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THE EFFECT OF LATERAL CONFINEMENT ON THE SETTLEMENT CHARACTERISTICS OF SHALLOW FOUNDATIONS ON SAND

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ABSTRACT: Today, most of the high rise buildings consist of basements as part of the substructure. Basement construction is usually supported by embedded type retaining walls such as secant pile walls or diaphragm walls. This provides lateral confinement and the performance of shallow foundations would be affected by this lateral confinement. In this study, the effect of lateral confinement on the settlement characteristics of shallow foundations on sand was studied experimentally and numerically. First, experimental investigation using small-scale laboratory models were carried out and the results were used to validate the finite element (FE), model. Changing the depth of lateral confinement and the distance to the edge of the shallow foundation from the lateral confinement, the stress immediately below the footings corresponding to a settlement of 25 mm was compared. Furthermore, the effect of lateral confinement due to embedded retaining wall on the settlement characteristics of a raft foundation on sand was also studied using the validated finite element model. In scaled physical models of confined foundations, there was an enhancement in allowable bearing capacity at the tolerable settlement with the increase in depth of embedment and the reduction of distance to the confinement. It was observed, for the study variables considered in this study that the bearing capacity can be improved up to 4 times by laterally confining the footing. However, in the analysis of confined raft foundations on sand, there was no significant change in bearing pressure for a 50 mm tolerable settlement with the change of study variables.

Keywords: Foundations, Retaining Walls, Sand Confinement, Settlement

1. INTRODUCTION

Shallow foundations are used to transfer loads of a structure to the ground. Raft foundations are a type of shallow foundation usually used in buildings with basements, which are supported with embedded retaining walls. During early days, deep embedded retaining walls were constructed with either soldier piles or steel sheet piles, but later concrete retaining walls such as secant pile walls and diaphragm walls came into use [1]. Sometimes these embedded retaining structures become part of the structure because of the difficulty to remove these walls and this will result in the confinement of the lateral movement of soil beneath the foundation.

While designing shallow foundations, the bearing capacity, as well as the settlement, needs to be considered. A number of studies have been conducted ([2], [3] and [4]) to improve the bearing capacity and to reduce the settlement of foundations.

The use of structural skirts has been studied extensively by many researchers for the improvement of bearing capacity and settlement behavior by confining the soil. In [2] a modified bearing capacity equation was proposed for skirted strip footings on sand. It was found that bearing capacity can be improved by a factor of 1.5-3.9 with the use of structural skirts. The performance of structural skirts was studied in [5] where it was found that the performance of skirted footings depends on the relative density of sand and the skirt length to footing diameter ratio.

Similar behaviour was observed in the experimental study mentioned in [4] on behaviour of circular footings on confined sand where sand was confined with unplasticized polyvinyl chloride (UPVC) cylinders of different heights and diameters. Results indicate a significant improvement in the ultimate bearing capacity of confined footings when compared with unconfined footings. It was observed that when small diameter confining cells are used relative to footing size, cell-sand-footing system behaves as a deep foundation, and failure occurs in the surrounding soil. For large diameter cylinders, at first they behave as one unit, but only the foundation settles as failure approaches. It was concluded that optimum cylinder diameter to footing diameter ratio is about 1.4. Below and beyond the limit the bearing capacity ratio between confined and unconfined footings reduces.

A physical model test and a three-dimensional finite element analysis were carried out in [3] to study the behavior of laterally and vertically confined shallow foundations resting on the sand. From the results, it was observed that the confinement enhances the bearing capacity, and the level of enhancement increases with increasing wall depth to foundation width ratio and with the decrease in sand relative density. It was evident that capacity is insensitive to the depth of foundation embedment which was also observed in [4]. From the experimental study in [6], it was concluded that in bounded square footings on sandy soil the bearing capacity increases with the depth of embedment of the wall and the effect of the wall approximately fades when the wall distance to the footing width ratio is more than 2 due to the decrease in soil confinement.

Results from studies of confined foundations on sand can be beneficial for the constructions near the coastline and for the buildings constructed in man-made peninsulas as soils in these areas are mostly cohesionless sands. Construction of high-rise buildings with basements in these areas requires raft foundations confined with embedded retaining walls to support excavations. If there is an improvement in bearing capacity and settlement behavior in raft due to confinement the use of pile raft foundations to support structures can be reduced. In this study, the effect of lateral confinement on the settlement characteristics of shallow foundations on sand was studied experimentally and numerically.

2. METHODOLOGY

First, a series of small-scale laboratory experiments were carried out to investigate the effect of the presence of lateral confinement on the settlement characteristics of shallow foundations. Test variables have been selected as the depth of embedment of the lateral confinement and the distance between the lateral confinement and the footing. The same laboratory tests were then modeled using commercially available FE software (PLAXIS) to validate the results of the numerical analysis. After that, the validated model was used to simulate the behavior of raft foundations on sand confined by retaining structures. The stress underneath the foundation for a tolerable settlement due to confinement was studied by varying the test variables. This study was focused on the effect of lateral sand confinement on the behavior of allowable stress at tolerable settlement rather than quantifying the stress values.

3. EXPERIMENTAL PROCEDURE

As studies on actual size foundations are time-consuming and complex, a laboratory testing program was adopted with scaled models of confined shallow foundations. A schematic diagram of the experimental setup is shown in Fig. 1. Six square rigid timber boxes of width (L) 300 mm and 500 mm, in which the heights varying as (D) 300 mm, 400 mm and 500 mm were used as the lateral confinement. A square timber plate of length (B) 200 mm and having a thickness of 25 mm was used as the shallow foundation. The test tank used was having a diameter of 2.1 m and height of 1.0 m. The dimensions of the tank were enough to overcome the effect of vertical confinement as the depth is more than three times the width of the foundation. When it is more than three times the width of the foundation it was found that reduction in settlement due to the presence of a rigid vertical confinement vanishes [3].

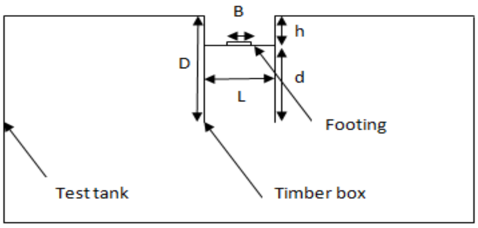

Fig. 1 Schematic drawing of the experimental setup.

Sand was used as the foundation soil for the experiment. The particle size distribution of sand obtained from a dry sieve analysis found according to [7] is shown in Fig. 2. The coefficient of curvature and the coefficient of uniformity of the soil are 0.78 and 2.45 respectively. The sand is classified as poorly graded sand (SP) according to Unified Soil Classification System [8]. From a direct shear test [9] the friction angle of the soil was found as 30^0 for normal stress ranging from 50 kPa to 150 kPa.

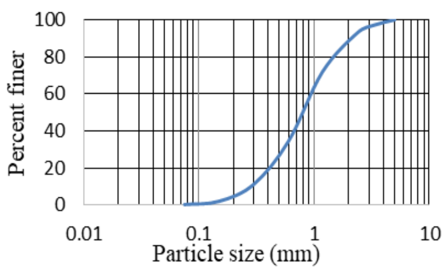

Fig. 2 Particle size distribution of test material

Even though small scaled foundations are used to verify the behavior of full-scale foundations, due to the scale effect the behavior may be different especially in granular soils [10]. According to [11] the stress level dependency and the particle size effect are responsible for the scale effect. The effect of the particle size in model tests can be overcome when the B/D_{50} >50-100 according to [12]. From the results of the particle size distribution, the effective size (D_{50}) is 0.80 mm for the sand used in this study. Therefore the B/D_{50} ratio is greater than 100.

The test tank was filled with sand using sand pluviation technique to achieve a uniform unit weight throughout the container, controlling the height and rate of sand fall [13]. First, the test tank was filled with sand up to the level of the base of the timber box that is to be placed. Then the timber box was placed on sand, filled up to the top and leveled the surface using a straight edge. This wall installation procedure is different from the wall installation procedure usually used in the field where the wall is pushed into the soil. However, in [3] after conducting tests on model foundations it was found that there was no significant difference in the bearing capacities when the walls were first placed and sand filled around it and when the walls were pushed into the soil. Therefore, considering the difficulty in pushing the wall into the soil the above method was used

The timber plate was placed at a depth (h) of 200 mm excavating the sand inside the timber box and it was centered within the retaining walls. A spirit level was used to ensure the setup is horizontally and vertically level. Then using a hydraulic jack placed at the center of the plate the load was applied, and using a proving ring attached to the jack the load applied was measured. The hydraulic jack and the proving ring system were mounted on to horizontal steel I bar which was supported on columns. Two dial gauges with an accuracy of 0.01 mm were also placed on the surface of the plate to measure the settlement of the timber plate when the load was applied. Rotation of the plate was not allowed during the vertical loading and this was ensured using two dial gauges. Then the number of proving ring divisions deflected for every 2 mm deflection in dial gauges was measured and converted to a force using calibration data. The plate was settled at a rate of 4 mm/min.

Similarly, a series of experiments were carried out changing the depth of embedment, changing the gap between wall and footing and without any lateral confinement of soil. A summary of the test program is shown in Table 1. The stress at 25 mm settlement was obtained for the comparisons of the experimental results as it better represents the stress values yielded at maximum allowable settlements in shallow foundation designs [14].

Table 1 Summary of the test program.

Foundation width (B) (mm)	Lateral confinement wall width (L) (mm)	Depth of Embedment (d) (mm)
200	300	300
200	300	200
200	300	100
200	300	0
200	500	300
200	500	200
200	500	100
200	500	0

4. NUMERICAL ANALYSIS

A numerical analysis was carried out using Plaxis 2D version 8.2, a commercially available finite element analysis software package for the simulation of the behavior of small-scale physical model foundations and shallow rigid raft foundations which are laterally confined.

For the finite element model used to validate the numerical model, a 2D axisymmetric model with 15 node triangular elements was used. A typical finite element mesh used for the analysis is shown in Fig. 3 and a schematic drawing of the geometric model used for the analysis are shown in Fig. 4. Full fixity at the base and roller conditions at the vertical sides was used as the boundary conditions. The square footing of side 200 mm was modeled as a circular footing with an equivalent area having a radius (r) of 112.8 mm, and cylindrical retaining walls of radius (R) 169.8 mm and 282.1 mm were used having an equivalent excavation area to that of the scaled model.

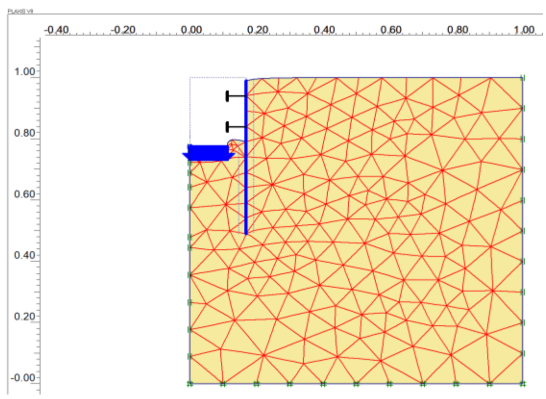

Fig. 3 Typical FE mesh used for the validation of numerical models

For different heights of the wall (i.e. (D) 300 mm, 400 mm and 500 mm) and for different wall radius, the average stress at 25 mm settlement immediately below the foundation was generated. From linear elastic calculations in [15], it was found that in using a circular footing of the equivalent area instead of a square footing only a difference of about 2% was observed in stress at the same depth.

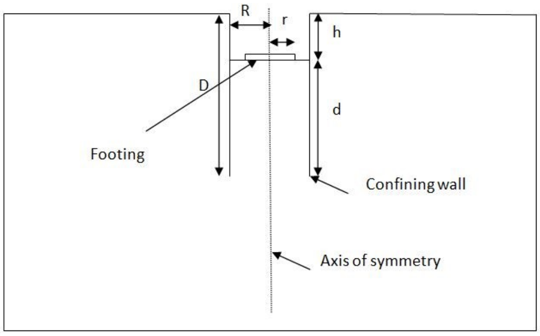

Fig. 4 Schematic drawing of the geometric model of confined footing used for the numerical analysis of the experimental setup.

Mohr-Coulomb material model was used to analyze the soil. For the analysis a soil having a unit weight (γ) of 15 kN/m^3, Young's modulus (E) of 10000 kN/m^2, friction angle (ϕ) of 30^0, cohesion (c) of 0 kN/m^2, dilatancy angle (φ) of 0^0 and Poisson's ratio (v) of 0.3 was considered. The footing and wall were considered as linear elastic materials of E of 10000 MN/m^2 and v of 0.3**.** The global coarseness of the mesh was set to medium and updated mesh analysis was carried out as the displacements are larger compared to the dimensions of the model.

A schematic drawing of the full-scale raft foundation confined with a deep embedded retaining wall is shown in Fig. 5. To understand the performance of full scale confined raft foundations resting on sand, 1.0 m thick concrete foundations of width (B) 20 m, 10 m and 3 m were modeled using Plaxis 2D software for confined and unconfined situations. For a prescribed displacement of 50 mm the stress immediately below the raft footing was obtained, changing the gap between confinement and footing (x) to 0.5 m, 1 m, 2 m, and 3 m and for the depths of embedment (d) 3 m, 6 m, 9 m and 12 m of wall. The stress values corresponding to 50 mm settlement in confined raft foundations was compared with foundations on sand without any lateral confinement. Instead of 25 mm settlement used in the small-scale experimental procedure, the stress at 50 mm settlement was compared as raft foundations on sand can tolerate a settlement of 50 mm according to [14].

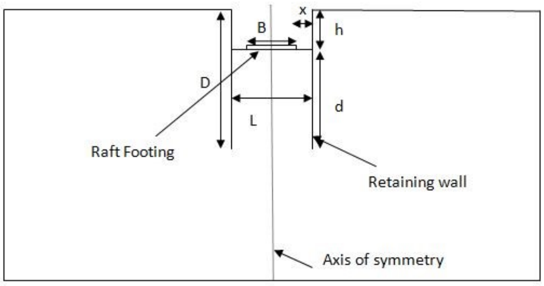

Fig. 5 Schematic drawing of the geometric model used in computer simulation of confined raft footing

The confined raft was analyzed with a plane strain model and 15 node triangular elements were utilized. A typical finite element mesh used for the analysis is illustrated in Fig. 6. Full fixity at the base and roller conditions at the vertical sides was used as the boundary conditions. Half of the model was used due to its symmetry about the y-axis. Boundaries were placed at a sufficiently remote distance so that no restrains or constraints for the movement in the area considered. To avoid the effect from groundwater table it was assumed that the water table is at a great depth.

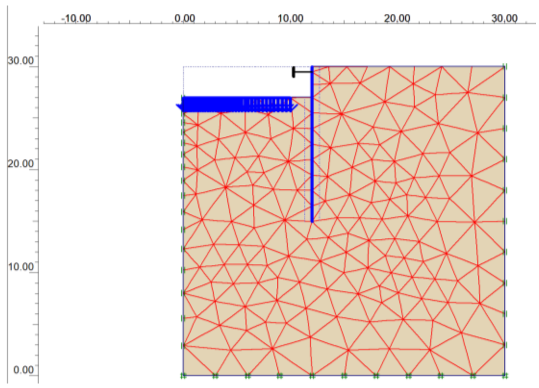

Fig. 6 Typical FE mesh used to analyze the performance of raft foundation.

To represent the behavior of sand Mohr-Coulomb model was used with γ=20 kN/m^3, E=20000 kN/m^2, ϕ=30^0, c=0 kN/m^2, φ=0^0 and v=0.15. For the concrete raft foundations and embedded confinement linear elastic materials with E= 27 GPa and v=0.15 were considered. Global coarseness was set to medium in the finite element mesh, for a reasonable accuracy.

For both numerical models, the initial stresses were generated using K_o procedure and three construction stages were used. In the first stage, the lateral confinement was installed followed by excavation and installation of props to support the wall. Finally, the prescribed displacement was applied.

5. RESULTS AND DISCUSSION

5.1 Experimental Results

Fig. 7 shows the stress-settlement relationship obtained for the lateral confinement wall width (L) of 300 mm and for different depths of embedment (d) of the confinement. As shown in Fig. 7, the approximate linear relationship between the stress and settlement was observed until 25 mm settlement was achieved. The ultimate bearing capacity was not reached in these experiments. The similar results were observed in the experiments conducted with the lateral confinement wall width (L) of 500 mm.

Fig. 8 depicts the variation of the foundation bearing capacity (Stress at 25 mm settlement) with the depth of embedment (d) for the two different confining wall widths (L): 300 mm and 500 mm. As shown in Fig. 8, the bearing capacity increases as the increase in the depth of embedment (d) of the wall and it decreases in increasing the width of lateral confinement (L).

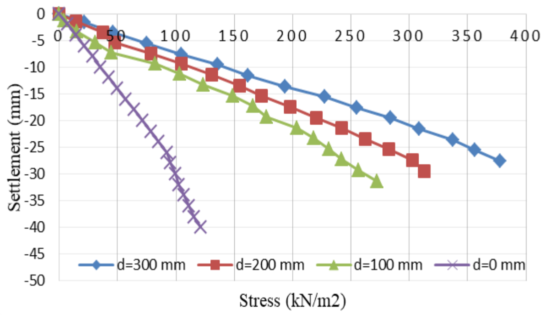

Fig. 7 Settlement- stress relationship for L=300 mm for different depths of embedment (d).

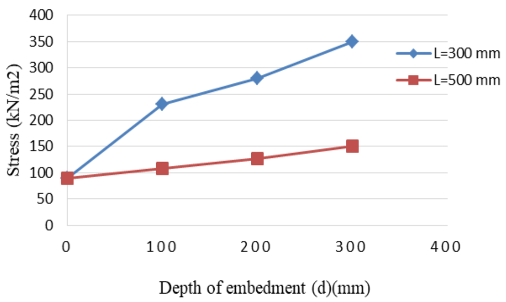

Fig. 8 Stress- depth of embedment relationship for a settlement of 25 mm in foundation models.

5.2 Validation of Numerical Model

The results from the numerical analysis supported the results from the experimental models which are compared in Fig. 9. There was an improvement in settlement behavior with the increase in depth of embedment (d) and when the confinement is closer to the footing.

Fig. 10, Fig. 11, Fig. 12 and Fig. 13 shows the typical stress distribution and displacement for confining wall radius (R) of 169.8 mm and 282.1mm respectively. It was observed that when the wall is closer to the footing (for R=169.8 mm) the wall disturbs the displacement of the soil and the stress bulb, but when the distance increases (for R=282.1 mm) the effect is minimized.

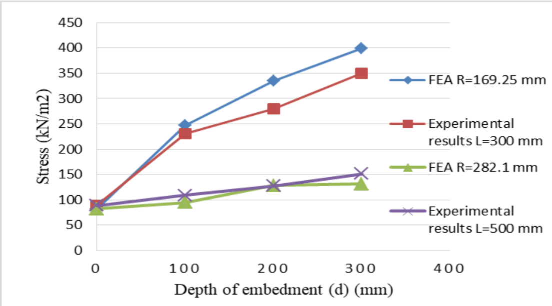

Fig. 9 Comparison of experimental and FE analysis stress vs depth of embedment relationship at 25 mm settlement.

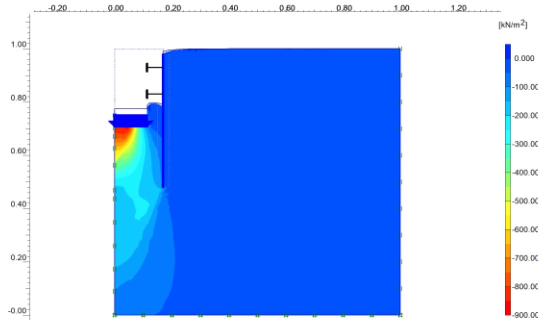

Fig. 10 Typical stress distribution for R=169.8 mm.

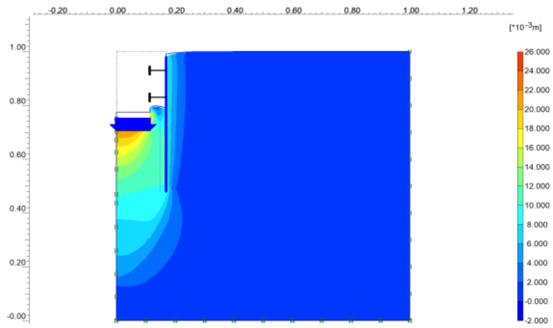

Fig. 11 Typical total displacement diagram of soil for R=169.8 mm.

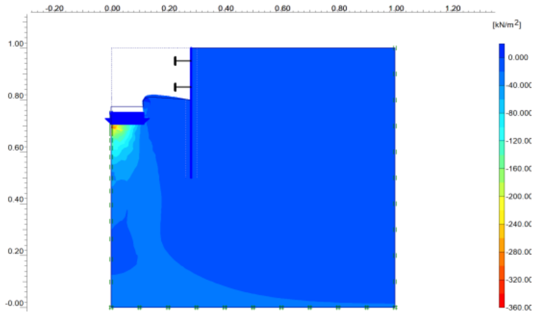

Fig. 12 Typical stress distribution for R=282.1 mm.

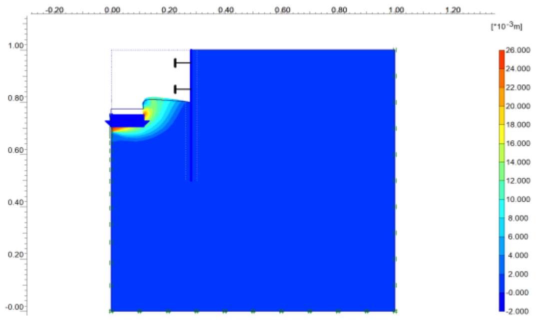

Fig. 13 Typical total displacement diagram of soil for R= 282.1 mm.

It was observed that when the gap between wall and footing is small and the foundation has well confined the footing and the wall vertically settle together up to some extent. However, when the gap is high the footing settles down while the wall is unaffected. This behavior is illustrated in the Fig. 14 for a well confined (R=169.25 mm and D=500 mm) and less confined (R=282.1 mm and D=500 mm) situations. When the footing is well confined, the wall has settled by 10 mm for a settlement of 25 mm in the footing with the increase in force. For a less confined situation, where the gap between wall and footing is high there is no significant settlement in the wall, although the footing has settled by 25 mm.

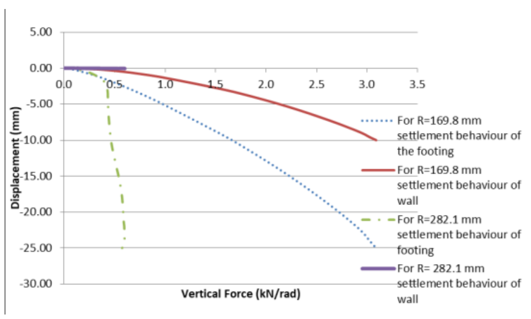

Fig. 14 Settlements - Vertical force relationship between footing and wall for R=169.8 mm and R=282.1 mm

When the stress on the bearing soil increases the soil will displace in the vertical direction mobilizing friction between soil and the wall. This will result in the system to behave as one unit when the footing is well confined. Due to the increase in shear resistance, the allowable bearing capacity against excessive settlement was increased. Furthermore, with the increase in the wall height the surface area of the system increases resulting in an increase in the shear resistance. This will improve the settlement behavior of confined footings with the depth of embedment.

5.3 Performance of Raft Foundation

Finite element model shows the performance of a raft confined by a deep embedded retaining wall with a moderate level of complexity. The raft foundation was assumed to behave as a rigid footing for the comparison purpose of results with the scaled models. For a uniform prescribed vertical displacement of 50 mm, the average stress immediately below the raft foundation was obtained by changing the depth of embedment and the distance to the lateral confinement from the raft edge. Similarly, for different raft widths, the effect of confinement on bearing capacity (Stress at 50 mm settlement) was investigated.

Fig. 15 illustrates the total displacement diagram obtained from the numerical analysis of footing width (B) of 20 m placed on sand without any confinement. For a confined footing of width (B) of 20 m, with a depth of wall embedment (d) of 12 m and gap between wall and footing of 0.5 m, the total displacement is shown in Fig. 16. It was observed that even though there is a change in the displacement pattern due to the restriction of sand movement in a lateral direction that displacement is very low near the wall. When the vertical stress distribution below unconfined and confined footings was compared, no significant change was observed as shown in Fig. 17 and Fig. 18

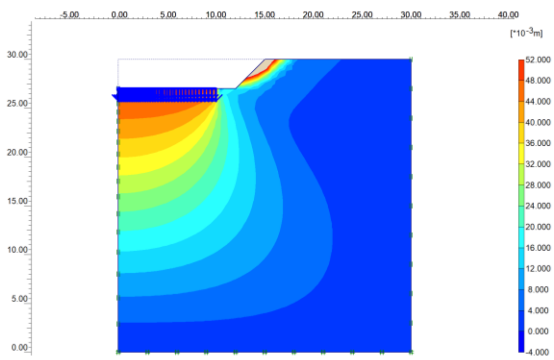

Fig. 15 Typical total displacement diagram of soil for an unconfined raft footing.

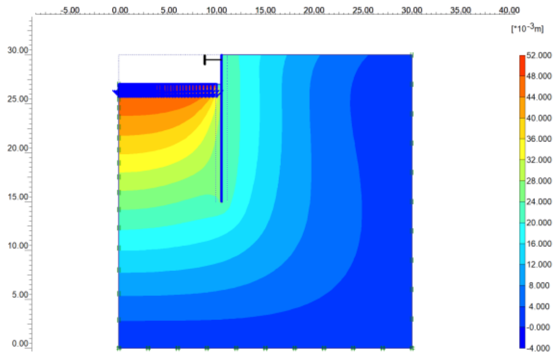

Fig. 16 Typical total displacement diagram of soil for a confined raft footing.

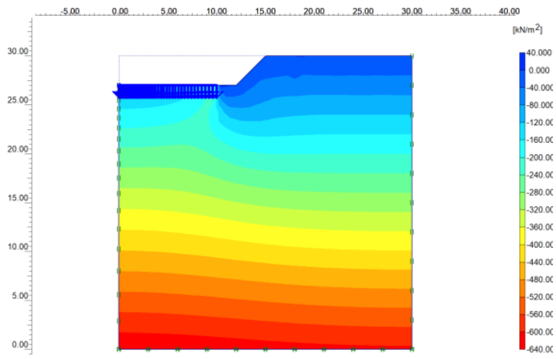

Fig. 17 Typical stress distribution diagram of soil for an unconfined raft footing

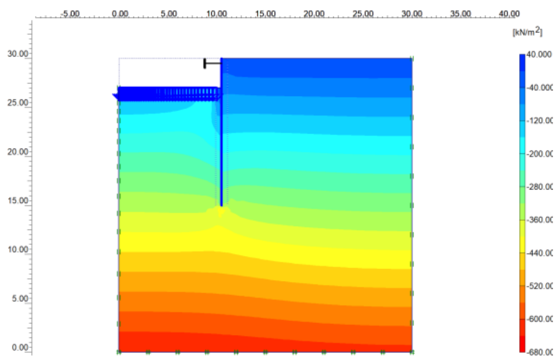

Fig. 18 Typical stress distribution diagram of soil for a confined raft footing

The variation of allowable bearing capacity for foundation widths of (B) 20 m, 10 m and 3 m with the depth of embedment of the lateral confinement is shown in Fig. 19. It can be observed there is no significant difference in the average vertical stress due to the lateral confinement of foundation on sand. Similarly, there is no significant difference in the allowable bearing capacity with the distance to the confinement from footing edge (x), as shown in Fig. 20.

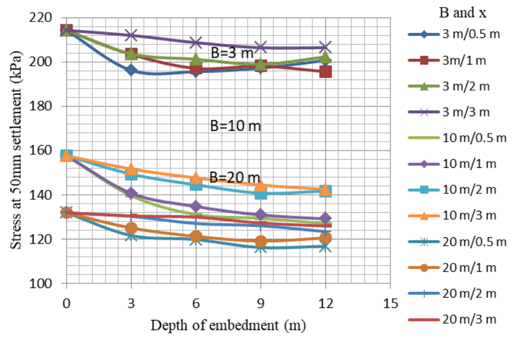

Fig. 19 The relationship between stress at 50 mm settlement and depth of embedment for B=3 m B=10 m and B=20 m and x=0.5 m, x=1 m, x=2 m and x=3 m.

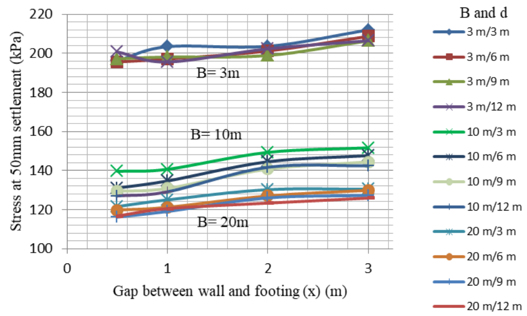

Fig. 20 The relationship between stress at 50 mm settlement and distance to the wall from footing edge for B=3 m B=10 m and B=20 m and d=3 m, d=6 m, d=9 m and d=12 m

The behavior of the computer simulation of raft foundations is not in agreement with the behavior of the experimental and numerical analysis results on scaled confined foundations. This is because the vertical settlement considered in the raft is very small when compared to the footing size and model dimensions. Therefore the stress developed and soil displacement is not significant. As in Fig. 16, the movement of soil is vertical and the effect of confinement is negligible. Therefore, no significant improvement in settlement characteristics could be observed within the allowable settlement limit when the soil is confined.

6. CONCLUSION

In this paper, the effect of lateral confinement on the settlement characteristics of shallow foundations on sand was studied using a laboratory experimental setup and numerical analysis. Then the settlement behavior of confined and unconfined raft foundations on sand was also numerically analyzed.

It can be concluded that when the excessive settlement is the governing factor for the allowable bearing capacity in small shallow foundations, then it can be improved by lateral confinement. The allowable bearing capacity at the maximum tolerable settlement can be improved with the depth of embedment of the lateral confinement. Similarly, when the distance to the wall from the footing edge is decreased there is an improvement in the settlement behavior. It was observed for the study variables considered in this study, the bearing capacity can be improved up to 4 times with the use of lateral confinements. From the numerical analysis it is evident that when the foundation is closer to the wall where the soil is well confined, the foundation settles along with the lateral confinement.

From the computer simulation of confined and unconfined raft foundations, no significant improvement in stress could be observed at the tolerable maximum settlement. This is because of the size of the footing and the lateral confinement is larger when compared to the allowable value of the settlement.

Hence, in small shallow footings with the use of lateral confinement, the allowable bearing capacity for the tolerable settlement can be improved. However, the advantage of having confinement is minimized with the increase in the size of the footing.

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