

Behaviour of Raft Foundation Supported by Stone Columns and Combination with Rigid Piles in Soft Clay Soils: 3D Numerical Study

Sudhanshu Sharma¹, Sudheer Kumar J²

¹PG student, Department of Civil Engineering, DAV Institute of Engineering Technology, Jalandhar, Punjab. E-mail:

²Assistant Professor, Department of Civil Engineering, DAV Institute of Engineering Technology, Jalandhar, Punjab.

Abstract - Construction of skyscrapers, bridges, power reactors etc. on very soft soil is a very difficult task. They cover a huge area along the coastal zones and other parts of the world. Marine soft silt and loose cohesive soils exist in these coastal areas with a higher level of the water table. In these conditions, foundations of various major structures are built with the concept of composite piled raft foundation comprised of varying slenderness ratios and composition with short columns of elastic materials which helps to improve soft cohesive soil and reduce differential or total settlement. This paper study utilized this concept by providing conventional stone columns (CSC) and their combination with piles beneath the raft foundation for investigated the performance of raft through a three-dimensional finite-element study. They may give an effective solution to resist the total and differential settlements within soft clay soil. Influence of material properties of stone columns, load carried by individual columns or with piled-raft, varying slenderness ratio of columns and thickness of raft have been examined. Results shown that strengthening the soft clay soil with conventional stone columns and its combination with piles was effective in reducing the total and differential settlement and enhancing the bearing capacity of the composite column supported raft foundation. Raft bearing interaction with soft clay significantly improved by increasing in diameter of conventional stone columns (CSC).

Key Words: Pile-raft foundation, CSC, CSC-pile raft foundation, vertical settlement ratio, load-carrying capacity.

1. INTRODUCTION

1.1 Introduction

In the view of ever-increasing demands of high-rise buildings, development of infrastructure, a huge shortage of space also increases. Due to this, they are forced to build the structures on soft clay soil. India has approx. 7500 km long coastline including that of its island territories. This coastline contains soft clay cohesive soils and marine silt. In these areas, various major structures are built on a piled raft foundation. It is stable in long term and provides sufficient stiffness and durability. The piled raft foundations are also utilized when the superstructure loads require to be transmitted to deeper depths.

The shallow foundations are not adequate in carrying high lateral loads. Using a Piled-raft foundation helps to decrease the differential settlement and increases the bearing capacity. Strengthening soft clay soil with the granular column is one of the ground improvement techniques. Conventional stone column (CSC) and its surrounding soil generally act as a composite material and the strength of this composite system is much higher than the soft clay soil alone. The main function of using conventional stone columns (CSC) in the piled-raft foundation while helps to reduce the cost of construction especially in case of piles and also providing in the coastal areas having loose cohesive soils exist with a higher level of the water table works as separation, filtration, and drainage. The free flow of groundwater and dissipate the pore water pressure. The idea of composite piled raft foundation includes piles and conventional stone columns (CSC) support various heavily loaded structures.

1.2 Background

Raft supported pile foundation is one of the most effective methods for the foundation of high-rise buildings over the area covered with soft clay soil. It can provide sufficient bearing strength and control the total settlement. The author referred to few published research studies on piled raft foundations on reducing the differential settlement and increasing adequate bearing capacity for the construction of various massive structures on soft soil. Several researchers **Hataf et al. (2020)[1]** showed that the load factor of maximum value which is 1.4 times compare with encasing the stone columns. They increase the bearing capacity of the stone column by 40%. **Banerjee et al. (2020)[2]** have reported various settlement behaviour, as load subjected vertically by piled raft for different slenderness ratios of piles, configurations, spacing and placing. Differential vertical settlement of the raft increases as the length of the pile is reduced from 25 m to 15 m. **Beygi et al. (2020)[3]** evaluate the behaviour of the piled raft foundation by changing the groundwater level with the help of 3D numerical analyses. They showed that by increasing the pile diameter from 0.5, 0.75 and 1m, the maximum settlement decreased by 5.95% and 10%. **Halder and Manna(2020)[4]** have reported the influence of the thickness of raft and pile configuration on the account of subjected vertical load to pile raft which is placed in the sand with 3D finite element simulation. They also showed that

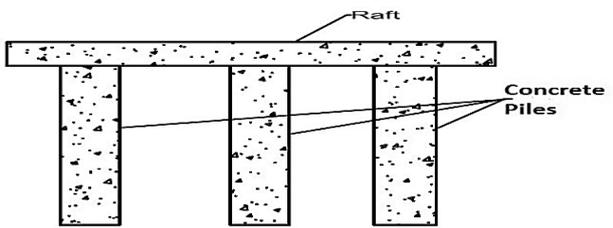
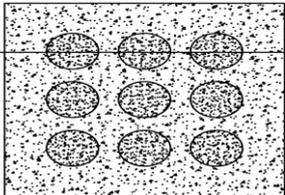
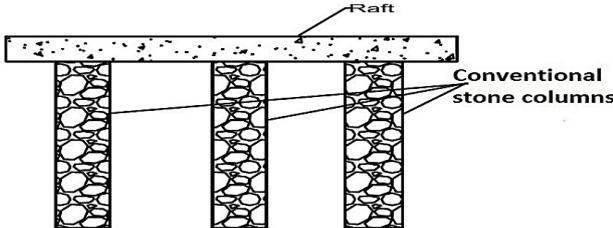
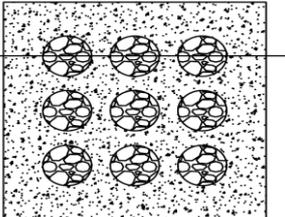
irrespective of the length and spacing between the pile, it carries 40-60 % of the total vertical load. **Samanta and Bhowmik (2019)[5]** investigated the response of stone columns of various changes underneath the pile raft foundation by FEM analysis, published on the influence of slenderness ratio, area replacement ratio, and other properties of stone column, also calculated the load sharing ratio by the piles and stone columns up to 30% and 40% respectively. **Sinha and Hanna (2017)[6]** reported 3D numerical modelling results of piled raft foundations. They found that with increasing the soil cohesion and the angle of shearing resistance, vertical settlement of the raft decreases. Several researchers **Das and Deb (2017)[7]** studied the embankment supported by modelled stone columns under the condition of axis-symmetric. And found that while increasing the modular ratio, the maximum settlement decreases and reduces the rate of change of settlement with an increase in modular ratio beyond 30. Analytical and numerical analysis of pile-raft foundations in layered soils under complex loads **Mu et al. (2014)[8]**. **Ghazavi and Afshar (2013)[9]** have investigated the bearing capacity of vertical stone columns encased with geosynthetic material, reported that with increasing the length and strength of vertical geosynthetic reinforcing encasement, the ultimate capacity and stiffness of stone columns also increases. **Khabbazian et al. (2010) [20]** studied the 3D finite element analyses were performed to compare the performance of GECs with conventional granular columns. With help of graphical representations also observed that the maximum value of lateral or radial displacement of a GEC is much less than that of a conventional granular column for the same vertical settlement. **Murugesan and Rajagopal (2006, 2007, and 2010) [19]** conducted various laboratory model tests on ordinary stone columns and geosynthetic encased stone columns for both single as well as grouping and found that the performance of geosynthetic encased stone columns gave a stiffer response whereas the conventional stone columns showed a significant response of strain-softening behaviour.

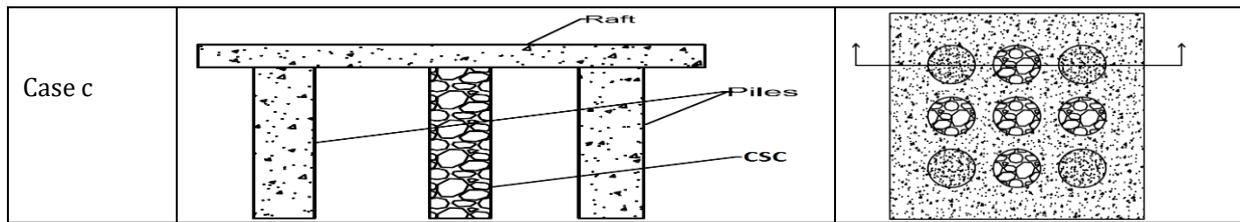
The above-stated studies disclose that the pile-supported raft foundation shows greater performance on improved soil. Considerable work was not conducted on a composite foundation system in raft foundations with CSC and piles. The effect of conventional stone columns and their combination with piles improved soft soil has not been reported in the literature. The present study investigated the performance of raft supported by piles, CSC and a combination of CSC-piles. A finite element method-based program (Plaxis 3D) has been used to investigate the interactions between raft – piles - soil, raft–soil - CSC, and raft – soil – piles – CSC.

2. Objectives of the study and Materials

Referred to Table 1 cases a, b and c show the schematic representation of the problem analyzed by using the Plaxis 3D program. Case a, shows that the raft is supported by 9 numbers of uniformly connected floating piles of 0.5m diameter distributed in a square pattern underneath the raft size of 4.8 m wide (B) and 1m thick square. Similarly, case b shows the fixed size of the raft supported by nine numbers of connected conventional stone columns (CSC's) to the raft of varying slenderness ratios. Case c shows raft supported by a combination of 5 CSC and 4 piles beneath the raft within soft clay soil. Total twelve cases were performed; case b and case consist of five subcases by varying diameter of 0.7m, 0.8m, 0.9m, 1m and 1.2m and only one analysis was performed in case a and one for raft alone over soft clay soil. In cases, a and c, the diameter of the rigid pile consider is 0.5m diameter.

Table 1. Schematic diagrams of raft supported by composite columns improved soft clay soil.

Cases	Elevation of structure	Plan of a raft with columns
Case a		
Case b		



The spacing between the columns is constant and symmetric. For analysis purposes author(s) consider the one-fourth of the site was modelled as shown in Fig. 1. The one-fourth configuration consisted of nine numbers of various columns as piles, CSC's and their combinations in various cases. The study focused on the performance of rafts supported by pile, CSC's and their combination. Vertical settlement ratio (VSR) defines the ratio between the vertical displacement of raft and raft thickness which is 1m.

$$\text{Vertical Settlement Ratio (\%)} = \frac{\text{Displacement}}{\text{Raft thickness}} \times 100 \quad \text{----- Eq (1)}$$

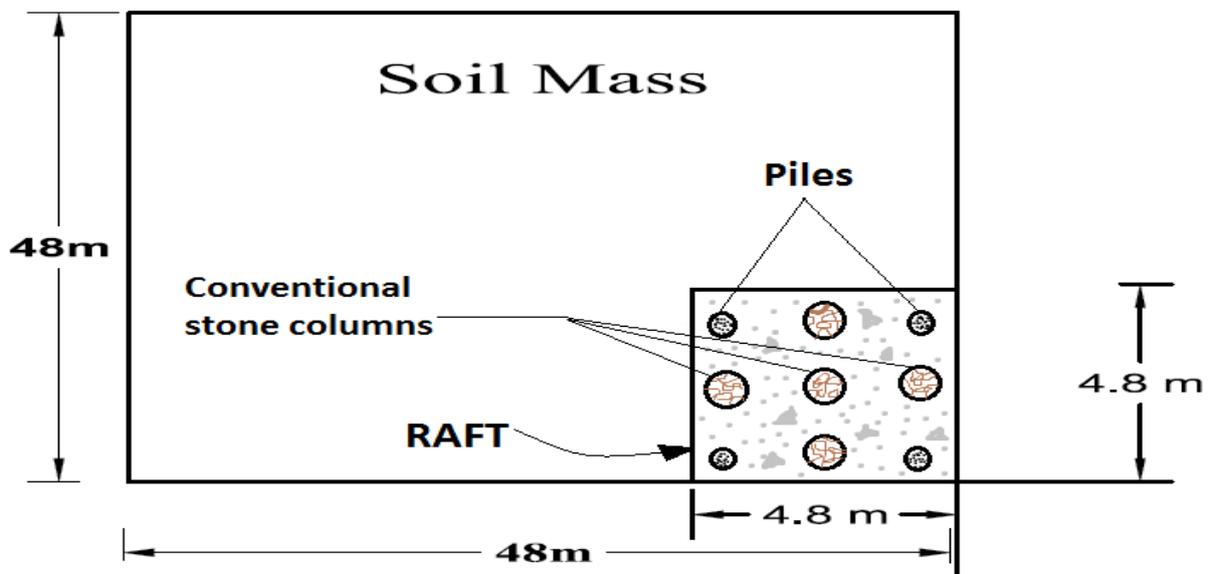


Fig. 1. Schematic diagram of parametric study (consider one-fourth of the total width of soft soil model)

Table 2 Material properties used in this study or analysis (Beygi et al. 2020, Manojit et al. 2017, Ghazavi et al. 2018[10], Black et al. 2011[18])

Test Parameter	Concrete pile & Raft (linear elastic)	Soft Clay (Undrained)	Stone aggregate (Drained)
Φ (Angle of internal friction)	34°	30°	44°
Ψ (psi)	4°	0	14°
μ (Poisson's ratio)	0.2	0.35	0.3
Tensile strength(kN/m)	--	--	--
γ_{bulk} (kN/m ³)	25	18	20

C (kPa)	--	15	0
Kx (m/day)	--	0.0100	1
Ky (m/day)	--	0.0100	1
Eref (Modulus of Elasticity) kN/m ²	30.00e6	4000	40,000

3. Numerical modelling

The numerical zone of the model consists of various cases that were fixed from try-out calculations, in which dimension parameters of the zone increased till the displacements and stresses of the system consist of raft supported by various columns were marginally affected. The finite element method-based program allows for complete modelling of all major model components: pile design, constitutive model parameters, soil continuity and soil-pile interaction through the gapping and slippage. The horizontal parameters were extended to 10 B (B is the width of the square raft) to the edge of the raft and be treated as horizontally constrained but vertically moving. To stimulate the state of floating piles, bottom parameters was set at a depth of 2.5 L_p (L_p is the length of the pile) from the head of piles. In the numerical model, upright boundaries of the model were fixed in the lateral movements and allowed to proceed in one plane only. Moreover, bottom boundaries were fixed against motions in all directions while the surface of the ground was free to move in every direction. In this study, interaction factors are defined by Plaxis 3D. Cases a, b and c, the interaction factor between the soft clay soil model – aggregates of the stone column are 0.6 and piles – aggregates are 0.8.

Mohr-Coulomb soil constitutive model of elastic-perfectly plastic was used for soft clay soil and CSC's. The soil represents a continuum, which was discretized by using 15-noded wedge elements (Brinkgreve et al. 2016). Raft discretized with elements of a six-noded triangle, piles which were created as embedded beams comprised of 10-noded (the middles at the edges and the nodes at the corners) tetrahedral elements with rotational degrees of freedom at each node with an average element mesh size of 0.89. The linearly-elastic model was considered for rafts and piles which were made of concrete materials.

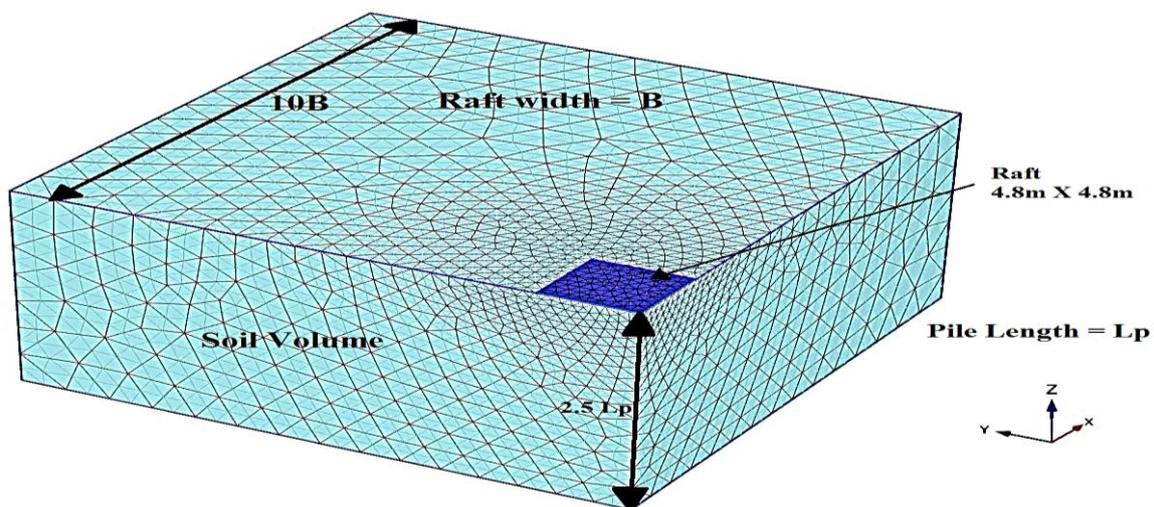


Fig. 2. Boundary conditions with discretization in finite element method

The parameters have been designed for the model geometry as the multipliers of column diameter D, the entire geometry can be frame worked as the function of column diameter D. The final refinement zone of mesh and the geometry of the model is presented in Fig.2. At the bottom of the model in all the directions, displacements were fully fixed on the model boundaries and were limited to vertical directions on the side planes.

4. Results and discussion

To determine the load-vertical settlement ratio (VSR) behaviour on soil element nodal points, the top of the soil model corresponding to the top of the raft and piles are subjected to various series of vertical and horizontal displacements by applying a uniformly distributed load.

Pile diameter considers as 0.5m, hence the slenderness ratio is 12. The group of nine piles with the spacing of 2d (d is the diameter of the pile) centre to centre rigidly joined with the 1m thick raft. Fig. 6(a) shows the total vertical displacement (U_z) of Piled-raft carried uniformly distributed load within the soft clay soil with a maximum value of 128.5mm. Table 3, shows the relation between the load Vs vertical settlement ratio.

Table 3 Results from soft clay bed and piled raft

S.no.	Raft alone		Piled raft	
	Load (kN)	Vertical settlement ratio (%)	Load (kN)	Vertical settlement ratio (%)
1	182.45	0.29	317.87	0.29
2	545.08	0.88	680.34	0.63
3	1258.75	2.05	1401.66	1.30
4	2581.98	4.40	2797.42	2.65
5	3425.71	6.77	4866.18	5.29
6	4253.45	11.57	5880.68	7.90
7	-	-	6906.05	11.99

From Fig. 3, it is evident that soft clayey soil with raft alone undergoes larger deformations under smaller vertical load. However, nine piles of dia. 0.5m provided beneath the raft, it carries 62.35 % more load than the load carries by the raft alone for the same value of vertical settlement ratio at 12 %. Using nine conventional stone columns (CSC) of various slenderness ratios to understand the behaviour and performance of raft within plastic soft clay soil with the applied pressure of 120 kPa over the raft. Since the model analysis is carried on axis-symmetric conditions deformations under the various elements are created.

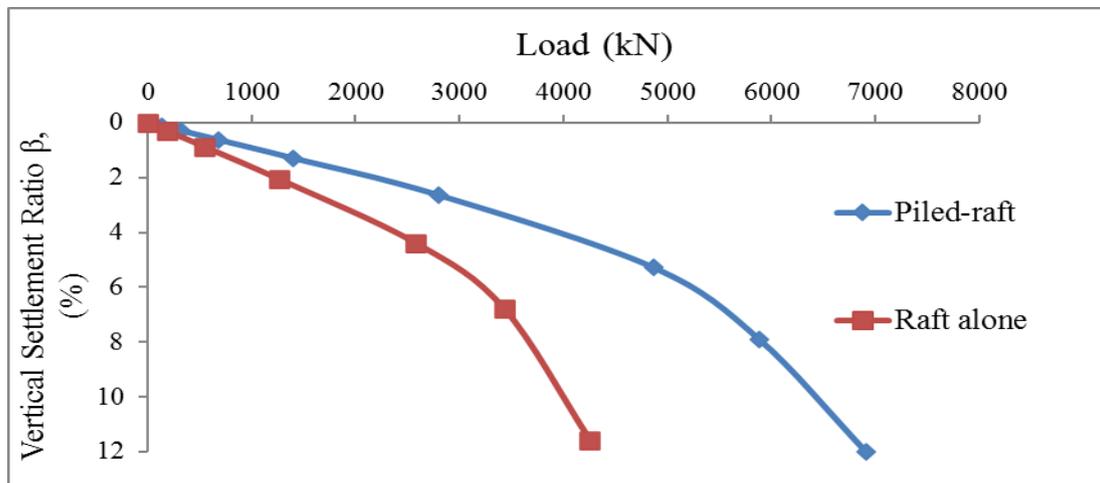


Fig. 3. Performance of raft lone and with piles on a load-carrying capacity of compressible soft clay soils

Fig. 6(b) shows the total vertical displacement (U_z) of raft supported by nine conventional stone columns carried uniformly distributed load within the soft clay soil with a maximum value of 120 mm. **Table 4**, shows the relation between the load Vs vertical settlement ratio (VSR) in the case of raft supported by CSC's only.

Table 4 Results from raft supporting by conventional stone columns

Sr. No.	Conventional stone columns supporting a raft									
	0.7m Diameter		0.8m Diameter		0.9m Diameter		1m Diameter		1.2m Diameter	
	Load (kN)	VSR (b)	Load (kN)	VSR (b)	Load (kN)	VSR (b)	Load (kN)	VSR (b)	Load (kN)	VSR (b)
1	203.16	0.29	207.84	0.29	208.26	0.28	210.67	0.27	235.97	0.27
2	603.67	0.86	617.82	0.87	618.33	0.84	625.60	0.82	703.05	0.83
3	1384.74	2.00	1414.05	2.03	1412.97	1.97	1030.59	1.36	1159.36	1.38
4	2130.06	3.15	2176.16	3.20	2171.10	3.09	1810.91	2.45	2029.52	2.48
5	3472.28	5.42	3534.86	5.53	3536.96	5.34	3240.95	4.64	2841.88	3.59
6	4327.91	7.71	4398.10	7.88	4444.52	7.59	4305.61	6.82	4285.49	5.81
7	5203.33	11.43	5243.04	11.51	5398.36	11.46	4988.89	9.02	5333.93	8.04
8	-	-	-	-	-	-	5504.01	11.22	6097.75	10.29
9	-	-	-	-	-	-	5520.56	11.33	6407.76	11.39

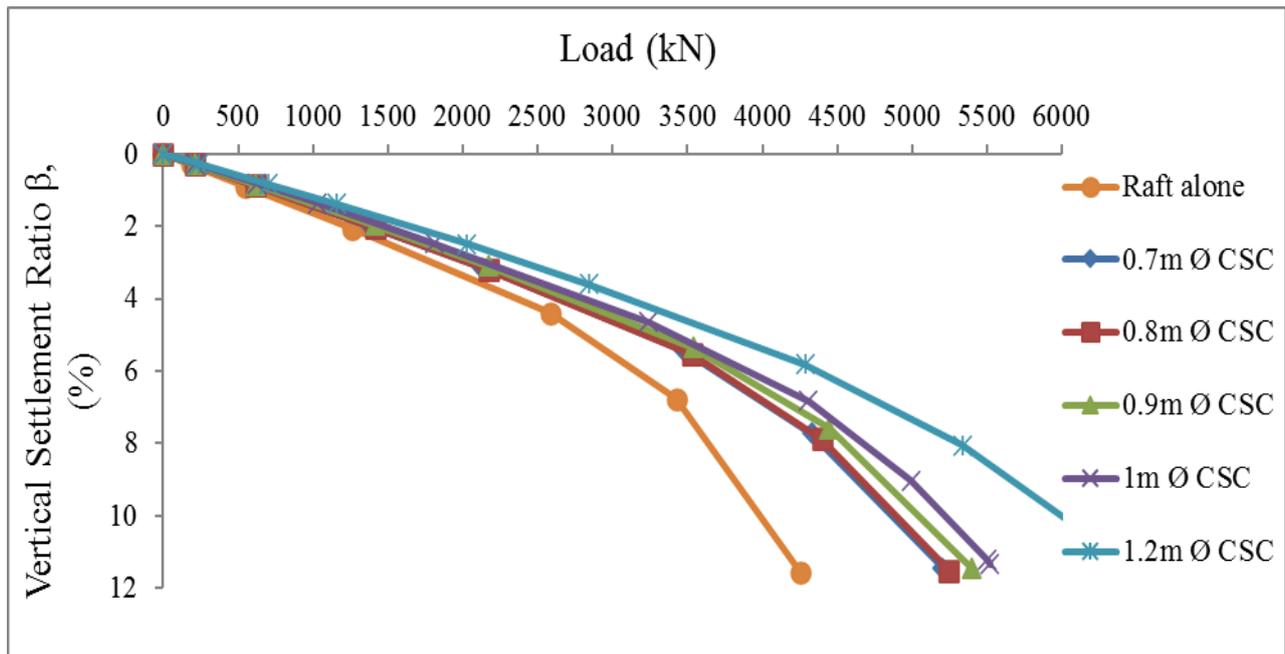


Fig. 4 Performance of raft lone and with conventional stone columns in compressible clay soils

The load-Vertical settlement ratio plot (Fig. 6) shows a load-carrying capacity of raft alone and various diameters of CSC's. Providing conventional stone columns of various diameters beneath the raft carries comparatively more loads than the raft alone. The load-carrying capacity increased by 22.31 % of 0.7m dia., 24.23 % of 0.8m dia., 27.93 % of 0.9m dia., 29.82 % of 1m dia. and 51.88 % of 1.2m dia. of CSC than raft alone.

Using nine conventional stone columns (CSC) of various slenderness ratios to understand the behaviour and performance of raft within plastic soft clay soil with the applied pressure of 120 kPa over the raft. Since the model analysis is carried on axis-symmetric conditions deformations under the various elements are created. Fig. 6(c) shows the total vertical displacement (Uz) of raft supported by nine conventional stone columns carried uniformly distributed load within the soft clay soil with a maximum value of 147.7 mm.

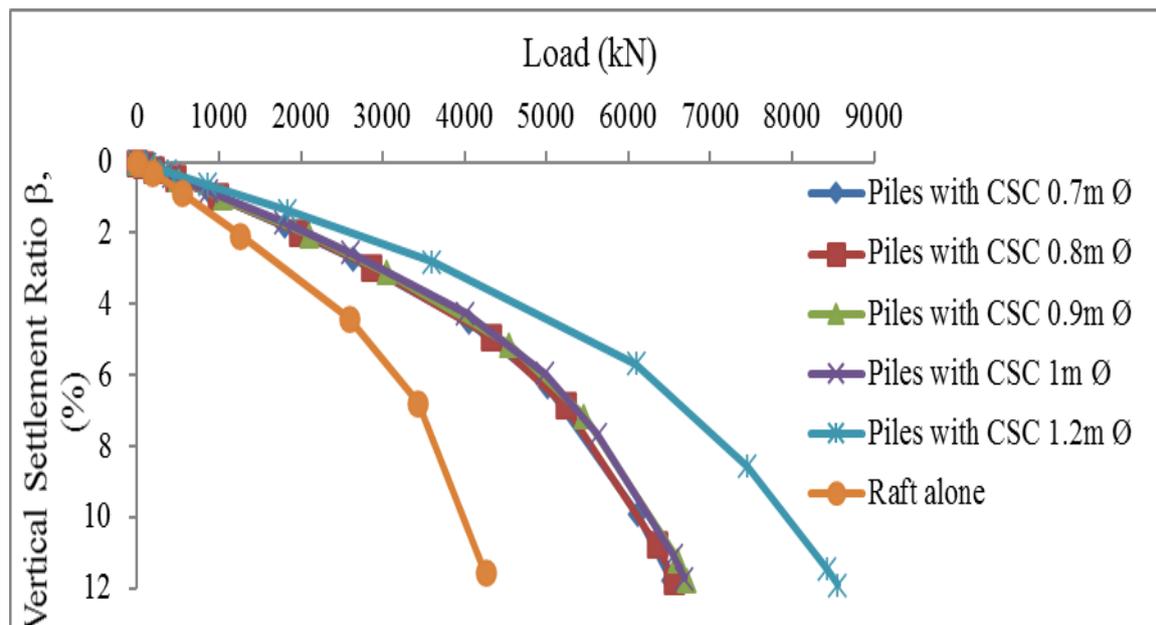


Fig. 5 Performance of raft lone and with piles and conventional stone columns in compressible clay soils

The load-vertical settlement ratio plot **Fig. 5** shows a load-carrying capacity of raft alone and combination with various diameters of CSC's and piles. Providing a combination of square arrangement of conventional stone columns of various diameters with piles beneath the raft carries more loads than the raft alone. The load-carrying capacity increased by 55.18 % of 0.7m dia., 55.69 % of 0.8m dia., 56.94 % of 0.9m dia., 63.62 % of 1m dia. and 69.73 % of 1.2m dia. of CSC with pile than raft alone.

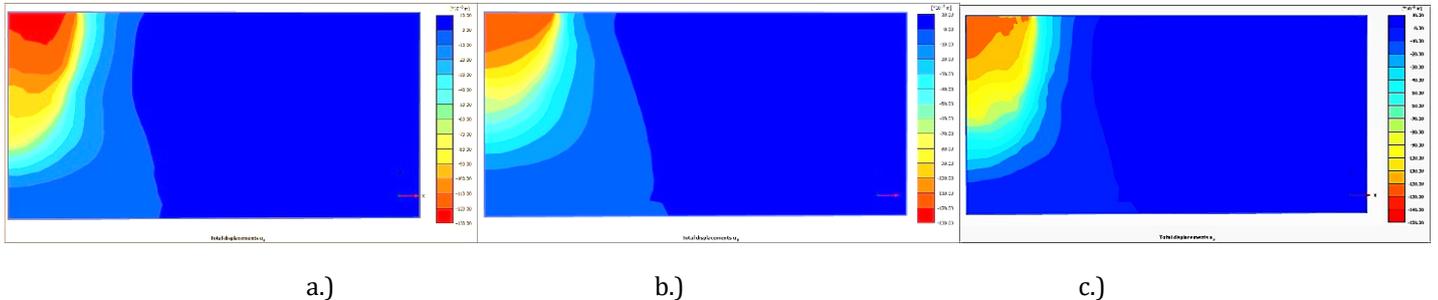


Fig. 6 Shading with legends shows total vertical displacement in the case of piled-raft, CSC-raft and CSC-piles.

Mostly, in all the cases maximum deformation occurs immediately just below the raft due to vertical applied stress of 120kPa, the high compressible zone (plastic zone and wedge failure) shows the maximum deformation. This shading is evident that analysis coincides with Terzaghi's failure model analysis i.e., general shear failure.

5. CONCLUSIONS

The studies were conducted on the raft supported composite column foundation (pile and CSC) system; there are twelve cases are investigated with the three-dimensional finite element methods (Plaxis program) to understand the behaviour and performance of raft foundation rested on the soft soil reinforced with the various columns. The following conclusions have been drawn.

1. In soft clayey soil with raft alone undergoes larger deformations under smaller vertical load. However, nine piles of dia. 0.5m provided beneath the raft, it carries 62.35 % more load than the load carries by the raft alone for the same value of vertical settlement ratio at 12 %. It is maybe due to monolithically connected rigid piles to the raft and effective in load transfer mechanism.
2. The load-carrying capacity of conventional stone columns increased by 22.31 % of 0.7m dia., 24.23 % of 0.8m dia., 27.93 % of 0.9m dia., 29.82 % of 1m dia. and 51.88 % of 1.2m dia. than raft alone within soft clay soil.
3. Providing a combination of conventional stone columns (CSC) with piles beneath the raft carries maximum loads than the raft alone and in other cases. The load-carrying capacity increased by 55.18 % of 0.7m dia., 55.69 % of 0.8m dia., 56.94 % of 0.9m dia., 63.62 % of 1m dia. and 69.73 % of 1.2m dia. of CSC with pile than raft alone.
4. With increasing the diameter of columns either conventional stone columns case or with piles the load-carrying capacity significantly increases.

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BIOGRAPHIES



Mr Sudhanshu Sharma completed his bachelor of technology degree in civil engineering from Vivekananda Global University, Jaipur, Rajasthan. He is currently pursuing MTech Degree from DAV Institute of Engineering and Technology, Jalandhar, Punjab.



Mr Sudheer Kumar J having 10 years of experience in teaching and currently working as Assistant Professor in DAV Institute of Engineering and Technology, Jalandhar. His research areas are Reinforced soil with Geosynthetic, encased stone columns, soil stabilization with supplementary cementations materials and Concrete composites.