1. Introduction

Behavior of reinforced soil foundation has been studied by many researchers since last three decades. In these studies, different types of material were used for reinforcement. Later, geosynthetic materials have become popular in geotechnical applications. Depending on the type and purpose of applications, there are different geosynthetic materials, e.g., geotextile, geomembrane, geocell, and geogrid. Among them, geogrid has been successfully utilized for reinforcement purpose. Generally, geogrid can be distinguished into three types: uniaxial, biaxial, and triangular geogrids. Biaxial geogrid and triangular geogrid were used in the present study.

Although reinforcement behavior had been studied by many researchers, such as Yetimoglu et al., Adams & Collin, and Murad et al., reinforcement behavior is still necessary to study for different test conditions. In the present study, one type of triangular geogrid and three types of biaxial geogrids were used for reinforcement. Considering the influence of aperture shape and tensile strength (stiffness) of these geogrids, their performances were compared and distinguished between each reinforcement.

2. Experimental program

Five monotonic load tests were performed to investigate the reinforcement behavior between triangular geogrid and different biaxial geogrids. The influences of aperture shape and stiffness of geogrid were analyzed from these experimental studies. In addition, improvement in ultimate bearing capacity was also compared between each reinforcement case. During loading process, surface deformation characteristics were monitored at six locations. Then, three-dimensional surface deformation was examined for both unreinforced sand and reinforced sand.

3. Material properties

3.1 Soil sample

Nikko Silica Sand No.(5) was used for model soil sample preparation. Soil particle density is 2.675 g/cm³. The average soil particle size, D10, is 0.488 mm. Since uniformity coefficient (Uc = 1.98) and curvature coefficient (Uc' = 0.943) are not in specified range, this sand can be regarded as poorly graded sand (SP), according to unified soil classification system (USCS). The grain size distribution curve is shown in Figure 1. The maximum and minimum dry densities are 1.628 g/cm³ and 1.338 g/cm³. The corresponding minimum and maximum void ratios are 0.643 and 1.0. Direct shear tests were also carried out to determine the internal friction angle (ϕ) of this sand. It was estimated that this angle was 33.5°, corresponding to the relative density (Dr) of 70%, which was used in all test cases.
3.2 Physical properties of geogrid

Four types of geogrids were used to investigate the reinforcement behavior between triangular geogrid (TX160) and different biaxial geogrids (SS1, SS2 & SS35), which are products of Tensar. These geogrids are made of punched polypropylene sheets. Product specifications of geogrids, provided by manufacturer, are presented in Table 1. As seen in this table, triangular geogrid has a uniform radial strength of 10 kN/m, while biaxial geogrids have different tensile strengths in machine direction (M) and cross machine direction (C). The schematic diagrams of triangular geogrid and biaxial geogrid are illustrated in Figure 2.

Table 1. Product specifications of geogrids

<table>
<thead>
<tr>
<th>Geogrid</th>
<th>TX160</th>
<th>SS1</th>
<th>SS2</th>
<th>SS35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction</td>
<td>X</td>
<td>C</td>
<td>M</td>
<td>C</td>
</tr>
<tr>
<td>T (kN/m)</td>
<td>10</td>
<td>12</td>
<td>22</td>
<td>19</td>
</tr>
<tr>
<td>a x b (mm)</td>
<td>40</td>
<td>40</td>
<td>28 x 40</td>
<td>28 x 40</td>
</tr>
<tr>
<td>t (mm)</td>
<td>3.1</td>
<td>2.8</td>
<td>3.9</td>
<td>4.2</td>
</tr>
<tr>
<td>w (g/m²)</td>
<td>245</td>
<td>215</td>
<td>340</td>
<td>620</td>
</tr>
</tbody>
</table>

M: machine dir; C: cross machine dir; X: diagonal dir; T: tensile strength; t: junction thickness; w: unit weight

4. Experimental setup and testing procedure

Square container (100 cm x 100 cm x 80 cm) was used for sample soil preparation. Rigid circular steel plate (diameter, D = 17.5 cm) was taken as a model footing. Since the depth of soil mass is about 70 cm in each test, the influence of applied footing pressure is negligible for this depth according to Boussinesq stress distribution analysis. In addition, boundary effect is minimal since the ratio between container size and footing diameter is large (100/17.5 = 6)\(^1\).

Model soil was uniformly prepared by using 100 kg of sand for each lift. The average density was 1.53 g/cm\(^3\) (D, = 70%). In reinforced sand tests, geogrid was laid at 5.25 cm depth (= u), resulting depth of geogrid layer to footing diameter ratio (u/D) as 0.3, which can be regarded as an optimum value according to Yetimoglu et al.\(^1\); Murad et al.\(^3\) and Das\(^5\). Layout of experimental setup is shown in Figure 3.

Footing was concentrically set with loading arm. Load was manually applied in steps, through load cell. Each loading step was maintained until increase in footing settlement was less than 0.02 mm per minute. One displacement transducer was set on the footing to measure the footing settlement, while other six transducers were set, two in each direction (at 17.5 cm & 30.5 cm in 0°, 45°, 90°), to monitor the surface deformation characteristics. Data were recorded at every 2 second by data acquisition system.

5. Test results

5.1 Influences of geogrid stiffness and aperture shape on load-settlement behavior

Figure 1. Grain size distribution curve of Nikko Silica Sand No.(5)

Figure 2. Schematic diagram of geogrids

Figure 3. Layout of experimental setup
Five monotonic load tests were conducted; one unreinforced test and four reinforced tests, with biaxial geogrids SS1, SS2 and SS35 to investigate the effect of geogrid stiffness and triangular geogrid TX160 to study the effect of geogrid aperture shape on reinforcement behavior.

As shown in Figure 4, it is noticed that the load-settlement curves of biaxial geogrid reinforcements have similar tendencies with the increase of footing settlement. Until settlement of 4 – 5 mm, all reinforcements have almost same performances. When footing settlement became larger, differences in performance between biaxial geogrid reinforcements were more obvious. SS2 geogrid showed flatter load-settlement curve than that of SS1 geogrid, regardless of same aperture size. Hence, tensile strength of these geogrids controls the load-settlement behavior after certain footing settlement. For SS35 geogrid, which has highest stiffness and smaller aperture size, load-settlement curve was almost same as that of SS2 geogrid until 7 mm footing settlement, after which SS35 showed higher performance. Therefore, it is realized that the influence of geogrid stiffness is more pronounced at large settlement of footing. In contrast, Murad et al.\(^3\) reported that tensile modulus of geogrid had minimal effect on reducing settlement in sand. In their study, load-settlement curves of reinforcements, with geogrids of different tensile strength, showed same behavior until ultimate load, after which (i.e. post failure) higher stiffness geogrid with smaller aperture size performed better than lower tensile strength geogrid. On the other hand, the current test results are in agreement with the results of finite element analysis, reported by Yetimoglu et al.\(^1\), in which higher performance was achieved with stiffer geogrid until 1000 kN/m.

However, the influence of aperture size cannot be fully understood from the current test results because there was only one type of triangular geogrid. When settlement became larger than 16 mm (s/D = 9%), load-settlement curve of TX160 geogrid reinforcement showed a rapid decline. Therefore, it is realized that the beneficial improvement due to triangular geogrid is obvious up to 8 – 9% settlement ratio, at which deformation of this geogrid might be initiated. After 9% settlement ratio, load-settlement behavior was influenced by tensile strength itself, showing rapid decline of load-settlement curve. Hence, for TX160 geogrid, the effect of interlocking action and confinement (i.e. due to its aperture shape, size and rib structure) is more pronounced on the load-settlement behavior before geogrid deformation. On the other hand, the influence of stiffness or tensile strength of geogrid is obvious on the reinforcement behavior after geogrid deformation.

### 5.2 Improvement in bearing capacity

Improvement in bearing capacity was observed in all geogrid reinforced tests. However, as shown in Figure 4, plunging failure behavior was not observed in load settlement curves, other than no reinforcement case. Therefore, the ultimate bearing capacity (q\(_u\)) of each reinforcement case was estimated by tangent intersection technique\(^2\), in which ultimate bearing capacity is defined as the tangent intersection between the initial, stiff, straighter potion of the load settlement curve and the steeper, straight portion of the curve. More conservative values of ultimate bearing capacity (q\(_u\)) for each case were obtained by using this technique, presented in Table 2. These values are normalized by the ultimate bearing capacity of unreinforced sand, and the resulting ratios are presented as (BCR)\(_{ult}\).

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Geogrid</th>
<th>q(_u) (kPa)</th>
<th>Bearing Capacity Ratio (BCR)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(s/D (%))</td>
<td>0.5</td>
</tr>
<tr>
<td>1</td>
<td>No</td>
<td>101.62</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>SS1</td>
<td>121.42</td>
<td>1.19</td>
</tr>
<tr>
<td>3</td>
<td>SS2</td>
<td>215.27</td>
<td>2.12</td>
</tr>
<tr>
<td>4</td>
<td>SS35</td>
<td>308.51</td>
<td>3.04</td>
</tr>
<tr>
<td>5</td>
<td>TX160</td>
<td>240.7</td>
<td>2.37</td>
</tr>
</tbody>
</table>

Since the performance of each reinforcement is not quite clear at low settlement level, values of bearing capacity ratio (BCR) were calculated for settlement ratio of 0.5, 1.0, 3.0, 5.0, 10.0 and 20.0%, and changes in performance with footing settlement were compared between each reinforcement case. The variation of BCR was plotted against settlement ratio (s/D), and illustrated in Figure 5.

As shown in Figure 5, BCR values of SS2 geogrid are higher than those of other geogrids at initial settlement ratios (0.5 and 1.0%). This is due to a bit higher in-

![Figure 4. Load-settlement behavior of different geogrid reinforcements](image-url)
placed soil density, which was incidentally occurred above this geogrid during sample preparation. After 3% settlement ratio, BCR values of all biaxial geogrid reinforcements increase linearly with different rates. From 5 to 20% settlement ratio, SS35 geogrid shows higher improvement (BCR values) than other biaxial geogrids, while SS1 has lowest improvement since initial settlement ratio (s/D = 1%). With increase in footing settlement, the differences in BCR values between biaxial geogrid reinforcements become larger. Therefore, it is known that more settlement (corresponding to higher stress level) is necessary for stiffer biaxial geogrid reinforcements (SS2 & SS35) than SS1 geogrid reinforcement to mobilize reinforcement mechanisms.

Adams and Collin² stated in their paper that for one layer of reinforcement there appears to be an improvement in the performance if the sand within the reinforced soil foundation (RSF) is compacted to a high relative density so that stress transfer to the reinforcement occurs before large soil strains occur. If the in-place soil density is higher, the required settlement will be lower for stiffer geogrid to activate reinforcement mechanisms, because most initial applied stresses will be instantly distributed to geogrid before large deformation in soil mass above geogrid layer.

For triangular geogrid (TX160), its performance is a bit higher than those of biaxial geogrids until 5% settlement ratio. Since its tensile strength is lowest among the geogrids used, reinforcement mechanisms will be developed at low settlement level, and consequently, the advantage of interlocking and confinement becomes effective due to triangular aperture shape and smaller opening size. Therefore, a better performance of triangular geogrid was observed at low settlement ratio. Here, the effect of opening size has not been emphasized since one type of triangular geogrid was used in this study. After 10% settlement ratio, the increase in BCR values of TX160 reinforcement decline, as compared to SS2 and SS35, because this geogrid would have been continuously deformed before this settlement ratio. In addition, friction between geogrid and sand would decrease with increasing settlement due to geogrid movement, and this would also result a dramatic decrease in performance.

5.3 Characteristics of surface deformation

Surface deformation characteristics of unreinforced sand and geogrid reinforced sand were monitored by measuring the vertical displacement at 17.5 cm and 30.5 cm locations from the center of circular footing in 0°, 45° and 90° directions. This is illustrated in Figure 6. The locations at 30.5 cm were considered instead of 35 cm (two times diameter of footing) due to space limitation.

For triangular geogrid (TX160), its performance is a bit higher than those of biaxial geogrids until 5% settlement ratio. Since its tensile strength is lowest among the geogrids used, reinforcement mechanisms will be developed at low settlement level, and consequently, the advantage of interlocking and confinement becomes effective due to triangular aperture shape and smaller opening size. Therefore, a better performance of triangular geogrid was observed at low settlement ratio. Here, the effect of opening size has not been emphasized since one type of triangular geogrid was used in this study. After 10% settlement ratio, the increase in BCR values of TX160 reinforcement decline, as compared to SS2 and SS35, because this geogrid would have been continuously deformed before this settlement ratio. In addition, friction between geogrid and sand would decrease with increasing settlement due to geogrid movement, and this would also result a dramatic decrease in performance.

Variations of surface deformation in radial directions are illustrated in Figure 7, for settlement ratio 0%, 5%, 10% and 25%. In this figure, SS35 was considered to represent the surface deformation behavior of biaxial
geogrids, due to its obvious deformation. In order to quantify the surface deformation behavior, the amounts of deformation (bulging) at same locations from center in radial directions were considered and surface non-uniformity index ($S$) was calculated for these radial locations. This surface non-uniformity index ($S$) is a standard deviation of respective locations in radial directions. Variations of this index for each case are presented in Figure 8, for 17.5 cm locations, and Figure 9, for 30.5 cm locations. Larger unevenness of surface deformation is represented by higher surface non-uniformity index ($S$).

![Figure 8. Surface Deformation at 17.5 cm Locations](image)

![Figure 9. Surface Deformation at 30.5 cm Locations](image)

For no reinforcement, obvious bulging was noticed, during loading, after 10% settlement ratio at both 17.5 cm and 30.5 cm locations. With the settlement increase, small amount of variation between radial directions was observed at same locations from the center of footing. This amount can be expected because perfect isotropic condition cannot be achieved within soil mass. Hence, the calculated surface non-uniformity indexes ($S$) for no reinforcement are small for both locations, regardless of footing settlement increase. In addition, almost same amounts of bulging were recorded at 17.5 cm and 30.5 cm locations for no reinforcement.

With triangular geogrid reinforcement (TX160), values of surface non-uniformity index were also minimal for all settlement ratios. This means that uniform surface deformation characteristics was achieved with triangular geogrid reinforcement. However, not like in unreinforced sand, amount of bulging at 30.5 cm was higher than that at 17.5 cm. This implies that wider stress distribution was achieved in the soil mass due to reinforcement. In addition, radial bending of triangular geogrid was noticed after testing. This would also result in pushing the soil particles above the geogrid in radial directions.

On the other hand, higher index values were observed in biaxial geogrid reinforcements. Hence, non-uniform surface deformations were formed in biaxial geogrid reinforcements. For SS1 geogrid, surface non-uniformity indexes for 30.5 cm locations are lower than that of other biaxial geogrids. Because SS1 geogrid was locally deformed with increase of footing pressure, surface deformation at 30.5 cm was, therefore, not highly affected by geogrid bending. With stiffer biaxial geogrids, higher indexes were noticed for both locations. This was because deformation (bulging) in 45° direction was higher than those in two other directions, shown in Figure 7. This behavior was same as bending pattern of these geogrids when they were visually checked after testing, as illustrated in Figure 10. Because of bending in 45° direction, soil particles might be allowed to move upwards in this direction, resulting higher bulging.

![Figure 10. Bending pattern of different geogrids](image)

6. Conclusion

Performances of different biaxial geogrids and triangular geogrid were investigated through model experiments. It was noticed that the effect of geogrid stiffness (tensile strength) was more significant at large settlement level, showing obvious differences on load-settlement behavior. This is because larger settlement is needed for stiffer geogrid to fully develop reinforcement mechanisms. Hence, in-placed soil density should be high enough so that applied stress could instantly transfer to reinforcement without large settlement. Regardless of initial load-settlement behavior, higher ultimate bearing capacity was obtained with stiffer biaxial geogrid reinforcement. For triangular geogrid (TX160), although
it has lowest tensile strength, it was able to perform even better than SS35 geogrid until s/D = 5 %. Moreover, comparing to other biaxial geogrids, the estimated ultimate bearing with TX160 reinforcement is twice of that with SS1 and greater than that with SS2. Therefore, triangular geogrid has outperformed biaxial geogrids. In addition, uniform surface deformation was recorded with no reinforcement and TX160 geogrid reinforcement, while biaxial geogrid reinforcements showed non-uniform surface deformation behavior, showing higher non-uniformity index. In all reinforced tests, larger bulging was observed at 30.5 cm locations than at 17.5 cm locations, while amount of bulging for no reinforcement was almost same for both locations. This has proved that wider stress distribution was achieved with the inclusion of reinforcement. Interestingly, surface deformation behavior of reinforced sand corresponds to the bending pattern of geogrid, which was visually checked after testing. Therefore, it is encouraged to do further studies in order to clearly understand the three dimensional reinforcement behavior of both triangular geogrid and biaxial geogrid.

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References