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An Embankment Stability Analysis Using Finite Element Method Constructed over Soft Consolidating Soil Improved from Lime Columns and Prefabricated Vertical Drains

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Abstract

The effectiveness of lime columns to improve the stability of embankments constructed on soft consolidating soil is investigated. Along with this, the effectiveness of prefabricated vertical drains (PVDs) with lime columns is also compared. Further, the combination of lime columns and PVDs is also studied to improve the embankment stability on consolidating soil. A numerical study is carried out using the two-dimensional plane strain finite element method. To study the effectiveness of lime columns on the embankment stability, the foundation soil settlement, excess pore water pressure, and factor of safety for embankment are obtained at various time intervals during the consolidation of foundation soil. This study shows that the settlement and excess pore water pressure decrease, and the factor of safety increases due to the provision of lime columns. Also, the settlement is lesser, and the factor of safety is larger for soil with lime columns compared to soil with PVDs, whereas, excess pore water pressure dissipates faster in soil with PVDs compared to soil with lime columns. This study concludes that, compared to PVDs, lime columns are more effective to improve the embankment factor of safety and foundation soil settlement, whereas PVDs are more effective in accelerating excess pore water pressure dissipation. The lime columns and PVDs combination is observed to be effective to improve all parameters.

Keywords: Factor of safety; Embankment; Soft consolidating soil; Lime columns and PVDs; Finite element method.
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1. Introduction

In recent years, land has been in great demand due to the rising population and fast-increasing industrial sectors. As a result, places that were formerly thought to be unsuitable for development, such as low-lying areas, river estuaries, and coastal regions, are increasingly being used for a variety of infrastructural projects.[1] Due to this fast growth of the infrastructures, the gradually best suitable constructions sites are reducing. Because of the scarcity of appropriate sites, embankments are being constructed on soft soil. Because of the possibility of excessive settlement, bearing failure, and global and local instability, for geotechnical engineers, embankment construction over soft soil is a challenging task.[2] These performance issues may sometimes be so severe that they would render the embankments ineffective for their intended purpose.[3] This soft soil has to be properly improved before the construction of the embankment.

To improve such soils and to enhance the stability of embankments, several techniques in ground improvement such as prefabricated vertical drains (PVDs), geotextiles, geomembranes, and columns have been proposed. Among these, columns are increasingly employed to support embankments over soft foundations recently, particularly where differential settlement and/or construction rates are involved.[4] Stone and lime are the two popular materials used for the construction of columns. Compared to lime columns, stone columns have a larger frictional resistance and are more porous, whereas the cohesion of lime columns is larger compared to stone columns. Each of these columns has inherent advantages and limitations. The use of stone or lime columns largely depends on the type of soft soil to be improved and on the purpose for which the ground improvement technique is used. Due to comparatively larger values of shear strength, lime columns may be preferred to improve the factor of safety of the embankment constructed over soft consolidating soil having low shear strength. The

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effectiveness of lime columns to improve soft soil is being investigated extensively through the field as well as laboratory model tests.[5-10]

These studies recommend lime columns as an effective ground improvement technique. However, in all these investigations, importance has been given to studying the effectiveness of columns to improve the settlement and drainage performance. The factor of safety of the embankment is one of the very important parameters to evaluate the stability of the embankment on consolidating soil and is not given much importance in these investigations. Moreover, when embankments are constructed on soft soil, the factor of safety varies with time during the consolidation of foundation soil. Hence, a factor of safety from the end of the construction of the embankment till the complete consolidation of foundation soil is required to assess its stability after the construction. In the proposed study, the stability of the embankment constructed on soft consolidating soil improved with lime columns is studied numerically in terms of factor of safety at different time intervals during the consolidation of foundation soil.

One of the drawbacks of lime columns is their limited permeability. The other commonly used ground improvement technique, particularly to accelerate the consolidation process, is using PVDs. PVDs do not give any additional stiffness to the soft soil, but their high permeability helps to speed up consolidation. It is a synthetic and slender drainage element with a rectangular cross-section, covering the drainage core with a geotextile filter. The flow around PVDs is axisymmetric and hence, the installation of PVDs will decrease the drainage path and accelerate the process of consolidation. The effectiveness of PVDs to improve the soft consolidating soil has also been studied in the past.[11-14] The performance of reinforced, deep mixing method floating-column supported embankments with and without PVDs was investigated by Liu and Rowe in 2015[15] using a fully 3-dimensional (3D) coupled model. Zhuang and Wang in 2017[16] presented the combination of PVDs and deep cement mixing piles for the Beijing–Shanghai high-speed railway in China. PVDs with wings were proposed by Fu and Chai in 2020[17] using laboratory model tests and finite element analysis (FEA). Hore *et al*. 2020[18] presented a case history of soft ground improvement technique using PVDs with an application to a railway track. Alielahi *et al.* in 2021[19] examined the performance evaluation of soil improvement using surcharge preloading techniques with PVDs for the oil storage tanks project as a case study. These studies also showed the effectiveness of PVDs to improve the soft consolidating soil. In the proposed study, the effectiveness of lime columns to improve the stability of embankment is compared with the effectiveness of PVDs. In addition, the combination of both lime columns and PVDs are also investigated in the proposed study.

The most predominant numerical technique proposed to solve the problem of embankments constructed on soft soil with various columns or with PVDs is the finite element method. The finite element method has been used extensively to study the performance of columns provided on soft soils.[20-25] The finite element method provides the most theoretically sound approach for modeling the columns improved ground.[2] The embankments constructed on soft consolidating soil improved with PVDs and similarly embankments constructed on soft consolidating soil improved with lime columns have also been studied numerically using the finite element method.[26-29] Since, three-dimensional analysis is costly and time-consuming, in practice, commonly a three-dimensional problem is transformed into a two-dimensional model, having equivalent properties and dimensions. The effectiveness of lime columns and PVDs for improving embankment stability is studied in the proposed study when constructed over soft consolidating soil.

2. Method of analysis

Figure 1(a) shows the cross-sectional elevation. Fig. 1(b) shows the plane just below the ground level for the embankment constructed over soft consolidating soil along with lime columns. The finite element discretization for the embankment, foundation soil, and lime columns is shown in Fig. 1(c).

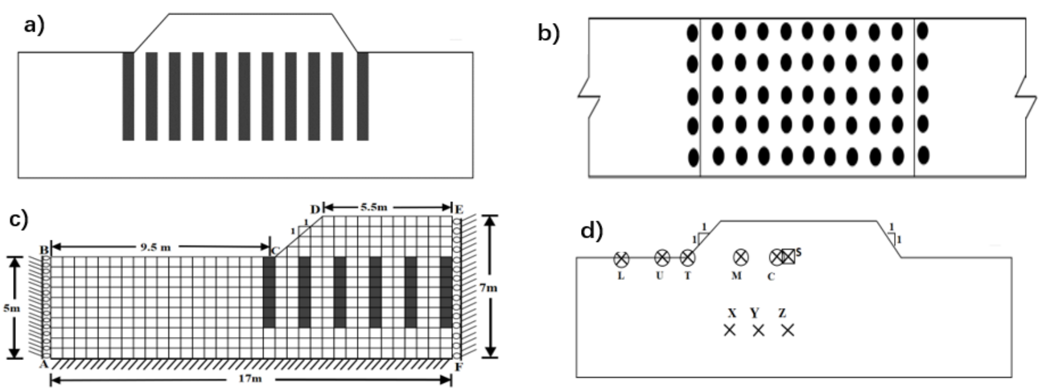

Fig. 1 (a) Cross-sectional elevation of the embankment and soft foundation soil with lime columns, (b) plane at just below ground level in soft foundation soil with lime columns, (c) Finite element discretization of embankment and foundation soil improved with lime columns at 1.5 m spacing, and (d) salient points considered in the analysis of embankment and foundation soil.

2.1 Modeling range and finite element

As shown in Fig. 1(c), the foundation and embankment soils are modeled using four noded plane strain quadrilateral elements and the embankment near the toe is modeled using three noded plane strain elements with two translational degrees of freedom (vertical and horizontal displacements) at each node. The lime columns are also modeled using four noded plane strain quadrilateral elements with two translational degrees of freedom (vertical and horizontal displacements). The behavior of the lime column is assumed as linearly elastic and two material parameters, Poisson's ratio (μ) and Young's modulus (E) are used to model the behavior of lime columns. Mohr-Coulomb model is used to model the soil. The column wall matching procedure proposed by Abushrar and Han in 2011[30] is used to obtain equivalent values of effective cohesion (c') and effective angle of friction (ϕ') for two-dimensional analysis when lime columns are used, whereas, the permeability matching procedure proposed by Hird *et al*. in 1992[31] is employed to model the soil when PVDs are used.

2.2 Boundary conditions

Only one-half of the embankment is considered for the analysis due to symmetry. Various support conditions for the analysis are (i) roller support along the sides AB to represent zero horizontal displacements. (ii) roller support along the side EF (marked in Fig. 1c) due to symmetry and (iii) hinge support at the base of soft soil to represent the hard stratum below the soft soil. The bottom surface and sides are considered impervious and water is allowed to drain at the ground surface.

2.3 Modeling of PVDs

The excess pore water pressure at the location of PVDs is considered zero and the equivalent coefficient of permeability for soil is obtained using the permeability matching procedure by maintaining the similar spacing of the drain. The coefficient of permeability is matched from the equation proposed by Hird *et al.* 1992 as shown in Equation (1):[31]

$$\frac{k_{pl}}{k_{ax}} = \frac{2}{3\left[\ln\left(\frac{R}{r_s}\right)+\left(\frac{k_h}{k_s}\right)\ln\left(\frac{r_s}{r_w}\right)-\left(\frac{3}{4}\right)\right]} \quad (1)$$

where R is the axisymmetric unit cell radius, $\frac{k_h}{k_s}$ is the ratio of the horizontal permeability of the undisturbed and smeared soil, $\frac{r_s}{r_w}$ is the ratio of the radius of the smear zone and the radius of the drain. k_{ax} is horizontal permeability of axisymmetric condition and k_{pl} is the horizontal permeability in plane strain condition. For square configuration, R = 0.565S where S is the drain spacing. In the proposed analysis of the PVDs, the size 98.7 mm^2 × 6.83 mm^2 is used and the smear effect is considered by adopting $\frac{r_s}{r_w} = 5$. A computer program using C language is developed to obtain a settlement of foundation soil and factor of safety of embankment at various time intervals during the consolidation.

3. Results and discussion

The effectiveness of the lime columns for embankment stability when constructed on consolidating soil is investigated. The most important criterion used to assess embankment stability is the factor of safety. The other factors that influence the stability of the embankment are the settlement of the foundation soil and the rate of dissipation of excess pore water pressure in the course of the consolidation of the foundation soil.

3.1. Problem dimensions and model geometry

The problem considered to study the effectiveness of lime columns for the stability of embankment is an embankment of top width 11 m, side slopes 1:1 and height 2 m resting on soft foundation soil of thickness 5 m with circular lime columns of diameter 0.5 m organized in a square pattern in 1.5 m spacing as shown in Figs. 1(a) and 1(b). The toe of the embankment is extended to 9.5 m and the length BC is arrived from several trails until increasing the distance beyond BC does not have much effect on the displacements.

3.1.1 Material model and parameters

Various material properties of lime columns, foundation soil, and embankment soil considered for the analysis are tabulated in Table 1. A similar coefficient of permeabilities is assumed for lime columns and foundation soil as observed in Table 1. The properties of the foundation soil, embankment soil, and lime columns are typical and are similar to the properties reported in the literature as shown in the table.

3.1.2 Embankment construction sequence

The embankment is assumed as highly permeable and pore water drains out at the ground surface. It is presumed that the embankment is completed in four stages during the construction. The first three layers, each of height 0.5 m, are built in two days with a pause period of two days each and the

Table 1. Properties of lime columns, foundation soil, and embankment soil.

	E (kN/m^2)	μ	γ (kN/m^3)	c' (kN/m^2)	ϕ' (degree)	k (m/day)	References
Embankment soil	15000	0.3	20	3	33	------	[32]
Foundation soil	1100	0.3	15	1	20	$k_x = 0.3 \times 10^{-3}$ $k_y = 1.0 \times 10^{-4}$	[32]
Lime column	20000	0.3	20	200	0	$k_x = 0.3 \times 10^{-3}$ $k_y = 1.0 \times 10^{-4}$	[33]

last layer with a height of 0.5 m is constructed after eight days in the next two days. Thus, the total time taken for the construction is twenty days. It may be noted that in practice, the embankments are constructed in layers so as to allow some time for consolidation. Excess pore water pressure development is a major concern as it results in the reduction of effective stress in the soil. Hence, the embankments are constructed in phases to allow for the dissipation of excess pore water pressure. With the reduction in excess pore pressure, the soils regain their shear strength.[34]

3.2 Effectiveness of lime columns on the stability of the embankment

The effectiveness of providing lime columns on settlement, excess pore water pressure, and factor of safety during the consolidation of foundation soil is studied.

3.2.1 Effectiveness of lime columns on the settlement of foundation soil

Figure 2 shows the settlement in foundation soil at point *S* (as shown in Fig. 1(d)) without lime columns at different intervals during the consolidation of the foundation soil. The settlement variation in foundation soil at point S with lime columns is also shown in Fig. 2 for comparison. Fig. 2 shows that the provision of lime columns reduces the settlement during and later the construction of the embankment in all time intervals. For the soil without lime columns, the settlement at the end of consolidation is equal to 0.3 m. whereas, it is reduced to 0.1 m when lime columns are provided. This shows the effectiveness of lime columns in improving the foundation soil settlement. In addition, from Fig. 2, it can also be observed that the influence of lime columns on settlement increases with time, and its effect is maximum at the end of consolidation. Also, from the settlement profile shown in Fig. 3, it can be observed that both the settlement beneath the embankment and the heave of the soil (upward movement of the soil) are less when lime columns are provided. This illustrates that the foundation soil with lime columns settles more evenly than the soil without lime columns both at the end of the construction of the embankment and at the end of the consolidation of the foundation soil.

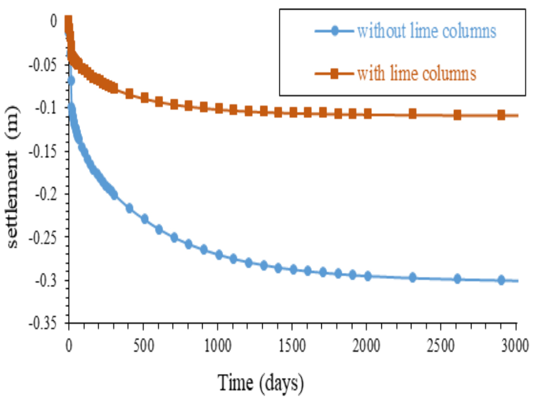

Fig. 2 Variation of settlement with time at point S with and without lime columns.

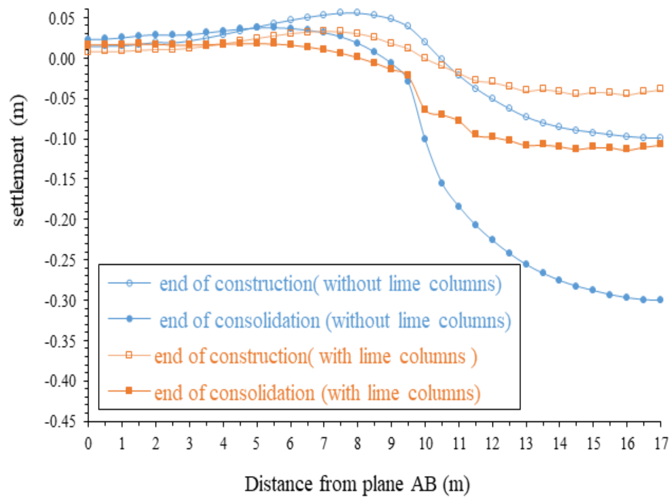

Fig. 3 Profile of the foundation soil at the ground surface with and without lime columns at the end of construction and at the end of consolidation.

3.2.2 Effectiveness of lime columns on the lateral displacement of foundation soil

The variation of lateral displacements with depth at points C, M, T, U, and L at the end of consolidation is shown in Fig. 4. Fig. 4 indicates that as expected, the lateral displacement, at all the depths below the ground surface, is the largest near the toe of the embankment and decreases on either side of the toe. However, these figures also show that when lime columns are provided, the lateral displacements at all the depths below the ground surface also decrease significantly.

3.2.3 Effectiveness of lime columns on excess pore water pressure

Figure 5 shows the excess pore water pressures at various time intervals at points X, Y, and Z during the consolidation of foundation soil with and without lime columns. As shown in Fig. 1(d), all these points are situated at a depth of 2.5 m below ground level, but, at different distances from the toe of the embankment. The comparison of excess pore water pressures in soil with and without lime columns shows that the maximum excess pore water pressure and the time required for the complete consolidation of soil at all three points are reduced when lime columns are provided. This shows that the lime columns are also effective to improve the drainage preformation of foundation soil. Distribution of excess pore water pressure hundred days after the construction of the embankment shown in Figs. 6(a) and 6(b) also indicate the effectiveness of lime columns to improve drainage performance.

As shown in Figs. 6(a) and 6(b), the excess pore water pressure is larger than 50 kN/m^2 for a major part of the foundation soil without lime columns, whereas it is less than 40 kN/m^2 for the soil with lime columns 100 days after the construction of the embankment.

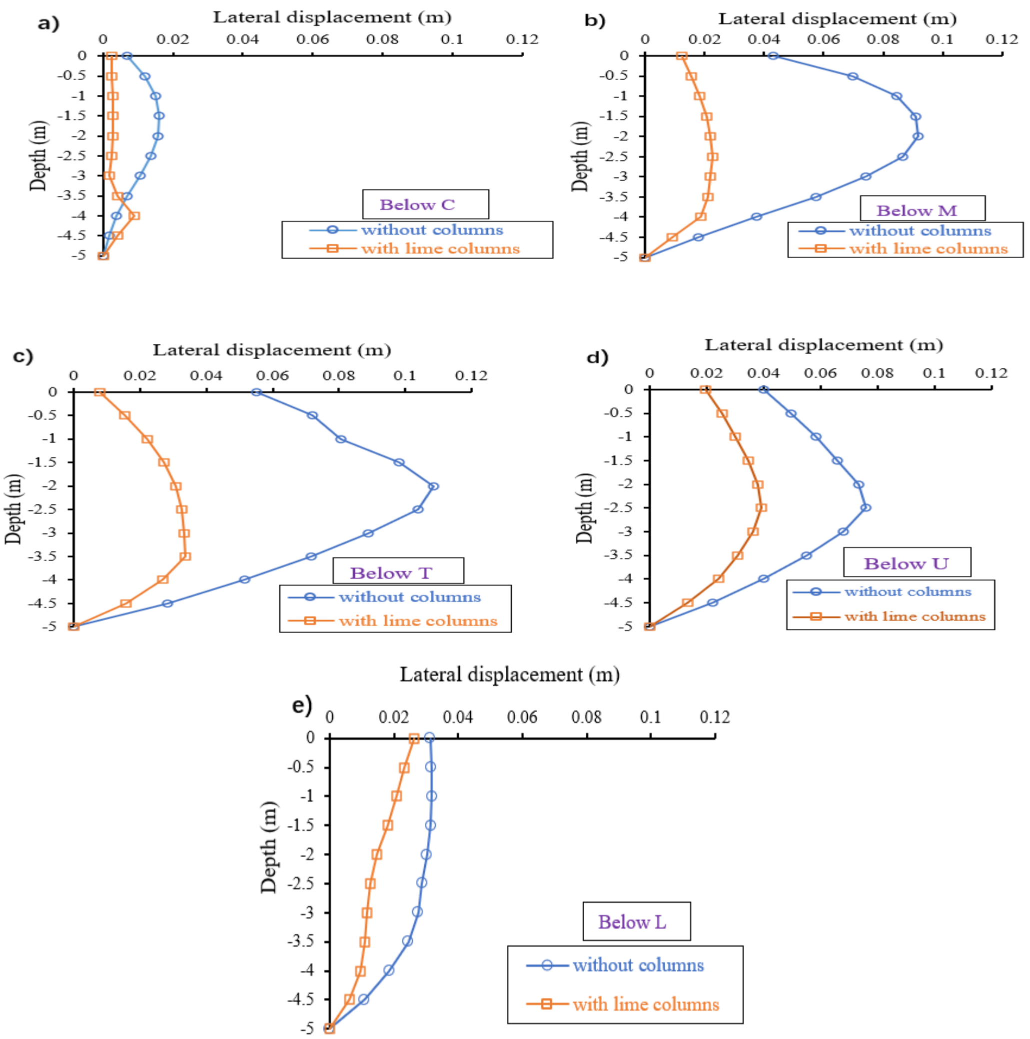

Fig. 4 Variation of settlement with depth at (a) below point C, (b) below point M, (c) below point T, (d) below point U, and (e) below point L for the soil with and without lime columns at the end of consolidation.

3.2.4 Effectiveness of lime columns on the factor of safety of the embankment

Finally, the actual stability of the embankment in terms of factor of safety is investigated at various time intervals during the consolidation of the foundation soil, to study the effectiveness of lime columns on the stability of the embankment. Fig. 7 compares the factor of safety of embankment at different time intervals constructed on soils provided with lime columns and without lime columns.

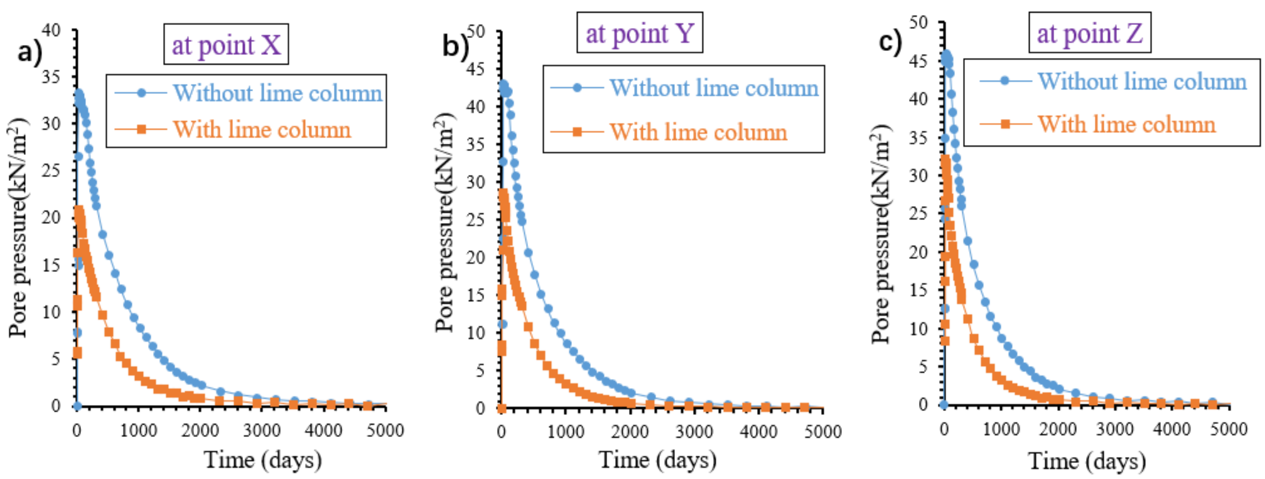

Fig. 5 Variation of excess pore water pressure with time (a) at point X, (b) at point Y and (c) at point Z for the soil with and without lime columns.

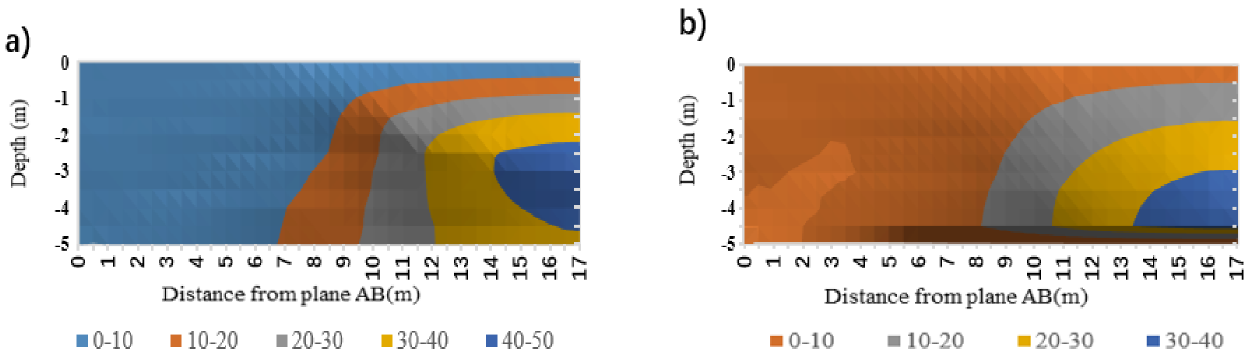

Fig. 6 Distribution of excess pore water pressure in the soil at one hundred days after the construction of embankment (a) without lime columns and (b) with lime columns.

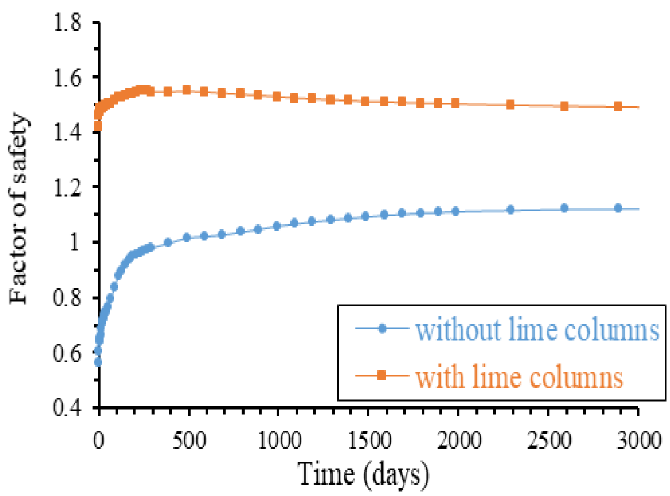

Fig. 7 Variation of a factor of safety with time for the embankment constructed on soil with and without lime columns.

Figure 7 shows that the factor of safety of the embankment without lime columns is equal to 0.56 at the end of construction and it increases to 1.12 at the end of the consolidation of foundation soil. The factor of safety of less than 1.0 at the end of construction shows that the embankment is unstable immediately after the construction. Though the factor of safety increases with time after the construction of the embankment, it is still less than the limits specified by various codes at the end of consolidation. However, the provision of lime columns improves the factor of safety significantly both during the construction of the embankment as well as at the end of the consolidation of foundation soil. In this case, the factor of safety is 1.41 at the end of construction and 1.55 at the end of consolidation. These factors of safety are more or less close to the factor of safety specified by various codes. This shows that the provision of lime columns improves the unstable embankment to the stable embankment both at the end of construction as well as at the end of consolidation. These results clearly show the effectiveness of lime columns to improve the stability of embankments constructed on soft consolidating soil.

Moreover, the variation of the factor of safety from the end of construction till the end of consolidation is less when lime columns are provided indicating that the factor of safety corresponding to the end of consolidation can be achieved earlier when lime columns are provided. In addition, these results also indicate that the consolidation of soil has not had much effect on the factor of safety of soil with lime columns, unlike the soil without lime columns where the factor of safety shows large variation during the consolidation of soil.

Thus, from the above observations, it can be said that the lime columns are effective to improve the settlement, lateral deformation, and factor of safety. In addition, lime columns are also effective to improve the drainage performance marginally.

3.3 Comparison of lime columns and PVDs to improve the stability of the embankment

Similar to lime columns, the other approach to improve the stability of embankment is the provision of PVDs. It may be noted that the PVDs are drainage elements without having any stiffness and shear strength, whereas, compared to PVDs, the lime columns have larger stiffness and shear strength with poor drainage performance. The permeability of lime columns is almost similar to the foundation soil. In this section, the effectiveness of lime columns is compared with the effectiveness of PVDs to improve the stability of the embankment.

In addition, the effects of providing a combination of lime columns and PVDs are also studied. Various cases considered for the study are i) provision of only lime columns, ii) provision of only PVDs, and iii) provision of lime and PVDs in combination. In all these cases, the c/c spacing of columns, as well as PVDs, is at 3 m.

Variation of settlement, the factor of safety, and excess pore water pressure with time for all these combinations are shown in Figs. 8 to 10. From these figures, it can be observed that the settlement at the end of consolidation decreases from 0.3 to 0.195 m, and the factor of safety increases from 1.12 to 1.43 when lime columns are provided at a c/c spacing of 3 m. Similarly, the settlement decreases from 0.3 to 0.27 m, and the factor of safety increases from 1.12 to 1.23 when PVDs are provided at a c/c spacing of 3 m. Also, the maximum excess pore water pressure at points X, Y, and Z decreases from 33.37

kN/m^2, 42.89 kN/m^2, and 45.52 kN/m^2 to 26.94 kN/m^2, 38.05 kN/m^2 and 42.61 kN/m^2 when lime columns are provided, whereas when PVDs are provided, it decreases from 33.37 kN/m^2, 42.89 kN/m^2, 45.52 kN/m^2 to 33.76 kN/m^2, 42.74 kN/m^2, 46.67 kN/m^2. Similarly, the maximum time required for complete dissipation of excess pore water pressure at points X, Y, and Z also decreases from 3200 to 2900 days when lime columns are provided, whereas it decreases from 3200 to only 500 days when PVDs are provided. These observations indicate that, as expected the lime columns are more effective to improve both the settlement and factor of safety compared to PVDs.

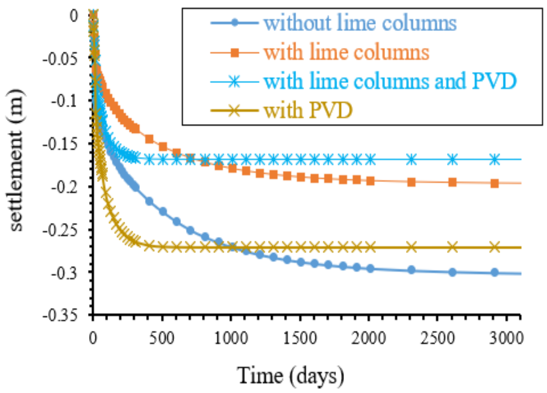

Fig. 8 Variation of settlement with time at point S for the soil with various combinations of lime and PVDs.

Comparatively, the larger stiffness and shear strength of lime columns contribute to achieving a better improvement in settlement and factor of safety compared to providing PVDs. However, when drainage performance is compared, PVDs are observed to be more effective than lime columns, because the time required for complete dissipation of excess pore water pressure is significantly less when PVDs are provided compared to the soil provided with lime columns. The poor permeability of the lime columns is not more effective in improving drainage performance, whereas the larger permeability of PVDs contributes to achieving a better drainage performance compared to lime columns. Lime columns are more effective to improve settlement and factor of safety, whereas PVDs are more effective to improve drainage performance. However, it is interesting to observe that though the permeability of lime columns is similar to the foundation soil, the drainage performance of soil with columns is much better than that of the soil without columns. Similarly, though PVDs have no stiffness and shear strength, both the settlement and factor of safety are improved marginally when PVDs are provided. These observations indicate that the improvement in stiffness of the soil + column composite system helps not only to reduce the settlement but also to improve the consolidation process. Similarly, the improvement in effective permeability of soil + PVD composite system helps not only to improve the consolidation process but also to improve both the settlement and factor of safety.

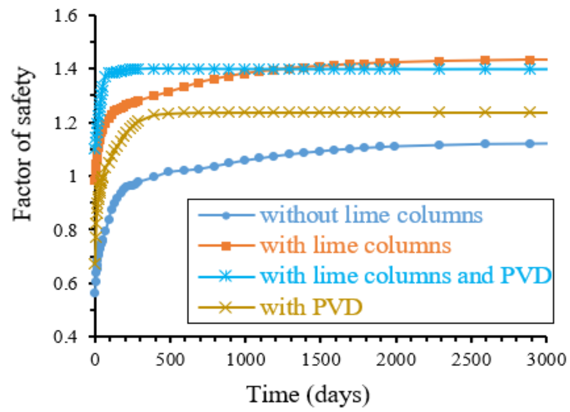

Fig. 9 Variation of a factor of safety with time for the embankment constructed on soil with various combinations of lime and PVDs.

3.3.1 Effectiveness of providing lime columns and PVDs composite system on the stability of the embankment

The effectiveness of providing a composite system consisting of lime columns and PVDs are also studied. In the composite system, the lime columns are provided at a spacing of 3 m c/c, and PVDs are provided in between the lime columns. From Figs. 8 to 10, it can also be observed that at the end of consolidation, the settlements are equal to 0.27 m, 0.195 m, and 0.168 m for the soils provided with only PVDs, only lime columns and with the combination of lime columns and PVDs, respectively.

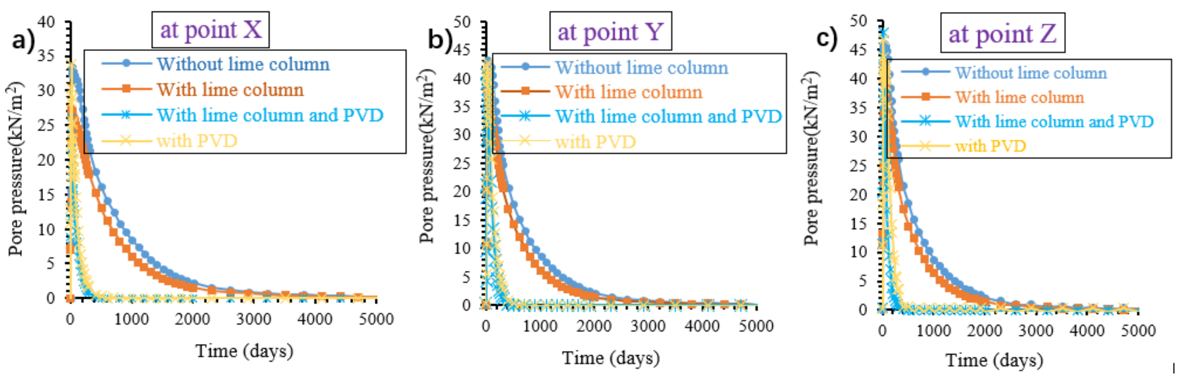

Fig. 10 Variation of excess pore water pressure with time (a) at point X, (b) at point Y and (c) at point Z for the soil with various combinations of lime and PVDs.

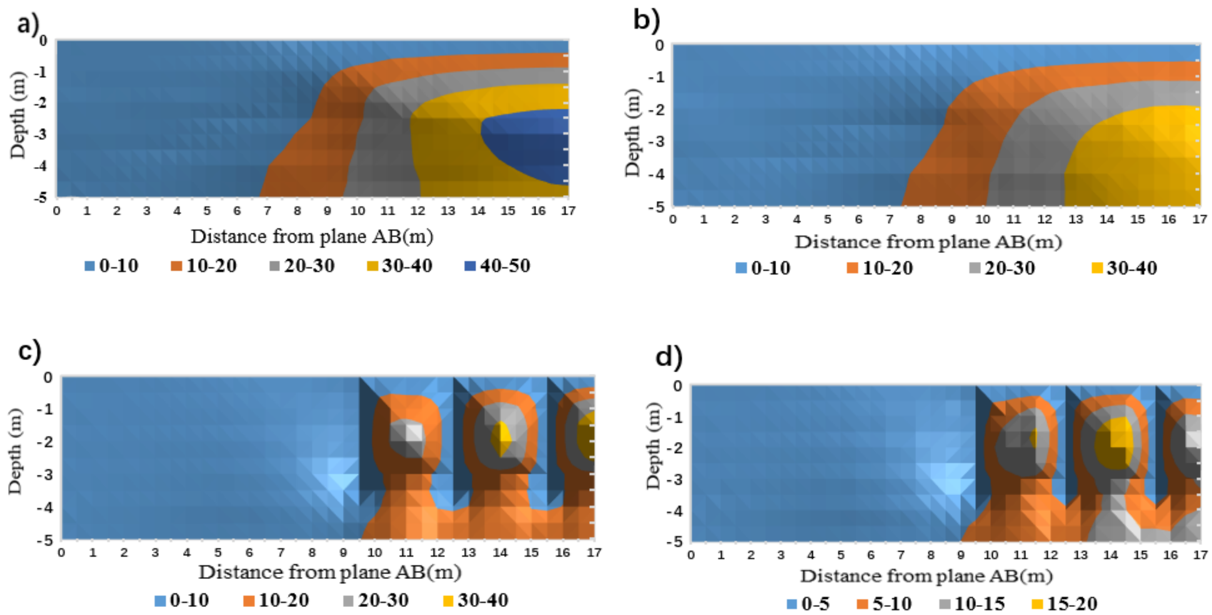

Fig. 11 Distribution of excess pore water pressure in soil with various combinations of lime and PVDs at one hundred days after the construction of embankment (a) Soil without lime columns and PVDS, (b) Soil with lime columns, (c) Soil with PVDs and (d) Soil with a combination of lime columns and PVDs and PVDs.

The provision of PVDs between the lime columns reduces the settlement of foundation soil marginally when compared with the soil provided only with lime columns. When the factor of safety of embankment on soil provided only with lime columns is compared with the soil provided with the combination of lime and PVDs, it can be observed that the factor of safety increases at the end of construction when PVDs are provided between lime columns, whereas the factor of safety is not improved at the end of consolidation. However, the time required to achieve the final factor of safety corresponding to the end of consolidation is decreased significantly when PVDs are provided between lime columns. i.e., the duration required to achieve the final factor of safety for the soil provided only with lime columns is 1300 days, whereas, it is reduced to 90 days when lime columns are provided.

The major effect of combining lime columns with PVDs can be observed in Fig. 10. As observed from Fig. 10, the time required for consolidation of the soil with lime columns is decreased significantly when PVDs are provided between the lime columns. The distribution of excess pore water pressure shown in Fig. 11 also shows that the provision of PVDs between the lime columns improves drainage performance.

In this case, the excess pore water pressure at one hundred days after the construction of the embankment is larger than 40 kN/m^2 at the major portion of the soil provided only with lime columns and less than 30 kN/m^2 at a major part of the soil provided only with PVDs. However, when the combination of lime columns and PVDs is provided, the excess pore water pressure at all the locations is less than 20 kN/m^2. This clearly shows the effectiveness of providing PVDs between lime columns to improve the drainage performance of soil provided with lime columns.

Thus, it can be said that all the parameters such as settlement, the factor of safety, and drainage performance of the soft foundation soil can be improved simultaneously when PVDs are provided between lime columns, unlike the provision of only lime columns that improves only settlement and factor of safety and only PVDs that improves only drainage performance.

4. Conclusion

The stability of lime columns supported embankment constructed on soft consolidating soil is investigated. At different time intervals, the embankment factor of safety is determined. During the consolidation of the foundation soil, the embankment stability is assessed at various intervals of time. Additionally, the effectiveness of lime columns to improve stability is compared with the effectiveness of providing PVDs. Further, the effectiveness of providing a combination of lime and PVDs are also studied. The following conclusions are drawn from the study:

1. The provision of lime columns in foundation soil enhances the factor of safety of the embankment at all time intervals during the consolidation of foundation soil.
2. The factor of safety of embankment constructed on soft soil with lime columns does not vary much during the consolidation of foundation soil. The final factor of safety corresponding to the end of consolidation of foundation soil can be achieved immediately after the construction of the embankment when lime columns are provided indicating clearly that the consolidation of foundation

soil has not much effect on the factor of safety of the embankment constructed on consolidating soil with lime columns.
3. The settlement and lateral deformation of foundation soil is also reduced due to the provision of lime columns. In addition, when lime columns are provided, the foundation soil settles more uniformly and excess pore water pressure in the foundation soil drains rapidly. All these factors also strengthen the stability of the embankment during the consolidation of foundation soil.
4. The lime columns are more effective to improve the factor of safety of embankment and settlement of foundation soil, whereas, the PVDs are more effective to improve the drainage performance. A combination of lime columns and PVDs is effective to improve all the parameters such as the factor of safety, settlement, and drainage performance of an embankment constructed on soft consolidating soil.

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Conflict of interest
There are no conflicts to declare.

Supporting information
Not Applicable.

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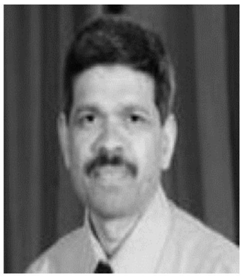

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