the factor of safety at the end of consolidation for the embankment with long columns is slightly lesser than that of the embankment with short columns. In both cases, the critical slip surface starts from the toe of the embankment and passes only through the embankment soil as shown in Fig. 9d. Due to this, there is no change in the shear strength parameters c' and ϕ' of soil along the critical slip surface for both the cases of short columns and long columns. The critical slip surface is also similar for both the cases. But, the stiffness of the foundation soil with long columns is larger compared to the stiffness of soil with short columns. Hence, the marginal difference in factor of safety between the soil with long columns and with short columns may be due to the change in stresses in embankment soil caused due to the change in the stiffness of foundation soil. However, the difference in factor of safety at the end of consolidation is marginal and the factor of safety of embankment provided either with short columns or with long columns may be considered almost similar.

3.1 Effectiveness of Lime and SC Composite Column System on the Stability of the Embankment

The effectiveness of providing lime and SC composite column system on the stability of embankment is studied and discussed in this section. The various combinations of lime and SC columns considered for the study are as follows:

- Short lime and short SC columns (SL + SS)
- Short lime and long SC columns (SL + LS)
- Short SC and long SC columns (SS + LS)

In this study, the lime and SC columns are arranged alternatively, i.e., along the length of the embankment, each row consists of either lime columns or only SC columns. The effectiveness of providing lime and SC composite system is also compared with the effectiveness of providing short lime columns (SL), short SC columns (SS) and long SC columns (LS) individually.

3.1.1 Effectiveness of Providing Various Combinations of Lime and SC Columns on Settlement of Foundation Soil

Figure 10 shows the variation of settlement with time at point, *S*, from the beginning of construction of embankment till the end of consolidation of foundation soil for various combinations of lime and SC composite column system. The variation of settlement without columns (SW) is also shown in Fig. 10 for comparison. Figure 11a and b show the settlement at various points in the ground surface at the end of construction of embankment (at 18 days) and at the end of consolidation of foundation soil (600 days). From Figs. 10 and 11, it can be observed that the most effective case to improve the settlement during and after the construction of embankment is LS followed by SS + LS, SL + LS, SS, SL + SS and finally SL which is least effective among all the cases. Short lime columns (SL) are effective to reduce the settlement both during and after the construction of the embankment. However, short SC columns (SS) being stiffer than short lime columns (SL) are more effective to reduce the settlement as observed from Figs. 10 and 11. But the almost similar reduction

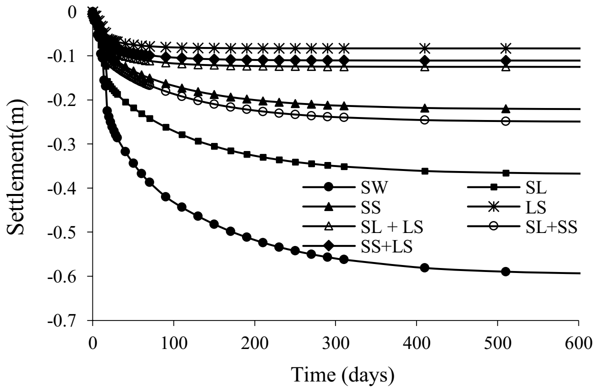


Fig. 10 Variation of settlement with time at point S for the various combinations of columns

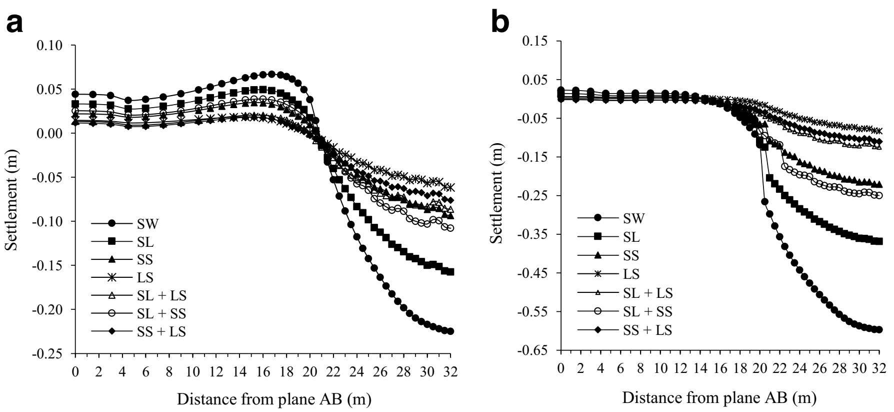


Fig. 11 **a** Settlement at the base of the embankment for the various combinations of columns at the end of construction. **b** Settlement at the base of the embankment for the various combinations of columns at the end of consolidation

in settlement to that of SS can also be achieved by providing a combination of short lime and short SC columns alternatively (SL + SS) as shown in Figs. 10 and 11 instead of providing only short SC columns (SS) at similar spacing. The almost similar settlement by providing combination of lime and SC columns (SL + SS) to that of providing only SC columns (SS) indicates that the composite action of flexible lime and much stiffer SC columns is almost similar to that of all stiffer SC columns at similar spacing. This is an important observation because, since the cost of lime columns is lesser than SC columns, the combination of lime and SC columns may be more economical than providing only SC columns. The effectiveness of the lime and SC composite system (SL + SS) can be enhanced further, and the settlement can be reduced significantly when the length of SC columns is increased till the hard stratum (SL + LS). However, no much further reduction in settlement can be achieved when short SC columns are provided with long SC columns (SS + LS) instead of providing short lime with long SC columns (SL + LS). This again shows that SL + LS may be a better combination compared to SS + LS and the composite action of alternate flexible short lime columns and much stiffer long SC columns (SL + LS) is almost similar to that of stiffer short and long SC columns provided alternatively (SS + LS). Similarly, providing only long SC columns (LS) instead of short lime and long SC columns (SL + LS) will also not reduce the settlement significantly, and may not be a better combination compared to SL + LS. The above observations clearly show the effectiveness of providing lime and SC composite system instead of providing only lime or only SC columns at similar spacing. In addition, it can also be said that considering both the effectiveness and cost, the combination of short lime and long SC columns (SL + LS) may be considered the most effective combination of lime and SC columns among all the combinations.

3.1.2 Effectiveness of Providing Various Combinations of Lime and SC Columns on the Factor of Safety of the Embankment

The effectiveness of providing various combinations of lime and SC columns on the factor of safety of embankment during the consolidation of foundation soil is compared. Variation of the factor of safety with time after the construction of embankment till the end of consolidation of foundation soil improved with various combinations of lime and SC columns is shown in Fig. 12. From the figure, it can be observed that, among all the cases, SS is the most effective to enhance the factor of safety of the embankment followed by SS + LS, LS, SL + LS, SL + SS and finally SL which is least effective to improve the factor of safety. When the effectiveness of various combinations of lime and SC columns on settlement is compared with the effectiveness of lime and SC columns on the factor of safety, it can be observed that, when settlement is considered, the effectiveness of providing all short SC columns (SS) is almost similar to the effectiveness of providing alternate short lime and short SC columns (SL + SS). Similarly, the effectiveness of providing short lime columns along with long SC columns (SL + LS) is also similar to the effectiveness of providing short SC columns with long SC columns (SS + LS). However, when the

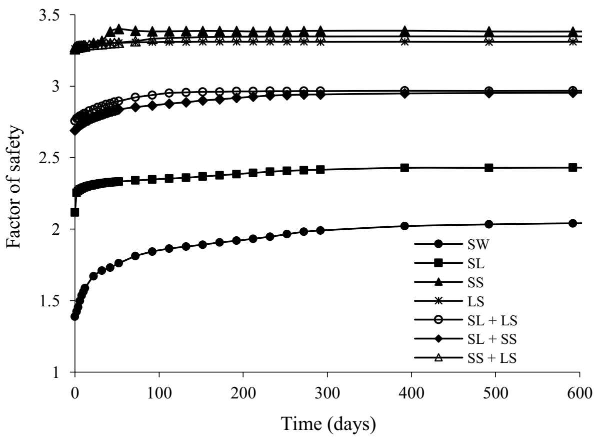


Fig. 12 Variation of factor of safety with time for the embankment constructed on the soil with various combinations of columns

effectiveness of various combinations on the factor of safety is considered, providing only short SC columns (SS) is observed to be more effective than providing alternate short lime and short SC columns (SL + SS). Similarly, providing alternate short SC and long SC columns (SS + LS) is also more effective compared to providing short lime and long SC columns (SL + LS). This shows that the composite action of lime and SC columns to reduce the settlement is not similar to the composite action of lime and SC columns to improve the factor of safety.

It is well known that the larger the stiffness of the composite system consisting of soil and columns, the lesser is the settlement and the larger the shear strength of soil and column composite system, the larger is the factor of safety. However, both the stiffness and shear strength of lime columns are lesser than that of SC columns. The stiffness of lime columns is lesser than that of SC columns due to the lesser value of modulus of elasticity, whereas shear strength of lime columns is lesser than that of SC columns due to the lesser values of cohesion and angle of internal friction as observed from Table 3, but the effectiveness of lime and SC composite system on settlement is different from the effectiveness of lime and SC composite system on factor of safety. These observations show that equivalent stiffness of soil and column composite system does not vary much when alternate stiffer SC columns are replaced with flexible lime columns, whereas, the equivalent shear strength of soil and column composite system reduces significantly when alternate SC columns with larger shear strength are replaced with lime columns having lesser shear strength. This clearly indicates that the composite action of soil and columns to improve settlement is different from the composite action of soil and columns to improve the factor of safety. Also, due to the reason discussed above, replacing short columns with long columns in all the cases is effective only to reduce the settlement and is not at all effective to improve the factor of safety. Thus, it can be said that the most effective case to improve the settlement may not be the most effective case to improve the factor of safety. Hence, the type of combination of columns is strongly influenced by the purpose for which the columns are provided.

3.2 Effect of Arrangement of Short Lime and Long SC Columns on the Stability of the Embankment

From the above study, it is observed that among all the combinations of lime and SC columns, the most preferable case to reduce the settlement is short lime and long SC columns (SL + LS). However, in the above study, the short lime and long SC columns are arranged row wise, i.e., along the length of the embankment, each of the alternate rows consists of either only lime columns or only SC columns (arrangement A) as shown in Fig. 13a and b. The other way to arrange the lime and SC columns is to arrange short lime and long SC columns alternatively, in each row along the length of the columns (arrangement B) as shown in Fig. 14a and b. The effectiveness of providing both the types of arrangement on settlement and factor of safety is also compared.

It may be noted that when columns are arranged as per arrangement B, since both lime columns and SC columns are of similar diameter and are at similar

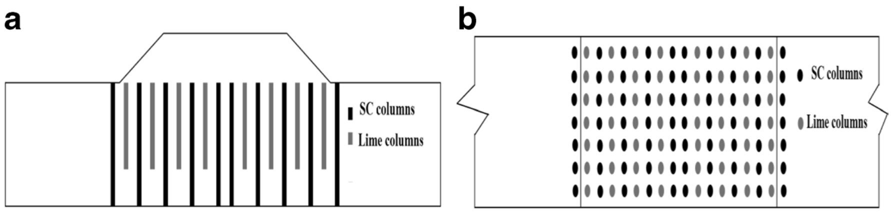


Fig. 13 **a** Elevation showing position of columns in foundation soil as per arrangement A. **b** Plan showing position of columns in foundation soil as per arrangement A

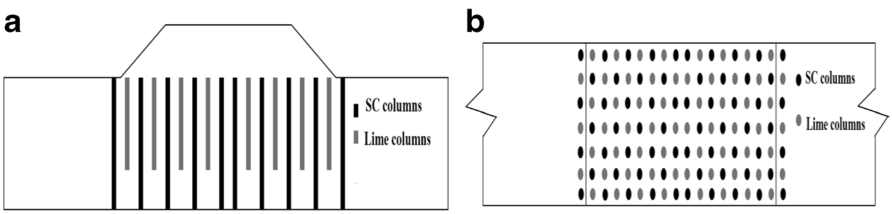


Fig. 14 **a** Elevation showing position of columns in foundation soil as per arrangement B. **b** Plan showing position of columns in foundation soil as per arrangement B

spacing, in each row, the average value of E, $c^{'}$ and $\phi^{'}$ of lime column and SC column is obtained first and using these average values, the equivalent stiffness matrix, k_s, effective cohesion $c^{'}$ and effective angle of internal friction $\phi^{'}$ for plane strain condition on each row of the columns up to 6 m depth are obtained based on weighted average areas of columns and soil in unit length. However, below 6 m depth, the E, $c^{'}$ and $\phi^{'}$ of only SC columns are considered while determining the equivalent values for plane strain condition.

The variation of settlement and factor of safety with time during the consolidation of foundation soil when similar columns are arranged along each row (arrangement A) and when short lime and long SC columns are arranged alternatively along each row (arrangement B) is shown in Figs. 15 and 16, respectively. From these figures, it can be observed that the settlement of foundation soil provided with composite columns as per arrangement A is lesser than that of arrangement B. The factor of safety of embankment on foundation soil provided with composite columns arranged as per arrangement A is marginally larger than that of arrangement B. This shows that, among the two types of arrangements, arrangement A is more effective compared to arrangement B to improve both the settlement and factor of safety of embankment at all the time intervals during the consolidation of foundation soil. These observations also show that, although the average (equivalent) values of both stiffness and shear strength of composite soil consisting of lime and SC columns are similar for both types of arrangement of columns, the composite action of arrangement A is different from the composite action of arrangement B. The arrangement of columns also plays an important role when different types of columns are considered to improve the stability of embankment constructed on consolidating soil.

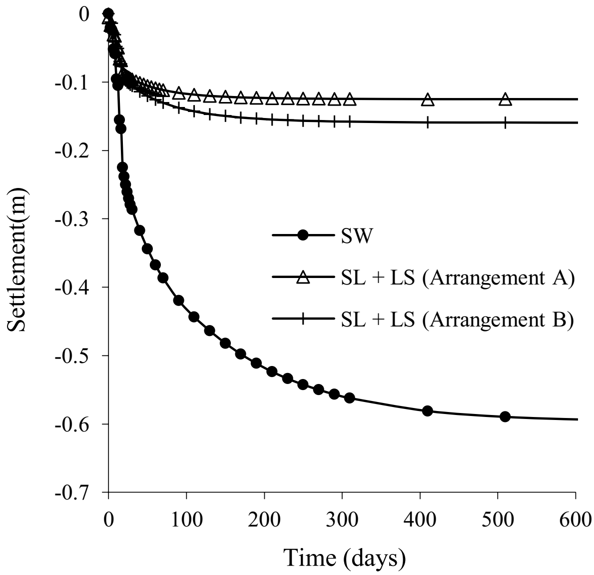


Fig. 15 Variation of settlement with time at point S for different arrangements of columns

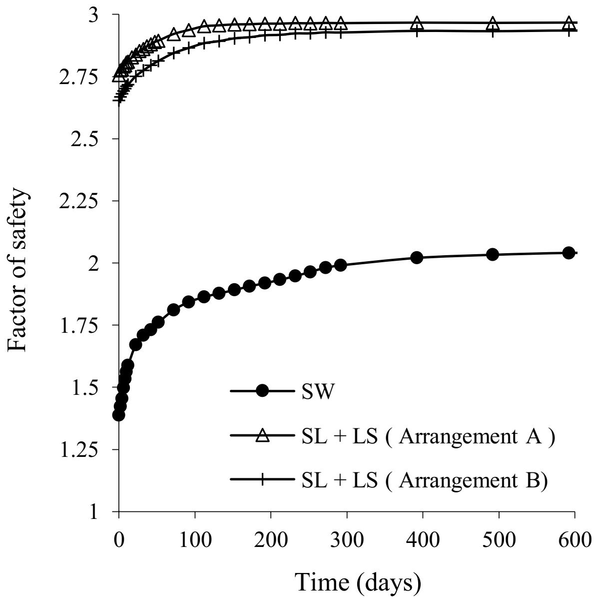


Fig. 16 Variation of factor of safety with time for the embankment constructed on foundation soil with different arrangements of columns

4 Summary and Conclusions

The effectiveness of SC columns to improve the stability of embankment is studied. In addition, the effectiveness of lime and SC composite column system on the stability of embankment is also investigated. From the study, it is concluded that,

1) SC columns are effective to reduce the settlement, accelerate the consolidation process and improve the factor of safety of embankment constructed on consolidating soil.
2) Compared to short SC columns, long SC columns are effective only to improve the settlement and not much effective to improve the factor of safety.
3) The effectiveness of providing either combination of lime and SC columns or only SC columns on settlement is more or less similar, whereas providing a combination of lime and SC columns is not as effective as providing only SC columns to improve the factor of safety.
4) The most effective combination of lime and SC columns to reduce the settlement need not be the most effective combination to improve the factor of safety at various time intervals after the construction of the embankment.
5) In a composite system consisting of short lime and long SC columns, arranging either only short lime columns or only long SC columns in each row (arrangement A) is more effective than arranging short lime and long SC columns alternatively in each row (arrangement B).

Author Contribution The first author Prakash K G contributed towards formulating the problem, data collection, formal analysis and writing the introductory part of paper. The second author A Krishnamoorthy contributed towards designing computer program, methodology and writing the remaining part of the paper. Both authors have read and approved the final manuscript.

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Data Availability All the relevant data are obtained from the current analysis.

Declarations

Conflict of Interest The authors declare no competing interests.

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