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Numerical study to predict the settlement of the embankment built on Indian marine clay reinforced with DM columns

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ABSTRACT: Deep mixing method (DMM), a soil modification technique is largely being used worldwide for the rapid construction of embankments on soft soil. For developing countries like India, where there is huge demand for land usage, the infrastructural development projects are shifting to marginal land with poor soil conditions. Ground improvement with deep mixed (DM) column can be the best solution for such soils. The present study focuses on the effect of the properties of DM column on the settlement of the embankment for Indian marine clay conditions. 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 DM column parameters such as elastic modulus, area ratio, and column length on the settlement of embankment corresponding to 90% consolidation were studied. The study shows that the length of the column is an important parameter for the reduction in settlement of the embankment. For this study, the optimum values for the area ratio and elastic modulus of the DM column were found to be 30% and 100 MPa, respectively.

Keywords: Soft soil; Indian marine clay; Deep mixed column; Settlement; Embankment.

1 INTRODUCTION

In recent years, there has been a significant increase in demand for land due to the rising population and fast-increasing industrial sectors. With effective ground improvement, previously deemed unsuitable land, such as that near river estuaries and coastal areas, now has a wide range of uses for industrial development. Deep mixing method (DMM), one of the several ground improvement techniques, is now being employed globally for many applications to meet strict settlement requirements, slope stability, and bearing capacity improvement (Bruce, 2001; Liu et al., 2012; Zhang et al., 2014). DMM is a soil solidification technique that creates columns or panel walls of improved soil in soft ground by mechanically combining binders in a dry or wet form with in-situ soil. These columns, along with the surrounding soft soil, share the load in which the column carries more load due to higher stiffness (Huang et al., 2009; N. N. S. Yapage & Liyanapathirana, 2014).

Various field studies have been performed by researchers verifying the load transfer mechanisms and consolidation behaviour of column-supported embankments (Jaritngam et al., 2008; Souliman & Zapata, 2011). (Lai et al., 2006) performed a field study on a 6 m high embankment constructed on deep mixed improved Bangkok clay, and the results showed that the reinforcement reduced the settlement in soft clay by 70%. Researchers also performed several centrifuge model tests that simulate the actual field stresses to investigate the behaviour of the DM column under embankment loading (Kitazume & 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 & Han, 2009; Venda Oliveira et al., 2011). However, the consolidation parameter of Indian Marine clay is not explored in detail, particularly when improved with DM column. Also, the study of effect of various parameters of DM column on consolidation characteristics of the embankment resting on soft soil improved with DM column for Indian soil condition is very limited.

In this paper, a parametric study was carried out to understand the effect of various DM column parameters such as elastic modulus, area ratio, and length of column on settlement of embankment corresponding to 90% consolidation. A three-dimensional finite element plain strain model was used to carry out numerical modelling by using PLAXIS 3D software. The geotechnical properties of soft soil were considered as per Indian marine clay conditions.

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) programme PLAXIS 3D. For the parametric study, a FE model of the embankment with 40 m horizontal range from the centreline was constructed, as shown in Figure 1. The lateral boundary of the model was kept free to move vertically, whereas it was fixed for horizontal movement.

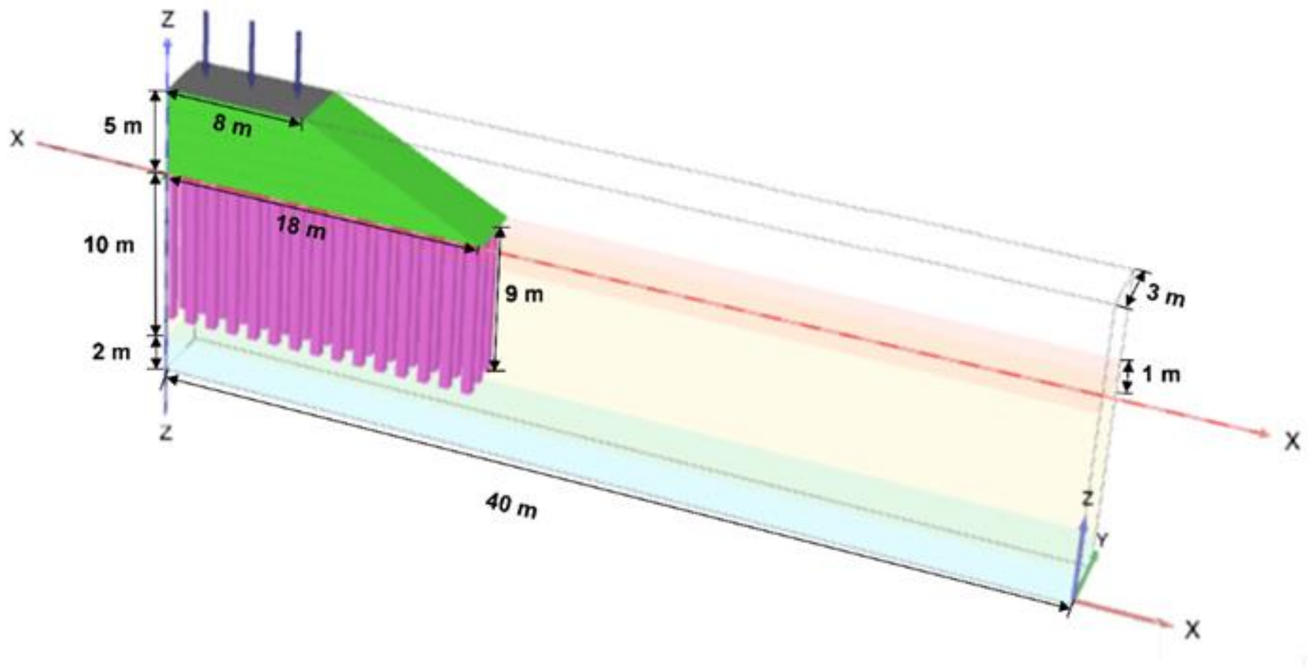

Figure 1. FE model geometry

A mesh sensitivity analysis of the FE model was done for different mesh sizes, i.e., coarse, medium, fine, and very fine mesh. The fine meshing was found to be the optimum size which gave satisfactory results, and therefore, it was finally selected for the parametric study.

2.2 Material models used for analysis

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

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 Figure 2, which shows that the result of the present FE 3D model matches fairly well with the literature both in trend and in magnitude. The parametric analysis was then conducted using the verified model to determine the effects of different column parameters, including column modulus, area ratio, and column length. The geotechnical properties of soft soil were considered as per Indian marine clay conditions.

Table 1. Properties of materials used in FE analysis

Material	Parameters
Surface crust (0-1 m)	ν=0.3, κ=0.04; λ=0.2, ϕ'=25°, c'=1, M=0.98, e_0=1.7, ρ=17 kN/m^3, k= 10^{-10} m/s
Soft clay (1-11m)	ν=0.3, κ=0.048; λ=0.24, ϕ'=25°, c'=1, M=0.98, e_0=2.0, ρ=15.5 kN/m^3, k=10^{-10} m/s
Dense Sand (11-13m)	E=50 Mpa, ν=0.33, ϕ'=35°, c'=5, e_0=0.7, ρ=19 kN/m^3, k=10^{-3} m/s
Embankment fill	E=20 Mpa, ν=0.3, ϕ'=35°, c'=5, e_0=0.7, ρ=19 kN/m^3, k=10^{-3} m/s
DM column	E=100 Mpa, ν=0.3, c'=500, e_0=1.5, ρ=17 kN/m^3, k=10^{-10} m/s

Note: E = Young's modulus; ν = Poisson's ratio, κ = Kappa; λ = Lambda, ϕ' = friction angle of soil, c' = cohesion, M = strength parameter for Modified Cam-clay model, e_0 = initial void ratio, ρ = Unit weight, k = Permeability.

2.4 Parametric study

In this parametric study, the time-dependent consolidation behaviour of a road embankment improved with DM columns was investigated. The settlement response corresponding to 90% degree of consolidation was determined by FE analysis using PLAXIS 3D. Table 2 shows the range of properties of DM columns selected for the parametric study.

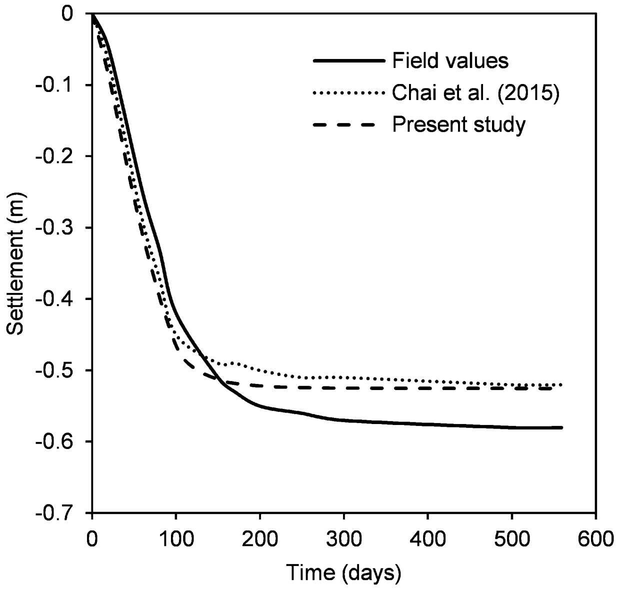

Figure 2. Validation of the present FE model with the case study

Table 2. Range of column parameters used for the study

Parameter	Range of Value
Elastic Modulus E (MPa)	40, 60, 80, 100*, 120, 140, 180
Length (m)	5, 7, 9*, 10
Area Ratio, A_r (%)	20, 30*, 40

Note: *Values used in the base case

3 RESULTS AND DISCUSSION

The effects of three column parameters i.e., the elastic modulus of the column, area ratio, and column length, on the settlement of embankment corresponding to 90% consolidation of ground improved with DM columns, are investigated here.

3.1 *Effect of column elastic modulus*

In this study, the elastic modulus of DM column E is correlated with the undrained shear strength of soil as per equation (1).

$$E = 200c_u \quad (1)$$

where c_u is the undrained shear strength of DM columns.

Hence, for different values of column modulus, the undrained shear strength is adjusted accordingly. Thus, the column modulus E represents both the stiffness and the strength of the DM column. (Bruce, 2001; Huang & Han, 2010; N. Yapage & Liyanapathirana, 2018).

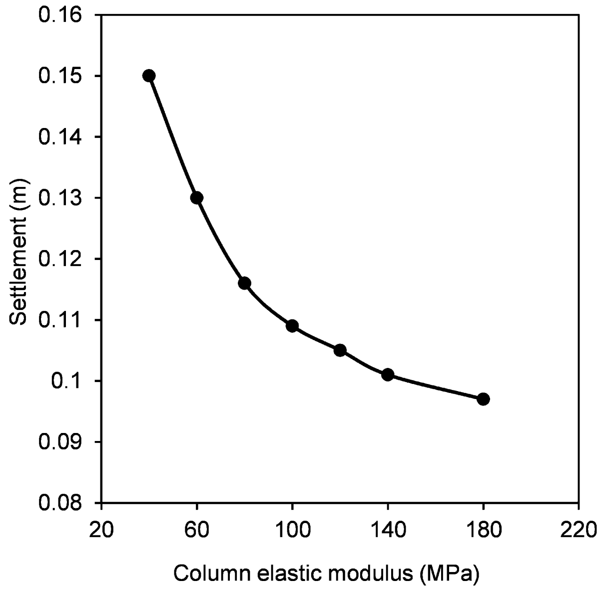

Figure 3. Variation of settlement with column elastic modulus

Figure 3 shows the effect of the column modulus on the settlement of the embankment corresponding to 90% consolidation. From Figure 3, it can be seen that with the increasing value of elastic modulus of column the settlement corresponding to 90% consolidation is decreasing to a great extent. The settlement at E = 40 MPa was 0.15 m, whereas at E = 180 MPa, it was only 0.097 m. This is so because the column can bear more load than the surrounding soil since its load-bearing capacity increases with increasing column modulus. It aids in reducing settlement as the associated load on the soil decreases.

3.2 *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 and reinforced with DM column is considered. For the square pattern installation of DM column, the area ratio is calculated as per equation (2).

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

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

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

Table 3 shows the percentage improvement in settlement for different area ratios for baseline case conditions. It can be seen from Table 3 that; with just 30% area ratio improvement, the settlement has reduced by 90% compared to unreinforced case. With a further increase in the area ratio, the settlement can decrease further, but the rate of improvement may reduce. Therefore, as per the project's requirement, these area ratio values can be decided accordingly.

Table 3. Improvement in settlement for different area ratios

Area Ratio, A_r (%)	Settlement (m)	Reduction in Settlement (%)
Unimproved ground	1.06	-
20	0.13	87.7
30	0.11	89.6
40	0.09	91.5

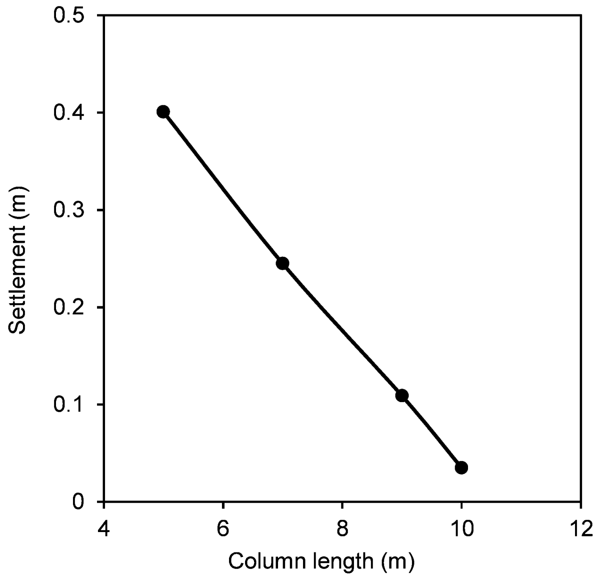

Figure 4. Variation of settlement with column length

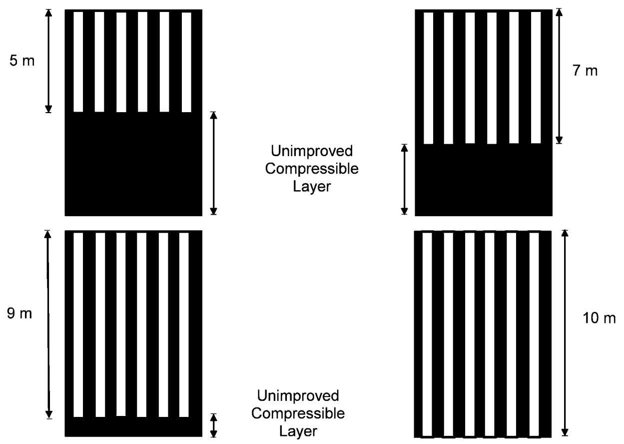

Figure 5. Depth of unimproved compressible layer for different column length

3.3 *Effect of length of DM column*

An effect of the length of the column on settlement is presented in Figure 4, which shows that, with the increase in column length, settlement of the embankment decreases. This happens because, as the column length increases, a larger load from the embankment gets transferred to the deep soil through the column. And with a decrease in the thickness of the unimproved compressible soft clay layer, the soil settlement also decreases (Figure 5). For instance, in this study the settlement decreased by 91.27% as the column length increased from 5 to 10 m.

4 CONCLUSIONS

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

The settlement of the embankment at 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 settlement of the embankment is reduced, and a 30% area ratio is found to be optimum. The present study shows that with the increase in column length from 5 to 10 m, the settlement decreased by 91.27%.

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