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Bearing Capacity Evaluation of Shallow Foundations on Stabilized Layered Soil using ABAQUS

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Abstract: In this paper, the finite element method (FEM) is applied to calculate the bearing capacity of two footings having the aspect ratio L/B (where L and B are the length and width of the footing, respectively) equal to 1, 2 resting on one-layer and two-layer soil. Soil profile contains two soil types including sand and clay. The soil strip is 500mm × 500mm × 350mm; however, only a quarter of the model (250mm × 250mm × 350mm) is examined in the study. Two primary situations are investigated in this study. In the first situation, the one-layer system is supposed to be sandy soil with footing overlays on medium-dense sand. The soft clay/stabilized clayey layer is supposed to be on top of the sandy soil in the second condition, with the footing resting on top of the soft clay/stabilized clay. The influence of layer thickness, aspect ratio, and material property on the bearing capacity value and footing failure mechanism is studied for eight different combinations of layered soil. The bearing capacity for a one-layer case is also estimated, and it agrees well with Vesic (1973), Hansen (1970), and Terzaghi's (1943) equations. The bearing capacity of footings is observed to decline when the height of unstabilized clayey soil increases, and it increases when clayey soil is stabilized with molasses, waste foundry sand, and lime alone and in combination with each other.

Keywords: sand; clay; bearing capacity; industrial waste; ABAQUS.

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1 Introduction

Foundations are a crucial aspect of structures because they securely transfer the load from the surface to the underlying soil medium, ensuring that neither the soil medium nor the foundation fails. It is, therefore, critical to assess the bearing capacity of the soil medium. Many geotechnical researchers have shown interest in this topic of bearing capacity failure in the past and in the present also [1-5]. Excessive settlement and insufficient load-bearing capacity are common problems with soft soil foundations. Soft soils have high compressibility and low shear strength, such as usually consolidated or slightly overconsolidated clays. For any site of soft clay/sand with low bearing capacity, the modern engineering technique is to remove the topsoil and replace it with stabilized soil. The bearing capacity of layered soil is governed not only by the top layer's bearing capacity, but also by the bottom layer's bearing capacity. Many studies have been published to estimate the bearing capacity of footings subjected to vertical or inclined loads and lying on a single layer or layered soils. Button[1] investigated the bearing capacity of a strip footing resting on two clay layers and found that the bearing capacity factor used is dependent on the upper soil layer and the ratio of the cohesions of the lower/upper clay layers. Reddy and Srinivasan [6] extended Button's [1] work by concluding that in the condition of anisotropic and nonhomogeneous subsoil, the bearing capacity values are significantly higher, and the inaccuracy grows as the non homogeneity of the two layers increases. Ismail and Raymond [2] used the finite element technique and found that in the two-layer deposit, an optimum ratio of u/B was 0.31; the reinforcement was more advantageous to the uniform soil deposit than the two-layer deposit. According to [7], a reinforcing layer at the sand–clay interface enhanced bearing capacity while lowering footing settlement. Boushehrian and Hataf [8] studied the effect of depth to the first layer of reinforcement on the bearing capacity of circular and ring foundations on sand using a finite element method (FEM). According to their findings, increasing reinforcement stiffness beyond a certain point did not result in an increase in bearing capacity. Chung and Cascante [9] studied the effect of reinforcement on low-strain stiffness and the bearing capacity of shallow foundations on dry sand. When one, two, or three layers of reinforcement were applied, laboratory studies showed a respective increase of 100%, 200%, and 275% in bearing capacity as well as low-strain stiffness of a square foundation. Szypcio and Dołżyk [3] calculated the bearing capacity of strip and square footings laid on four different subsoil cases of two-layered subsoil at varying thickness ratios using PLAXIS Version 8. Based on the findings, it is determined that the thickness ratio h/B=2 is enough to assess the bearing capacity of a two-layered subsoil. Benmebarek et al. [10] showed that the decline in bearing capacity increases as the depth ratio H/B decreases, and that the bearing capacity increases for soft over strong clay profiles where H/B = 0.5. Raman et al. [11] performed plate load tests on layered soils and observed that the settlement behavior and bearing capacity of the soil can be improved by using different layers of soil. Mosadegh and Nikraz [12] used the ABAQUS program, which is based on the FEM, to determine the bearing capacity of a strip footing on one-layer and two-layer soil. The bearing capacity of footing is found to decrease when the height of soft clayey soil rises, while the displacement beneath the footing rises. According to [13], the bearing capacity ratio (BCR) value of square footing (L/B=1) is approximately 20% higher than the BCR value of rectangular footing (L/B=2). According to [14], the ultimate bearing capacity of sand over clay increases as the sand thickness increases, while the ultimate bearing capacity of clay over sand decreases as the clay thickness ratio increases.

Construction on soft soils frequently necessitates the use of ground improvement techniques, and soil stabilization is the most common and cost-effective method among all soil improvement techniques. The process of enhancing the engineering and index properties of poor soils is known as soil stabilization. Many soils have been altered by the addition of various materials and admixtures such as molasses (M), waste foundry sand (WFS), lime (L), construction demolition waste (CDW), rice husk ash (RHA), glass waste, fibers, and so on [15-18]. Fattah et al. [19] investigated the behavior of a square footing installed over soft clay that had been stabilized by grouting the clay with slurry of lime–silica fume before and after the footing was installed. Due to a rise in lime–silica fume grout, the footing bearing capacity improves as the depth of grouting holes around the footing area increases. Plate loading experiments were carried out on clayey soil modified with lime (3%, 6%, and 12%), geotextile reinforcement, geocell reinforcement, geosynthetics reinforcement, and geosynthetics reinforcement with lime stabilization at different rates [20]. It was revealed that improving the soil with lime and then reinforcing it with geosynthetics gives better results on these types of soils. Rasouli et al. [21] concluded that increasing the bearing capacity of the foundation to an acceptable level requires stabilizing the soil beneath the foundation to certain dimensions with the required cement content. The findings of [22] show that providing a compacted pond ash layer and adding fibers to pond ash have a substantial impact on the ultimate bearing capacity of soft clayey soil. Bhardwaj and Sharma [23] performed experimental and numerical tests on clayey soil blended with molasses, WFS, and lime alone and in combination with each other. From the study, it is concluded that the bearing capacity of subgrade clayey soil is increased by stabilizing the clayey soil.

In the past, there has been very little research on the bearing capacity characteristics of clayey soils (C) treated with molasses (M), WFS, and lime (L). Triaxial testing, unconfined tests, California bearing ratio (CBR) tests, and direct shear tests make up the majority of the experimental work on stabilized soil in the literature. These tests provide only indirect information on the geotechnical properties of clayey soil. As a result, model testing gives valuable quantitative data that may be used to analyze the effect of critical variables on prototype tests. Also, in the above numerical experiments, the bearing capacity was discovered to be reliant on the empirical correlation utilized to characterize the soil parameters. Furthermore, based on the literature, a lot of work has been done on the strip and circular footings on layered soil using approaches like limit equilibrium, kinematic, and FEMs. Since then, a small number of numerical studies have been published on the bearing capacity of footings under vertical loading, particularly on layered soil (soft clay/stabilized clay over medium-dense sand), as well as on the effect of the thickness ratio and depth of the upper soft clay/stabilized clay layer on displacement contours and failure pattern. The goal of this work was to investigate the effect of footing size, first layer height, and soil type on the bearing capacity in one and two layers of soil, as well as to estimate an equation to calculate the bearing capacity in two layers of soil. As a result, the current work used finite element analysis to investigate the bearing capacity of two types of footings having aspect ratios (L/B) equal to 1,2 placed on a single layer of soil (medium-dense sand) and on two layers of soil (soft clay/stabilized clay over medium-dense sand) under vertical loading.

2 Statement of the problem

The work involves two types of shallow surface footing having aspect ratio (L/B) equal to 1, 2 (width of footing B=100mm). To eliminate boundary effects, a minimum of 500mm (5B) of space was allowed in all directions from the footing's edges. The soil strip was 500mm × 500mm × 350mm, and the analysis only considered a quarter of the model (250mm × 250mm ×350mm).For this study, the C3D8R element from the ABAQUS element library was employed. It is an eight-noded linear brick with a simple integration procedure. The water table was considered to have no effect on the bearing capacity calculation.

This study looks into two different primary scenarios. In the first situation, it is assumed that the footing is supported by a single layer of soil, and in the second case, the foundation is resting on two layers of soil. The one-layer system in the first situation is supposed to be sandy soil with footing overlays on medium-dense sand. In the second situation, it is assumed that the soft clay/stabilized clay layer is on top of the sandy soil and the footing is resting on top of the soft clay/stabilized clay. Combinations and material properties used in the present study are taken from the author's previous work [23]. Geotechnical properties of soft clay, stabilized clay, and medium-dense sand used in the FEM analysis are shown in Table 8. The case of the subsoil consisting of sand alone (homogeneous soil), which is treated as the reference case, was also analyzed. Designation and details of the type of soil placed in the upper and lower layers under both types of footings in two-layered soils are shown in Table 1. A total of eight cases were considered for two-layered soil; in each case, except the first one, stabilization was used to improve the weak clay. The materials available locally were used for stabilization of clay: molasses, WFS, and lime, in various configurations and proportions. In Table 1, combination C: M:: 90:10 means that out of 100% material in the upper layer of case 2, 90% is clay and 10% is molasses blended with clay. The thickness of the top layer varies as h/B=0.7, 1.225, 1.75, and 2.275. Figure 1 shows the arrangement of soil layers modeled in FEM-based software ABAQUS.

3 Materials

Soft clayey soil (C) is collected from the side of NH-205 near Jukhala village in Himachal Pradesh's district Bilaspur for this study. The sieve analysis and hydrometer study indicated that around 29% of particles pass through the 0.002-mm screen and 94% pass through the 0.075-mm screen (Fig. 2). In Tables 2 and 3, the geotechnical and mineral compositions of clayey soil have been summarized. Budhewal Co-operative Sugar Mill Ltd. in Ludhiana district in Punjab provided the molasses utilized in the study. In Table 4, the chemical characteristics of molasses are shown. Shakti Foundries in Ludhiana district (Punjab) provided WFS (Fig. 2) for the research.

Table 1: Designation and details of type of soil in upper and lower layers under both types of footings in two-layered soils.

Designation	Soil type in upper and lower layers for two-layered soil		Designation	Soil type in upper and lower layers for two-layered soil	
Case 1	Upper layer	Unstabilized clay	Case 5	Upper layer	Stabilized clay (C:M:WFS:: 80:10:10)
	Lower layer	Medium-dense sand		Lower layer	Medium-dense sand
Case 2	Upper layer	Stabilized clay (C:M:: 90:10)	Case 6	Upper layer	Stabilized clay (C:M:L:: 84:10:6)
	Lower layer	Medium-dense sand		Lower layer	Medium-dense sand
Case 3	Upper layer	Stabilized clay (C:WFS:: 80:20)	Case 7	Upper layer	Stabilized clay (C:WFS:L:: 74:20:6)
	Lower layer	Medium-dense sand		Lower layer	Medium-dense sand
Case 4	Upper layer	Stabilized clay (C: L:: 91:9)	Case 8	Upper layer	Stabilized clay (C:M:WFS:L:: 67:10:20:3)
	Lower layer	Medium-dense sand		Lower layer	Medium-dense sand

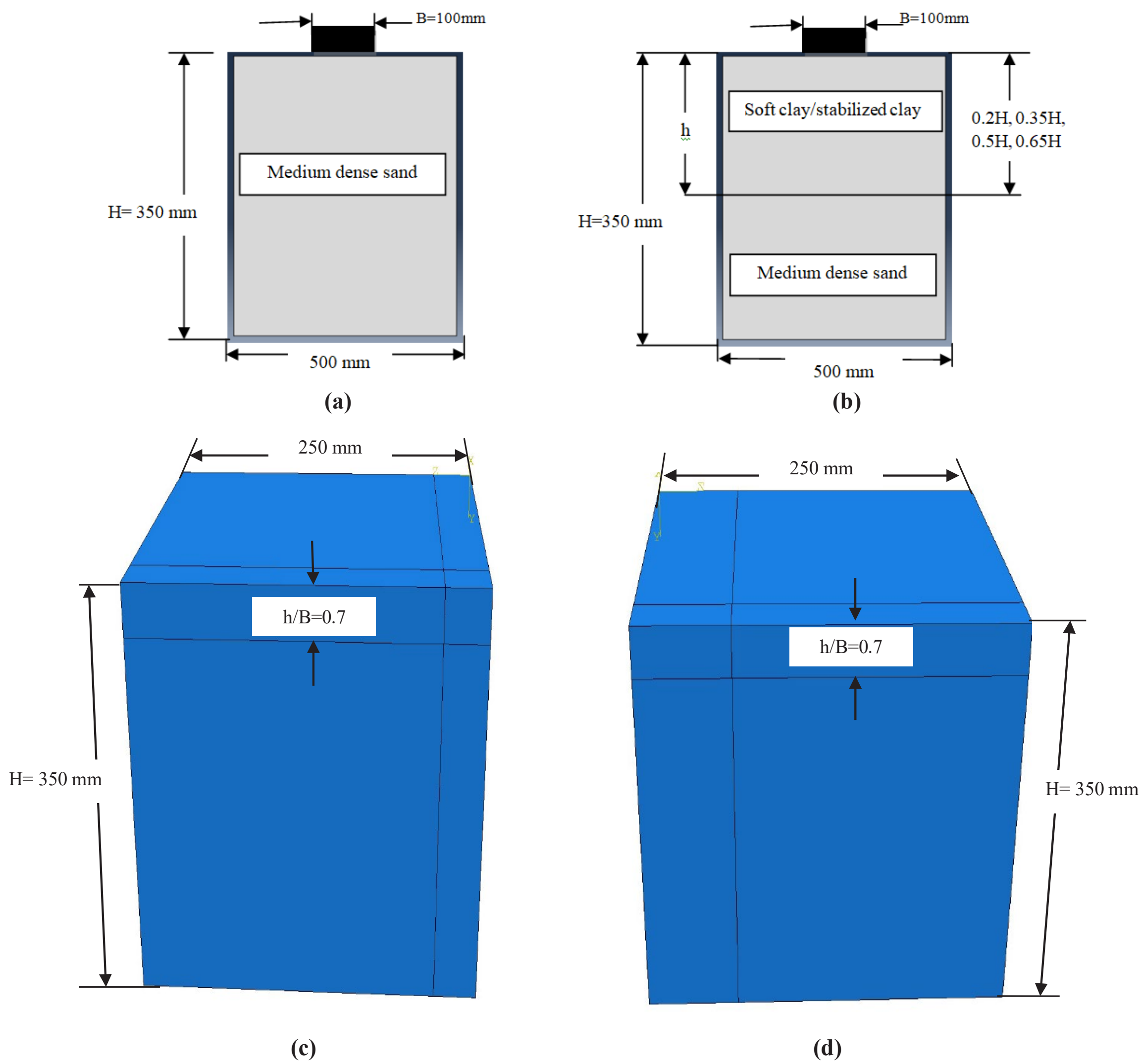


Figure 1: Problem definition. **(a)** Single layer; **(b)** thickness of top layer varying at h/B=0.7, 1.225, 1.75, and 2.275; **(c)** FEM model of footing for aspect ratio (L/B) =1 at h/B=0.7; **(d)** FEM model of footing for aspect ratio (L/B) =2 at h/B=0.7. h: thickness of the upper layer in two-layered soil; L, B:length and width of footing, respectively
Note: all dimensions are not to scale.

WFS has a dark color and sandy texture due to the angular form of the waste particles and fines adhered to the sand particles. In Tables 5 and 6, the different geotechnical and chemical parameters of WFS have been summarized. The lime used in the experiments was obtained from a local hardware store. Table 7 shows the chemical composition of lime.

4 Meshing

The finite element model of both the footings (L/B = 1, 2) resting on single-layered soil (medium-dense sand) and two-layered soil (soft clay/stabilized clay over medium-dense sand) is shown in Figures 3 and 4. The upper layer in both the situations (medium-dense sand/soft clay/stabilized clay) and both the footings were thought to be rigidly connected, allowing the load to be transferred directly to the upper layer under the footing. The meshing of both footings on single-layered and two-layered soil under vertical load is shown in Figures 3 and 4. It is important to note that the footing was thought to be a solid structure that was simply needed to transfer the load to the top layer of soil, according to [24]. As a result, no actual foundation was employed in this simulation; instead, the vertical load was transferred directly to the upper soil layer's surface, as stated in [24]. In the direction of the load application, displacement at all nodes beneath the footings was considered to be constant. The distance from the edge of both the footings and the boundary was

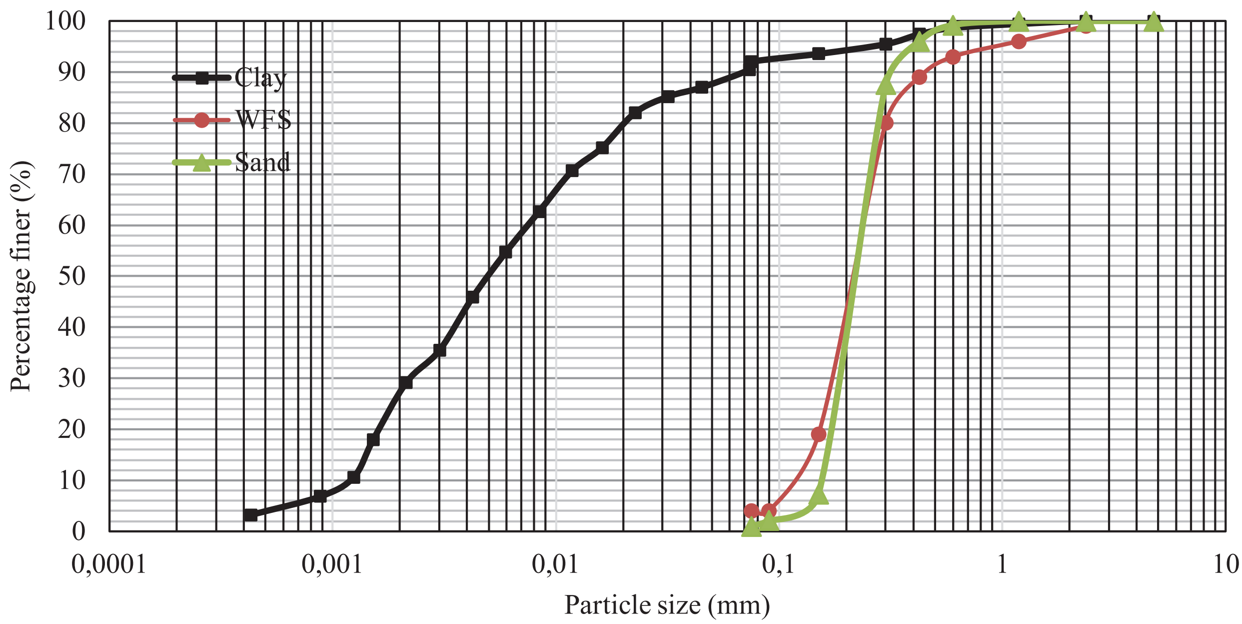


Figure 2: Particle size curve for clayey soil and WFS.

Table 2: Geotechnical properties of clayey soil.

Soil properties	Value
Soil type	CH
Liquid limit	55%
Plastic limit	20%
Plasticity index	35%
Specific gravity	2.6
Differential free swell index	35%
Optimum moisture content	16.5%

Table 3: Mineral composition of clayey soil.

Mineral composition	Content (%)
Oxygen, O	45.4
Silicon, Si	18.5
Aluminum, Al	8.69
Carbon, C	10.9
Iron, Fe	1.42
Potassium, K	1.86
Magnesium, Mg	2.30
Titanium, Ti	2.51

Table 4: Chemical properties of molasses used.

Constituents	Result
Color	Black
Brix	83.2
pH (1:1 at 20°C)	5.6
Specific gravity	1.39
Viscosity	17,500 mPas
Moisture	21.76%
Total sugar	47.83%
Invert sugar	10.20%
Sulfated sugar	15.50%
Ca	1.63%

Table 5: Geotechnical properties of WFS.

Property	Value
Specific gravity	2.64
Optimum moisture content	8.20%
Maximum dry density	1.59 g/cc

Table 6: Chemical properties of WFS.

Chemical composition	Percentage
SiO2	84.90
Al2O3	5.21
Fe2O3	3.32
CaO	0.58
MgO	0.67
SO3	0.29
MnO	0.08
TiO2	0.19
K2O	0.97
P2O5	0.05
Na2O	0.50
¬Loss of ignition	2.87

Table 7: Chemical composition of lime used.

Chemical composition	Content (%)
SiO2	2.1
Al2O3	1.3
Fe2O3	1.2
CaO	82.8
MgO	0.3
SO3	0.4
Na2O	0.4
K2O	-
TiO2	-
C	2.2
CaCO3	4.3
Impurities	5.0
¬Loss of ignition at 800°C	-

extended five times the width of the footing to compensate for the boundary effect. To simulate actual soil conditions, the model was exposed to a geostatic static tension, which restrained it in all directions. The simulation was carried out using the Mohr–Coulomb model, which estimates a constant average stiffness, and thus provides a "first-order" approximation of the soil behavior, reducing the simulation time to obtain the first estimate of deformations, whereas other soil-hardening models take much longer [25]. The mesh was adjusted on the model, with finer mesh closer to the particular footing edges and the mesh becoming coarser as the distance from the footing edge increased. The number of elements in the mesh was observed to enhance the bearing capacity by 3%–5%, but the time it took to replicate the same increased by double. The optimal number of components in the current study, according to the convergence analysis, was 7438. Beyond this range, the bearing capacity of model footings did not change considerably.

5 Results and discussion

The influence of various factors on the failure mechanism and bearing capacity of footing is described in the subsequent sections. Firstly, the effect of varying thickness ratios (h/B) of the upper layer, the effect of the aspect ratio (L/B = 1, 2), and the effect of soil characteristics on bearing capacity and on failure mechanism will be discussed. The validation of the current study, regression analysis, and displacement contours analysis will then be explained in the following sections. Gravity load and surcharge are applied to the soil body at the start of the analysis. Three steps are used to generate the model. All boundary conditions are set in the first phase, which is the initial condition, and a surcharge load is imposed on top of the model. The model is subjected to a geostatic phase after that, in which the gravity load is applied.

The third phase involves applying a downward movement of $\delta/B=0.2$ on the top of soil under the footing, where δ denotes a vertical displacement and B denotes the width of the footing. It is worth noting that if the definite peak in the curve is visible, the bearing capacity equivalent to the peak pressure is taken and if the peak pressure in the plot cannot be located, the bearing capacity is computed using the double tangent method. Bearing capacity results obtained from numerical study for cases 1–8 are compared to the bearing capacity of sand alone (homogeneous soil), and this is treated as the reference case.

5.1 Effect of varying thickness ratios (h/B) of the upper layer on bearing capacity

Figures 5–12 depict the typical load-settlement dependence behavior and bearing capacity values obtained from the numerical study for various upper soil layer thickness ratios (h/B= 0.7, 1.225, 1.75, and 2.275), varying properties of stabilized and unstabilized clayey soil layers, and relative density (RD) of sand under vertical load.

Table 8: Material properties of unstabilized/stabilized clayey soil and sandy soil (Mohr–Coulomb model) [23].

Properties	Combinations								
	C	C:M	C:WFS	C:L	C:M:WFS	C:M:L	C:WFS:L	C:M:WFS:L	S::100
Mass density (γ) (kg/m³)	1710	1790	1781	1606	1840	1750	1730	1820	1615
Modulus of elasticity (E) (MPa)	3.2	5.3	7.2	9.6	10.3	14.7	16.2	18.5	32.3
Poisson ratio (v)	0.3	0.3	0.3	0.32	0.33	0.34	0.36	0.38	0.3
Angle of internal friction (ϕ)	14.86	17.06	19.11	21.43	23.62	25.64	27.85	29.68	35
Cohesion (c) (kPa)	21.77	19.92	19.08	17.61	16.43	15.59	14.78	13.89	0.1

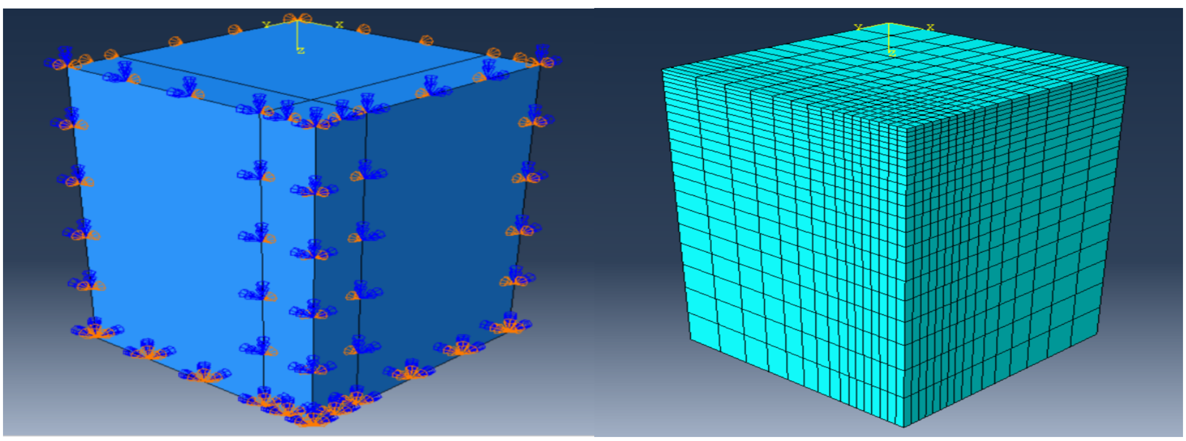


Figure 3: Finite element discretization and boundary condition selection of the footing model with L/B=1.

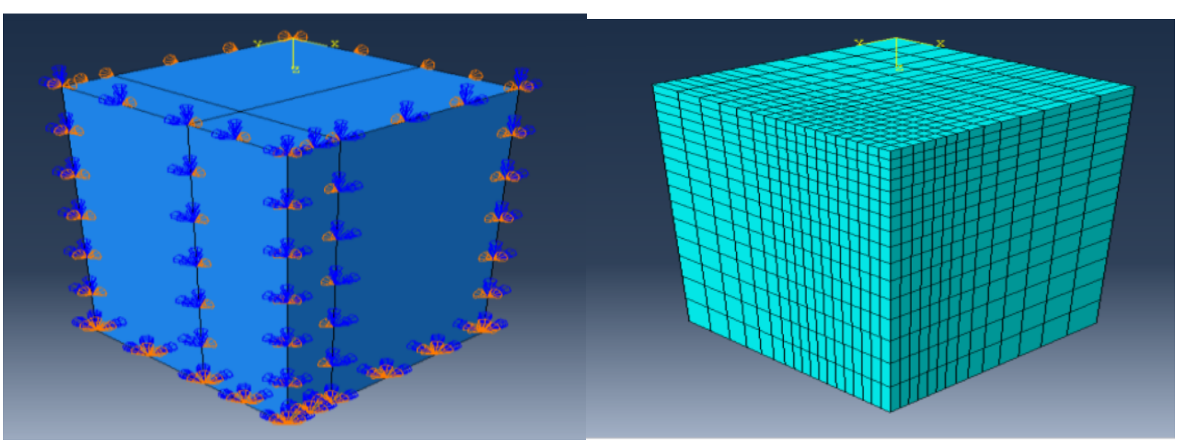
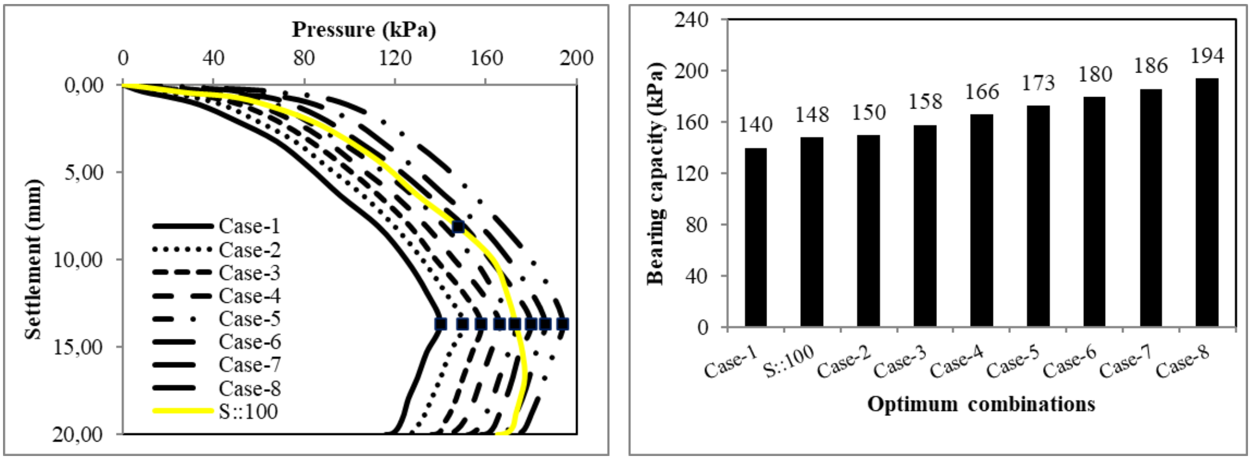


Figure 4: Finite element discretization and boundary condition selection of the footing model with L/B=2.

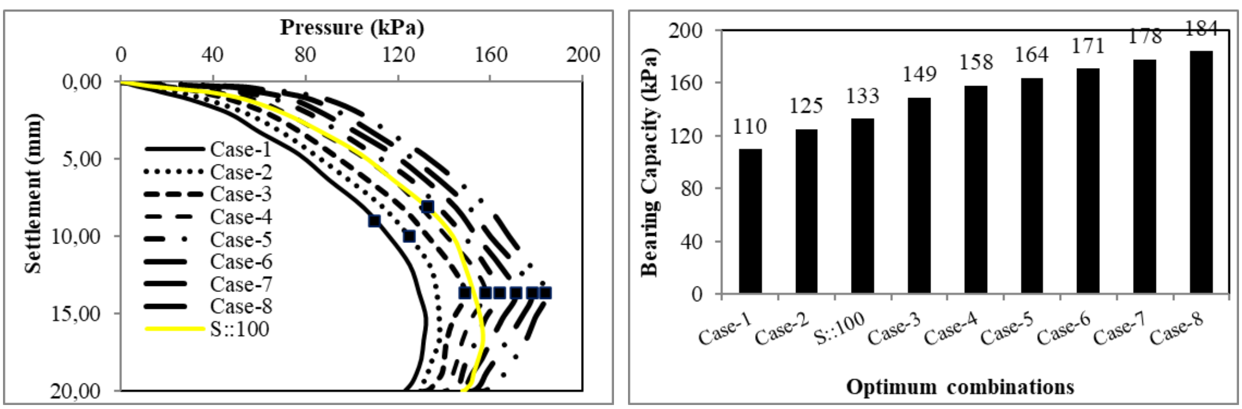
5.1.1 At a thickness ratio h/B= 0.7

Figures 5 and 6 show that the bearing capacity of both the footings (L/B = 1, 2) decreases in cases 1–7 of layered soil and increases for case 8 as the thickness ratio (h/B) increases from 0 to 0.7, when compared to the bearing capacity of single-layer soil (medium-dense sand, RD=50%). Bearing capacity of footing with L/B = 1drops from 148 to 140 kPa and footing with L/B = 2 drops from 133 to 110 kPa by adding 70 mm of soft clay layer, resulting in a dramatic 5%



(a) **(b)**

Figure 5: **(a)** Pressure–settlement curves and **(b)** bearing capacity values of two-layered soil for all cases at h/B=0.7 and single-layer sandy soil for L/B=1.



(a) **(b)**

Figure 6: **(a)** Pressure–settlement curves and **(b)** bearing capacity values of two-layered soil for all cases at h/B=0.7 and single-layer sandy soil for L/B=2.

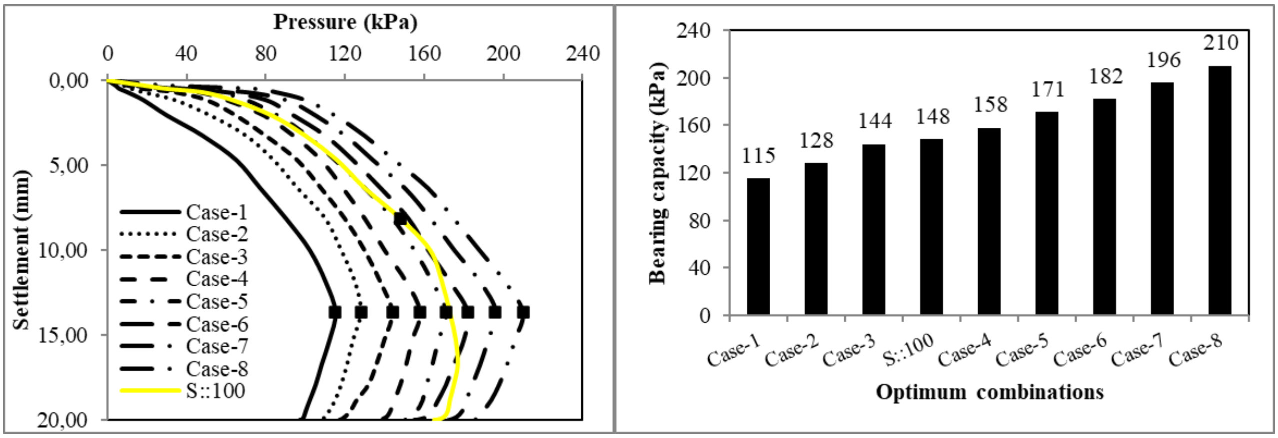
reduction in bearing capacity for both footings. However, an increase in the bearing capacity of layered soil is found after stabilizing the clayey soil with molasses, WFS, and lime. The bearing capacity of a footing with L/B = 1 rises from 140 to 194 kPa and of a footing with L/B = 2 rises from 110 to 184 kPa, resulting in a 38% and 67% rise in bearing capacity for both footings, respectively.

5.1.2 At a thickness ratio h/B= 1.225

Figures 7 and 8 show that the bearing capacity of both the footings decreases in cases 1–5 of layered soil and increases for cases 6–8 as the thickness ratio (h/B) increases to 1.225, when compared to the bearing capacity of single-layer soil (medium-dense sand, RD=50%). Bearing capacity of footing with L/B=1 drops from 148 to 115 kPa and of footing with L/B = 2 drops from 133 to 104 kPa by adding 122.5 mm of soft clay layer, resulting in a dramatic 22% and 21% reduction in bearing capacity for both footings, respectively. However, an increase in the bearing capacity of layered soil is found after stabilizing the clayey soil with molasses, WFS, and lime. The bearing capacity of footing with L/B = 1 rises from 115to 210 kPa and of footing with L/B = 2 rises from 104 to 196 kPa, resulting in a 82% and 88% rise in bearing capacity for both footings, respectively.

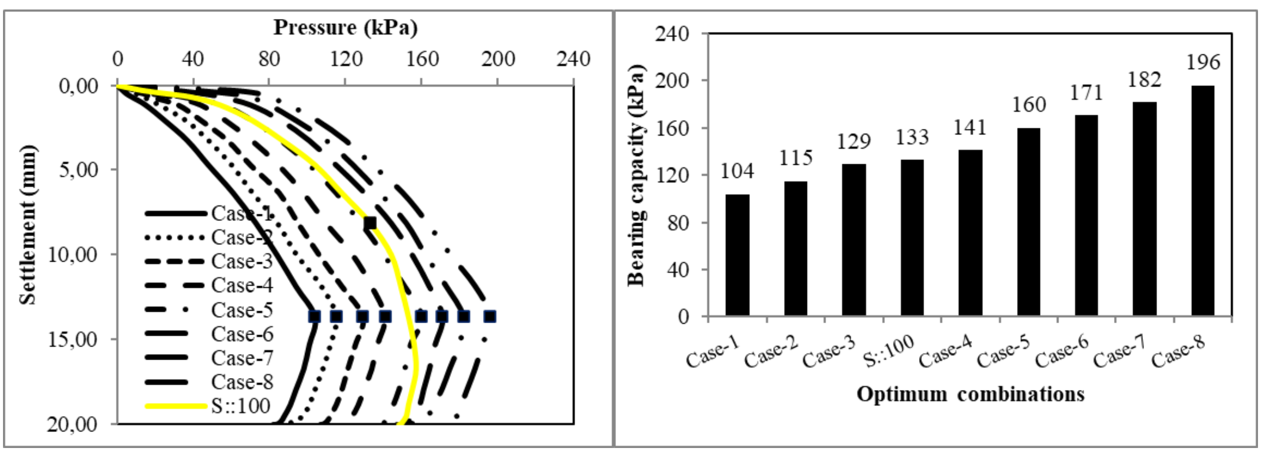
5.1.3 At a thickness ratio h/B= 1.75

As the thickness ratio (h/B) increases to 1.75, the bearing capacity of layered soil decreases in cases 1–3, 1–2 and increases in cases 4–8, 3–8 of both footings, respectively



(a) (b)

Figure 7:(a) Pressure–settlement curves and (b) bearing capacity values of two-layered soil for all cases at h/B=1.225 and single-layer sandy soil for L/B=1.



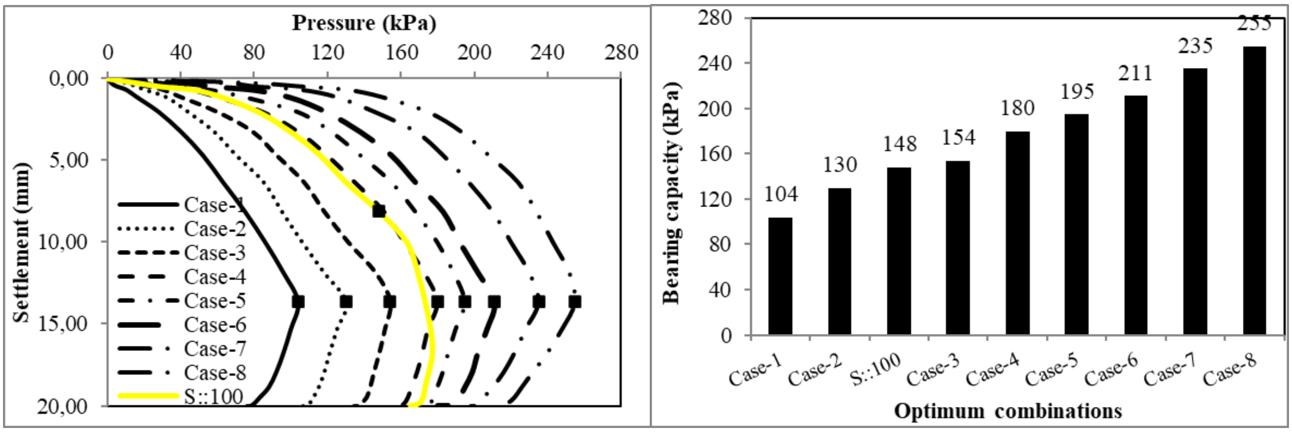
(a) (b)

Figure8:(a) Pressure–settlement curves and **(b)**) bearing capacity values of two-layered soil for all cases at h/B=1.225 and single-layer sandy soil for L/B=2

(Figs 9 and 10), when compared to the bearing capacity of single-layer soil (medium-dense sand, RD=50%). Bearing capacity of footing with L/B=1 drops from 148 to 104 kPa and of footing with L/B=2 drops from 133 to 94 kPa by adding 175 mm of soft clay layer, resulting in a dramatic 29% reduction in bearing capacity for both footings, respectively. However, an increase in the bearing capacity of layered soil is found after stabilizing the clayey soil with molasses, WFS, and lime. Bearing capacity of a footing with L/B=1 rises from 104 to 255 kPa and of a footing with L/B=2 rises from 94to 243 kPa, resulting in a 145% and 158% rise in bearing capacity for both footings, respectively.

5.1.4 At a thickness ratio h/B= 2.275

As the thickness ratio (h/B) increases to 2.275, the bearing capacity of both the footings decreases in case 1 of layered soil and increases for cases 2–8 (Figs 11 and 12), when compared to the bearing capacity of single-layer soil (medium-dense sand, RD=50%). Bearing capacity of footing with L/B=1 drops from 148 to 90 kPa and of footing with L/B= 2 drops from 133 to 84 kPa by adding 227.5 mm of soft clay layer, resulting in a dramatic 17% and 13% reduction in bearing capacity for both footings, respectively. However, an increase in the bearing capacity of layered soil is found after stabilizing the clayey soil with molasses, WFS, and lime. The bearing capacity of a footing with L/B=1 rises from 90 to 266 kPa and of a footing with L/B=2 rises from 84 to 250 kPa, resulting in a



(a) (b)

Figure 9:(a) Pressure–settlement curves and **(b)** bearing capacity values of two-layered soil for all cases at h/B=1.75 and of single-layer sandy soil for L/B=1.

195% and 197% rise in bearing capacity for both footings, respectively.

The maximum bearing capacity in the single layer was noted for footing with L/B=1, which is 11% higher than the bearing capacity of footing with L/B=2, and in two-layer situations, it was noted for case 8 at a thickness ratio h/B= 2.275 for both types of footings. When compared to the bearing capacity of single-layer soil for both footings (L/B=1, 2), for all the cases of two-layer soil situations, it was observed that there was a 79% and 87% increase in the bearing capacity, respectively. This improvement in bearing capacity was due to the increase in the thickness of the upper layer when the composition of clayey soil changed to stabilized clayey soil with the addition of additives (molasses, WFS, and lime) alone and in combination.

5.2 Effect of aspect ratio (L/B) on the bearing capacity

The dimension of the footing is an essential component that influences the soil's bearing capacity. The findings of this study provided important insight into the performance of single-layer and two-layered soil for varying footing dimensions. Also, when compared to actual site conditions, footings with L/B=1, 2 in the numerical study were reduced to a specific scale. As a result, the numerical results may not respond in the same way as the behavior of the field testing, and scale effects may have an impact on the results. The current study contains scale effects that prevent it from being directly generalized to field cases.

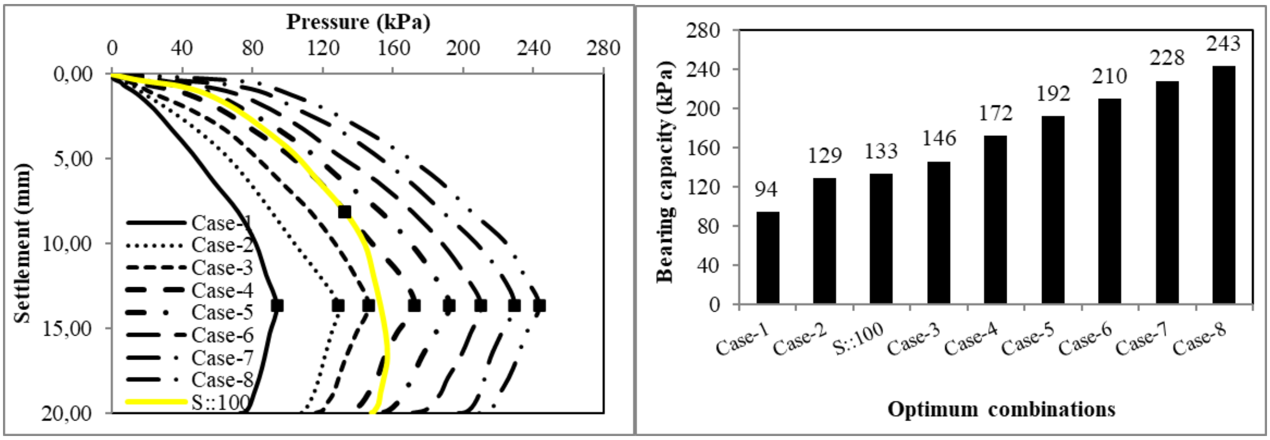
In both situations (single- and two-layered soil), the bearing capacity of footing with L/B=1 is higher than with L/B=2, as shown in Figures 5–12. In a single-layer soil situation, the bearing capacity determined for footing with L/B=2 is 11% less than that of footing with L/B=1. In two-layered soil situations, the bearing capacity for case 8 obtained at a thickness ratio h/B= 2.275 for both footings is the maximum, while the bearing capacity for footing with L/B=1 is 6% more than that for footing with L/B=2 for the same case.

5.3 Effect of soil type on the bearing capacity

In this investigation, two types of soil were used: sand with medium RD and clay with varying cohesion values (soft and stabilized).The influence of these various soil types and their features on bearing capacity is described below.

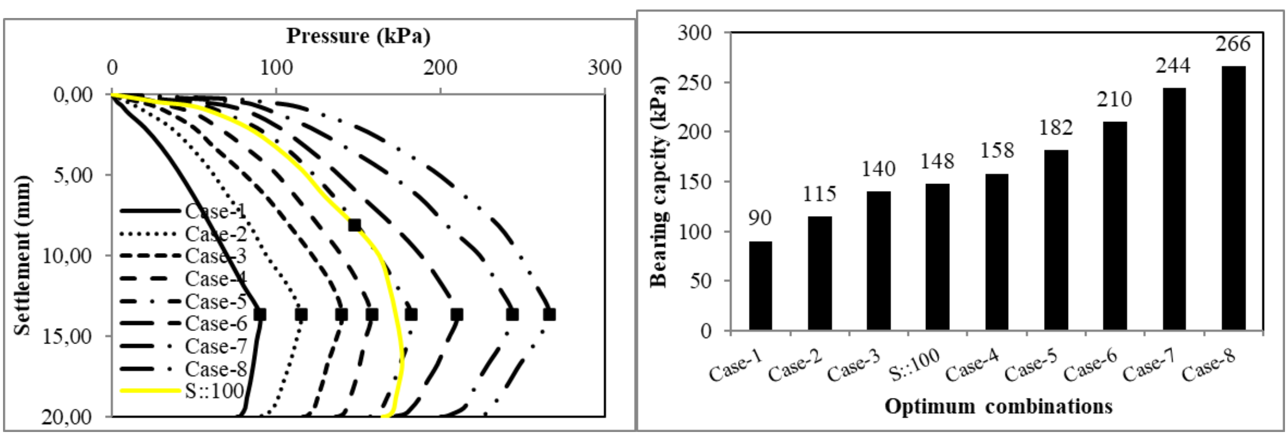
5.3.1 Effect of clay cohesion value, C

Figures 5–12 depict the impact of providing soft/stabilized clayey layer above sand of medium RD on the bearing capacity of both types of footings. It may be inferred that stabilizing the clayey soil with molasses, WFS, and lime enhances the bearing capacity of layered soil. It is important to note that, when the upper soft clayey layer was stabilized with molasses, WFS, and lime and the bottom sand layer was provided with medium-dense sand, better bearing capacity values were observed in



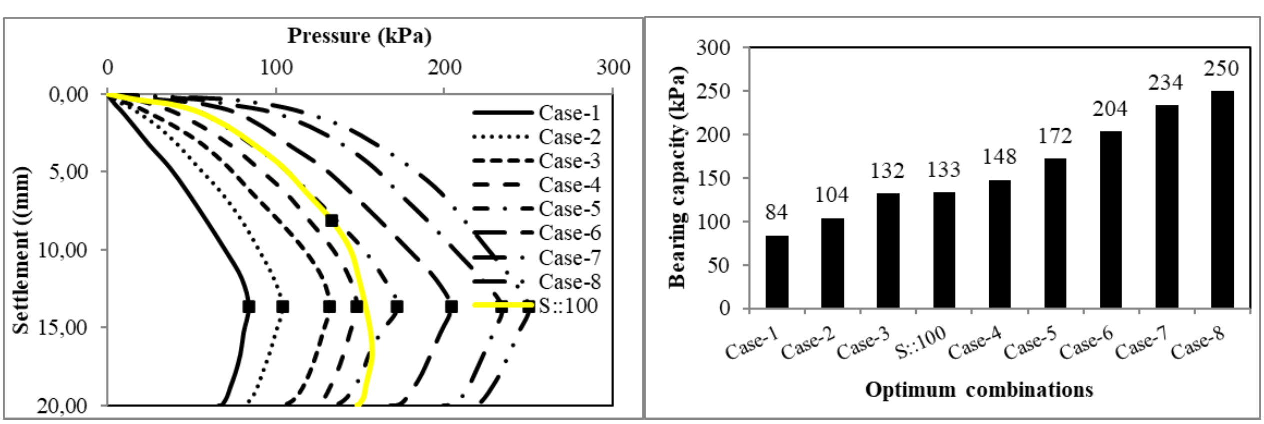
(a) **(b)**

Figure 10: (a) Pressure–settlement curves and **(b)** bearing capacity values of two-layered soil for all cases at h/B=1.75 and of single-layer sandy soil for L/B=2.



(a) **(b)**

Figure 11: (a) Pressure–settlement curves and **(b)** bearing capacity values of two-layered soil for all cases at h/B=2.275 and single-layer sandy soil for L/B=1.



(a) **(b)**

Figure 12: (a) Pressure–settlement curves and **(b)** bearing capacity values of two-layered soil for all cases at h/B=2.275 and single-layer sandy soil for L/B=2.

all cases of layered soils. The rate of increase in bearing capacity varied with the amount of molasses, WFS, and lime added, but it reached its maximum in all cases (Table 8) when the top clayey layer was stabilized with 10% molasses, 20% WFS, and 3% lime. Also, it was observed that at a thickness ratio h/B =1.75, there was a rapid surge in the bearing capacity of both the footings when compared to the rest of the thickness ratios (h/B= 0.7, 1.225, and 2.275). In other words, at h/B= 1.75, there was 21% and 32% increase for case 8 in the bearing capacity of both the footings, respectively, when compared to the bearing capacity for the same case at h/B=1.225. This increase in the bearing capacity of both footings for other thickness ratios was lesser when compared to the latter thickness ratio (h/B=1.225 and 2.275), which was 8% and 6% at h/B=1.225 and 4% and 2% at h/B=2.275, respectively.

5.3.2 Effect of sand RD

For the single sand layer and two-layered soil, it could be deduced that RD of the sand layer affected the bearing capacity of both footings. The maximum value of bearing capacity was observed for footing with L/B= 1 when single-layer sand was provided, which was 148 kPa. According to the findings, if the two-layer (soft clay/stabilized clay over medium-dense sand) situations exist, the bearing capacity of layered soil may be increased by stabilizing clayey soil and placing a sand cushion beneath the clayey layer. However, to increase the bearing capacity, this sand cushion should be compacted to a high RD. The increase in bearing capacity increases with RD; for stratified layers, it is maximum when the thickness ratio is h/B=2.275.

6 Validation of numerical models

The bearing capacity value of the soil will be checked with Terzaghi (1943), Hansen (1970), and Vesic (1973) calculations and previous experimental and numerical studies to validate the finite element results for a single layer. Eqs (1) and (2) are Terzaghi's bearing capacity equations for both footings (L/B=1, 2), respectively, and Eqs (3) and (4) are Hansen's and Vesic's bearing capacity equations, respectively. Table 9 shows the outcomes of the comparison. Table 9 shows that the bearing capacity determined through numerical modeling in this investigation was higher in every situation estimated by formulas. This is due to the greater mobilized friction factor that develops as a result of settlement during load application. The settlement causes the sand surrounding the footing to densify, increasing the friction coefficient of the sand. As a result, increased bearing capacity is seen in the current investigation when compared to theoretical equations.

$$qu=1.2\times c\times Nc+q\times Nq+0.4\times \gamma\times B\times N\gamma \quad (1)$$

$$qu=(1+0.2\times B/L)\times c\times Nc+q\times Nq+0.5\times \gamma\times B\times N\gamma\times(1-0.2\times B/L) \quad (2)$$

$$qu=c\times Nc\times sc\times dc\times ic+q\times Nq\times sq\times dq\times iq+0.5\times \gamma\times B\times N\gamma\times s\gamma\times d\gamma\times i\gamma \quad (3)$$

$$qu=c'\times Nc\times sc\times dc\times ic+q\times Nq\times sq\times dq\times iq+0.5\times \gamma\times B\times N\gamma\times s\gamma\times d\gamma\times i\gamma \quad (4)$$

where c–cohesion; Nc, Nq, Nγ – Terzaghi's bearing capacity factors in Eqs (1) and (2); q –overburden pressure; γ – unit weight of foundation soil; B–width of footing; L–length of footing; Nc, Nq, Nγ –Hansen's bearing capacity factors in Eq. (3); sc, sq, sγ–shape factors; dc, dq, dγ – depth factors; ic, iq, iγ–inclination factors; and Nc, Nq, N – Vesic's bearing capacity factors in Eq. (4).

Further results observed on layered soils had a good agreement with the results published by other researchers in the past. The findings of [3, 12, 14]on strip and square footing resting on single and layered soil from FEM-based software's PLAXIS 3D and ABAQUS software were compared to validate the present analysis. When the thickness ratio (h/B) is increased, in all the present cases and including the findings of the previous studies, it is found out that there is a dramatic fall in bearing capacity when unstabilized clayey layer is overlying the sandy layer. Also, the bearing capacity of layered soil is enhanced after stabilizing the clayey layer with molasses, WFS, and lime. The studies [19, 20, 23] stabilized the clayey soil with various additives and concluded that the bearing capacity of clayey layer can be increased with the addition of molasses, WFS, lime, silica fume, and geosynthetics alone and in combination with each other.

7 Regression analysis

In regression analysis, one variable is used as the independent variable and the other variable is used as the dependent variable. This allows researchers to investigate the cause-and-effect connection. Regression model containing multiple independent variables is called multiple regression model (MLR).Multiple regression

Table 9: Comparison of observed bearing capacity values with Vesic (1973), Hansen (1970), and Terzaghi (1943) calculations.

Type of soil	Bearing capacity (kPa)							
	Present study		Vesic (1973)		Hansen (1970)		Terzaghi (1943)	
Sand	L/B=1	L/B=2	L/B=1	L/B=2	L/B=1	L/B=2	L/B=1	L/B=2
	148	133	138	121.78	113.27	106.11	94.25	97.67

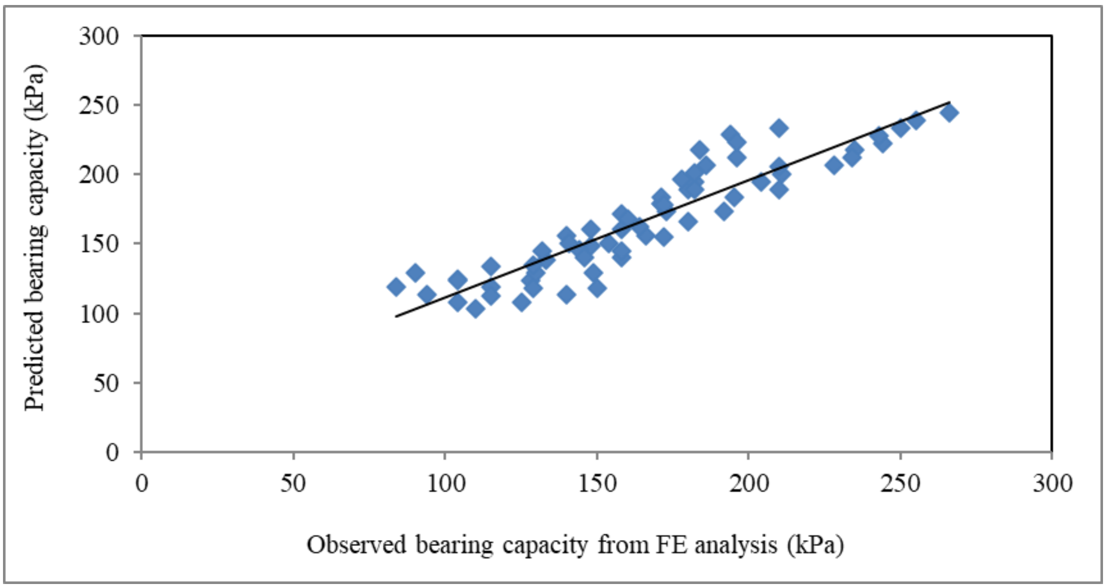


Figure 13: Variation of numerical and predicted bearing capacity for both footings (L/B= 1, 2).

analysis was used to formally establish a statistical relationship between the dependent variable Y and one or more independent variables X1, X2, ………, Xp [26].This is the equation for multiple regression because Eq. (5) is a linear function of the unknown values (b_0, b_1, b_2,…,b_p) the term linear is utilized.

$$Y=b_0+b_1X_1+ b_2X_2+.... + b_pX_p \quad (5)$$

The observed data for nonlinear regression analysis is a nonlinear combination of model parameters, described by a function that depends on one or more independent variables [27]. When compared to artificial neural network ANN model, adaptive neuro-fuzzy inference system (ANFIS) model, and MLR, the multiple nonlinear regression model (MNLR) produced the most accurate maximum daily stream flow projections [28].

In the current study, a simple quadratic equation was used to estimate the nonlinear relation parameters. All model test results were examined with the DataFit software to quantify certain characteristics such as thickness ratio (h/B), aspect ratio (L/B), friction angle (ϕ), cohesiveness (c), and mass density (γ).The bearing capacity (qu) of homogeneous (single layer) and non-homogeneous (two-layered soil systems) soil was used as a dependent variable in this regression study. Eq. (6) demonstrates the specified expression for both footings (L/B=1, 2), respectively:

$$qu=10\times(h/B)-10.79\times(L/B)+ 6.24\times\phi+4.9\times c+0.019\times\gamma-96 \quad (6)$$

where the unit of bearing capacity (qu) and cohesiveness (c) is kPa, B, L, and h is mm, and mass density (γ) is kg/m^3.

As demonstrated in Figure 13, the coefficient of efficiency (R^2) for both footings is 0.924.The correlation of inputs (thickness ratio, aspect ratio, friction angle, cohesiveness, and mass density) with the bearing capacity of the single and layered soil may be shown using the equation factors. In practice, the regression analysis used to extrapolate the findings from the models is not well justified; nonetheless, there is a capacity for highlighting the relevance of each of the factors studied.

8 Displacement contours

Figures 14–29 show typical displacement contours for case 1 and case 8 for both types of footings at varying thickness ratios of h/B= 0.7, 1.225, 1.75, and 2.275. Figures 14–29 illustrate the entire displacement contour and its importance to estimate the actual displacement under load. This data is essential to ensure that the vertical subsidence in the footing design is within the acceptable limits or not under load. The displacement contours for both footings corresponding to varying h/B ratios of 0.7, 1.225, 1.75, and 2.275 remains well established within the specified limits. The isobar distance for footing with L/B=1 is greater than the isobar distance for footing with L/B=2 at all thickness ratios, suggesting that the former has a higher ultimate bearing capacity. Moreover, this figure

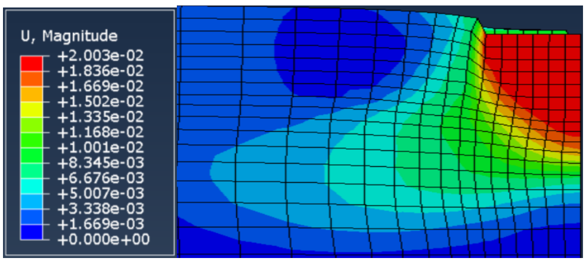


Figure 14: Displacement contours of case 1 at h/B = 0.7 for L/B=1.

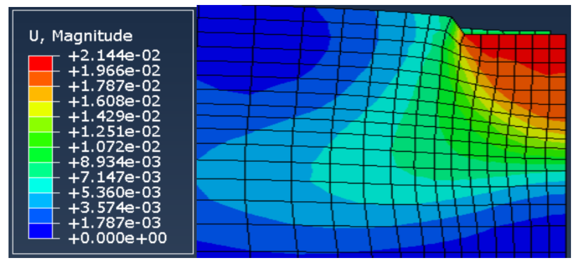


Figure 15: Displacement contours of case 8 at h/B = 0.7 for L/B=1.

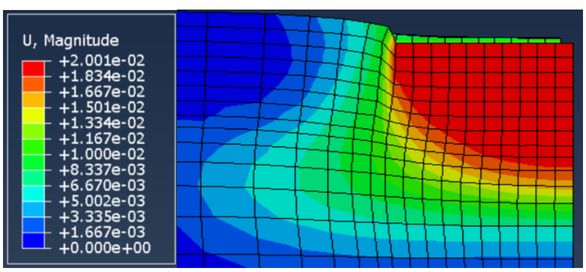


Figure 16: Displacement contours of case 1 at h/B = 0.7 for L/B=2.

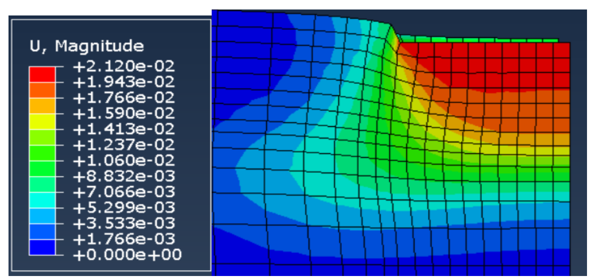


Figure 17: Displacement contours of case 8 at h/B = 0.7 for L/B=2.

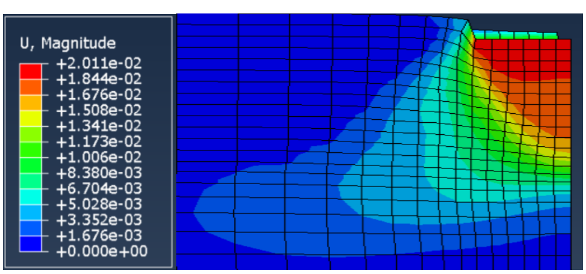


Figure 18: Displacement contours of case 1 at h/B = 1.225 for L/B=1.

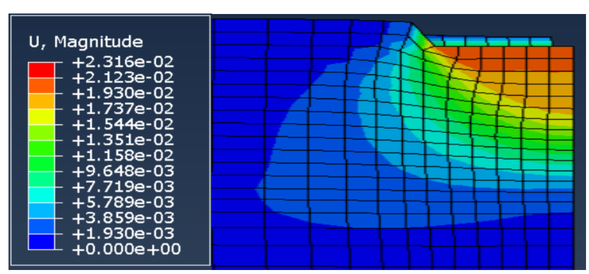


Figure 19: Displacement contours of case 8 at h/B = 1.225 for L/B=1.

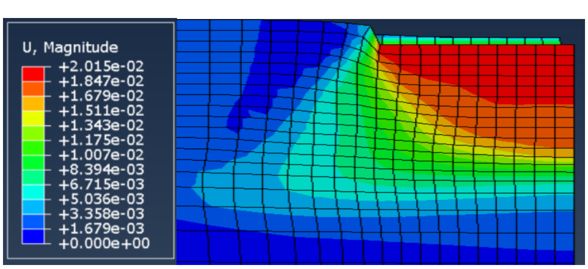


Figure 20: Displacement contours of case 1 at h/B = 1.225 for L/B=2.

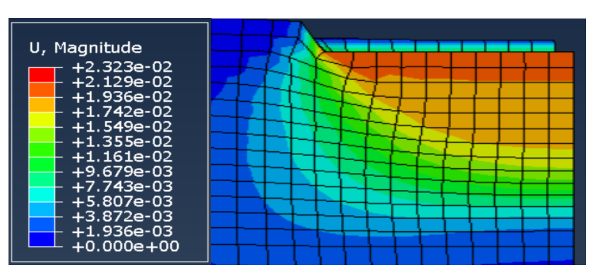


Figure 21: Displacement contours of case 8 at h/B = 1.225 for L/B=2.

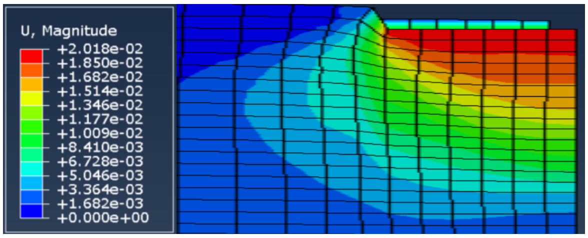


Figure 22: Displacement contours of case 1 at h/B = 1.75 for L/B=1.

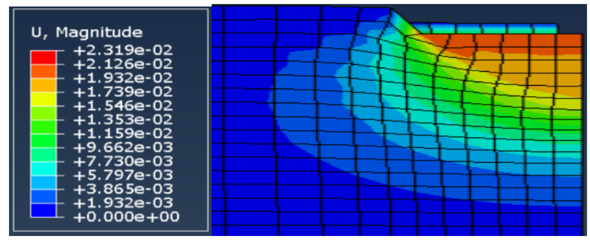


Figure 23: Displacement contours of case 8 at h/B = 1.75 for L/B=1

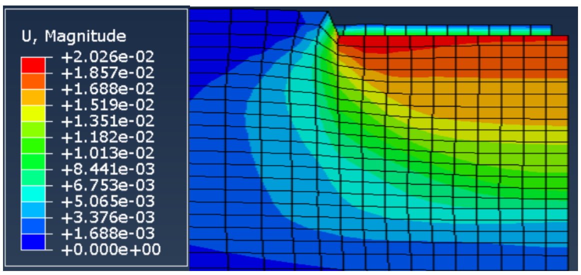


Figure 24: Displacement contours of case 1 at h/B = 1.75 for L/B=2.

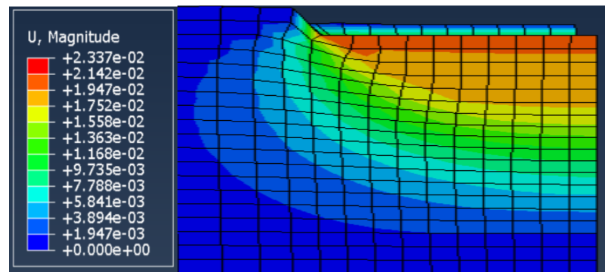


Figure 25: Displacement contours of case 8 at h/B = 1.75 for L/B=2

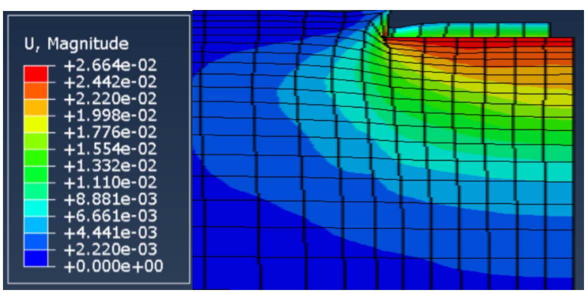


Figure 26: Displacement contours of case 1 at h/B = 2.275 for L/B=1.

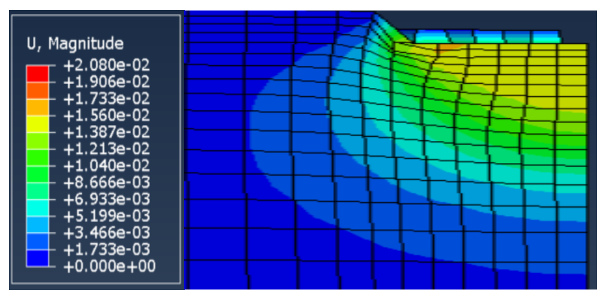


Figure 27: Displacement contours of case 8 at h/B = 2.275 for L/B=1.

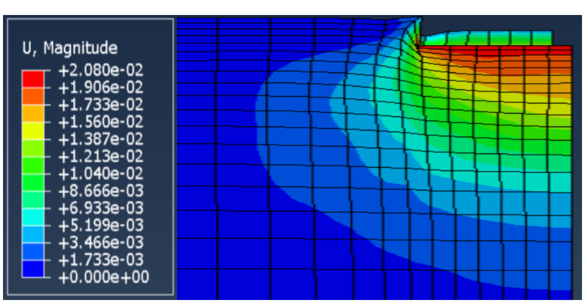


Figure 28: Displacement contours of case 1 at h/B = 2.275 for L/B=2.

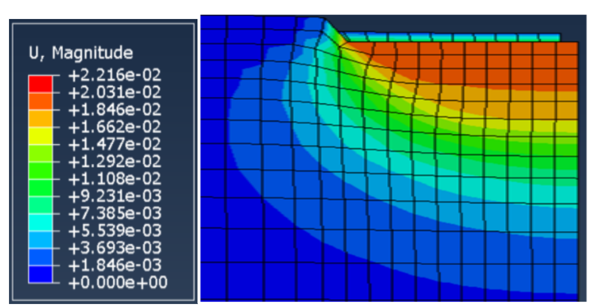


Figure 29: Displacement contours of case 8 at h/B = 2.275 for L/B=2.

also illustrates that isobars are within the dimensions of the soil strip (500mm × 500mm ×350mm), which means that the assumed soil strip is enough to estimate the bearing capacity. According to [29], there is a critical depth below which the strength of the bottom layer has no effect on the model's bearing capacity, and this depth in this analysis is h/B=1.75 (Figs 22–25). For both types of footings, the displacement contours are within the region of the first layer at a thickness ratio of h/B=1.75. For lower h/B values, the failure mechanism extends to the bottom layer.

9 Conclusion

In this study, a numerical analysis was conducted to evaluate the bearing capacity of single-layered and two-layered soils, as well as the impact of an unstabilized/stabilized clayey layer over medium-dense sand on layered soil bearing capacity and soil failure mechanisms. The soil was represented as an elasto-plastic material, and calculations were performed using the FEM-based software ABAQUS.

1. The bearing capacity value of one-layer sandy soil calculated using ABAQUS was compared to that predicted by Vesic (1973), Hansen (1970), and Terzaghi's (1943) equations. It is concluded that the values for bearing capacity computed using these equations are in good agreement with each other.
2. The bearing capacity reduced by 5%–39% of its value in two-layered soil by adding unstabilized clayey soil layer thicknesses of h/B=0.7, 1.225, 1.75, and 2.275 on top of the sand, and the bearing capacity increased by 31%–79% for both types of footings by stabilizing clayey soil with molasses, WFS, and lime alone and in combination when compared to one-layer sandy soil.
3. From the bearing capacity values of both types of footings (L/B=1, 2), it was clear that partial replacement of stabilized clay overlaying the sand layer enhances the bearing capacity significantly.
4. The bearing capacity of two-layered clay was determined mainly by the strength of the upper clayey layer after h/B = 1.225, while the aspect ratio (L/B=1, 2) of footings had very little influence on the bearing capacity.
5. A regression analysis revealed the interrelationship between variables mentioned in this study, including the bearing capacity of both circumstances, thickness ratio (h/B), aspect ratio (L/B), friction angle (ϕ), cohesiveness (c), and mass density (γ). Furthermore, the regression analysis was relatively hypothetical; making it unsuitable for extending the results of the foundation models; yet the models gave appropriate bearing capacity predictability for foundation systems of varied configurations.
6. The displacement contours for both types of footings were located at the first layer at a thickness ratio of 1.75 for h/B. The bottom layer was affected by the failure mechanism for lower h/B values.

The technique used in the proposed study is simple for a two-layer soil and is also suitable for multilayer soil profiles. Furthermore, the influence of footing soil interaction and varying the thickness ratio might be included in future analyses.

Refrences

[1] Button, S.J.(1953). The bearing capacity of footing on a two-layer cohesive subsoil. *Proc. 3 rd International Conference on Soil Mechanics and Foundation Engineering 1953*, 1, 332-335.

[2] Ismail, I., Raymond, G.P. (1995). Geosynthetic reinforcement of granular layered soils. In: *Proceedings of geosynthetics*, 317–330.

[3] Szypcio, Z., Dołżyk, K.(2006). The bearing capacity of layered subsoil. *Studia Geotechnica et Mechanica*, 28(1), 45-60.

[4] Dobrzański, J., Kawa, M.(2021). Bearing capacity of eccentrically loaded strip footing on spatially variable cohesive soil. *Studia Geotechnica et Mechanica*.

[5] Debnath, L.(2021). Seismic bearing capacity of shallow strip footing embedded in slope resting on two-layered soil. *Studia Geotechnica et Mechanica*, 43(3), 285-306.

[6] Reddy, A.S., Srinivasan, R.J. (1967). Bearing capacity of footings on layered clays. *Journal of the Soil Mechanics and Foundations Division*, 93(2), 83-99.

[7] Lee, K.M., Manjunath, V.R., Dewaikar, D.M. (1999). Numerical and model studies of strip footing supported by a reinforced granular fill—soft soil system. *Canadian Geotechnical Journal,* 36, 793–806

[8] Boushehrian, J.H., Hataf, N. (2003). Experimental and numerical investigation of the bearing capacity of model circular and ring footings on reinforced sand. *Geotextiles and Geomembranes*, 21(4), 241-256.

[9] Chung, W., Cascante, G. (2007). Experimental and numerical study of soil-reinforcement effects on the low-strain stiffness and bearing capacity of shallow foundations. *Geotechnical and Geological Engineering*, 25(3), 265-281.

[10] Benmebarek, S., Benmoussa, S., Belounar, L., Benmebarek, N.(2012). Bearing capacity of shallow foundation on two clay layers by numerical approach. *Geotechnical and Geological Engineering*, 30(4), 907-923.

[11] Raman, K.V., Dayakar, P., Raju, K.V.B.(2012). Study on settlement behaviour of layered soils. *International Journal of Biotech Trends and Technology (IJBTT)*, 2(4), 40-45.

[12] Mosadegh A., Nikraz H. (2015). Bearing capacity evaluation of footing on a layered-soil using ABAQUS.*Journal of Earth Science and Climatic Change,* 6(3), 264. DOI: https://doi.org/10.4172/2157-7617.1000264

[13] Roy, S.S., Deb, K. (2019). Influence of footing interference on bearing capacity improvement for geogrid-reinforced sand bed underlain by soft clay. In*: Geo-Congress 2019: Earth Retaining Structures and Geosynthetics*, *Reston, VA: American Society of Civil Engineers*, 322-330.

[14] Mandeel, S.A.H., Mekkiyah, H.M., Al-Ameri, A.F.I. (2020). Estimate the bearing capacity of full-scale model shallow foundations on layered-soil using PLAXIS. *Solid State Technology*, 63(1), 1775-1787.

[15] Bhardwaj, A., Walia, B.S.(2017). Influence of cement and polyester fibers on compaction and CBR value of clayey soil. In*: Indian Geotechnical Conference*.

[16] Sharma, A., Sharma, R.K., Bhardwaj, A. (2018). Effect of construction demolition and glass waste on stabilization of clayey soil. In: *InternationalConference on Sustainable Waste Management through Design*, Springer, Cham, 87-94. https://doi.org/10.1007/978-3-030-02707-0_12
[17] Sharma, A., Sharma, R.K. (2019). An experimental study on uplift behaviour of granular anchor pile in stabilized expansive soil. *International Journal of Geotechnical Engineering*, 1-14. https://doi.org/10.1080/ 1938636.2.2019.1597481
[18] Bhardwaj, A., Sharma, R.K., Sharma, A.(2021). Stabilization of clayey soil using waste foundry sand and molasses. In: *Sustainable Development through Engineering Innovations*,Springer, Singapore. 641-649.
[19] Fattah, M.Y., Al-Saidi, A., Jaber, M.M. (2015). Improvement of bearing capacity of footing on soft clay grouted with lime-silica fume mix. Geomechanics Engineering, 8(1), 113-132.
[20] Pancar, E.B., Akpınar, M.V.(2016). Comparison of effects of using geosynthetics and lime stabilization to increase bearing capacity of unpaved road subgrade. *Advances in Materials Science and Engineering*.
[21] Rasouli, H., Takhtfirouzeh, H., TaghaviGhalesari, A., Hemati, R.(2017). Bearing capacity improvement of shallow foundations using cement-stabilized sand. In: *Key engineering materialsTrans Tech Publications Ltd,* 723, 795-800.
[22] Arora, S., Kumar, A. (2019). Bearing capacity of strip footing resting on fibre-reinforced pond ash overlying soft clay. *Innovative Infrastructure Solutions*, 4 (34). https://doi.org/10.1007/s41062-019-0221-4
[23] Bhardwaj, A., Sharma, R.K. (2022). Designing thickness of subgrade for flexible pavements incorporating waste foundry sand, molasses, and lime. *Innovative Infrastructure Solutions, 7*, 132. https://doi.org/10.1007/s41062-021-00723-6.
[24] ASTM D2487–11 (2011). Standard practice for classification of soils for engineering purposes (unified soil classification system), *ASTM International*, West Conshohocken.
[25] Johnson, K., Christensen, M.,Sivakugan, N., Karunasena, W. (2003). Simulating the response of shallow foundations using finite element modeling.*Proceedings of the MODSIM 2003 International Congress on Modelling and Simulation, Townsville, QLD, Australia*, 2060-2065.
[26] Thakur, A., Dutta, R.K. (2020). Experimental and numerical studies of skirted hexagonal footings on three sands.*SN Applied Sciences*, 2(3), 487. DOI: https://doi.org/10.1007/s42452-020-2239-9
[27] Jeya Rami Reddy, P.(2013). *Stochastic Hydrology*. Laxmi Publications Private Limited, Ajit Printing Press, New Delhi, 122-130.
[28] Bilgili, M.(2010). Prediction of soil temperature using regression and artificial neural network models. *Meteorological Atmospheric Physics*, 110, 59–70.
[29] Rezaeianzadeh, M., Tabari, H., ArabiYazdi, A., Isik, A., Kalin, L.(2013). Flood flow forecasting using ANN, ANFIS and regression models. *Neural Comput&Applic. springer-verlag London*, DOI 10.1007/s00521-013-1443-6.
[30] Michalowski, R.L. (2002). Collapse Loads over Two-layer Clay Foundation Soils. *Soils and Foundations,* 42, 1-7.