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A Finite Element Bearing Capacity Analysis of Layered Soil Deposit Reinforced with Stone Columns

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***Abstract*— In the present study, an attempt has been made to comprehensively investigate the bearing behavior of a rigid and rough circular footing placed over a layered soil deposit, reinforced with stone columns. For the analysis, a series of finite element analyses has been carried out to obtain the failure load as well as to understand the failure mechanism. For all the analyses, end bearing column has been considered by assuming it to be resting on a rigid bedrock. Influence of several critical parameters, such as ratio of undrained shear strength of top soil to that of bottom soil, diameter of stone column, thickness ratio of top layer and angle of internal friction of stone column aggregates, on the overall bearing capacity response has been comprehensively investigated and reported. Obtained results and the corresponding governing mechanism has been comprehensively explained. Based on the results, it has been found that for a stone column reinforced layered soil deposit, for a depth ratio of more than 2, the influence of bottom soil diminishes and undrained shear strength of top soil governs the bearing capacity. Similarly, increment in the bearing capacity due to increase in column diameter as well as angle of internal friction of stone aggregates have been duly quantified and represented in graphical form. Present study would be highly beneficial for practicing geotechnical engineers while designing a shallow foundation for transmission towers over a layered soil deposit.**

Keywords*— Finite element analysis, stone column, layered soil, PLAXIS

I. INTRODUCTION

While designing a shallow foundation for a structure, two criteria must be satisfied, i.e. it should be safe against failure and settlement corresponding to the working load of the superstructure should lie within the permissible limits prescribed in various design codes. Substantial effort has been applied in the field of classical geotechnical engineering to satisfactorily answer the problem of bearing capacity of a shallow footing placed on a homogeneous, semi-infinite ground surface based on limit equilibrium approach [1,2,3,4] limit analysis method [5,6,7,8] and slip line theory [9].

However, often the shear strength of underlying soil, and consequently ultimate bearing capacity of shallow footing may not be adequate to support the external load coming from the superstructure. Under these circumstances, a geotechnical engineer may design a deep foundation. However, designing a deep foundation incurs a significant cost and consequently the overall cost of the project exceeds substantially. Under these conditions, ground improvement technique, such as installation of stone columns, may yield an alternative solution to the foundation engineer to enhance the strength of the soil and also to reduce the differential settlement and yields and imrovement in the bearing capacity of the foundation.

Reinforcement of soil using stone column has gained wide popularity to enhance the shear strength of soil and to reduce the compressibility of the soil. Several researchers [10,11,12] performed laboratory investigation on stone column reinforced geomaterials and established the efficacy of stone column in improving the overall bearing capacity of the footing. However, in all the previous analysis, a single layyer of homogeneous semi-infinite soil deposit has been considered. Furthermore, the relative influence of several critical parameters, such as ratio of undrained shear strength of soils, column diameter, and relative compactness of stone column has not been considered explicitly under a single title.

Therefore, in the present study, the efficacy of stone columns in improving the bearing behavior of layered soils has been considered explicitly by considering the influence of several critical governing parameters, such as ratio of undrained shear strength of top soil to the bottom soil layer (c_{u1}/c_{u2}), stone column diameter (D), thickness ratio of top soil layer (H/B, where B = footing width) and friction angle of the stones of the stone column (ϕ'). A finite element model has been developed in commercially available software package "*PLAXIS*^{2D}". The relative influence of each critical parameter has been presented in graphical form and the influence of variation of parameters on the overall bearing capacity and the corresponding failure mechanism has been discussed in details.

II. PROBLEM DESCRIPTION AND MATERIAL PROPERTIES

A. Schematics of the problem

To model the geometry of the problem, a axisymmetric analysis has been performed in *PLAXIS*^{2D} due to the symmetry of the problem. Schematics of the problem geometery considered in the present study has been shown in Fig. 1. The lateral and vertical boundaries are selected such that the stresses generated during loading are well confined within the boundaries of the problem. In the bottom boundary, both horizontal and vertical fixities were applied while lateral boundaries were restrained in horizontal direction. A '*fine*' mesh refinement was adopted based on a mesh sensitivity study.

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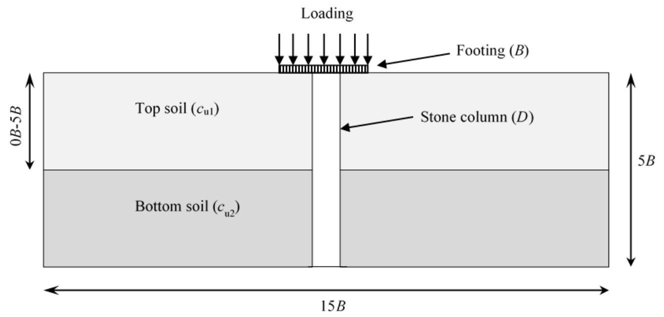

Fig. 1. Schematics of the problem considered in the present study

B. *Material Properties*

In the present study, two different clay layers have been adopted. Properties of the soil layers have been adopted from pertinent literatures. For stone columns, the geotechnical properties were adopted from [12]. The properties of the clay and stone aggregates has been summarized in table 1.

Table 1. Properties of clay and stone aggregates considered

Soil	Parameter	Value
Top Soil	Undrained cohesion (c_u)	28 kPa
	Undrained friction angle (ϕ_u)	0°
Bottom Soil	Undrained cohesion (c_u)	14 kPa
	Undrained friction angle (ϕ_u)	0°
Stone Aggregate	Effective cohesion	0 kPa
	Effective friction angle (ϕ')	42°

III. NUMERICAL ANALYSIS

As already mentioned, the numerical analysis has been carried out using the commercially available software package "*PLAXIS*^{2D}". It is a very useful tool to solve the complex problems of geomechanics involving stress-deformation based analysis [13,14]. Footing has been modelled as having sufficiently high rigidity. A rough interface between the footing and soil matrix was modelled to ensure a rough footing behaviour. The finite element model and boundary condition for the half model has been presented in Fig. 2.

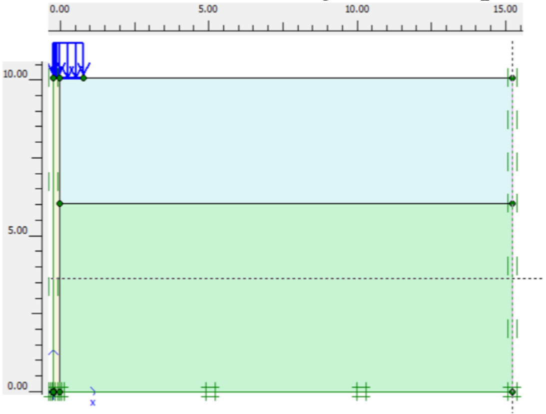

Fig. 2. Finite element model and corresponding boundary conditions considered in the present study.

IV. RESULTS AND DISCUSSIONS

A. *Influence of undrained shear strength ratio (USSR)*

To understand the relative significance of ratio of undrained strength of top layer to bottom layer, a series of investigations were carried out to study the relative influence of parameters on the overall bearing capacity of the footing. Analyses were carried out for five different *USSR* values. Variation of bearing capacity with *USSR* has been presented in Fig. 3.

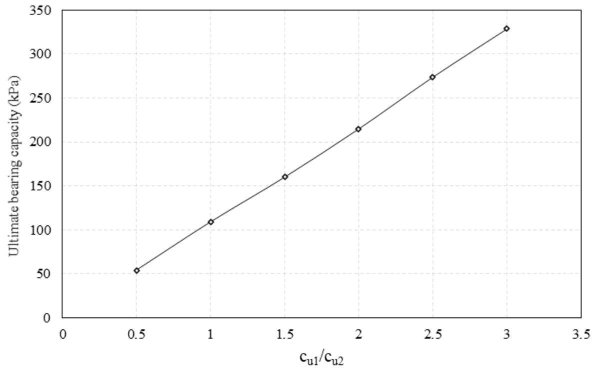

Fig. 3. Variation of ultimate bearing capacity with USSR (c_{u1}/c_{u2})

As depicted in fig. 3, ultimate bearing capacity (*UBC*) exhibits a linear trend with increase in *USSR*. This may be attributed chiefly to the fact that as the undrained shear strength of the top soil increases, the passive resistance to the footing against the external load increases proportionally. Therefore, an almost linear increase in *UBC* with *USSR* has been observed for all the cases considered in the present study.

B. *Influence of diameter of stone column (D)*

To invetigate the influence of stone column diameter on the overall bearing capacity of the layered soil deposit, analyses were carried out for five different column diameters (viz. *D* = 0.2, 0.4, 0.6, 0.8 and 1.0 m). Variation of *UBC* with *D* has been shown in Fig. 4.

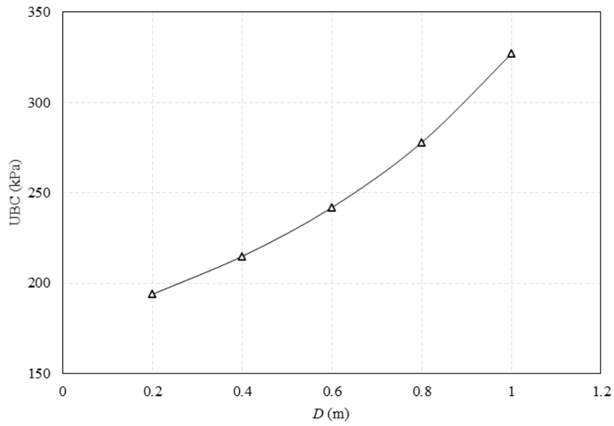

Fig. 4. Variation of ultimate bearing capacity with diameter of stone column (*D*)

A gradual increase in *UBC* of foundation with diameter of stone column was observed within the range of stone column diameters considered in the present study. It may be noticed that upto a diameter of 0.6m, *UBC* increases almost linearly. As the diamter increases beyond 0.6m, a steep rise in *UBC* of the soil deposit takes place. It may be primarily due to the fact that as the diameter of the stone column increases, the percentage of stress transferred to the stone columns, by the external load, increases. As stone columns are stiffer and have substantially higher shear strength than the adjacent soil mass, therefore the UBC increases non-linearly for high range of stone column diamters.

C. *Influence of thickness ratio of top soil (H/B)*

Thickness of top layer of soil was varied to understand the influence of thickness of top soil layer on the overall bearing

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behaviour of stone column reinforced ground. Five different thickness ratios (*H*/*B* = 0, 1, 2, 3 and 4) were considered. Variation of *UBC* with thickness ratio has been presented in Fig. 5.

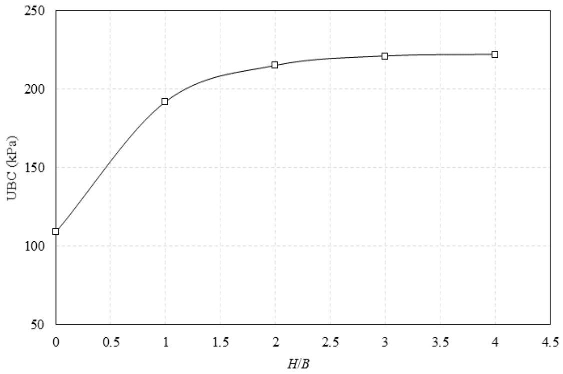

Fig. 5. Variation of UBC with thickness ratio of top soil

It may be seen that UBC increases with increase in the thickness of top soil layer. It was anticipated as in the present study, undrained shear strength of the top soil has been assumed to be higher than that of the underlying soil layer. However, it may be noted here that as the thickness ratio achieves a value of more than 2, the influence of layered deposit of soil diminishes and the UBC of footing tends to assume a constant value. It may be primarily due to the fact that as the thickness of top soil layer increases, the stress distribution gets mostly confined within the top soil layer and plastic zone does not propagate upto the bottom soil layer.

D. Influence of friction angle of stone column

This analysis aims at obtaining the influence of friction angle of the stone aggregates of stone columns on the overall bearing capacity. In the analysis, five different values of angle of internal frictions (ϕ' = 26°, 30°, 34°, 38°, and 42°) were considered for a stone column diameter of 0.4m. Variation of UBC with friction angle has been presented in Fig. 6.

As could be seen from Fig. 6 that the UBC of stone column improved soil increases with increase in the angle of internal friction of the stone aggregates. The variation of UBC with friction angle is somewhat non-linear and the rate of increase of bearing capacity increases as the value of angle of internal friction increases.

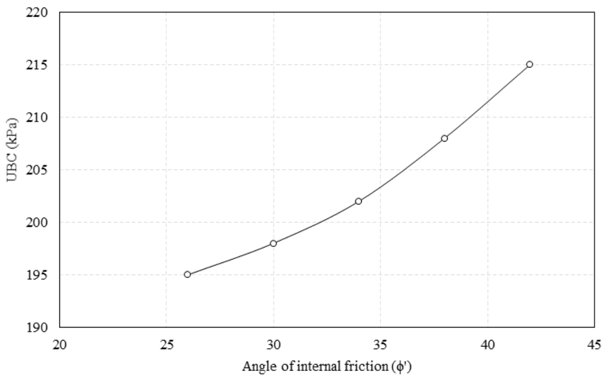

Fig. 6. Variation of UBC with friction angle of stone aggregates

V. Summary And Conclusions

In the present study, a comprehensive study has been carried out based on a series of finite element analysis on a stone column reinforced layered soil deposit. Efficacy of addition of stone columns on the bearing capacity behaviour has been duly considered. Influence of several governing critical parameters on the overall bearing capacity response of the system has been investigated and results are presented. A proper explanation has been provided with each obtained results explaining the mechanism behind the obtained observations. The major conclusions of the study may be summarized as

- In a layered soil deposit, reinforced with stone column, the undrained shear strength of the top soil governs the overall bearing capacity of the system for a depth ratio (H/B) more than 2. For *H*/*B* less than 2, the undrained shear strength plays a substantial role in the overall bearing capacity.
- Bearing capacity increases linearly with increase in the undrained shear strength ratio (*USSR*) within the range considered in the present study.
- An gradual increase in bearing capacity has been obtained with increase in the angle of internal friction of the stone aggregates of the stone column.
- As the column diameter increases, the bearing capacity increases non-linearly due to the larger resistance of the external load by the stiffer stone column aggregates.

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