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Evaluating of Bearing Capacity of Two Adjacent Strip Foundations Located around a Soil Slip

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***Abstract*—**Selection of soil bearing capacity is an important issue that should be investigated under different conditions. The bearing capacity of foundation around of soil slope is based on the active and passive forces. On the other hand, due to extension of urban structures, it is inevitable to put the foundations together. Concerning the two cases mentioned above, investigating the behavior of adjacent foundations which are constructed besides soil slope is essential. It should be noted that, according to the conditions, the bearing capacity of adjacent foundations can be less or more than mat foundations. Also, soil reinforcement increases the bearing capacity of adjacent foundations, and the amount of its increase depends on the distance between foundations. In this research, based on numerical studies, a method is presented for evaluating ultimate bearing capacity of adjacent foundations at different intervals. In the present study, the effect of foundation width, the center to center distance of adjacent foundations and reinforced soil has been investigated on the bearing capacity of adjacent foundations beside soil slope. The results indicate that, due to interference of failure surfaces created under foundation, it depends on their intervals and the ultimate bearing capacity of foundation varies.

***Keywords*—**Adjacent foundation, bearing capacity, reinforcements, settlement, numerical analysis.

I. Introduction

DUE to the rapid population growth and urbanization, construction of shallow and deep foundations in the vicinity of soil slopes is unavoidable in engineering designs. So, bearing capacity determination and stabilization of soil under and adjacent of slopes is essential. Slopes consistence can be improved in a variety of ways such as correction of gradient geometry, chemical injection, soil nailing, reinforcing with geo-grid and installation of piles and sheet piles. Soil reinforcement is an effective and reliable technique for improving the strength, stiffness and stability of soil. A long time ago, natural fiber was used to reinforce the soil, recently geotextiles are a popular option as they are cost-effective, more profitable and highly adaptable.

Several researches have been carried out to demonstrate that the ultimate bearing capacity and settlement characteristics of the foundation can be improved by the inclusion of reinforcements in the ground. The concept of plastic equilibrium is used to investigate the ultimate bearing capacity of a particular soil under a shallow footing theoretically [1], [2]. Later, it was modified, generalized and updated [3]-[7].

Some studies have been carried out to discuss the influence of reinforcements on the bearing capacity of single foundations on sand [8]-[13]. It has been revealed that reinforcing the foundation soil can significantly increase the ultimate bearing capacity.

A number of large-scale model tests were performed to evaluate the ultimate bearing capacity, settlement and tilt of two types closely spaced footing (square and circular shapes) [14]. The results show that the ultimate bearing capacity of the interfering footings increased by about 25–40%, whereas the settlement of the interfering footings at the ultimate load increased in the range of 60–100%. However, the closely spaced footings tilted by approximately 45% and 75% for reinforced sand with one and two layers of geo-grid, respectively.

Reference [15] conducted a number of model tests to determine the load carrying capacity of geo-grid-reinforced sand subjected to eccentric loads. Based on the laboratory test results, an empirical relationship called reduction factor, R_k was found out, which correlates the ratio of the load carrying capacity of a foundation subjected to eccentric load, with that of centrally loaded one.

The influence of geo-grid reinforcement on the eccentrically loaded bearing capacity of strip footing is investigated by PLAXIS 2D [16]. The results showed that increasing the number of geo-grid layers (*N*) significantly increased the load carrying capacity, but there was an optimum value after which little effect was observed. These optimum values were varied (*N*=3- 4) depending on the value of load eccentricity ratio (*e/B*) and depth of footing (*Df/B*).

It is found for static load that by increasing the space between footings, maximum settlement and tilt of an interfering decrease and for seismic loading they increase with increase in height [17]. To investigate the influence of different geo-parameters on the ultimate bearing capacity, footings located near the sloping ground were modeled with PLAXIS 3D on the basis of the finite element numerical simulation [18].

II. Soil Specification

The soil specification has been expressed in Table I. In the current study, soil is simulated as shell elements and each element is defined by eight nodes. Drucker-Pruger's behavioral model has been used to consider non-linear behavior of soil. Also, reinforcement layers are defined as type of linear elements with five nodes. It should be noted that reinforcement behavior is considered elastic because the

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stiffness of them is far more than the soil. In order to model the soil block, the model size has been considered in such a way that the stress bubbles have the least collision with side and bottom boundaries. For this purpose, as for the width of foundation and the length of geo-grid in the model, the model was simulated as a soil block with dimension of 40*10*8m in the length, width and height, respectively (Fig. 1). The number of available mesh elements is 8652 and they are considered small enough.

TABLE I
SPECIFICATION OF USED SAND

Soil type	Sand
Ψ (Degree)	2
C (kg/m^2)	0
φ (degree)	32
γ (kg/m^3)	1820
υ	0.35
E (kg/m^2)	50000000

TABLE II
SPECIFICATION OF GEOGRID

Tensile strength (kN/m)	7.68
Extension at maximum load (%)	20.2
Tensile strength at 10% extension (kN/m)	6.8
Extension at 1/2 peak load (%)	3.2
EA (kN/m)	35

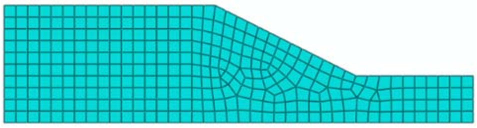

Fig. 1 Overview of soil block's mesh elements

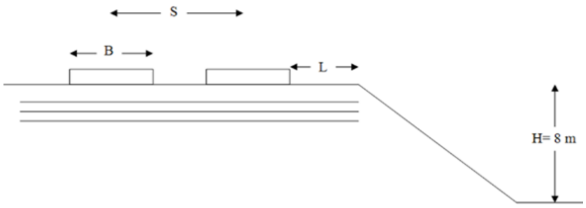

Fig. 2 Geometrical scheme for interfering footings on reinforced soil

In this research, the effect of using geo-grid on the bearing capacity of strip footings by considering the effect of interference between two adjacent footings beside soil slope is discussed. For this purpose, the two-dimensional numerical analysis by using finite element software ABAQUS, as shown in Fig. 2, has been done on two strip footings with different width (B) which are located at different center to center distance of foundations (S) and different distance from the slope edge (L) in unreinforced and reinforced states with 2, 3 and 4 geo-grid layers. In order to investigate the effect of B on the bearing capacity, various ratios of (S/B= 2, 3) have been used. Also, the closest distances to the slope edge (L) are considered 2, 4 and 6 m. It should be noted that the height of the excavation is assumed 8 m.

III. FOUNDATION WITH 2M WIDTH

In accordance with Figs. 3-5, bearing capacity changes for strip footings with 2m width are shown for states L are 6, 4 and 2 m. In these cases, the ratio S/B is 2.

As the results show, by increasing the number of reinforcement layers from 3 to 4 layers, the percentage increase of the bearing capacity for the adjacent strip foundations reduces while S/B=2 and L=6.

Results of strip foundation with 2 m width, while L is 4 m, show that, in unreinforced soil, the bearing capacity is about 6000 kg/m^2 however by reinforcing the below of strip footings, it increases 50% and reaches 9000 kg/m^2. It is obvious that increasing the number of reinforcement layers causes an increase of 83% to 93% in the bearing capacity for reinforced soil than unreinforced soil. In brief, it can be mentioned by reducing L, the number of layers should be increased.

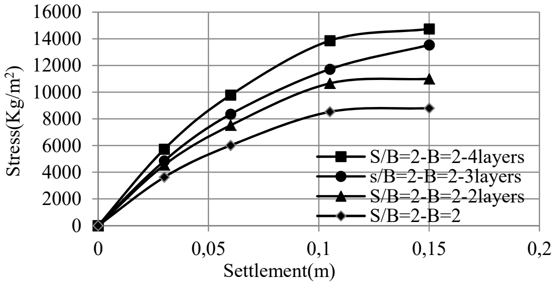

Fig. 3 Bearing capacity for strip foundation in width of 2m for both reinforced and unreinforced soil at a distance of 6m from the slope edge with S/B=2

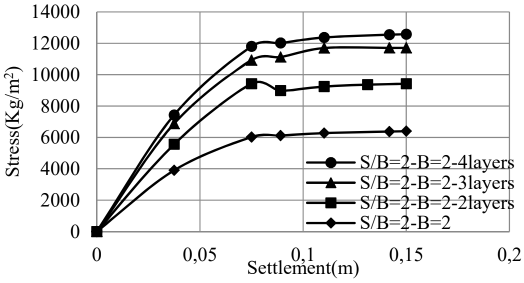

Fig. 4 Bearing capacity for strip foundation in width of 2 m for both reinforced and unreinforced soil at a distance of 4 m from the slope edge with S/B=2

According to the results of strip footing with (B=2m), in the case of the least distance between the foundation edge and slope edge (L=2), the bearing capacity variation by increasing the number of unreinforcement layers from 2 to 3 are approximately equivalent to the state of increasing reinforcement layers from 3 to 4. Therefore, it can be expressed that if the footing edge is closer to the slope edge, the impact of increasing number of reinforcements will be more tangible. Its changes due to increase in the number of reinforcements from 2 to 3 and 3 to 4 are about same.

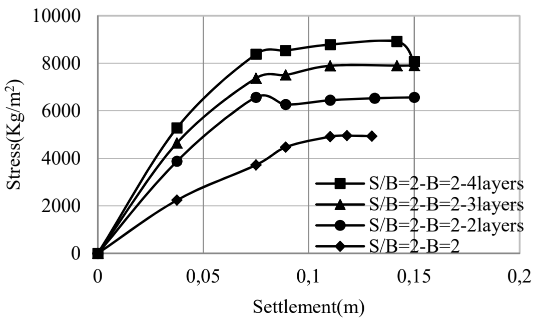

Fig. 5 Bearing capacity for strip foundation in width of 2m for both reinforced and unreinforced soil at a distance of 2m from the slope edge with S/B=2

The ultimate stress variations for the strip footing with B=2 m and S/B=2 that reinforced with two layers show that increasing (L) from 2 to 4 m causes a 28% increase in ultimate bearing capacity (Fig. 6). A further increase of L to 6 m results in a 16% enhancement in the ultimate bearing capacity compared to L=4m.

Briefly, it can be said that for a strip footing with 2 m width and S/B=2, critical conditions dominate on the footings by reducing L to 2m, and due to the interference of stress bubbles with failure surface the bearing capacity is strongly affected (Figs. 7 and 8). However, with increasing L, stress bubbles interfere with the surface less, and as a result, the effect of reducing procedure bearing capacity becomes less.

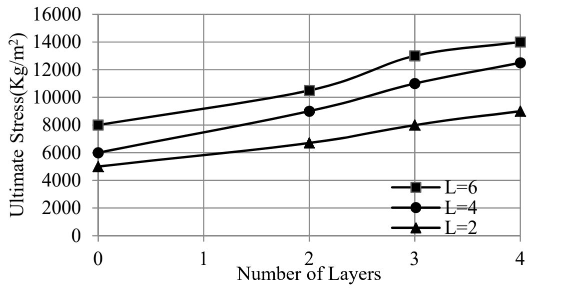

Fig. 6 Ultimate stress for strip foundation in width of 2 m for both reinforced and unreinforced soil at different distance from slope edge and S/B=2 with S/B=2

In Figs. 9-11, the effect of the interference of footings with B=2m and s/b=3 is investigated.

In the event the foundation edge distance from the slope is 6 m, the bearing capacity for unreinforced state is about 9000 kg/m^2. By adding two layers of the geo-grid in below of foundation, the bearing capacity increased 33%. In the case of increasing the number of reinforcement layers to 3 and 4, the bearing capacity of strip foundations in width of 2 m is about 14200 kg/m^2 and 16100 kg/m^2, respectively.

The result shows that, by increasing the distance from the center to center relative to the foundation width, the effect of foundations conflict has decreased. There are fewer attenuating bubbles in each other and that makes the bearing capacity less affected by the adjacent foundation.

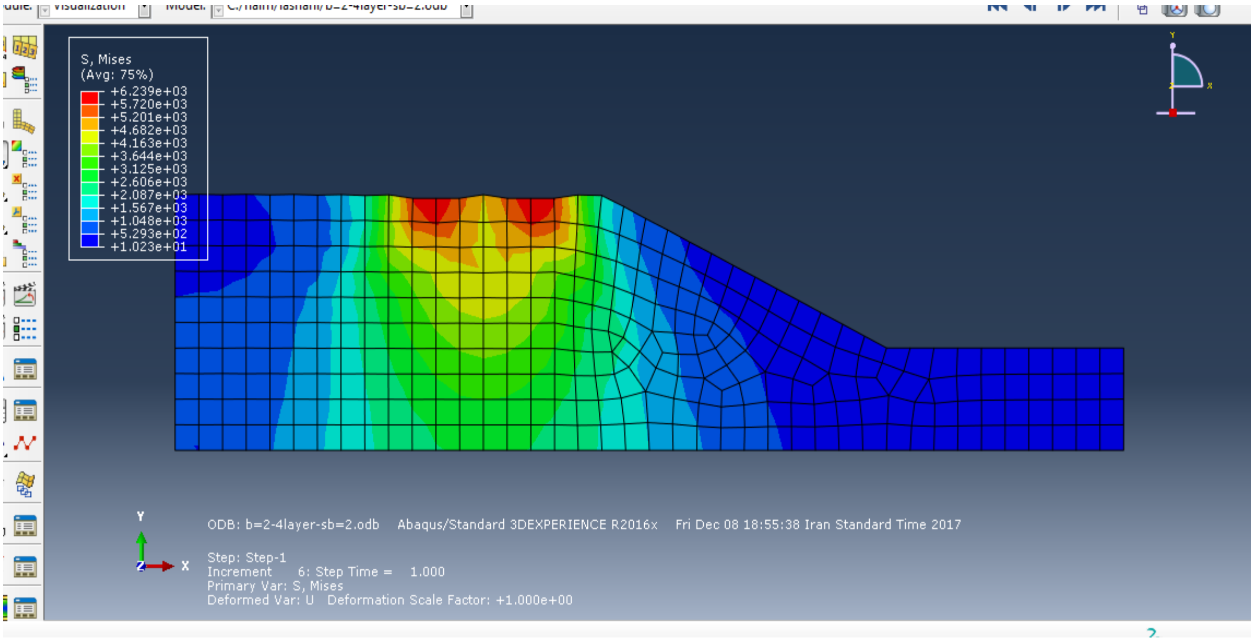

Fig. 7 Interference of stress bubbles for strip foundation in width of 2 m in case of L=2m and S/B=2

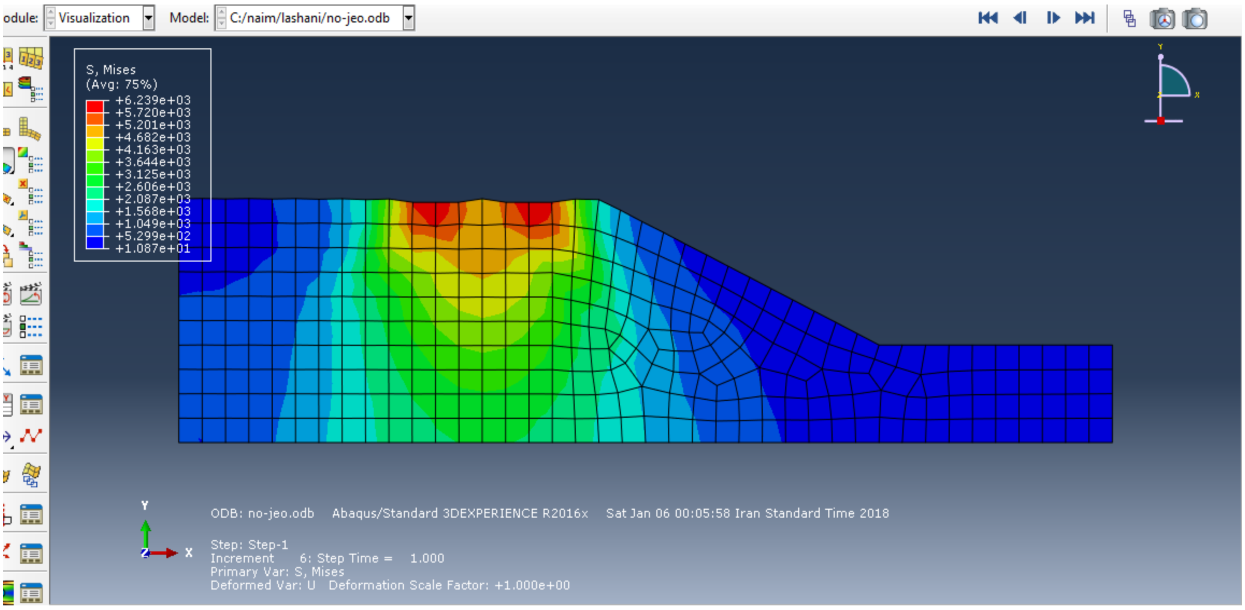

Fig. 8 interference of stress bubbles for strip foundation in width of 2 m in case of L=4m and S/B=2

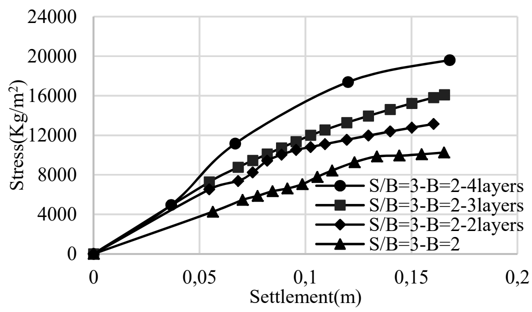

Fig. 9 Bearing capacity for strip foundation in width of 2 m for both reinforced and unreinforced soil at a distance of 6m from the slope edge with S/B=3

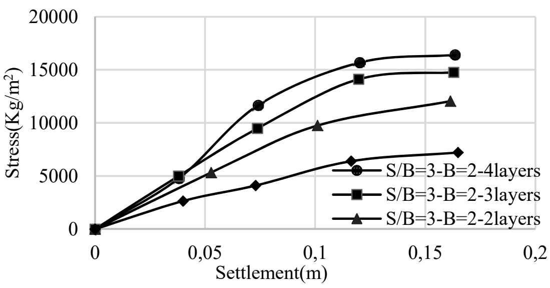

Fig. 10 Bearing capacity for strip foundation with 2 m width for both reinforced and unreinforced soil at a distance of 4m from the slope edge with S/B=3

In Fig. 12, the ultimate stress variation for strip foundation with B=2m are shown in different distance between foundation edge and slope (L) in two modes of reinforced and unreinforced. According to the results, by increasing (L), bearing capacity increases. For example, in the case of S/B=3 and adjacent foundations are located in unreinforced soil, the amount of bearing capacity for L= 2, 4 and 6 m is 6000, 6200 and 9000 kg/m^2. However, by decreasing the S/B ratio to 2, the ultimate bearing capacity at unreinforced state is 5000, 5800 and 8000 kg/m^2, respectively. As it is seen, the increase in the S/B ratio causes increasing of bearing capacity in unreinforced soil.

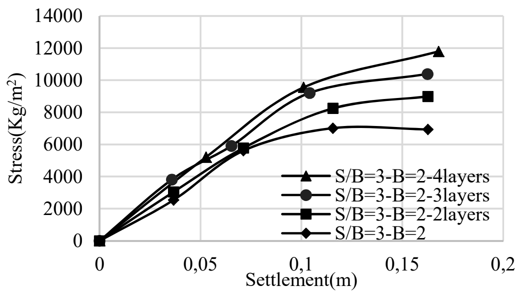

Fig. 11 Bearing capacity for strip foundation in width of 2 m for both reinforced and unreinforced soil at a distance of 2 m from the slope edge with S/B=3

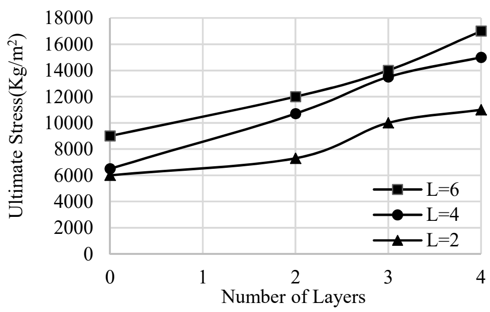

Fig. 12 Ultimate stress for strip foundation in width of 2m for both reinforced and unreinforced soil at different distance from slope edge and S/B=3

IV. Foundation with 4m Width

According Fig. 14, when L=6m, the bearing capacity is 1000 kg/m^2 in unreinforced soil, and by reinforcing soil with 2 layers in addition to increasing foundation stability, the bearing capacity increases to 13500 kg/m^2. With a further increase in reinforcement layers to 3 and 4, the bearing capacity has increased up to 16500 and 17500 kg/m^2, respectively. Pursuant to Fig. 2, by reducing L to 4m the bearing capacity decreased for both reinforced and unreinforced soil. The results show for strip footing with B=4m, S/B=2 and L=4m, the bearing capacity is 8000 kg/m^2 in unreinforced soil but by locating 2 reinforcement layers in below of foundation, it increases 37% and attains to 12000 kg/m^2. By increasing the number of reinforcements to 3 layers, the bearing capacity is 13000 kg/m^2 which improves about 62% relative to unreinforced soil (Fig. 15). It should be mentioned that by increasing the number of reinforcements to 4 layers, the bearing capacity about 14000 kg/m^2, which is equivalent to an increase of 72% compared to the unreinforced soil. In Fig.16, with a further reduction of L to 2m, the bearing capacity for S/B=2 is 6000 kg/m^2 in unreinforced soil, however by reinforcing the soil by 2 reinforcement layers increase by about 36% (In this case the bearing capacity is about 8200 kg/m^2, Fig. 16). By increasing reinforcements to 3 and 4, the bearing capacity increase up to 10000 and 11500 kg/m^2, respectively. It should be noted that, in this case by increasing the reinforcement layers to 3, the bearing capacity in comparison with two reinforcement layers improves 21% and with further increase reinforcement to 4 layers, its increment relative to three reinforcement layers is about 15% more.

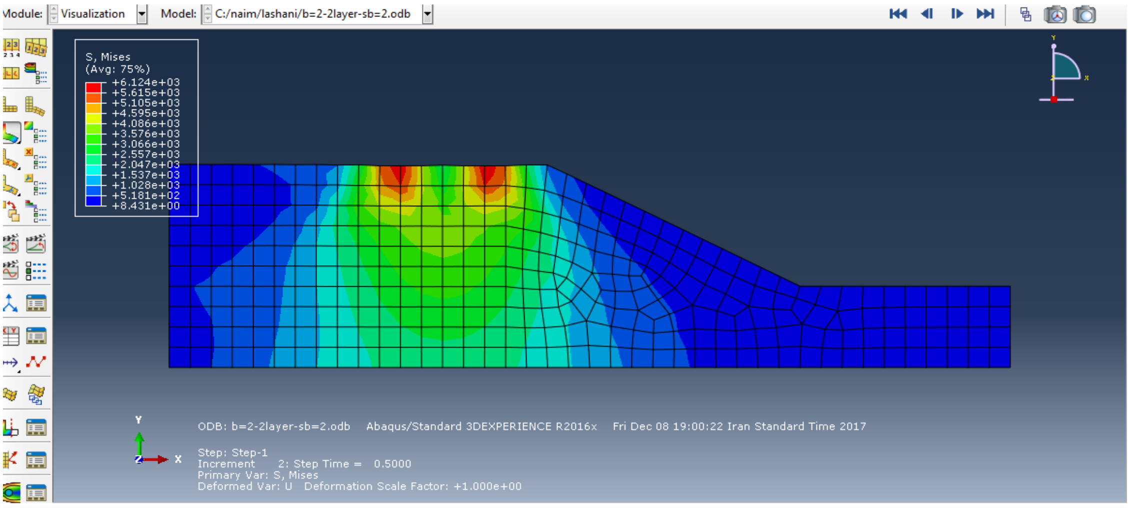

Fig. 13 Interference of stress bubbles for strip foundation in width of 2m in case of L=2m and S/B=2

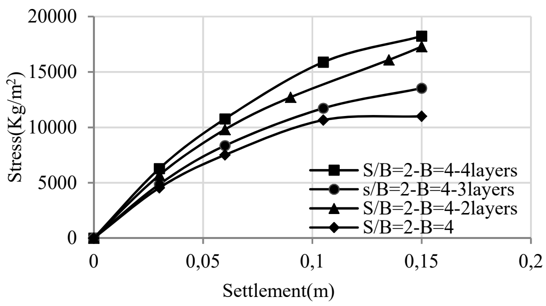

Fig. 14 Bearing capacity for strip foundation with 4 m width for both reinforced and unreinforced soil at a distance of 6 m from the slope edge with S/B=2

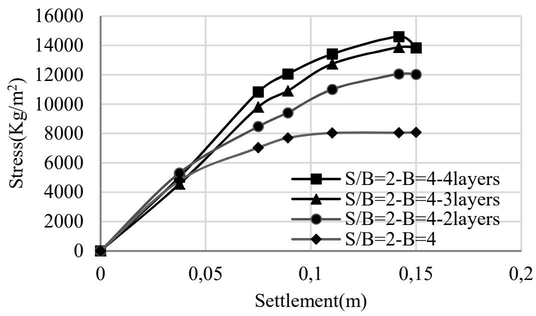

Fig. 15 Bearing capacity for strip foundation with 4 m width for both reinforced and unreinforced soil at a distance of 4 m from the slope edge with S/B=2

As can be seen, similar to the 2-m wide foundation, by increasing the reinforcement layers from 2 to 3, the bearing capacity increment is far greater than the case where the number of reinforcements increases from 3 to 4.

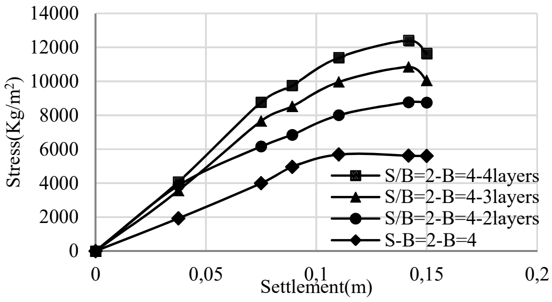

Fig. 16 Bearing capacity for strip foundation with 4 m width for both reinforced and unreinforced soil at a distance of 2 m from the slope edge with S/B=2

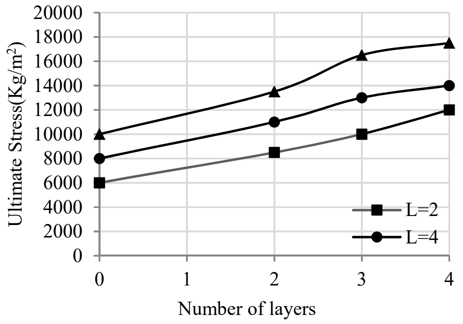

Fig. 17 Ultimate stress for strip foundation in width of 4m for both reinforced and unreinforced soil at different distance from slope edge and S/B=2

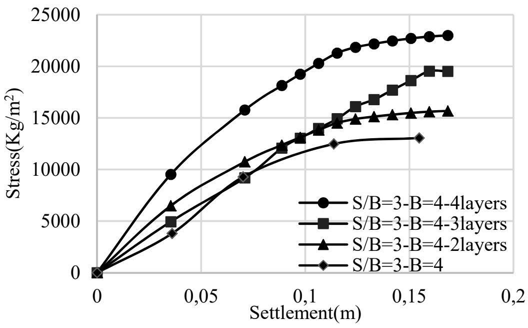

Fig. 18 Bearing capacity for strip foundation in width of 4 m for both reinforced and unreinforced soil at a distance of 6 m from the slope edge with S/B=3

As shown in Fig. 18, the bearing capacity for a strip footing with B=4m and L=6m is 14000, 15000, 20000 and 23000 kg/m^{2}for unreinforced soil and reinforced with 2, 3 and 4 reinforcements layers. The results show, in this situation by increasing the reinforcement layers from 2 to 3, the ultimate capacity increases about 20% while by increasing layers to 4 the bearing capacity increment is about 11% more than three layers. Also, the variations of bearing capacity for strip foundation with B=4 m and L=4 m are shown in Fig. 19. As seen, for S/B=3 and L=4 the bearing capacity for strip footing with B=4 m is about 10000 kg/m^2 in unreinforced soil and by reinforcing the below of foundation with two reinforcement layers, it arrives 14000 kg/m^2 which is equivalent with 44% increment in the bearing capacity of adjacent foundations. By increasing the reinforcement layers to 3 and 4, it gets about 17000 and 19000 kg/m^2, respectively. It can be indicated that for case reinforced by three layers the bearing capacity is near 23% more than reinforced by two layers. Also, in comparison with reinforced by three layers, by increasing reinforcements to four layers the bearing capacity increases about 14%. By reducing L to 2m, the bearing capacity is about 7000 kg/m^2 in unreinforced soil. The results show that by reducing L from 6 m to 4 m, the bearing capacity reduces about 15% and with a further decrease of L to 2m, in comparison with L=4 m, it reduces about 24%. The related results with reinforced soil for strip footing with B=4 m, S/B=3 and L=2 m show by placing two reinforcements layers in below of foundation, the bearing capacity is almost 1000 kg/m^2 and by increasing layers from 3 to 4, the ultimate bearing capacity is nearly 14000 and 15000 kg/m^2, respectively. According to the results of Fig. 21, when four reinforcement layers are located in below of foundation, with an increase in L from 2 to 4 m, the bearing capacity increases 18% and with a further increase of L to 6 m, the bearing capacity for reinforced by four layers is about 11% more than case of L=4 m. According to the results, due to less collision of stress bubbles with slope edge the variation of the bearing capacity by increasing L from 2 to 4 is more in comparison with its variation by increasing L from 4 to 6 m.

V. Conclusion

With economic development and population growth, there are a large number of new buildings, most of which are constructed adjacent to each other regardless the influence of interference. Therefore, the safety of adjacent buildings has become a fundemental issue. The effects of interference between fundations in a group have a significant consequence on design factors and without sufficient informations from these, the engineer is not able to use them in the calculations and as a result designs will not be effective. In this research, using the ABAQUS software, the bearing capacity of interupted strip footings with a width of 2 m, which are located at different distances from slope edge in both reinforced and unreinforced soil are discussed. It should be noted that one of the important factors studied in this research is the center to center distance of adjacent footings, which has been investigated in two cases. According to the load-settlement diagrams, the results are as follows:

The result shows that by increasing the ratio of center to center distance to the foundation width from 2 to 3, for strip foundation in width 2 m and 6 m away from slope edge, the bearing capacity increases about 10% at unreinforced state.

By increasing the width of foundation to 4 m, the effect of L parameter is less significant. The result for foundation with 4 m width, shows that, by increasing L from 2 to 4, the bearing capacity rises more than by changing L from 4 to 6 m. Also, the results shows that, for foundation by 4 m wide, by increasing the S/B, the bearing capacity changes more than foundation in 2 width because by rising B, the stress bubbles are extended it causes by increasing S/B from 2 to 3, changing in bearing capacity become less than foundation in 2 m width.

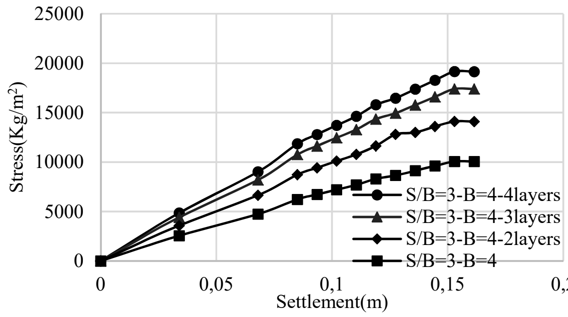

Fig. 19 Bearing capacity for strip foundation in width of 4m for both reinforced and unreinforced soil at a distance of 4m from the slope edge with S/B=3

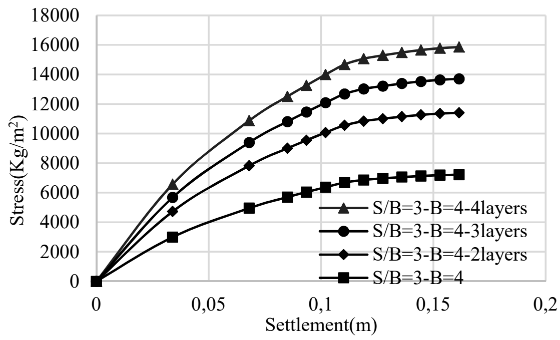

Fig. 20 Bearing capacity for strip foundation in width of 4 m for both reinforced and unreinforced soil at a distance of 2 m from the slope edge with S/B=3

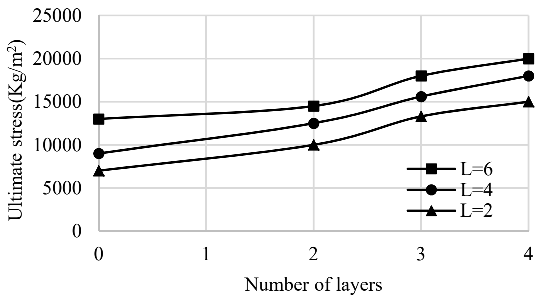

Fig. 21 Ultimate stress for strip foundation in width of 4m for both reinforced and unreinforced soil at different distance from slope edge and S/B=3

In general, it can be said that increasing the center to center distance relative to width, the influence of foundation interference descreases and so the stress bubbles have less interference in each other and this causes the bearing capacity to be less affected by its adjacent foundation. Therefore, a slight increase in the bearing capacity of foundation is observed.

The results show for S/B=2 in strip foundation with width of 2m, by adding two reinforcement layers in case of it has the closest interval to the slope edge, the bearing capacity changes relative to the unreinforced state were minimum and observed about 13% increase in the foundation's bearing capacity. By increasing the distance between foundation and slope edge (L= 4,6), the value of bearing capacity reinforced in to layers relative to unreinforced increases about 25%.

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