Full Length Research Paper

3d Numerical Analysis of Bearing Capacity of Square Foundations on Geogrid Reinforced Soil

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Abstract. Results of numerical simulations on square footing supported by reinforced and unreinforced sand bed are presented and discussed. The primary objective of this study is to evaluate the performance of geogrid layers in improving the bearing capacity of the square footings and to study the influence of different parameters such as the width and embedment depth of the foundation, on the overall performance improvement of the footing. The optimum values of reinforcement parameters (such as vertical spacing between top layer of reinforcement and bottom of the foundation, the width of the reinforcement layers, the distance between consecutive reinforcement layers and the depth of reinforcement zone) have been obtained from previous experimental studies, and was applied in numerical modeling. The results of the numerical simulations are compared with the experimental and analytical results published by different authors. It was found that with increasing the width and embedment depth of the foundation, the rate of increment of bearing capacity due to reinforcing with geogrid, was reduced.

Keywords: Geogrid, Bearing capacity of square foundations, 3D Numerical modeling, embedment depth and width of the foundation

1. INTRODUCTION

Geogrid materials have been widely used in geotechnical engineering applications. An essential usage is for improving the bearing capacity of footings. Since the mid-1970s a number of studies have been conducted to evaluate the possibility of constructing shallow foundations on reinforced soil to increase their bearing capacity. However, most of these studies are on strip or circular footings despite the fact that the square footings are more common in practice. The studies on square footings resting on reinforced soils are limited (Akinmusuru and Akinbolade, 1981; Omar et al., 1993; Adams and Collin, 1997; Chung and Cascante, 2007; Latha and Somwanshi, 2009).

It should be noted, most studies have been conducted in laboratory (small) scale. Due to equipments, numerical modeling with real size and after verifying and comparing with results of laboratory model test can be useful. Another point is, there isn’t proper attention to the effect of the depth of embedment and width of the foundation which are the normal situation in all practical cases of construction.

As mentioned, results of the numerical Simulations with the code PLAXIS3D on square footing supported by sand bed with and without geogrid reinforcement are presented and discussed. The influence of different parameters such as the width and embedment depth of the foundation, are investigated.

The ultimate bearing capacity of reinforced soil obtained from the numerical modeling has been compared with the analytical and experimental observations. The obtained results show that numerical modeling results are in concordance with the analytical and experimental results.
2. ANALYTICAL RELATIONS AND EXPERIMENTAL RESULTS FOR BEARING CAPACITY OF SQUARE FOUNDATIONS ON SAND BED

2.1. Analytical Relations

For vertical loading condition, the ultimate bearing capacity, $q_u$, of a square foundation on unreinforced sand can be expressed as:

$$q_u = \frac{1}{2} \gamma B N_q F_{\gamma d} F_{\gamma z} + q N_q F_{q d} F_{q z}$$

(1)

where $q = \gamma d_f$, and $\gamma$ is unit weight of sand, $d_f$ is embedment depth of foundation, $N_q$ and $N_\gamma$ are the bearing capacity coefficients, $F_{\gamma d}$ and $F_{q d}$ are the depth factors, $F_\gamma$ and $F_q$ are the shape factors, and $B$ is the foundation width.

The mentioned factors can be given by the following relations (Vesic, 1973 and Hansen, 1970).

$$N_\gamma = 2(N_q + 1) \tan \varphi \quad (\text{Vesic})$$

$$N_\gamma = 1.5(N_q - 1) \tan \varphi \quad (\text{Hansen})$$

(3)

Where $\varphi$ is the internal friction angle of soil. Depth and shape factors can be expressed as:

$$F_{\gamma d} = 1 + 2 \tan \varphi \left(1 - \sin \varphi\right)^2 \frac{d_f}{B}$$

$$F_{q d} = 1$$

$$F_{\gamma z} = 1 + \tan \varphi \quad (\text{Vesic})$$

$$F_{q z} = 1 + \sin \varphi \quad (\text{Hansen})$$

$$F_{\gamma q} = 0.6$$

(4)

For vertical loading condition, Huang and Menq (1997) have provided a tentative relationship to determine the ultimate bearing capacity of a square surface foundation on reinforced sand ($q_{u(R)}$) based on “wide-slab mechanism” as shown in Figure 1. (This mechanism accounts the increase in the bearing capacity of footings. The wide-slab mechanism dominates only when a quasi-rigid earth slab below the footing extends beyond the width of the footing.)

The ultimate bearing capacity of a square foundation on reinforced sand ($q_{u(R)}$) can be expressed as:

$$q_{u(R)} = 0.4(B + \Delta B)\gamma N_q + \gamma d N_q$$

(6)

$$\Delta B = 2d \tan \beta$$

(7)

$$\tan \beta = 0.63 - 2.071 \left(\frac{h}{B}\right) + 0.743(CR) + 0.03\left(\frac{b}{B}\right)$$

(8)

In the above relationship, $N_\gamma$ proposed by Vesic (1973) is used. CR is the cover ratio (w/W); w = the width of longitudinal ribs of georid; W = the center-to-center spacing of the longitudinal ribs of georid. W and w are shown in Figure 2(a). The other parameters such as B, b, d, h, are shown in Figure 2(b).
As shown on Figure 2(b), the first layer of geogrid is located at a depth \( u \) below the foundation, and the vertical distance between consecutive layers of geogrids is \( h \). The total depth of reinforcement \( d \) can be given as:

\[
d = u + (N - 1)h
\]  

(9)

Das (2009) modified equation (6) slightly and estimated another relationship for bearing capacity of embedded square foundation on geogrid reinforced sand:

\[
q_{uR} = 0.4(B + \Delta B)rN_r + \gamma(d + d_f)N_q
\]  

(10)

The beneficial effects of reinforcement to increase the bearing capacity can be expressed in terms of a non-dimensional parameter called the bearing capacity ratio:

\[
BCR = \frac{q_{uR}}{q_u}
\]  

(11)

As mentioned \( q_{uR} \) and \( q_u \) are ultimate bearing capacities of a square foundation on reinforced and unreinforced sand respectively.

2.2. Experimental result from literature

Latha and Somwanshi (2009) presented Laboratory model test results for the ultimate bearing capacity of a square foundation supported by multi-layered Geosynthetics-reinforced sand. The model foundation used for their study was made of 25 mm thick rigid steel plate and measured 150 x 150 mm. The load tests were conducted in a combined test bed cum loading frame assembly. The sand beds were prepared in a steel test tank with inside dimensions 900 x 900 x 600 mm. The sand used in their study was dry sand with coefficient of uniformity (\( C_u \)) 3.04, coefficient of curvature (\( C_c \)) 1.13, effective particle size (\( D_{10} \)) 0.27 mm and specific gravity 2.63. The average dry unit weight of the sand was 15.6 kN/m3. According to the Unified Soil Classification System, the soil is classified as poorly graded sand with letter symbol SP. The friction angle of the sand at 70% relative density (Dr), as determined from standard triaxial compression tests on dry sand sample was 44°. They used four types of geosynthetics to reinforce sand bed in the model tests, Weak biaxial geogrid (WG), Strong biaxial geogrid (SG), Uniaxial geogrid (UG) and Geonet (GN). They used different types of geosynthetics to compare the operation of various types of geosynthetic under square foundation. Figure 3 shows the results of these tests. As seen in Figure 3, biaxial geogrids have the best performance for increasing the bearing capacity of square foundation on reinforced sand.

Figure 4 shows the ultimate bearing capacity of square foundation on unreinforced sand obtained from these tests in compare with equation (1) and by using \( N_r \) and \( F_{qs} \) presented by Vesic. As seen from Figure 4, the experimental values are higher than those obtained using equation (1). It should be noted that if friction angle \( \varphi = 47^\circ \) is used in equation (1) instead of \( \varphi = 44^\circ \), the result from tests are in concordance with the
analytical results obtained using equation (1). It shows that in unreinforced sand the results obtained from equation (1) are slightly conservative. As seen from equations (3) and (5), \( N_\gamma \) and \( F_{qs} \) presented by Hansen are lower than those presented by Vesic. It shows that the ultimate bearing capacity of square foundation on unreinforced sand obtained from equation (1) and by using \( N_\gamma \) and \( F_{qs} \) presented by Hansen is very conservative. Unfortunately, in reinforced sand the comparison between experimental results and analytical relationship is impossible because sufficient information of Properties of geosynthetics (cover ratio) is not available.

![Comparison between ultimate bearing capacity of square footing on unreinforced sand obtained from experimental and analytical results](image)

It should be mentioned that Latha and Somwanshi (2009) conducted some numerical analysis in large scale (foundation with dimensions 1.5 × 1.5 m) with FLAC3D to investigate the optimum values of reinforcement parameters. The results of these simulations are shown in Figure 5. As seen from Figure 5, the optimum ratios of the \( u/B \), \( h/B \) and \( b/B \) are 0.2, 0.2 and 4 respectively. These ratios will be used in future modeling.

Latha and Somwanshi (2009) mentioned that the addition of reinforcement layer beyond the depth of 2B under foundation does not contribute to the bearing capacity improvement, so the effective depth of reinforcement is 2B.

![Variation of bearing capacity ratio with the (a) u/B. (b) h/B. (c) b/B](image)

3. NUMERICAL MODELING

In this section 3D numerical analysis of surface and embedded square foundations on unreinforced and reinforced sand with multi-layered geogrid have been conducted by PLAXIS-3D and the results are presented.

3.1. Modeling parameters

The model dimensions have been chosen 8 × 8× 8 m to be far enough from the foundation and geogrids and have no effect on output results. The model foundation had a height of 0.5 m with different widths. To achieve the ultimate bearing capacity, prescribed displacement loading has been applied. Due to the symmetry of the soil-footing-reinforcement system and to reduce the time required for analysis, quarter symmetrical geometry simulated as a cubical soil grid was used to construct one fourth of the 3D media. Loose sand (cohesion less soil) was used in this modeling. The Mohr-Coulomb model has been used for sand behavior. The foundation material was assumed to be concrete. The elastic model has
been used for foundation modeling. The biaxial geogrids (SS40 produced by Tensar) have been used for modeling and the elastic model has been used for them. All parameters of modeling have been shown in them. All parameters of modeling have been shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Parameters of modeling</th>
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<tbody>
<tr>
<td>Material</td>
</tr>
<tr>
<td>--------------</td>
</tr>
<tr>
<td>Sand</td>
</tr>
<tr>
<td>Concrete</td>
</tr>
<tr>
<td>Geogrid</td>
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Two series of modelings with different parameters have been simulated by PLAXIS-3D to determine the effects of the width and embedment depth of the foundation, on the overall performance improvement of the footings. The details of these modeling series have been shown in Table 2.

<table>
<thead>
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<th>Table 2: Detail of modeling series</th>
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<tr>
<td>Material</td>
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<tr>
<td>A</td>
</tr>
<tr>
<td>B</td>
</tr>
</tbody>
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3.1. Results of numerical modeling

Modeling of series A were conducted on square footings with different ratio of ($d_f/B$), based on both unreinforced ($N=0$) and reinforced ($N=1, 2, 3, 4$) sand bed to investigate the effect of embedment depth of the foundation on bearing capacity.

Figure 6 presents the variation of the ultimate bearing capacity with normalized footing settlement (ratio of $s/B$) for different ratio of $d_f/B$.

![Fig. 6: Variation of bearing capacity with normalized footing settlement (ratio of $s/B$) for different ratio of $d_f/B$.](image)

Figure 7 shows the plot of ultimate bearing capacity of square footings on unreinforced soil ($N=0$) versus embedment ratio, obtained from these models in compare with equation (1) and by using $N_f$ presented by Vesic.

As shown in Figure 7, the numerical values are higher than those obtained using equation (1). It should be noted that if $\phi = 33^\circ$ is used in equation (1), instead of $\phi = 30^\circ$, the results from numerical modeling are in concordance with the analytical results obtained using equation (1). It shows that in unreinforced sand the results obtained from equation (1) are slightly conservative. These results are similar to experimental results (Fig. 4) presented by Latha.
and Somwanshi (2009). It demonstrates the validity of modeling by PLAXIS-3D.

Figure 8 shows the plot of ultimate bearing capacity of square footings on reinforced soil (N=4) versus embedment ratio, obtained from modeling series A in compare with equation (10).

As seen in Figure 8, the value of ultimate bearing capacity of surface square footing (d_f / B = 0) on reinforced soil is in a good concordance with the analytical results obtained using equation (10). It should be mentioned that when d_f / B = 0 equation (10) is equal to equation (6) that presented by Huang and Menq (1997). So Huang and Menq (1997) relationship gives a good estimate of bearing capacity of surface square footing. But in embedded square footing, numerical values are higher than those obtained using equation (10) that estimated by Das (2009). The difference increases with the increase in d_f / B; thus, equation (10) provides a conservative estimate of q_u(R).

The shapes of total displacements obtained from PLAXIS for both unreinforced and reinforced sand with 4 layers of geogrid are shown in Figure 9.

As seen from this Figure, the total displacements and the resultant failure wedge in reinforced sand are more developed than those obtained in unreinforced sand. The total displacements and the resultant failure wedge and failure mechanism in reinforced sand obtained from numerical modeling are similar to wide-slab failure mechanism that was presented by Huang and Menq (1997) (Figure 1).

Figure 10 shows the variation of BCR with d/B for different ratio of embedment depth (modeling series A). It should be mentioned that in modeling series A, N=0, 1, 2, 3 and 4. So by using Equation (9), the ratios of d/B are 0, 0.2, 0.4, 0.6 and 0.8 respectively.

As seen in Figure 10, the value of BCR decreases with the increase in d_f / B. It shows that with increasing the embedment depth of the foundation, the rate of increase of bearing capacity due to reinforcing with geogrid, is reduced.

Modeling of series B were conducted on square footings with 2 meters width, based on both unreinforced (N=0) and reinforced (N=1, 2, 3, 4) sand bed to investigate the effect of width of the foundation on bearing capacity.

Figure 11 presents the variation of bearing capacity with normalized footing settlement (ratio of s/B) for different number of geogrid layers under square footings with 2 meters width. Figure 12 shows the variation of BCR with d/B for different width of surface square foundations.
As seen in Figure 12, the value of BCR decreases with the increasing of B. It shows that with increasing width of the foundation, the rate of bearing capacity increasing, due to reinforcing with geogrid, is reduced.

4. CONCLUSION

The results of numerical modeling of square foundations on unreinforced and reinforced sand have been presented in this section. The ultimate bearing capacities obtained from these models have been compared with the relationships presented by Vesic (1973) and Hansen (1970), the theory developed by Huang and Menq (1997) and the experimental results presented by Latha and Somwanshi (2009). Based on the obtained results the following conclusions can be drawn:

1- In unreinforced sand (N=0 or d/B=0) for both surface and embedded square foundations the numerical results are higher than those obtained using relationships presented by Vesic (1973). It shows that in unreinforced sand the results obtained from analytical relations are slightly conservative. In unreinforced sand numerical results are similar to experimental results presented by Latha and Somwanshi (2009). It demonstrates the validity of modeling by PLAXIS-3D.

2- In reinforced sand the value of ultimate bearing capacity of surface square footing (d_f/B = 0) obtained from numerical modeling is in a good concordance with the analytical results obtained using relationships presented by Huang and Menq (1997). So Huang and Menq relationship give a good estimate of bearing capacity of surface square footing on reinforced soil. But in embedded square footing, numerical values are higher than those obtained using relationships estimated by Das (2009). The difference increases with the increase in d_f/B; thus, estimated relationships by Das provide a conservative values of q_u(R).

3- The value of BCR decreases with the increase in width and embedment depth of the foundation. It shows that with increasing the width and embedment depth of the foundation, the rate of bearing capacity increasing, due to reinforcing with geogrid, is reduced.
REFERENCES


Hansen JB (1970). A revised and extended formula for bearing capacity. Danish Geotechnical Institute, Bul. No. 28, Copenhagen, Denmark


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