Comparison of Design of Stone Columns by Limit Equilibrium and Finite Element Methods

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ABSTRACT: Use of stone columns is a ground improvement technique that can be applied when high embankments are to be constructed on thick layers of soft soils. Stone columns installed in an appropriate pattern, reinforce the soft soil enhancing the shear strength and reducing the settlements. There are several methods for the analysis and design of stone columns. These designs come up with a factor of safety, which cannot be verified in the field. Comparison of Factor of Safety computed with different approaches will be useful in optimizing the design procedures. Designs done with limit equilibrium approach and finite element approach are compared in this research. GEOSLOPE - SLOPE/W software was used for the limit equilibrium approach and PLAXIS 2D software was used for the finite element analysis.

1. INTRODUCTION

Due to the non-availability of lands with good sub soil conditions Engineers are compelled to use lands underlain with soft sub soil conditions for infrastructure development projects. In order to avoid shear failures during construction and limit settlements during service, different ground improvement techniques will have to be used. Use of stone columns is one such technique where the soft ground is reinforced by installation of granular columns of high strength and stiffness over a designed grid pattern. The diameter of the column and the spacing are the major design parameters.

Stone columns are extensively used to improve the bearing capacity and minimize the possibility of shear failure during construction. It also reduces the settlement of structures built on them. Furthermore, stone columns, accelerate the consolidation and also reduce liquefaction potential of soils.

2. STONE COLUMN DESIGN CONCEPTS

Stone columns can carry very high loads since columns are ductile (Mani and Nigee, 2013) and construction can be started soon, since no waiting period is required after installation. Stone columns will carry a greater share of the load applied and thus minimize the post construction settlements (Mokhtari and Kalanthari, 2012). Stress concentration effect is one of the very important factors in designing of stone columns. Stone columns cannot be used to improve very sensitive clay soils (sensitivity > 4) or very soft clays (Mani and Nigee, 2013). Stone columns can fail by bulging (especially in very soft clays), bending, punching or shearing. Bulging is significant in long columns whereas punching is prominent in shorter columns (McKelvey et al, 2004).

3. METHODOLOGY

In this research stone column designs of similar configuration were done with two alternate approaches; the Limit Equilibrium (LE) approach and the Finite Element (FE) approach. Several variations were adopted within each approach. The behavior of soft clay was modeled under conditions of; drained, undrained and coupled consolidation in the FE approach, which is more comprehensive and tedious to apply. With much simpler LE approach different simplifying assumptions were made.

3.1. *Model Preparation and Parameters*

In both approaches, the stone columns installed in a grid pattern are represented in strips for the plane strain idealization. Stone Column diameter and grid spacing was taken as 0.5m and 1.5m respectively. The soft layer thickness was 10m.

Several different methods are available within the LE approach namely; average shear strength method (considering subsoil as one uniform material without strips), without considering stress concentration on stone column strips and considering stress concentration on stone column strips. The stress concentration effect is used in computing average parameters.

In the FE approach construction process can be simulated assigning appropriate material characteristics without making any prior assumptions on stress distribution. PLAXIS 2D was used for the analysis and discretized continuum models were used under plain strain conditions. Drained and Undrained soil parameters used for the analysis are

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summarized in the Table 1. (The model types prepared are presented in the Table 2.) (The model is illustrated in Fig. 1.)

Table 1. Soft soil parameters

Soft Soil Property	Value
Γsat	15 kN/m^3
Γunsat	13 kN/m^3
c_u	10 kN/m^2
$c^/$	0.1 kN/m^2
ϕ_u	0
$\phi^/$	26^0

Table 2. Modeling conditions of soft soil used

Model 1(D1)	Drained parameters without allowing time for consolidation
Model 2 (D2)	Embankment construction rate 0.5m/week, coupled consolidation
Model 3(U1)	Undrained Parameters

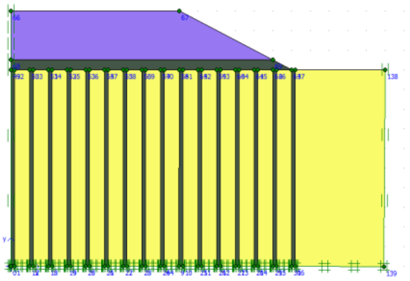

Fig.1 - Model Preparation for the analysis

3.2. *Different Analysis Models Used*

Different analyses done with the LE approach are; Average shear stress method (M1), Embankment loading without considering stress concentration effect (M2) and Embankment loading with considering stress concentration effect (M3). In M2 and M3 stone columns were idealized by strips in a plane strain formulation (Fig.2). Stress concentration effect is also illustrated in Fig.2.

Average strength calculation and Stress concentration factor calculation are presented in equations 1 to 4.

$$\phi_{avg} = tan^{-1}(\mu_s a_s tan\phi_s) \quad (1)$$

$$\gamma_{avg} = \frac{A_s \times \gamma_{stone\ column} + A_c \times \gamma_{soil}}{\ldots} \quad (2)$$

$$C_{avg} = (1 - a_s)C \quad (3)$$

Stress concentration factor;

$$n = a + b\left(\frac{\sigma_s}{\ldots}\right) \quad (4)$$

Where μ_s is the stresses in stone columns, a_s is the area replacement ratio, ϕ is the friction angle, γ is density, ***n*** is stress concentration factor – the ratio of stresses in stone columns and soft clay, ***a*** & ***b*** are experimental parameters, ***C*** is cohesion of soil.

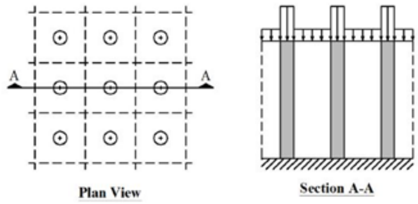

Fig.2 – Stress distribution of stone columns

Results are obtained with the FE approach through PLAXIS with modeling conditions D1, D2 and U1 as in Table 2.The analyses were done varying the friction angle of stone Column material in the range 32^0- 40^0 simulating stone column materials compacted to different densities.

FE analysis with PLAXIS does not provide a direct value of FOS. It was obtained through the c, ϕ reduction technique available in the program. The shear strength parameters are reduced gradually by a factor and the value of the factor when the displacement increased rapidly is taken as the factor of safety.

4. COMPARISON OF RESULTS

4.1. *Comparison of Results of FE Analyses*

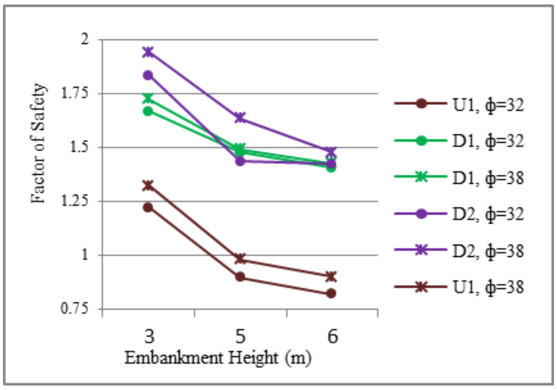

Fig.3 – FOS Variations of PLAXIS Models

In all analyses, the FOS reduced as the height of the embankment height increased. Stone columns with greater strength (higher ϕ value) gave a greater FOS in general. But at higher embankment heights values are very similar. The lower FOS given by D2 compared to D1 can be explained by the fact that pore pressure dissipation was not modeled in D1. In D2 there was some time for pore pressure dissipation with the specified rate of construction. As the construction progressed pore pressures accumulated are significant and values given by D1 and D2 area approximately the same.

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Ideally, the results of D1 and U1 should be same as pore pressure dissipation was not permitted in both. But the results obtained by U1 are much lower than those by D2. This variation is most likely due to the incompatibility in the set of undrained parameters and drained parameters used for the analysis.

A sensitivity analysis done in this regard showed that the undrained cohesion value should be increased to around 15 kN/m^2 to be compatible with drained parameters.

4.2. *Comparison of the Simplified Methods*

The FOS values obtained from different LE approaches were compared in Fig. 4.

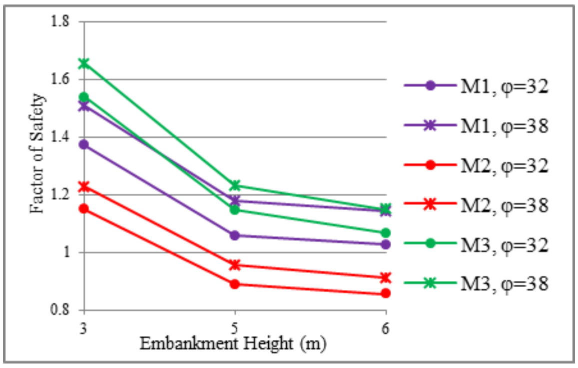

Fig.4-Comparison of Simplified Methods

In all models FOS increased with the increased density of the stone column (from ϕ=32 to 38). It can be seen that the M3 gives higher FOS than the other two methods, but are closer to M1. But the values given by two methods, M3 and M1 are more similar when the embankment height is increased. But when compared with the other two methods, M2 gives much lower FOS values and hence more conservative approach. M1 is much easier to implement and it shows that when the stress concentration is considered in computation of average strength parameters, results similar to more tedious strip method with stress concentration effect are obtained.

4.3. *Comparison of the Results of the LE analyses with FE analyses*

Stone column material ϕ=32 was used for the comparison. Actual condition is more closely modeled by D2. The LE methods M1, M2 and M3 do not account for any pore pressure dissipation during the construction. The FOS values given by drained FE model is much greater as seen in Fig.5. If the limited consolidation that has taken place and the resulting gain in undrained shear strength within that period had been accounted the results of M1 and M3 could be more similar to that of D2. Values given by M2 are much lower as the stress concentration is not considered. (Fig. 6)

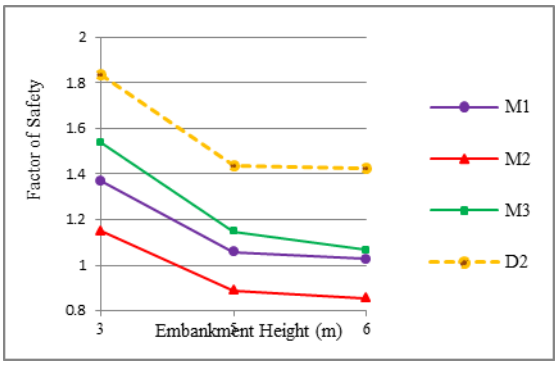

Fig.5-Comparison of Different Methods with PLAXIS Drained Model

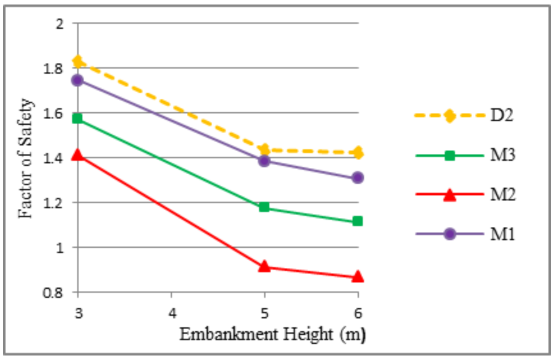

Fig.6-Comparison of Different Methods with Improved Undrained Shear Strength Values

4.4. *Comparison of Stress Concentration Effect*

Normally a constant stress concentration factor is assumed in LE approach. Based on empirical factors (Eq'n 4) a value of 2.1 was used in the analyses done with SLOPE/W. The stress distribution is calculated in the PLAXIS within the framework of FE modeling without making any such assumptions. The vertical stresses on stone columns are much higher than that on soft clay as seen in Fig. 7 for embankment height of 3m. The ratio, the stress concentration factor is not constant throughout the section. Therefore, an average value is calculated. The values calculated for embankment heights 3m, 5m and 6m are 5.4, 8.5 and 11.5 respectively. Vertical stress distribution for 5m embankment is shown in Fig.8. This indicates that the stress concentration factor increased when the embankment height increases. Stress concentration factor calculated using the empirical equations is much smaller than the values given by the FE computation.

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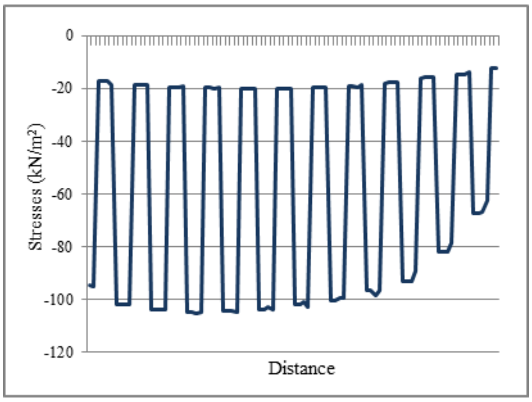

Fig.7-Stress Distribution Under the Embankment for 3m Embankment Height

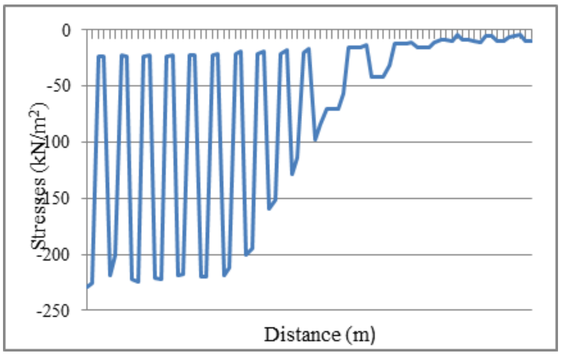

Fig.8-Sress distribution under the embankment for 5m embankment height

4.5. *Analysis incorporating the change of Stress Concentration factor in Limit Equilibrium Approach*

Another analysis was carried out with LE approach accommodating the change of stress concentration factor with the embankment height. In this analysis stress concentration factors of 5.4, 8.5 and 11.5 were used for embankment heights 3m, 5m and 6m respectively. In Fig.9 the results are compared with those of D2 which is the most realistic method.

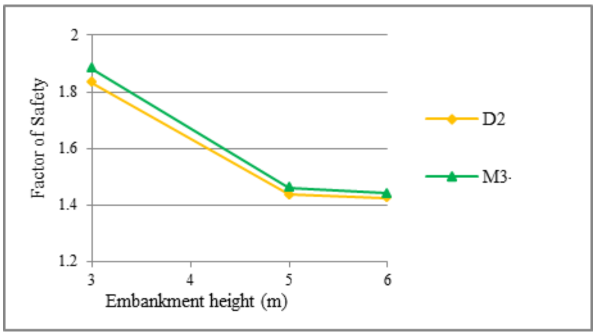

Fig.9-Comparison of PLAXIS drained Model with LEA

It can be observed that the results of LE analyses match well with PLAXIS Drained model if all the effects such as strength gain and stress concentration factor variation are accounted.

5. CONCLUSION

From the results obtained, it can be said that the method which consider the stress concentration effect gives more reliable results in the analysis but only when the incompatibilities with data are removed and similar stress concentration factors are used. There is no practice of changing the stress concentration factor with the embankment height in the limit equilibrium approach. An empirical equation provides a stress concentration factor based on soil stiffness ratio. PLAXIS analysis indicates that an updating of stress concentration factor is needed when the embankment height increases.

Therefore, further studies need to be done to calculate stress concentration factor. These values can be obtained experimentally by measuring the vertical stresses in the stone columns and soft clay with the gradual construction of the embankment. The stress distribution can be obtained independently with a finite element simulation done with PLAXIS as described here and compared with the experimental results. Such studies will help to optimise the analysis techniques.

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