Suitability Analysis of Stone Column Materials with PLAXIS

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Abstract-Stone columns are usually provided in groups to support various geotechnical structures, such as embankments, storage tanks, etc. Several experimental and numerical studies have been performed to study the response of stone columns as soil reinforcement. For relatively moderate loading of a structure, application of stone columns either singly or in groups is widely used. The enhancement of strength of the soil is governed by the type of original subsoil and the properties of the coarse aggregate materials used for the stone columns. Several researchers have analyzed different coarse-grained materials using various plane strain approaches to model the stone columns. This article deals with the non-linear analysis of an isolated stone column embedded in a semi-infinite medium of sandy soil. The parameters which crucially affect the settlement characteristics and the bulging failure of stone columns have been determined. The suitabilities of two different natural aggregates, pebble gravels, and crushed pebble gravels as materials for the stone column have been compared on the basis of their settlement behavior using 2D numerical modeling with the PLAXIS software.

Keywords-soil improvement; stone columns; numerical modeling; natural aggregates

I. INTRODUCTION

Engineers face challenges due to the presence of low bearing soils. These marginal soils have low bearing capacity and high compressibility characteristics. In order to make these marginal soils suitable for construction, ground improvement techniques need to be applied [1-3]. Stone column is such a technique to treat the weak soil. Stone columns are constructed by compacting coarse aggregates in bore holes. Granular stone columns have been used as a soil reinforcement technique for soft clay improvement to improve the bearing capacity of the native soil [4, 5]. An analytical method to assess the stone column load bearing mechanism for calculating the immediate settlement and rate of consolidation for stone columns embedded in soft soil was developed in [6, 7]. The ultimate bearing capacity of columns depends on the geometry of the column, its material properties, and the properties of the soft soil. The effect of the length of the stone column is almost negligible on bearing capacity because most of the load is transferred from the column to the surrounding soil through sides and very little load is transferred to the bottom which is similar to the effects of piles in granular soil [8-12]. The general range for the diameter of the stone column ranges from 0.9 to 1.2m and the length of stone column from 4 to 10m [13, 14]. Bulging failure is most common in long columns where, length to diameter (L/D) ratio is more than 4 to 6 [15]. Various researchers have analyzed the failure of reinforced ground.

The numerical modeling of a single and a group of stone columns has been analyzed using finite element software in [16-20]. Three different coarse grained materials were analyzed in [21] to assess their suitability for stone column materials by performing large scale site tests and laboratory tests. Important results from these works have been considered as input properties in the model presented in this study to analyze the behavior of pebble gravels and crushed pebble gravels as stone column material.

II. EXPERIMENTAL SETUP AND MATERIAL PROPERTIES

Several in-situ and laboratory tests were performed by the authors in [21] to determine the properties of soft soil and coarse-grained aggregates used in the analysis of stone columns. They determined the bulk density of natural aggregates using pit tests on already existing columns. The density index of the stone columns was determined in the laboratory. The obtained results from the tests are presented in Table I. To find the shear strength properties of column material, direct shear test was performed. The dimensions of the apparatus were 300×300mm with a height of 200mm. Shear stresses have been calculated by applying normal stresses with 50kN/m^2 increments. The angle of internal friction for pebble gravel was calculated to be 50° and it came out as 52° for the crushed pebble gravel. The influence of angle of shear (φ), L/D ratio, and undrained cohesion (C_u) have been considered in parametric study section. The analysis is followed by different materials study and the load – settlement curve.

III. PROBLEM STATEMENT

Two dimensional linear finite element models were used to analyze the behavior of stone column in clay soil. Stone columns with two different granular materials were used in two separate cases. The analysis was carried out with pebble

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gravels and crushed pebble gravels. The elementary boundary condition has been used for the analysis where radial deformation (u_x = 0) is restricted but settlement is allowed. Fixity condition was applied at the bottom of the model i.e. u_x = 0, u_y = 0. The stone column is modeled as axisymmetric and Mohr-Coulomb's criteria considering elasto-perfectly plastic behavior for soft clay were considered. Drained condition is assumed for both aggregates.

TABLE I. MATERIAL PROPERTIES [21]

Parameter	Unit	Materials		
		Clay	Pebble gravel	Crushed pebble gravel
γ	kN/m^3	19	18	17.36
γ_{sat}	kN/m^3	20.45	19.9	19.55
E_{oed}	kN/m^2	5170	45300	65800
φ	^{o}	26.6	49.9	51.8
ψ	^{o}	0	19.9	21.8
c	kN/m^2	10.8	1	1
$K_x = k_y$	m/day	0.01037×10^{-3}	864	864
μ	-	0.355	0.23	0.23
Properties of loading plate				
Normal stiffness (EI)		5×10^{6}kN/m		
Flexural rigidity (EA)		8500kNm^2/m		

It was considered that sufficient time has passed since the load has been applied, hence stress concentration and settlement have become steady. At the junction of stone column and soft clay there is no interface element due to deformation. This is found to occur mainly due to the radial bulging of the stone column. Finite element analysis for the stone column without considering any interface material has been performed in [22, 23]. Figure 1 shows the geometrical dimensions of the model problem. The model geometry is 325mm×350mm. Length and diameter of the stone columns were taken as 225mm and 25mm respectively. Stone columns are provided at the center of the clay bed and loading has been done through a flat plate double the size of the stone column. Displacement of 75mm is applied at the top of the stone column.

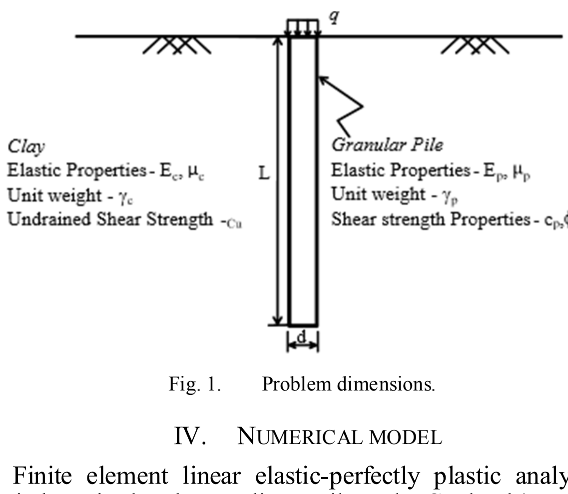

Fig. 1. Problem dimensions.

IV. NUMERICAL MODEL

Finite element linear elastic-perfectly plastic analysis is carried out in the clay medium soil. Mohr-Coulomb's material model is used to observe the response of clay and stone column. According to the Mohr-Coulomb failure criteria, when the shear stress on the soil element becomes equal to the critical value of stress, then the soil will fail. In Mohr-Coulomb, effective cohesion (c) and effective internal friction angle (φ) are modeled for both types of behavior, drained or un-drained. To do an effective stress analysis of the soil, friction angle and effective cohesion are taken in terms of effective stress. The total stress analysis value of cohesion parameter has been taken equal to the un-drained shear strength of the soil, in combination with φ equal to 0^o. The finite element program PLAXIS V8 was used for the analysis. The stone column and clay soil were modeled as axisymmetric 2D structures. The finite element mesh is generated with 15-node triangular elements having fine mesh size. There are 3 types of loading that can be applied in PLAXIS: (i) Distributed load, (ii) point load, (iii) prescribed displacement, which provides more information to draw the load-settlement response, so it is considered as the loading type in this study. Since we are using axisymmetric model, 2π is multiplied with the load recorded by the PLAXIS to get the actual load in the field. PLAXIS has the fixities option to apply the boundary condition.

V. RESULTS

A. *Analysis for Stress Concentration*

Gravel pebbles and crushed gravel pebbles were used as materials for the stone columns and their effectiveness was analyzed on the basis of their stress concentration and settlement occurring in the stone column-soil system up on the application of load.

1) *Using Pebble Gravel as Stone Column Material*

Effective stress analysis was carried out and the deformation behavior of the finite elements was observed. Figure 2 shows the deformed mesh at the failure when pebble gravel is used as stone column material. The extreme total displacement in the deformed shape is 50.68mm. The value is observed on scale factor of 0.5. The length of each line represents the magnitude of principal stress and the direction indicates the principal direction. The observed effective principal stress is 3.42×10^3 kN/m^2 as shown in Figure 2(b).

2) *Using Crushed Pebble Gravel as Stone Column Material*

Figure 3 shows the deformed mesh at failure. Extreme total displacement in the deformed mesh is 38.71mm. Here, total displacement means absolute accumulated displacement combined from the horizontal and vertical displacement components at all nodes at the end of the calculations. The relative deformation decreases by almost 31% in case of crushed pebble gravels. The stress concentration is less localized in the case of crushed pebble gravels. Hence, crushed pebbles gravel is more suitable material for stone column than pebbles gravel. The observed effective stress is 2.5×10^{3}kN/m^2 as shown in Figure 3(b).

B. *Analysis for Load-Settlement Curve*

Load settlement behavior was monitored in order to find out the most suitable material for stone columns. Based on the axial stress developed in the stone column and the settlement behavior, it can be concluded that stone column reaches the failure stage at the top. Settlement behavior of stone column with respect to load on the top of stone column is shown in Figure 4. It can be observed from the load-settlement curve that the stone column with pebble gravels settled more than the stone column with crushed pebbles gravel for the same value of stress. Crushed pebble gravel can be treated as a more suitable material for stone column than pebble gravels.

(a)

(b)

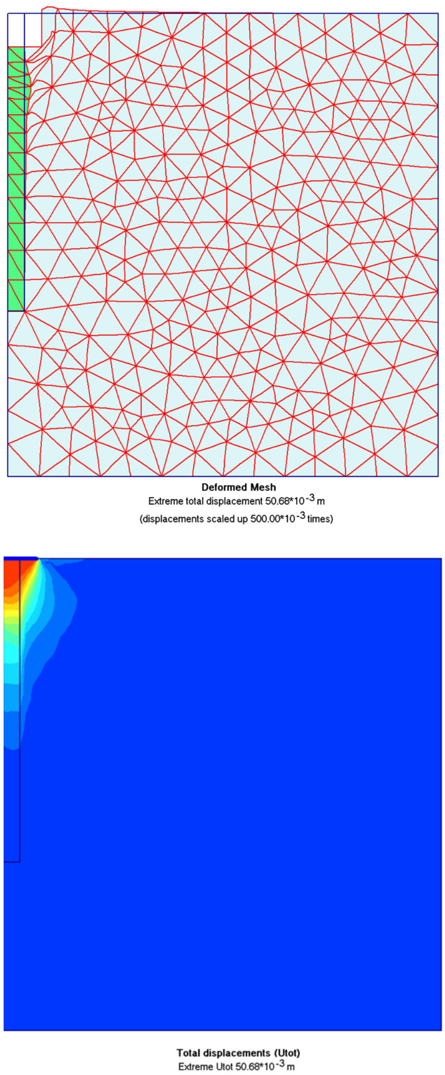

Fig. 2. Pebble gravel deformation and principal effective stress: (a) deformed mesh, (b) effective stress contour.

C. Parametric Study

The physical parameters of the stone columns, φ, L/D ratio, and Cu of soft clay are varied to study their influence on the load settlement behavior of stone columns.

1) Angle of Internal Friction of Granular Material

Figure 5 shows the influence of the angle of internal friction (φ) of natural aggregates on the load-settlement behavior. This effect has been shown by varying φ from 47.9° to 51.9°.

(a)

(b)

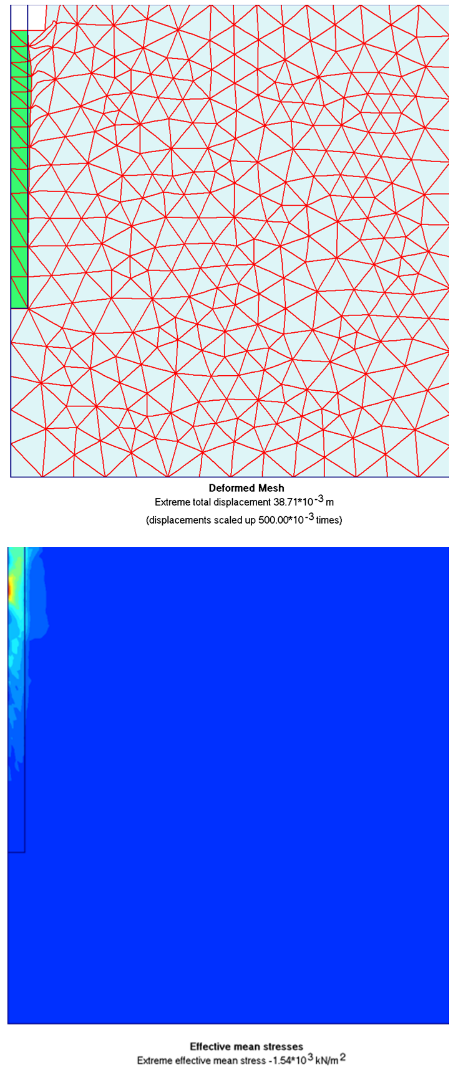

Fig. 3. Crushed pebble gravel deformation and principal effective stress: (a) deformed mesh, (b) effective stress contour.

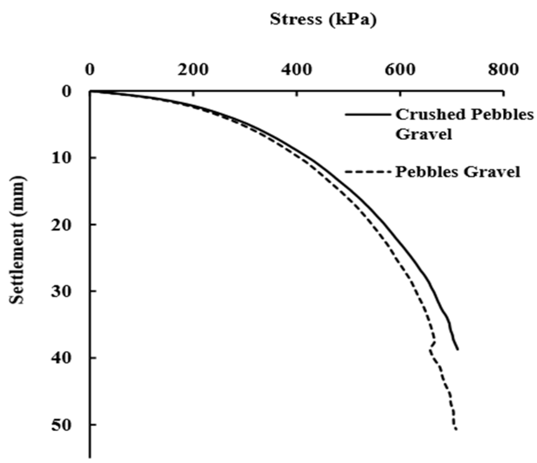

Fig. 4. Stress vs settlement curve for different materials.

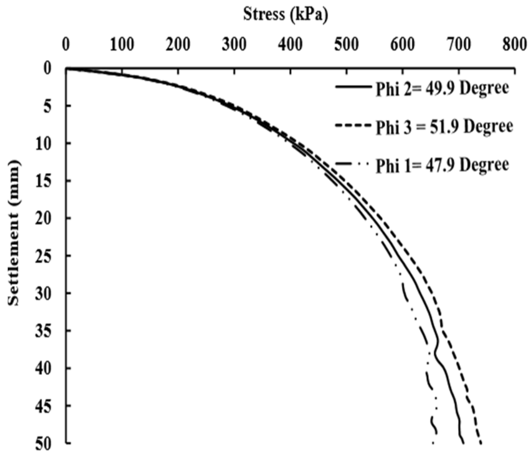

Fig. 5. Stress-settlement curve for different values of φ.

With increase in the shearing angle of the granular material, the settlement value of the stone column material is reduced for a particular value of load. This is mainly due to the increase in shearing resistance offered by the granular material with increase in φ. At the same time, for lower values of stress, the angle of internal friction does not influence the settlement of stone column significantly.

2) Undrained Cohesion of Clay Bed

The behavior of load settlement curve is analyzed in Figure 6 with increments of 2kN/m^2 in the value of undrained cohesion of the soil. C_u ranges from 8.8kN/m^2 to 12.8kN/m^2.

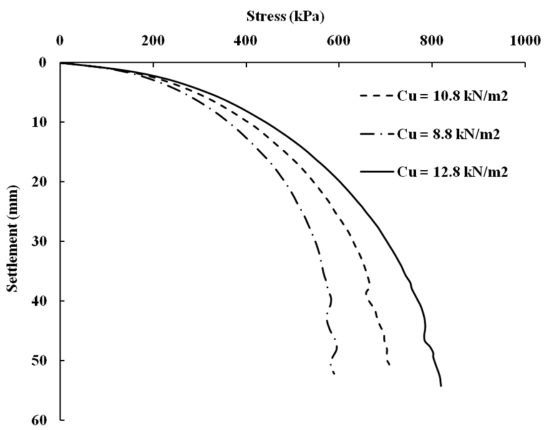

Fig. 6. Stress-settlement curve for different values of C_u.

3) L/D Ratio

To study the effect of L/D ratio on the load settlement behavior, the L/D ratio varied from 2 to 9 (Figure 7). It is observed that when the L/D ratio is increased, the settlement of stone column is decreased for the same applied load up to L/D = 4. After L/D = 4, there is no significant decrease in the settlement.

VI. Discussion

The comparison of different types of coarse-grained materials explains the utility of pebble gravels and crushed pebble gravels for stone columns. No such previous work has been carried out on the above specified aggregates, hence the study is unique within the area of stone columns. The results obtained from the current study state that the effect of the angle of internal friction, the undrained cohesion of surrounding clay, and the L/D ratio on the load settlement response are approximately the same with the findings in [3, 21].

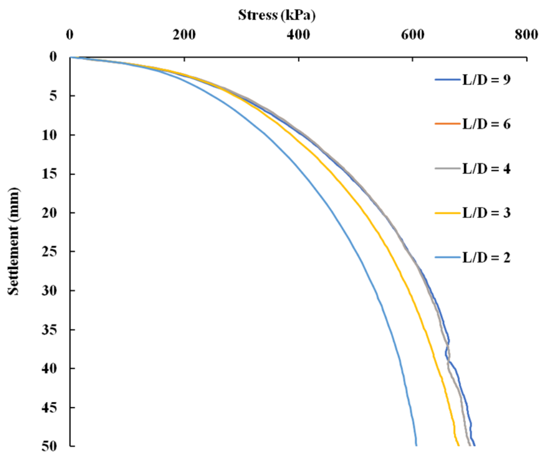

Fig. 7. Stress-settlement curve for different values of L/D ratio.

VII. Conclusions

The increased requirement for ground improvement by stone columns led to the incorporation of various types of natural aggregates as material for stone columns. The comparative analysis of the load-settlement response for gravel pebbles and crushed pebble gravels shows that:

- Relative deformation and settlement in the case of crushed pebble gravels are less than those imposed by pebble gravels. Hence, crushed pebble gravels are more efficient as a material for stone columns in soft soils.
- The settlement tendency of stone columns on the application of load was found to decrease with the increase of the angle of internal friction.
- When the value of undrained cohesion of the surrounding clay increases, the settlement of the stone column for the same value of load decreases.
- With the increase in the value of the L/D ratio, the settlement of the stone column for the same value of load decreases and there is no significant response on the load-settlement curve of the stone column when the L/d ratio is increased beyond 4.

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