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A Parametric Study of Deep Mixed Column Supported Embankment Built on Indian Marine Clay

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Abstract. Deep mixing (DM) method has largely been used in recent years for the rapid construction of the embankments on soft soil. For the developing countries like India where there is a huge demand of land for the infrastructure development, ground improvement by using DM columns can be a good solution. This paper presents the parametric study of an embankment situated on the Indian Marine clay improved with DM columns. Thus, a numerical analysis has been done using a finite element package called PLAXIS 3D. The DM columns and the sand embankment has been modeled with Mohr-Coulomb Model and the modified Cam-clay model was used for the soft clay. The responses of various parameters such as permeability of soft soil, area ratio, and elastic modulus of column on the time for consolidation for unimproved and improved ground were studied. The study shows that the permeability of soft soil is the most influential parameter considering time for consolidation. For this study the optimum values for area ratio and elastic modulus of DM column were found to be 30% and 100 MPa, respectively.

Keywords: Soft Soil, Indian Marine Clay, Deep Mixed Column, Consolidation, Embankment.

1 Introduction

A previously considered unsuitable land such as around river estuaries, and coastal regions, now has the great scope of use for the industrial development with proper ground improvement. Among many ground improvement techniques available, Deep Mixed method (DMM) has now being used worldwide for different applications (Bruce, 2001). DMM is one of the soil solidification technique where the binder in dry or wet form is mixed mechanically with the in situ natural soil to make columns or panel walls of improved soil in the soft ground. The applied load or overburden load is mostly taken only by the piles and not transferred to the surrounding soil. In case of deep mixing technique, the applied load is partially carried by the columns and partly by the surrounding soils. In this method, the columns normally take a larger share of load due to higher stiffness as compared to the soil (Yapage et al., 2013; Yapage and Liyanapathirana, 2014).

A number of field studies were carried out to verify the load transfer mechanisms and consolidation mechanism of the column-supported embankments (Liu et al., 2012; Souliman and Zapata, 2011). Several centrifuge model tests were also performed by researchers which simulates the actual field stresses to investigate the behaviour of DM column under embankment loading (Kitazume and Maruyama, 2007; Nguyen et al., 2017). Numerical analysis which are less time consuming and gives results which matches fairly well with the field studies are also performed by many researchers (Chai et al., 2015; Huang and Han, 2009; Venda Oliveira et al., 2011).

However, the study of effect of embankment resting on soft soil improved with DM column for Indian soil condition is very limited. In this paper, a parametric study has been carried out to understand the effect of various parameters such as column length, area ratio, column modulus and soft soil permeability on the time for 90% consolidation. A three-dimensional finite element plain strain model has been used to carry out numerical modelling by using PLAXIS 3D software. The geotechnical properties of soft soil were considered as per Indian marine clay condition.

2 Numerical Modelling

2.1 FE model boundary and meshing details

In this study, the field condition of the embankment resting on soft soil improved with DM columns was simulated using the finite element (FE) software PLAXIS 3D. For the parametric study, a FE model with the horizontal extent of 40 m from the centreline of the embankment was constructed, as shown in Fig.1. The lateral boundary of the model was kept free to move vertically whereas it was fixed for horizontal movement.

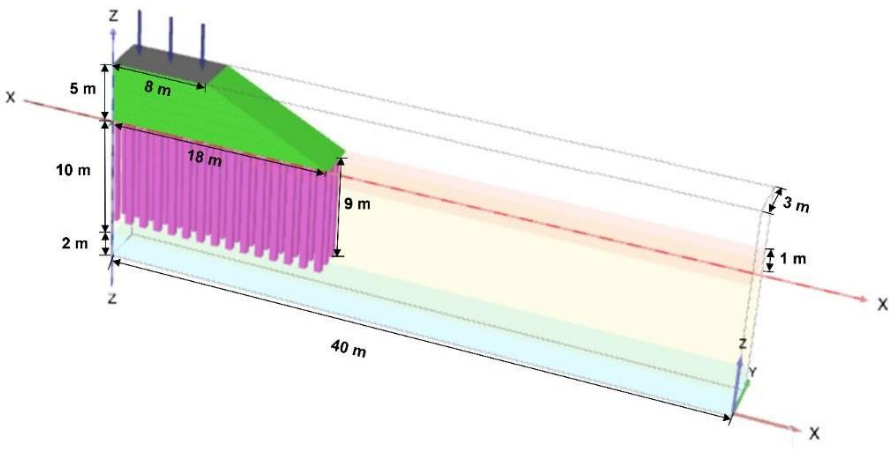

Fig. 1 Finite element model geometry

The discretization of the finite element model is carried out first into the number of elements. A mesh sensitivity analysis of FE model was done for different mesh size, i.e., coarse, medium, fine, and very fine mesh as shown in the Fig. 2. The fine meshing was found to be the optimum size which gave satisfactory results and therefore, it was finally selected for the parametric study.

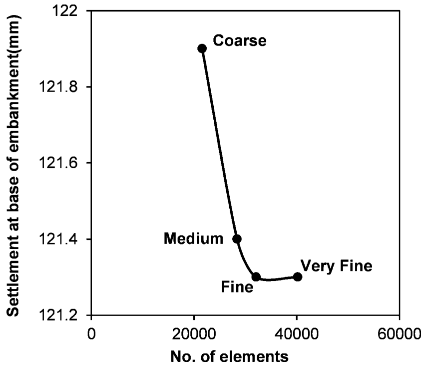

Fig. 2 Mesh convergence study

2.2 Material models used for analysis

The soil model has been modelled with 10 node tetrahedral elements. Elastic perfectly plastic Mohr-Coulomb model was used to model embankment fill and DM columns, while soft clay was modelled with a Modified Cam Clay model (MCC). Table 1 shows the material properties used in the FE analysis.

Table 1. Material properties.

Depth (m)	Soil strata	*E* (MPa)	Poison' s ratio	Kappa/*c'*	Lambda/ϕ'	M	e_o	Unit weight (kN/m^3)	Permeability *k* (m/sec)
0-1	Surface crust	-	0.3	0.25/0	0.05/26	0.98	1.7	17.0	10^{-10}
1-10	Soft clay	-	0.3	0.25/0	0.05/26	0.98	2.0	15.5	10^{-10}
10-12	Dense Sand	50	0.33	-/5	-/35	-	0.7	19.0	10^{-3}
Embankment fill		20	0.3	-/5	-/35	-	0.7	19.0	10^{-3}
DM column		100	0.3	-/500	-/-	0	1.5	17.0	10^{-10}

Note: E = Young's modulus; c' = cohesion; ϕ' = friction angle of soil; M = strength parameter for Modified Cam-clay model; e_o = initial void ratio.

2.3 Validation of FE model

The FE model was validated first with the results of a case study by Chai et. al (2015). A comparison of settlement at the depth 9 m from base of the embankment has been shown in Fig. 3, which shows that the result of the present FE 3D model matches fairly well with the literature both in trend and in magnitude.

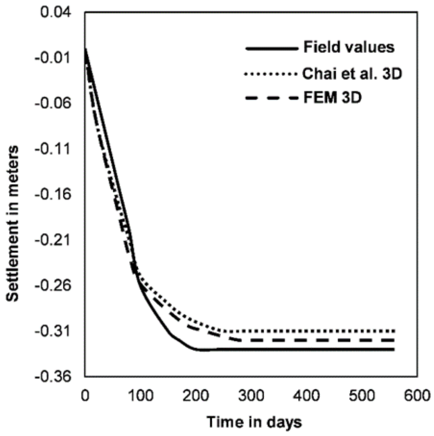

Fig. 3 Validation of the present FE model with the case study

2.4 Parametric Study

A parametric study was carried out to study the time-dependent consolidation behavior of an embankment improved with DM columns. The time taken for 90% consolidation was determined by FE analysis using PLAXIS 3D. Table 2 shows the range properties of DM columns, soft clay, and embankment fill selected for the parametric study.

Table 2. Range of parameters used for the study.

Item	Parameter	Range of Value
Soft Soil	Permeability (m/sec)	10^{-8}, 10^{-9}, 10^{-10}*, 10^{-11}
DM Column	Elastic Modulus E (MPa)	40, 60, 80, 100*, 120, 140, 180
	Area Ratio, A_r (%)	20, 30*, 40

***Values used in the base case

3 Results and Discussion

The effects of three parameters i.e. soil permeability, elastic modulus of column and area ratio, on the 90% consolidation time for both unimproved and improved ground with DM columns are investigated here.

3.1 Effect of Soft Soil Permeability

Permeability of soil has a great effect on the 90% consolidation time as the dissipation of the excess pore water pressure depends on the permeability of the strata. Fig 4 show the results of the effect of permeability on time taken for the 90 % consolidation of both unimproved and improved ground.

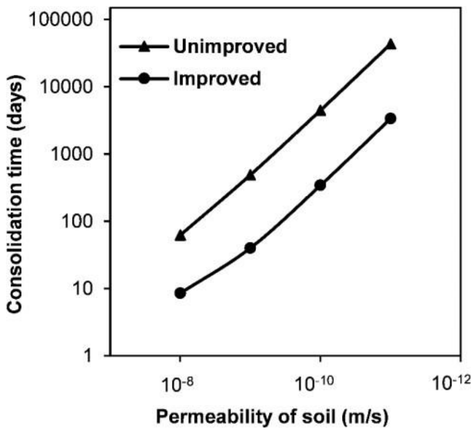

Fig. 4 Effect of soil permeability on 90 % consolidation time

It can be seen that the time taken for 90 % consolidation after the application of traffic load increases as the permeability of the soft soil decreases. The improvement factor, which is the ratio of time taken for 90 % consolidation in unimproved to improved cases, is found 7.36 and 12.83 for the permeability of 10^{-8} m/sec and 10^{-11} m/sec, respectively.

3.2 Effect of Elastic Modulus of Column

In this study, the elastic modulus of column is corelated with the undrained shear strength of soil as per the equation 2. Hence, for different values of column modulus the cohesion is adjusted accordingly. Therefore, the column modulus (E), indicates the stiffness as well as the strength of the DM column (Huang and Han, 2010).

$$E = 200c_u \tag{2}$$

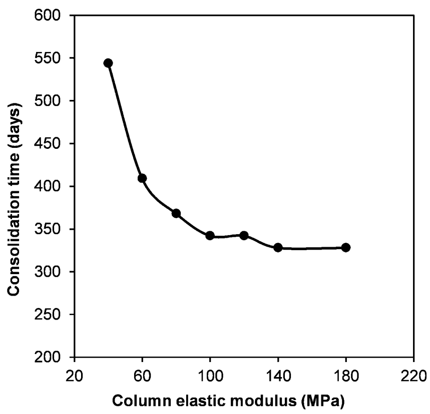

Fig.5 Effect of column elastic modulus on 90 % consolidation time

The effect of column elastic modulus on the 90% consolidation time is presented in Fig. 5 for different column modulus values. From Fig. 5 it can be seen that, as the elastic modulus of DM column increases the time for 90% consolidation decreases. The decrease in 90% consolidation time becomes less significant for the column modulus more than 100 MPa.

3.3 Effect of Area Ratio

According to the (Bergado et al., 1996), Area ratio (A_r), is the most influential parameters when embankment resting on soft soil improved with DM column is considered. For the square pattern installation of DM column, the area ratio is calculated as per equation 1.

$$A_r = \frac{\pi}{4} \times \left(\frac{D}{S}\right)^2 \quad (1)$$

where, D = the column diameter
S = the centre-to-centre column spacing

The results of the output for the analysis of time for 90% consolidation has been obtained and listed in Table 3 for the area ratios of 20%, 30%, and 40%.

Table 3. Improvement of the consolidation time for different area ratios.

Area Ratio, A_r (%)	90 % consolidation time (days)	Reduction in 90 % Consolidation time (%)
Unimproved ground	4472	-
20%	386	91.4
30%	342	92.3
40%	307	93.1

Table 3 shows the improvement in 90% consolidation time for different area ratios for baseline case condition. It can be seen from the Table 3 that; with just 20% area ratio improvement the consolidation time has reduced by 91.4% compared to the unimproved case. With further increase in the area ratio also helps in reducing the time taken for 90% consolidation. As per the requirement of the project these area ratio values can be decided accordingly.

4 Conclusions

Three-dimensional finite element analysis of embankment resting on soft soil improved with DM column are carried out to examine the effect of permeability of soft soil, area ratio, and column elastic modulus on the 90% consolidation time. Assessing the results obtained from FE analyses, the following significant conclusions can be drawn:

- Permeability of the soft soil plays an important role on the time for consolidation, as it was evident from the drastic increase in consolidation time for the permeability of 10^{-9} m/sec to 10^{-11}m/sec
- The improvement factors for the time taken for 90 % consolidation are found to be 7.36 and 12.83 for the permeability of 10^{-8}m/sec and 10^{-11} m/sec, respectively.
- The time for 90 % consolidation is decreased with an increase in column modulus. The optimum value of the elastic modulus is found 100 MPa.
- With an increase in area ratio, the consolidation time reduced and a 30 % area ratio was found to be optimum for the present condition.

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