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Improvement of Bearing Capacity for Soft Soils Supported by Confined Footings and Sand Columns: A Numerical Study

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Abstract The structures constructed on soft soils experience several severe problems, including vertical and lateral instability, as well as excessive displacement. Many coastal areas have soft clay deposits, which have low strength, compressibility, excessive plasticity, and tendency to shrink or swell. Confined footings and sand piles are both commonly used to improve the soft soils beneath the shallow foundations by reducing the settlement and increasing the bearing capacity of such soils. Improvement using confined footings located in different depths, and using sand columns (End bearing and floating) all presented in this investigation. Analyses using finite element method GeoStudio 2018 (SIGMA / W) finite element 2D program were built to investigated the settlement of soft clay which improved using confined footings, floating and end bearing sand piles. GeoStudio was used to verify a physical laboratory model which was built by [1]. For the situation of confined footings, floating and end bearing sand piles, settlement values obtained from software analysis were compared with the experimental results of [1] in order to determine the the average settlement of flexible foundations on soft clay soils. Discussion of results show good agreements between the numerical and the laboratory models tests. Discussion of results show that the possibility of using GeoStudio 2018 Finite Element 2D program to simulate the settlement of foundation laid on soft clay soil is feasible.
Furthermore, when a sand column (i.e. both floating type and completely penetrated type) is applied, the results reveal an increase in the soil's bearing capacity.

Keywords GeoStudio 2018, Numerical analysis, Confined footing, Sand column, and Soft clay.

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1. Introduction

Peat soils are well known for their low shear strength and high compressibility. Construction of any structures on these soft soils requires attention on stability and settlement which cause serious problems [2].

[3] investigated the effects of partially replaced sand piles with and without confinement on the soft clay layer. They performed a study to determine the effect of sand pile on settlement control and bearing capacity of soil. [4] investigated the behaviour of geogrid encased columns through a series of scale model column experiments. They concluded that unit-cell loading offered additional lateral confinement to the encased columns, preventing radial column failure and allowing the encasement mesh to be loaded to tensile capacity. [5] presented a laboratory model tests to analyses the improvement of bearing capacity of a square footing laying on the soft soil using sand pile and with or without structural skirts as confinements. They observed that the enhancement of load carrying capacity of the footing was increased in both partial fill of sand piles with or without skirts.

According to experimental results and analysis by [6] the additional of a layer of granular fill over the soft clay sub-grade increases its load carrying capacity. The inclusion of reinforcing layer at the sand clay interface has resulted in an improvement in bearing capacity as well as a reduction in settlement of the footing. Also, the model tests conducted on footings of different sizes show that in bearing capacity improvement is the same for all the three sizes.

Deep vibratory compaction is not recommended for soft cohesive soils with low bearing capacity, According to [7]. One of the most effective methods of improving soil strength has been demonstrated to be stone column technique. According to his results, while the width of the foundation, the diameter and number of stone columns all increase the foundation's bearing capacity, the effect of their encasement stiffness and length is more pronounced, and this can be considered as an important factor in the analysis of shallow foundation on reinforced soils.

According to [8] settlement behaviour of small loaded areas on soft soil supported by stone columns (such as pad and strip footings) is poorly understood. In their research, they employed a 3-D finite element analysis in conjunction with an elastic–plastic soil model to identify the effect of variables in the design process and their interactions. [9] presented an investigation that looked into the effectiveness of using sand columns in improving soft clayey soils. The authors studied some factors which has an effect on the behaviour of soft soil such as relative density of column, number, and cross section of sand column. [10] found that stone columns repeatedly used for improvement of soft soils, and friendly towards the environment.

One of the most common ways is soft-soil reinforcement using stone columns, which has several advantages such as increased bearing capacity, reduced post construction settlement, and consolidation [11].

[12] presented a numerical study of stone columns in fine-grained soil to improve the bearing capacity of a footing with the length of 10 m, and thickness of 0.5 m. The findings show that the stone columns are effective in increasing soft soil capacity.

The carrying capacity of circular footings decreases with the addition of fines, but can be significantly increased by soil confinement, according to [13].

[14] concluded that increasing the thickness of the soft clay layer replaced with compacted sand layer reduces settlement and improves resistance stress. It can be concluded that using the replacement methodology under the loaded area reduces the settlement factor.

The confining of foundations reduced overall stresses near the foundation by 65 percent and reduced vertical displacement by 90 percent, according to the results founded by [15]. Furthermore, it was shown that the most effective distance between the confinement wall and the base is 0.5 B.

Aim of the Current Study

In the present research, a 2-D Finite Element program GeoStudio 2018 was used to simulate a laboratory model which was built by [1]. The numerical model was created to study how the soft clay bearing capacity improved after the sand column was formed (floating and completely penetrated type) and confined footing system, and to check the validity of the chosen computational procedures.

2. Numerical Simulation

2.1. Physical laboratory model (After Chandrawanshi and Kumar (2015))

Physical laboratory model was built in order to investigate the effect of sand column on soft soil, as well as comparing it with the effect of confining cell of different diameter and height. As illustrated in **Fig.1**, the laboratory model consists of circular footing of 50 mm diameter and a thickness of 10 mm resting on soft soil.

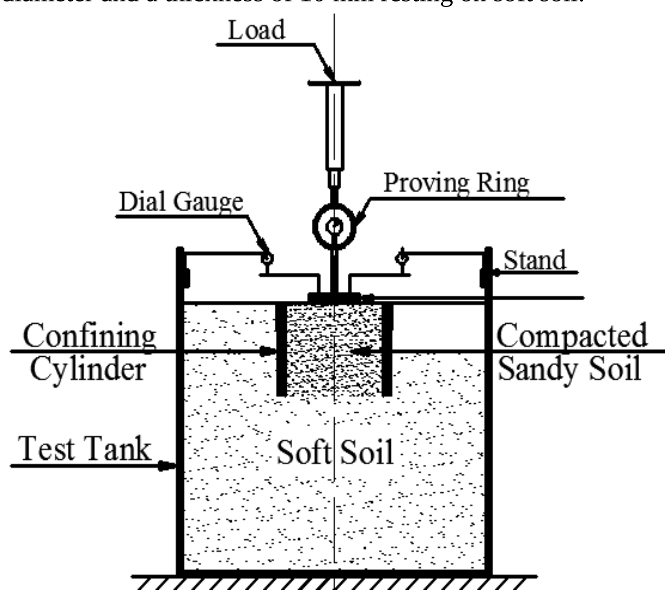

Fig.1. Cross section of physical laboratory model (After Chandrawanshi and Kumar (2015)).

2.2. Numerical modeling of the physical laboratory test

2.2.1. Geometry of the 2D Problem

The 2-D Finite Element program GeoStudio 2018 was used to perform 2D numerical analysis in this study. The geometry of the numerical 2D model for using confining cell of different diameter and height is presented in **Fig. .2**. Also, the numerical model using sand pile of different diameter and height as shown in **Fig. 3.** Simulation of end bearing pile using the model as shown in **Fig. 4**, and the geometry of soft clay bed without any improvement system is presented in **Fig. 5.**

2.2.2. Boundary conditions and mesh generation

Boundary conditions were assigned by applying vertical load at the soil surface. The model was only allowed to deform on the vertical sides (i.e.roller boundaries) while being fully fixed along the model base in terms of boundary fixities. When the geometry model is completed, the finite element model (or mesh) can be generated, See **Figs. from 2 to 5.**

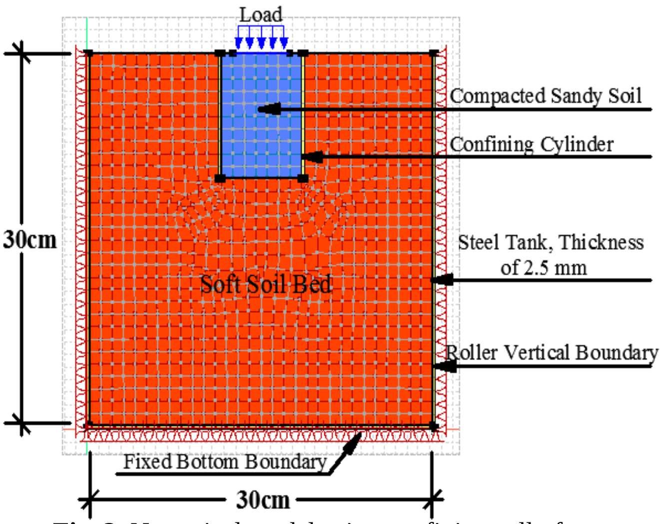

Fig. 2. Numerical model using confining cell of diameter 75 mm and different height.

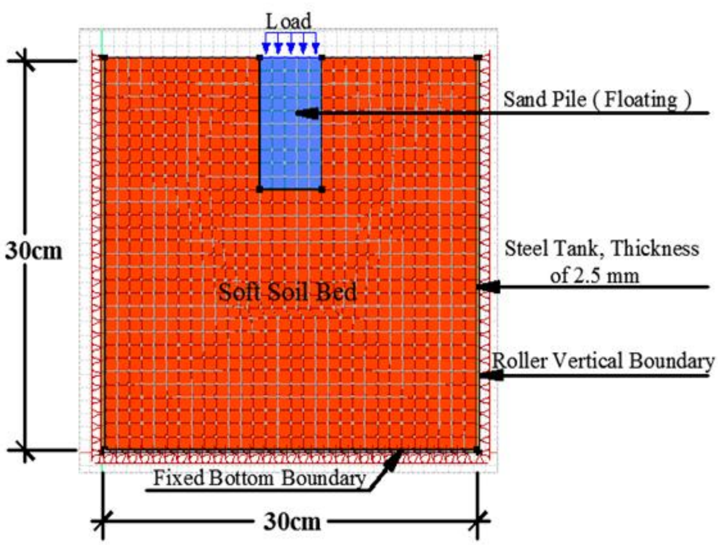

Fig. 3. Numerical model using sand pile (Floating) of diameter 50 mm and different height.

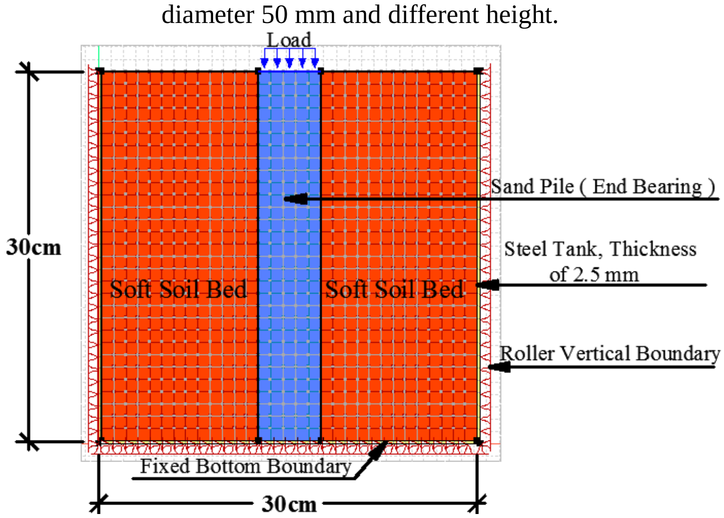

Fig. 4. Numerical model sand pile (End Bearing).

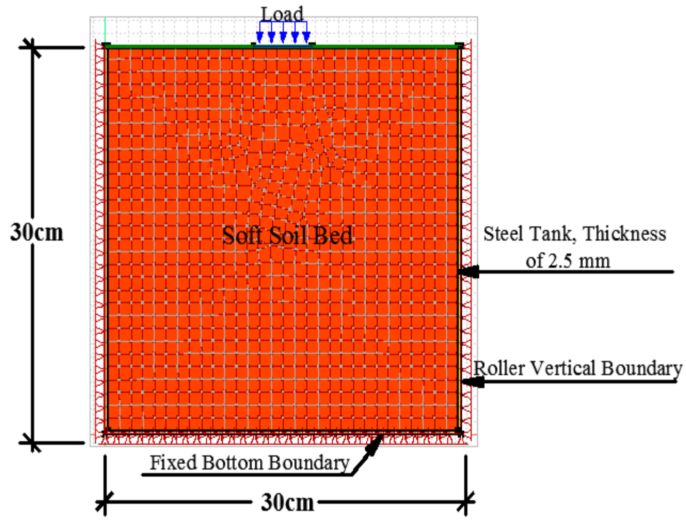

Fig. 5. Numerical model soft clay bed without any improvement system.

2.3. Material model parameters

All properties of soil used in these models are illustrated in Table 1. The model was adjusted to simulate the relation between settlement and applying loads, therefore to examine the aspect of increased in the bearing capacity through conventional sand column (Floating and End Bearing) and comparing it with confining footing to strengthen the soft clay soil. Finally, the physical model measurements were compared to the numerical results.

Table 1. Properties of Material used in the numerical models.

Material		Properties		
		Unit Weight	E-Modulus	Poisson's Ratio
Soft Clay Soil	Value	15.3	15000	0.40
	Unit	KN/m^3	KN/m^2	-----
	Reference	[1]	[16]	[17]
Sand Soil	Value	16.47	45000	0.30
	Unit	KN/m^3	KN/m^2	-----
	Reference	[1]	[16]	[17]
Steel Tank	Value	78.5	2×10^8	0.30
	Unit	KN/m^3	KN/m^2	-----
	Reference	[16]	[18]	[17]

2.4. Testing Parameters. (After Chandrawanshi and Kumar (2015))

As mentioned before, the geotechnical finite element model (FEM) was developed, using GeoStudio 2018 software package, and verified against results of physical laboratory experiments as the same way of [1], all the testing parameters used in these models are listed in Table 2.

Table 2. GeoStudio 2D simulation cases, of physical laboratory experiments.

GeoStudio Series	Description	Variable Parameters		No. of Models
		Footing Diameter (mm)	Height of Confining cell and Sand Pile (mm)	
(A)	Soft Clay Bed Only	50	-----	1
(B)	Confined Footing (Dia. = 75 mm)	50	50,100,150	3
(C)	Sand Pile (Floating)	50	50,100,150	3
(D)	Sand Pile (End Bearing)	50	300	1

3. Results and Discussion of the Findings

3.1. Comparison between experimental and numerical results

Figure 6. indicate the relationship between settlement and applying load for both measured in laboratory model and estimated by numerical model for soft clay bed only. For soft clay bed only, a good agreement between numerical and experimental results has been noticed with a maximum average difference of about 0.98 mm as shown in **Fig.6**.

In case of using confined cell having 75mm in diameter, and 50 , 100 , and 150 mm in depth to improve soil bearing capacity, a reasonable agreement between the numerical modeling results and the experimental results with a maximum average difference of about 0.73, 0.79, 0.99 mm using confined cell with depth 50, 100, 150 mm as shown in **Figs. 7 to 9**, respectively.

To improve the load carrying capacity of the soft soil, floating sand pile was constructed. **Figs. 10 to 12** indicated good match between the results of the numerical modeling and the experimental study conducted by [1] with a maximum average difference of about 0.98, 0.95, 0.75 mm using floating sand pile with depth 50, 100, 150 mm, respectively.

Also, a similar difference of about 0.68 mm is noticed in case of using end bearing sand pile with diameter 50 mm, and depth 300 mm as shown in **Fig. 13**.

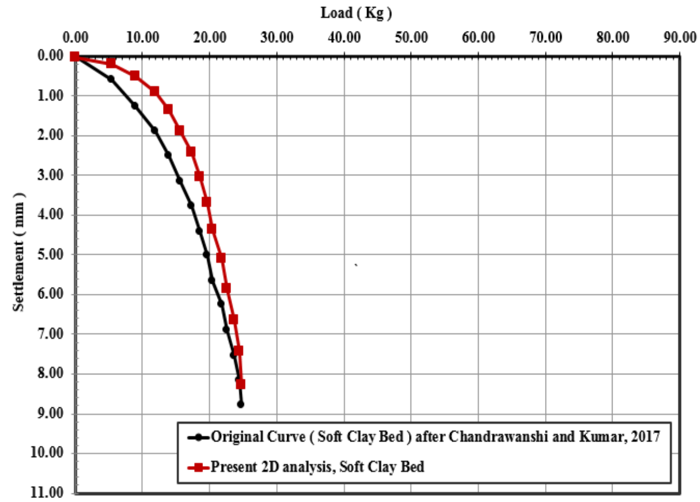

Fig. 6. Load – Settlement relationship for soft clay bed only.

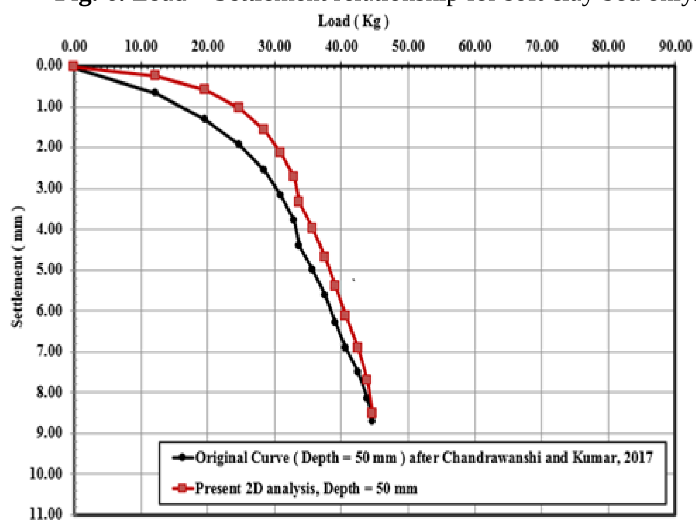

Fig.7. Load – Settlement relationship for confined footing with depth 50 mm and diameter 75 mm.

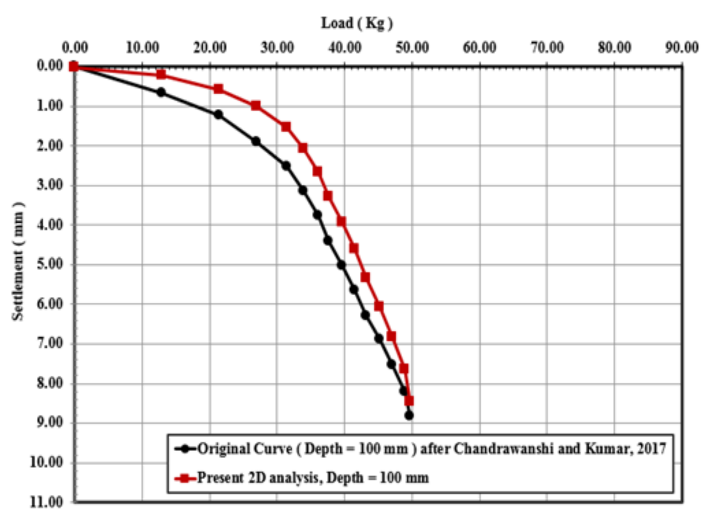

Fig. 8. Load – Settlement relationship for confined footing with depth 100 mm and diameter 75 mm.

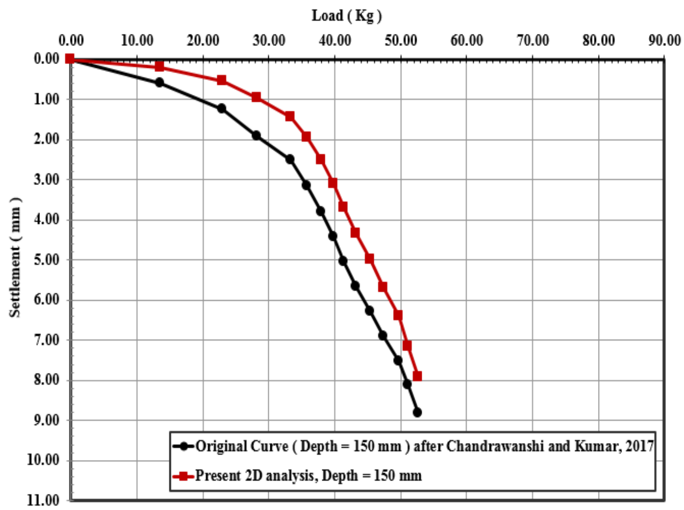

Fig. 9. Load – Settlement relationship for confined footing with depth 150 mm and diameter 75 mm.

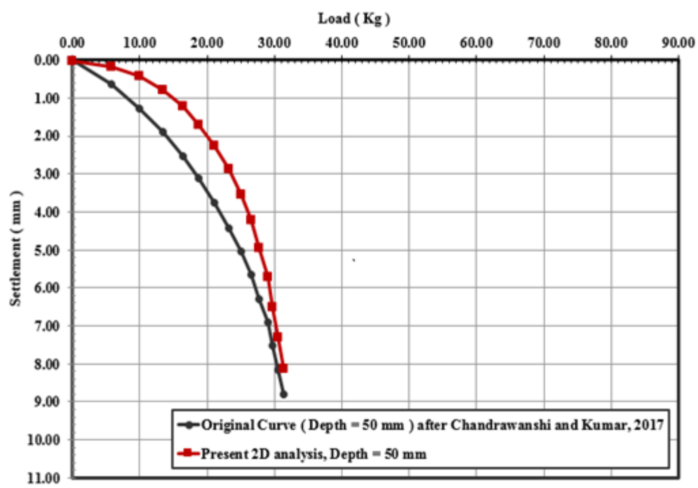

Fig. 10. Load – Settlement relationship for floating sand pile with diameter 50 mm and depth 50 mm.

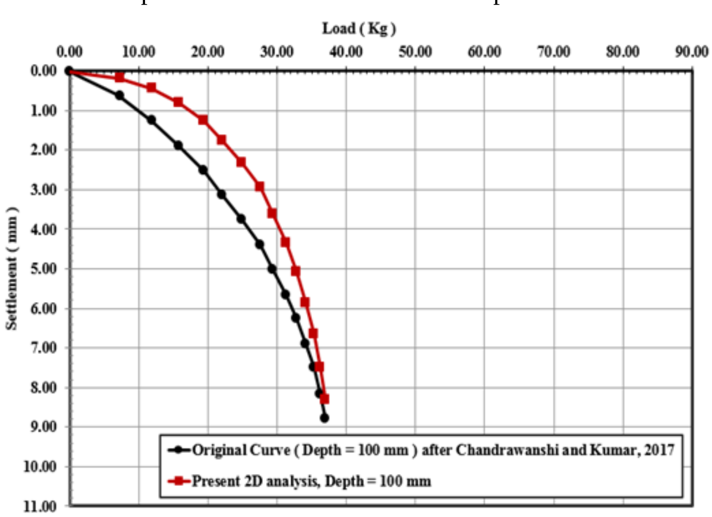

Fig. 11. Load – Settlement relationship for floating sand pile with diameter 50 mm and depth 100 mm.

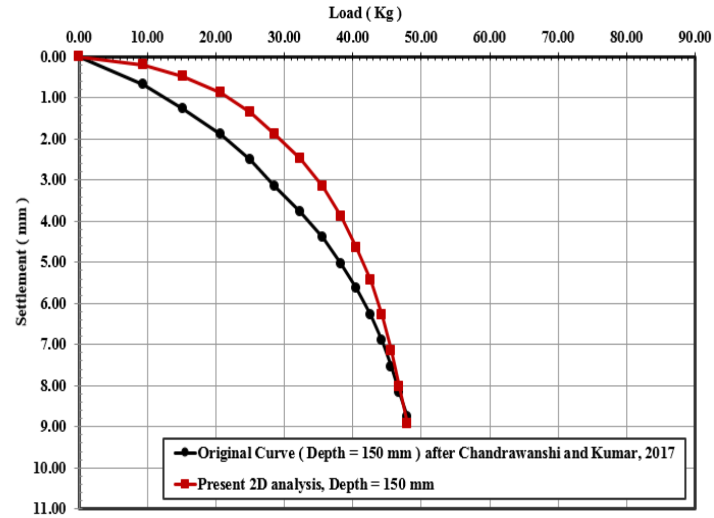

Fig. 12. Load – Settlement relationship for floating sand pile with diameter 50 mm and depth 150 mm.

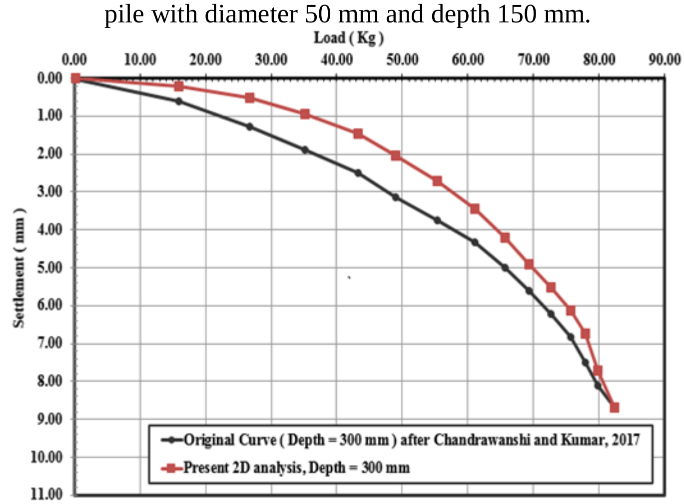

Fig. 13. Load – Settlement relationship for end bearing sand pile with diameter 50 mm.

In general, **Figs. 6 to 13** indicate that the developed GeoStudio 2D model is satisfactorily estimated the relationship between settlements with the increase of applying loads. The consistent difference of settlement values between GeoStudio 2D model results and laboratory model measurements may be referred to some of the following factors: -

a- Some errors in the settlement measurement in laboratory monitoring.

b- Probability of irregular density distribution for soft clay bed, sand which was used as a floating pile, and that used as end bearing pile.

c- Perhaps due to some friction between clay and tank walls.

d- Also, the friction between clay bed, confined cell, and sand used in confined cell which may affect the settlement measurements.

3.2. Effect of confined footing

Figure 14 indicates a significant increase in the soil's load carrying capacity. The cause of this phenomena is that compressed sand is replacing clay, and its bulging is restricted due the presence of confining cell. This system increases the bed bearing capacity with 80.9 %, 102 %, and 114 % according to confined cell depth 50, 100, and 150 mm, respectively.

3.3. Effect of floating sand pile

Additionally, using a floating sand pile increases the soil's load carrying capacity. The load carrying capacity improves as the depth increases. Increases in clay bed carrying capacity with depths of 50, 100, and 150 mm were on the order of 27.5 percent, 50 percent, and 85 percent, respectively. Results were shown in **Fig. 15.**

3.4. Effect of end bearing sand pile

Because there is a maximum replacement of soft clay with sand in end bearing and piling, the maximum gain in bearing capacity of soft soil bed is achieved. This system of soil improvement increases the soil bearing capacity with 233% with respect to clay bed bearing capacity as shown in **Fig. 16**.

3.5. Comparison of multiple cases

Figure 17 shows comparison of all the previous cases.

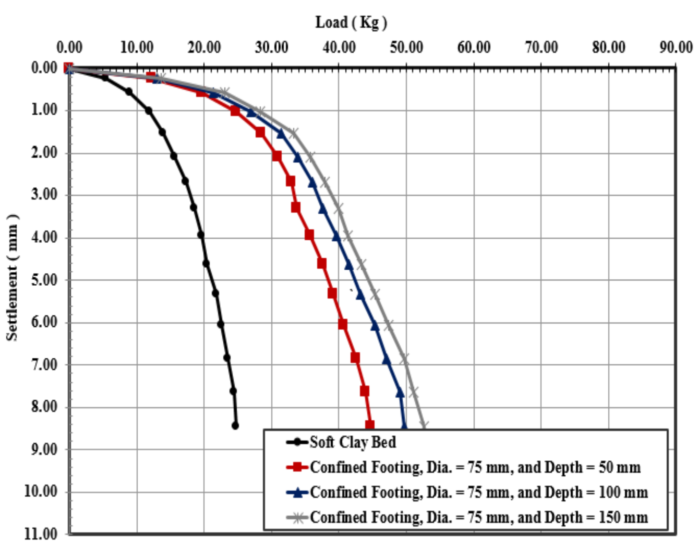

Fig.14. Load – Settlement relationship for confined footing (Dia. = 75 mm) of varying depths.

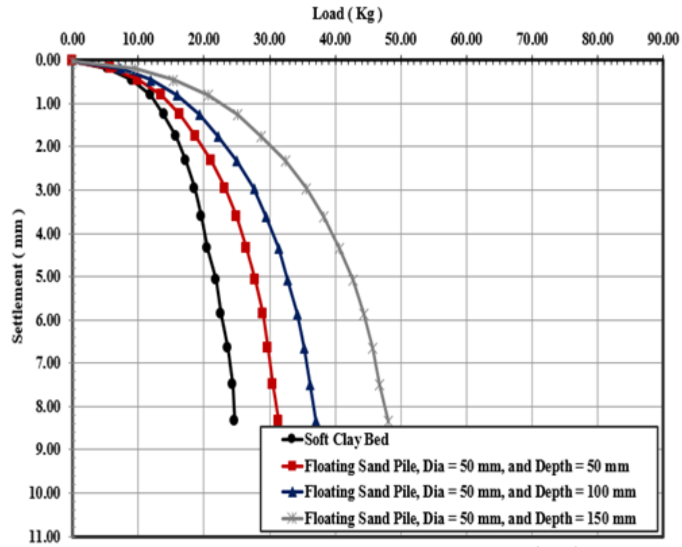

Fig. 15. Load – Settlement relationship for floating sand pile (Dia. = 50 mm) of varying depths.

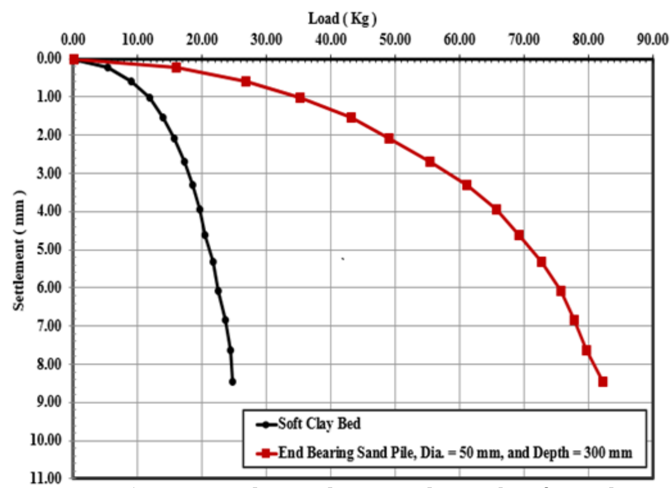

Fig. 16. Load – Settlement relationship for end bearing sand pile (Dia. = 50 mm).

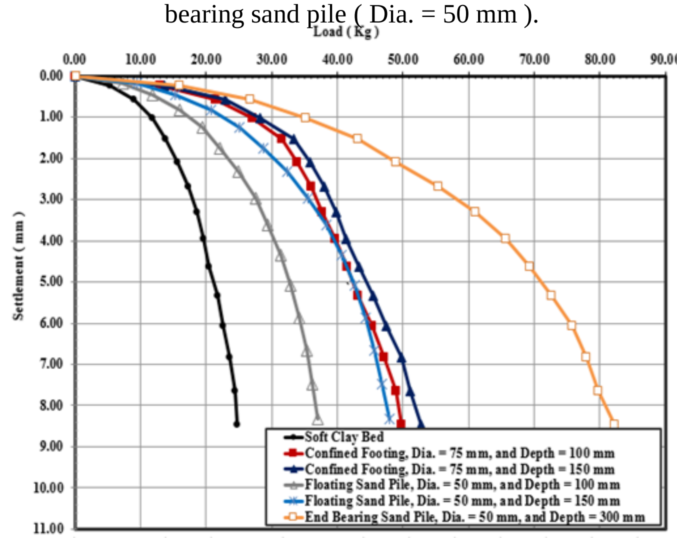

Fig.17. Comparison of Load – Settlement relationship of soft clay bed, confined footing, floating sand pile, and end bearing sand pile.

4. Conclusions

In the present study GeoStudio 2018 (SIGMA / W) finite element 2D program was adopted to simulate the settlement of flexible foundations on soft clay soils. Discussion of results showed that numerical model gives satisfactory results compared with to the laboratory model for all the studied cases. Comparing the FEM results with the laboratory measurements allowed us to validate the proposed numerical model to establish the relationship between the settlement and applied load. Then the results showed the feasibility of floating sand pile, end bearing sand pile, and confined footing to strengthen the soft clay soil.

Analysis of numerical results indicate that with the use floating sand pile, end bearing sand pile, and confined footing the load carrying capacity increases.

From the present study, the major conclusions that can be drawn are as follows: -

1- With increasing confined cell depth, the load carrying capacity of confined footing increases.

2- Also, the results showed that increase in depth of floating sand pile causes increase in the load carrying capacity.

3- The confined footing is better than the floating sand pile for the same depth.

4- In case of the end bearing sand pile, the maximum capacity was achieved.

5- Construction of confined footing with depth equal to three times the footing diameter considerably improves the bearing capacity of soft clay soil.

6- The addition of a floating sand pile improves the soft clay soil's load settlement characteristics significantly.

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