Load carrying capacity of rectangular foundation on geogrid reinforced sloped sandy soil

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Abstract. A slope near the construction area is a problem for the geotechnical engineers. The paper studies the effect of reinforcing soil near slopes. Laboratory model has been designed and manufactured. The investigated parameters include vertical static (monotonic) loading, geogrid reinforcement, inclination of the slope of soil and the distance from the edge of slope to edge of foundation. The experimental results showed that the presence of a geogrid layer in sloped soil increased the foundation bearing capacity by a percent depending on the slope angle and the distance from edge of slope to the edge of foundation.

Keywords
Bearing capacity, Experiments, Foundations, Slopes, Sand.

1. Introduction
Bearing capacity of foundations located on slopping ground may be significantly reduced. Thus, using shallow foundations may not be possible, and uneconomical foundations (such as piles) become the only solution for the problem. Therefore, soil reinforcement to improve bearing capacity and to stabilize the soil slope has become one of the most interesting fields for scientific studies. The soil reinforcement term is concerned with a composite soil structure that consists of: soil back fill and a tensile reinforcement material used as a mesh, sheets, rods, strips, or fibers.

The first conventional work using mechanically strengthened soil to increase the bearing capacity of shallow footings was mentioned by Binquet and Lee (1975a, 1975b). In that work, 65 laboratory model tests were conducted to modify bearing capacity relations for strip footing resting on sandy soil strengthened with metallic strips. The bearing capacity of their first mode of failure is estimated by the theories developed by Mandel and Salencon (1972).

Huang and Tatsuoka (1988 and 1990) suggested a new mechanism of failure for strip footing resting on reinforced soil where the reinforcement width, b, equals to the footing width, B. Schlosser et al. (1983) suggested a “wide slab mechanism” of soil failure under ultimate load for the case of reinforcement depth, d, greater than the width of footing, B.

Omer, et al. (1993) presented an experimental study to investigate the critical depth of reinforcement of shallow footings on sand and the extends of the geogrid layers for developing the maximum bearing capacity ratio (with reinforcement/without reinforcement). They observed that (1) to mobilize the maximum bearing capacity, the efficient reinforcement depth is 2B for strip footings and 1.4B for square footings, (2) the maximum placement depth for the top layer of geogrid must be lower than about B to make benefit of reinforcement, and (3) maximum reinforcement layers width necessary for development of maximum bearing capacity ratio is about 8B for strip footings and 4.5B for square footings.
Das and Omar (1994) established that the bearing capacity ratio (with geogrid reinforcement/without geogrid reinforcement) for geogrid reinforced sandy soil decreases with the increase in footing width. While, a constant value of bearing capacity ratio was noted for a footing width of about (130-140 mm).

The results of laboratory model tests and theoretical analysis on the behavior of strip foundation supported on sheet pile wall – stabilized sandy slope, loaded vertically to failure was reported by El Sawwaf (2009). Based on the results, critical values of the sheet pile wall parameters for maximum stability effect are determined.

Fattah et al. (2010) used granular trench (with a condition of 2-D plane strain stone column) to model bearing capacity. The friction angle of the soil trench, elastic modulus of reinforcement, width, shape and depth of the granular trench, positions, and number of reinforcement layers were changed. The sloped granular trench was classified into two conditions; lined and unlined. The experiments revealed that inclusion of granular trench below the footings improves the bearing capacity and decrease the settlement. In addition, using of reinforcement made of polymers has an important action on settlement as well as bearing capacity. For both reinforced and unreinforced granular trenches, the depth ratio has a major effect on the settlement ratio, which decreases with the increase of depth ratio. The most workable value for the depth ratio was suggested to be equal to 2.

Altalhe et al. (2013) found that the overall improvement in bearing capacity of strip footing on reinforced sand slopes when using geotextile reinforcement to stabilize soil slope was better than using soil nails.

The aim of this paper is to present test results on a model rectangular foundation supported by sloped sandy soil reinforced by one layer of geogrid. It is required to determine the variation of bearing capacity with respect to geogrid reinforcement, slope angle of the soil, and the distance from edge of slope to edge of foundation.

2. Experimental work
The influence of the different parameters, such as geogrid reinforcement, foundation, container, and testing machine were studied in a small model laboratory. The geometry, description, and properties of the materials adopted are discussed below.

2.1 Soil
A fine round sand was adopted in the study. The Physical properties of the sand that include specific gravity, grain size distribution, and minimum and maximum dry unit weights were evaluated. A summary of the testing results with the standard specifications of each test is shown in Table 1. Based on the results of grain size distribution, the sand is medium to coarse grained size. The classification of the sand is poorly graded sand (SP) following the Unified Soil Classification System (USCS).

2.2 Geogrid reinforcement
The geogrid used in this study is manufactured by Al-Latifia factory having engineering properties shown in Table 2. The geogrid sheet was used for multiple tests but, it was replaced whenever any of the strands are damaged or visibly overstressed. Figure 3 shows the geogrid.
Table 1. Physical properties of the sand used.

| Property                              | Value | Standard specification of the test |
|---------------------------------------|-------|-----------------------------------|
| Specific gravity \( (G_s) \)         | 2.66  | ASTM D854                         |
| \( D_{60} \) (mm)                     | 1.15  |                                   |
| \( D_{30} \) (mm)                     | 0.42  |                                   |
| \( D_{10} \) (mm)                     | 0.23  | ASTM D422                         |
| Uniformity coefficient \( (C_u) \)   | 5.00  |                                   |
| Curvature coefficient \( (C_c) \)    | 0.66  |                                   |
| Classification of the soil (USCS)     | SP    | ASTM D2487                        |
| Maximum dry unit weight \( (kN/m^3) \)| 19.00 | ASTM D4253                        |
| Minimum dry unit weight \( (kN/m^3) \)| 16.00 | ASTM D4254                        |
| Maximum void ratio \( (e_{max}) \)   | 0.66  |                                   |
| Minimum void ratio \( (e_{min}) \)   | 0.40  |                                   |
| Internal friction angle \( (\phi) \) |       |                                   |
| at \( D_r = 30 \% \)                 | Dry   | 35.60°                            |
|                                       | Saturated | 30.10°                        |
| Internal friction angle \( (\phi) \)|       |                                   |
| at \( D_r = 80 \% \)                 | Dry   | 43.50°                            |
|                                       | Saturated | 37.40°                        |

Figure 1. Geogrid reinforcement used.

Table 2. Engineering properties of the used geogrid as provided by manufacturing company.

| A. Physical and Chemical |
|--------------------------|
| Property                 | Data                                      |
| Structure                | Extruded geogrid                         |
| Mesh type                | Square                                   |
| Polymer type             | HDPE                                     |
| Chemical resistance      | The geogrid is inert to all chemicals naturally present in soils and water |
| Biological resistance    | The geogrid is not influenced by micro organisms |

| B. Dimensional |
|----------------|
| Property       | Data                                    |
| Aperture size  | 6 mm × 6 mm                             |
2.3. Loading machine
The loading machine, as shown in figure 4, composed of the following parts:
1. Load cell
2. Digital weight indicator
3. Control system
4. Steel container (testing box)
5. Model foundation
6. Dial gauge

![Figure 2. The laboratory model and loading machine.](image)

The load cell is used to measure the applied load. It is connected with a loading arm attached to a gear box to produce controlled movements. It is also supported by a digital weighting indicator for displaying the amount of the load that applied to the model foundation, “Korea, model SI 4010R” with a sensitivity of 50g. The digital weighting indicator is connected with a load cell by a wire to measure and display the applied loads. The control system is used to control the rate of movement of the applied loads. The dial gauge is used to measure the settlement of the foundation.

2.4. Model foundation and container
Steel foundation (10 mm) in thickness was used with a width of (60 mm) and a length of (80 mm). The steel container (testing box) is manufactured of (6 mm) thick steel plates made as one piece, the inner dimensions of the container are (700 × 700 mm) and the depth is (800 mm).

2.5. Soil preparation in the model
A medium size of gravel was put at the bottom of the test box of thickness (200 mm) before placing the soil (a fabric filter was put over the gravel layer to inhibit fleeing of the small particles of the soil). The soil was put in the box by trial and error method to control the density of the sand using twelve layers of soil each layer is (50 mm) in thickness.
2.6. Testing program

The geometry of the model is shown in figure 3. The parameters that have been studied in this paper focus on the reinforced and unreinforced soil near slopes, slope angle, and the distance from the edge of slope to edge of foundation. The studied parameters can be summarized as shown in table 3.

![Figure 3. Schematic diagram of the model geometry](image)

Table 3. Details of the testing program for model tests.

| Foundation      | Type of soil | Geogrid reinforcement                  | Slope (β) | Distance (b) |
|-----------------|--------------|----------------------------------------|-----------|--------------|
| Rectangular     | Loose sand   | No reinforcement provided              | 45º       | Zero         |
| B = 60 mm       |              |                                        |           | 0.5B = 30 mm |
| L = 80 mm       |              |                                        |           | B = 60 mm    |
|                 |              |                                        | 60º       | Zero         |
|                 |              |                                        |           | 0.5B = 30 mm |
|                 |              |                                        |           | B = 60 mm    |
| Rectangular     | Loose sand   | One layer located @ 0.5B = 30 mm from  | 45º       | Zero         |
| B = 60 mm       |              | surface                               |           | 0.5B = 30 mm |
| L = 80 mm       |              |                                        |           | B = 60 mm    |
|                 |              |                                        | 60º       | Zero         |
|                 |              |                                        |           | 0.5B = 30 mm |
|                 |              |                                        |           | B = 60 mm    |

3. Results and discussion

The analysis for the experimental model tests is directed to the relationship between the applied load and the measured settlement. All the models are tested at loose condition and the foundation is on the surface, which is considered the worst case. Twelve model tests were carried out, half of them reinforced with geogrid while the other half was unreinforced. The results of the tests for all experimental models are illustrated in figures 6, 7, 8 and 9. There are many methods which have been proposed by researchers to define the failure load from the load-settlement curves. Here, Terzaghi proposal and Tangent Method are used to define the failure load.

According to Terzaghi (1943), the failure load is characterized as the load resulting from a settlement of 10% of the foundation width, while in the tangent lines method, the failure point can be determined...
by the intersection of two tangent lines of load-settlement relation curve, the first line represents the upper flatter tangent line while the second represents tangent to the lower flatter part of the curve. The values of failure load are summarized in table 4.
### Table 4. Summary of the bearing capacity values for rectangular foundation on loose sand.

| Geogrid reinforcement | Slope (\(\beta\)) | Distance (\(b\)) | Pult* (N) | qult (kN/m²) |
|-----------------------|-------------------|------------------|-----------|--------------|
| No reinforcement       | 45°               | Zero             | 58        | 12           |
|                       |                   | 0.5B = 30 mm     | 76        | 16           |
|                       |                   | B = 60 mm        | 92        | 19           |
|                       | 60°               | Zero             | 49        | 10           |
|                       |                   | 0.5B = 30 mm     | 62        | 13           |
|                       |                   | B = 60 mm        | 79        | 16           |
| One layer located @ 0.5B = 30 mm from surface | 45°               | Zero             | 126       | 26           |
|                       |                   | 0.5B = 30 mm     | 175       | 36           |
|                       |                   | B = 60 mm        | 226       | 47           |
|                       | 60°               | Zero             | 114       | 24           |
|                       |                   | 0.5B = 30 mm     | 147       | 31           |
|                       |                   | B = 60 mm        | 182       | 38           |

*Experimental failure load for figures 6, 7 and 9 is calculated by Tangent Method while for figure 8, it is calculated by Terzaghi proposal.

It can be noticed that the failure load increases with the increase in distance of the load from the slope edge (\(b\)) and the decrease in the slope angle. The presence of geogrid layer increases bearing capacity by (117.2 – 145.6) % for a slope of (45°) and (130.4 – 137.1) % for a slope of (60°). This is because the reinforcement mesh intersects with the failure plane and hence, prevents propagation of failure lines at shallow depths. In addition to the presence of geogrid, reinforcement provides stability to the slope of the soil as observed during the tests.

The bearing capacity ratio is defined as:

\[
BCR = \frac{\text{Bearing capacity of reinforced soil}}{\text{Bearing capacity of natural soil}} 
\]  

(1)

It is found that the BCR for reinforced soil near a slope range between (2.2 and 3.8). These results are compatible with the findings of Altalhe et al. (2013).

The tensile stresses developed along the geogrid due to a distributed load on the surface. Tensile stresses as that developed at the interface between the geogrid and the surrounding material promote an increase in the frictional resistance and an overall increase in bearing capacity of the foundation system as argued by Fattah et al. (2017).

Nareeman and Fattah (2012) found that the internal friction angle increased by inserting geonet mainly for a soil model strengthened with a geonet layer positioned at 45°. Moreover, the improvement in the shearing stress and vertical displacement of the soil. The measured settlement for soil reinforced with geonet is less than that for soil without reinforcement due to strengthening of the soil by the geonet layer.

4. Conclusions
1. The failure load increases with the increase in distance of the load from the slope edge (\(b\)) and the decrease in the slope angle.
2. The presence of geogrid layer increases the bearing capacity by (117.2 – 145.6) % for a slope of (45º) and (130.4 – 137.1) % for a slope of (60º). In addition to the presence of geogrid, reinforcement provides a stability to the slope of the soil as observed during tests.

3. The bearing capacity ratio BCR for reinforced soil near a slope range between (2.2 and 3.8).

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