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Experimental Study on Parametric Influences of Stone Column Reinforced Foundation Systems

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Abstract. A study on stone-column embedded soil system with different parametric variations is presented in this article. The investigation parameters included variation in footing diameter (*D*), column geometry, surrounding soil stiffness (c_u), and size of in-filling stone chips. The unit cell concept was referred in designing column and foundation bed dimensions in such a way that both the end-bearing and floating conditions can be simulated. The effect of footing area was considered by varying the footing diameter keeping the column dimensions constant for each cases. A clayey soil, with c_u = 5, 10 and 25 kPa, was selected for simulating the very soft, soft and medium stiff ground conditions. Different stone sizes were considered to find the influence of infilling material. The behavior was monitored and recorded in terms of load-settlement responses. The responses thus received indicated considerable effects of each of the parameter varied. Though, a physical study was aimed initially, however, only few tests could be performed due to pandemic condition and rests have been simulated through Plaxis3D.

Keywords: Stone column, Clay, Bearing capacity, Deformation, Plaxis3D

1 Introduction

The granular column in soft soil has been very effective in improving bearing capacity and limiting the settlements of concern geo-structure. It is constructed by filling and compacting the granules in a pre-bored vertical-hollow. The aggregates bear majority of the imposed load and transfer it deeper through interconnections. The column is with high permeability which allows the pore water to dissipate faster and accelerates the consolidation. Studies have revealed various parametric influences, including geometry (diameter, length, column-arrangement), in-fill material (granules) quality, stiffness of surrounding soil (shear strength) and/or encasement type etc., on the per-

formance of granular column. In this regard articles by Najjar [1] and Ghose et al. [2] would be good reads to have a glimpse of performance of stone column in soft clay.
The natural lateral confinement to granular column is the undrained shear strength (c_u) of surrounding soils; however, its effect is minimal with respect to limiting axial stress [3]. Ambily and Gandhi [3] found that column-aggregates and soft clay squeezed into each other causing disturbance in expected mechanisms. It is mentioned the overall ground stiffness depends on spacing between the columns and improves with surcharge loading. Reportedly, the angularity, packing and frictional angle of aggregates influences the behavior of granular columns [4-6]. It is further mentioned that the more the friction angle is, the more will be the column-stiffness, bearing capacity and stability; while, the same has resulted in reduced settlement and lateral bulging. The dependence of column performance on its geometry (i.e., diameter and length) has also been investigated [7-11] and reported that increase in diameter (while installation) may effect in the pre-estimated bearing capacity and drainage function for the granular column. Researchers [12-14] have mentioned a bulge formation for longer columns which limits the overall settlement; while, a punching failure is found for shorter columns which influences bearing capacity [15-16]. In this regard, there is a mentioned critical length (l_{crit}) of 5-8 times the diameter beyond which it does not contribute further on bearing capacity.

In this article the performance of model stone column on clay of varying strength is reported. The investigation programme included variation in the strength of surrounded clay (c_u) as 5, 10 and 25 kPa. Two different stone-sizes were selected (ranged between 10-4.75 mm and 4.75-1.18 mm) for infilling the column. The foundation bed cum test mould was prepared with respect to unit cell concept as described in Indian Standard [17]. Three column diameters, lengths, and footing sizes were selected to simulate the floating and end bearing column conditions. The initial study was based on physical tests; however, the authors are forced to focus on the numerical simulation (Plaxis3D) due to pandemic condition. As per the observation made till date, it is found that the behavior of stone columns is immensely influenced by the parameters considered.

2 Material and Methodology

In the study locally available clay-soil used for preparing the foundation bed by varying its water content (to vary the shear strength). The Pakur variety stone chips were selected for constructing/in-filling the granular columns. Basic characterization of the soils was performed as per designated Indian Standards and the determined properties are presented in Table 1. The table also includes the parameters required to define the material in the numerical simulation.

Table 1. Material Properties

Material Properties	E_{Nu} (kPa)	c_u (kPa)	φ (°)	υ_{Nu}	γ (kN/m^3)
Clay	600c_u	5, 10, 25	0	0.35	17, 18.0, 19.0
Stone Chips	50×10^3	0	52, 58	0.40	14.55, 14.71

E_{Nu}, υ_{Nu} : Numerical Inputs

2.1 Preparation of clay

For preparing the clay bed, a relationship is established between the undrained shear strength of clay with water content (Fig. 1), following the procedure described by Biswas [18]. The curve acted as the backbone for selecting clay strength and calculating the corresponding water content (with bulk densities) keeping the clay saturated.

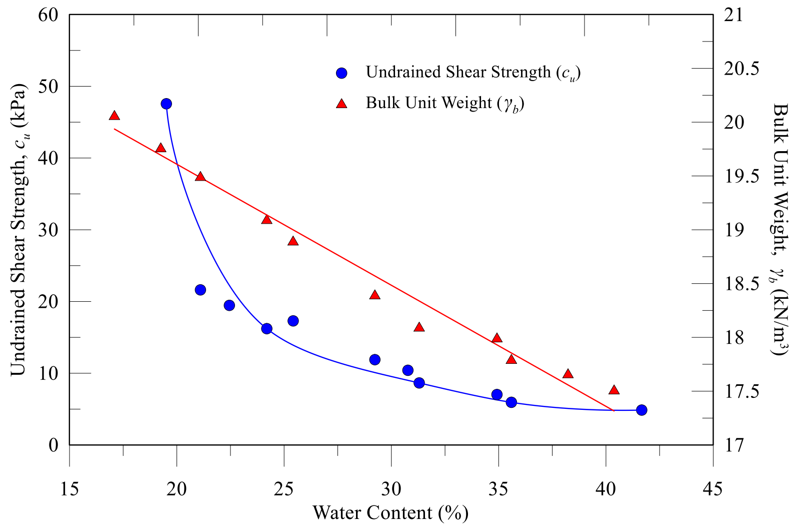

Fig. 1. Calibrated relation between c_u, w (%) and γ of clay

2.2 Preparation of clay bed

The foundation bed was prepared in a split-mould made of metal sheet of 2 mm thick. The mould was braced with steel clamps (4 mm thick-20 mm wide flat steel bars) to avoid bending of walls during the bed preparation and while the tests progress. The mould and other accessories are shown schematically in Fig. 2. Thick PVC pipes of different diameters were used to create the column-core. Three nos. of 18 mm thick wood-plates, having hole at the center (avg. hole diameter = external diameter of corresponding pipe + 2 mm) were fabricated for compacting the clay layers (with the pipe inserted) within the mould. Before placing the clay in the mould, the pipes were made vertical with holders (fabricated and can be fix strongly with the mould) (Fig. 2). The clay was placed in the mould in layers (about 50 mm thick). After placing clay for a layer, the wooded-plate (with a plastic sheet at the bottom) was placed on the clay surface for compaction. The wooded plate was supposed to distribute the compactive effort all over the clay surface. The plastic sheet was used to avoid the sticking of clay on the wooden-plate. The layers were compacted with equal number (pre-determined) of blows with the hammer designated for standard proctor test. After preparing each layer, the clay surface was scratched to get adequate grip with the successive layer. Completion of clay bed preparation allows stone-chips to be placed in the PVC pipes in desired density with tamping.

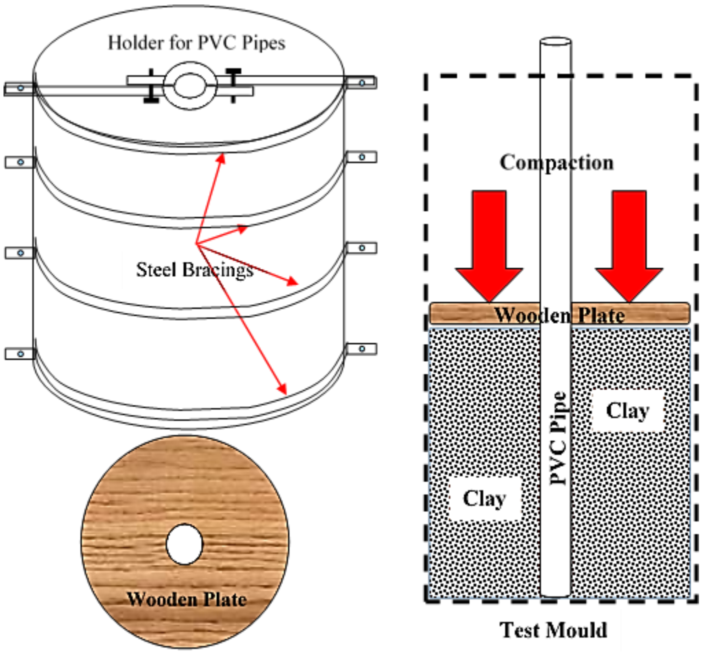

Fig. 2. Schematic of test mould, holder for PVC pipes, wooden plate for compaction and preparation of test bed

2.3 Preparation of stone column

Stone columns were prepared in layers with tamping. The entire length was formed by 50 mm equal lifting. For each layer, the required mass of stone chips was calculated, weighted, poured and compacted until the desired thickness was achieved. The desired effort for tamping was confirmed through several of trial tests. After each layer, the PVC pipe was lifted up to the thickness prepared to start preparation of the next layer. Due to the softness of surrounding soil, the compaction increased the column volume (diameter). Thus, care and trials were made in such a way that the enhancement in column volume should be limited to 5% of the stone-weight calculated for each layer. After preparation of stone column footing were placed centrally and load was applied.

2.4 Test procedure

The schematic test set up is shown in Fig. 3. The load-test was conducted in a universal load frame having 36 nos. strain rates. The prepared test mould, with footing, was placed under the load frame. The load was applied through a load cell of 10 kN capacity. A LVDT (50 mm run) was used to record the footing settlement. The load-settlement was measured and recorded in a data logger. After successful placement of all instruments, the test was started with the predetermined strain rate.

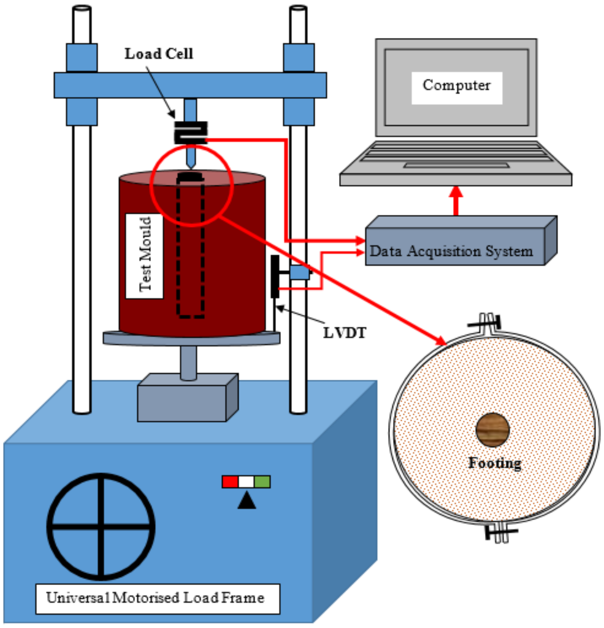

Fig. 3. Schematic of experimental set up and other accessories used

3 Results and Discussion

The tests parameters selected were footing size (*D*), diameter of stone column (D_c), length of stone column (*L*), stone sizes, undrained shear strength of clay (c_u) and the strain rate of load applied. Obstructed by the pandemic situation, the variables were curtailed and only a few tests were possible to perform physically. Behavior of circular footing of different diameters (*D* = 30, 45 and 60 mm) rested on homogeneous clay with c_u = 5 kPa were obtained under single strain rate of loading (1.2 mm/min.). The load-settlement behavior is presented in Fig. 4. The responses depicted increase in pressure-settlement behavior with the footing diameter. A test with stone column (D_c = 30 mm; *L* = 175 mm), made of "4.75 mm passing and 1.18 mm retained" fraction of stone chips, was performed in clay with c_u = 5 kPa. Comparing with the corresponding homogeneous response, it can be said that pressure-settlement behavior improved with the installed stone column.

In the numerical simulation, the material properties used were same as determined through laboratory tests. The axi-symmetric numerical simulation is performed in Plaxis3D with 60, 90, 120 and 180 mm diameter footing in clay having c_u = 5, 10 and 25 kPa (selected from Fig. 1). The laboratory determined properties of two stone chips of sizes, designated as 4.75 mm (10 mm passing and 4.75 mm retained) and 1.18 mm (4.75 mm passing and 1.18 mm retained) fractions, were used to model the stone-column having lengths as 1 m, 1.5 m and 2 m within a 2×2×2 m^3 soil block. A typical model schematic and corresponding analysis response is shown in Fig. 5.

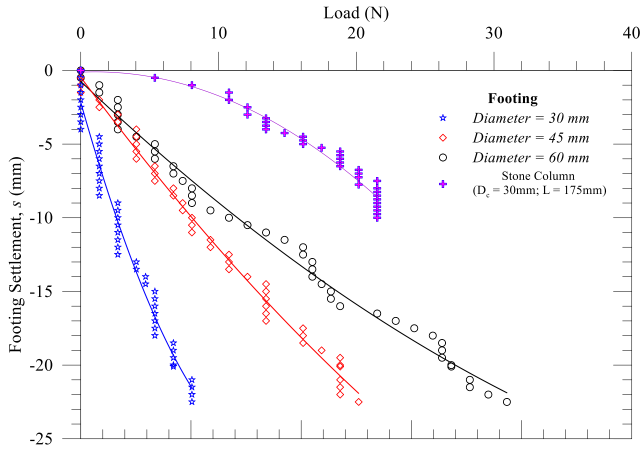

Fig. 4. Responses of physical test with different footings on homogeneous clay of c_u = 5 kPa

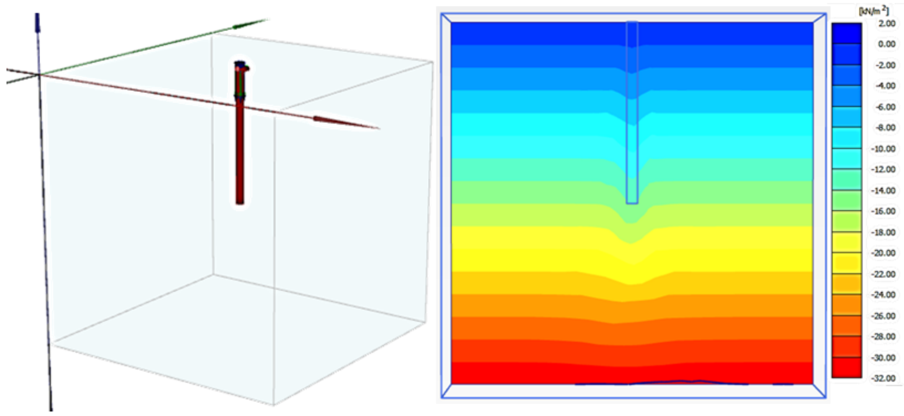

Fig. 5. Typical analysis model and responses of footing having 60 mm diameter rested on stone column of 1 m length with 4.75 mm in-fill material on clay with c_u = 5 kPa

The simulation results have depicted a considerable increase in load bearing capacity with increase in undrained shear strength of surrounding clay (Fig. 6). However, it was also found that the short floating column of 1m length has behaved better than the other two configurations in a clay of same undrained shear strength. This can be attributed to bulging of short column to improve the bearing capacity and failure of slender column before achieving desired benefits (Fig. 6). A typical comparison of behavior of short (1 m) and slender (2 m) column having in a clay with c_u = 10 kPa is presented in Fig. 7 (a-d).

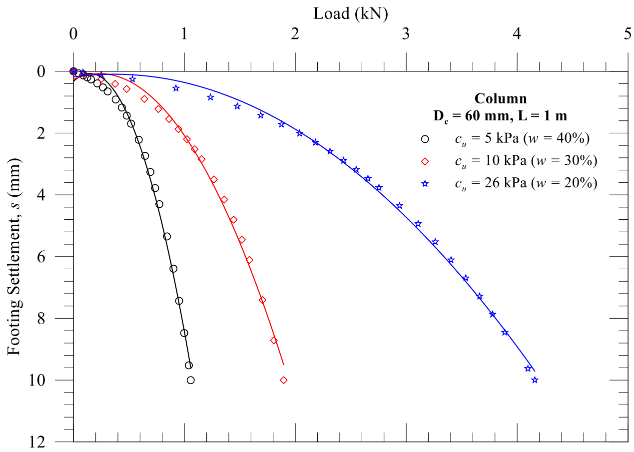

Fig. 6. Responses of circular footing (Dia. = 60 mm) on stone column (L = 1 m) on clay bed with different c_u (4.75 mm fraction in-fill material)

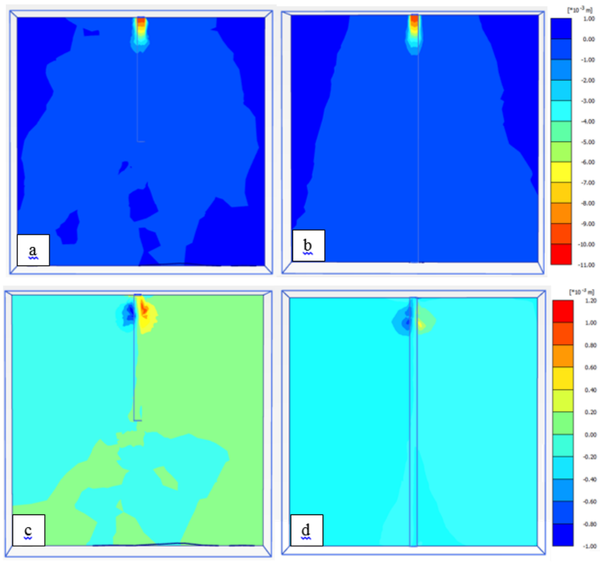

Fig. 7. Response of 60 mm dia. column with 4.75 mm stones in c_u = 10 kPa: vertical (a) and lateral (c) deformation of for L = 1 m and vertical (b) and lateral (d) deformation for L = 2 m

A comparison of influence of footing diameter (120 mm and 180mm) and column length (1 m, 1.5 m and 2 m), keeping the column diameter same (60 mm) with constant clay consistency of 25 kPa (c_u), is presented in Fig. 8. It is seen that the bearing capacity of the foundation systems improves considerably with the increase in footing diameter and column lengths. It may be attributed to the influence of increased footing area supported by the surrounded clay. This in turn enhances the confining surcharge toward the possible bulging of concern stone column. This eventually restrict the column deformation to keep its integrity for the load transfer to enhance the bearing capacity of the foundation system. However, the influence of column diameter beyond L = 1.5 m is found to be negligible.

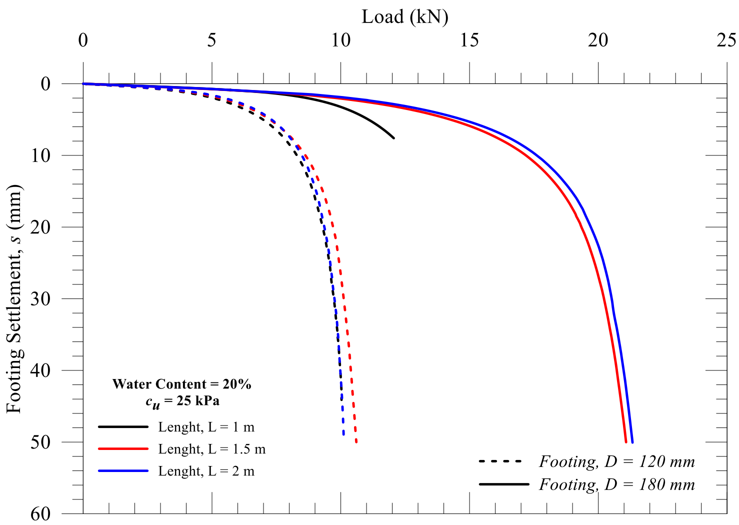

Fig. 8. Comparison of influence of footing diameter and column length with c_u = 25 kPa

4 Conclusions

The study investigated responses of footing rested on stone column in clay of varying strengths. Responses indicated considerable effect of parametric variations. The column diameter and length was varied along with the infill materials. Improvement in bearing capacity is found with increase in clay consistency, column length and footing diameter. However, the influence of column diameter beyond 1.5 m was found to be negligible which is attributed to excessive bulging. The increase in loading area through enhanced footing diameter effected in confinement (lateral pressure) of surrounding clay (in addition to direct support provided to the footing). The authors admit that the numerical simulation should have been verified with the physical test results; however, the research progress has been badly affected due to the pandemic condition and the restrictions thereby on physical contacts till date.

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