Research Article

Triaxial Shear Behavior of a Gravelly Sand with Different Forms of Reinforcement

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To study the effect of three-dimensional reinforcement arrangement on the behavior of a gravelly sand, triaxial tests were performed on specimens reinforced with geogrid sheet, geogrid cell, and one and two layers of geogrid sheet and geocell combination. Specimens with a diameter of 100 mm and a height of 200 mm are sheared under drained condition to monitor the variation of axial and volumetric strains with axial loading under different confining pressures. The results showed that the reinforcement schemes have different effects on soil strength improvement. The inclusion of double layers of geogrid sheet and geocell reinforcement could increase both the apparent cohesion and friction of the reinforced soil. The stress-strain relationship could be modelled with a modified hyperbolic model, which can capture the softening strain behavior of the specimens after peak strength.

1. Introduction

Gravelly sand has been widely used in geotechnical engineering, such as pavement base material. As an uncremented granular material, with minimal cohesion, such soil needs to be reinforced in many cases to improve its performance [1–7]. Different types of reinforcing mechanisms have been used in practice. Most research studies on the application of reinforced structures have been focused on horizontal reinforcement. Jiang et al. [8] studied the mechanical properties of the reinforced coarse-grained soil with geogrid sheet, geogrid cell, and one and two layers of geogrid sheet and geocell combination. Specimens with a diameter of 100 mm and a height of 200 mm are sheared under drained condition to monitor the variation of axial and volumetric strains with axial loading under different confining pressures. The results showed that the reinforcement schemes have different effects on soil strength improvement. The inclusion of double layers of geogrid sheet and geocell reinforcement could increase both the apparent cohesion and friction of the reinforced soil. The stress-strain relationship could be modelled with a modified hyperbolic model, which can capture the softening strain behavior of the specimens after peak strength.
reinforcement is generated by the interface constraint between reinforcement and soil particles.

Vertical reinforcement has been used in many forms to improve the apparent cohesive resistance of encased soils, such as geosynthetic-encased stone columns [16–21] or clay with vertical reinforcement [22], and geocell [23–25]. Latha and Murthy [26] performed triaxial tests on sand reinforced with horizontal reinforcement, geocells, and randomly distributed discrete fibers and found that the cellular form of reinforcement is more effective in improving the strength of the sand. Song et al. [27] performed a series of large-scale triaxial compression tests on sandy soil of different relative densities confined with circular geocell. The authors found that the reinforcement effect is more significant for dense sand than that for loose sand at medium strain levels, and geocell-reinforced loose sand shows a strain hardening behavior at large strain levels. The stress-strain relationship of the geocell-soil composites follows a hyperbolic nonlinear model.

To study the combination effect of horizontal and lateral reinforcement, Zhang et al. [28, 29] proposed the concept of H-V (horizontal-vertical) orthogonal reinforcing elements to provide passive resistance against shearing. The authors performed a comprehensive set of triaxial tests on dry sand reinforced with H-V orthogonal and vertical elements. It was found that the inclusion of H-V orthogonal reinforcing elements could increase the friction angle effectively but slightly in apparent cohesion. This is different from the findings that encasement could increase the apparent cohesion of stone columns [30, 31], and horizontal reinforcement could potentially increase both apparent cohesion and friction angle if multiple layers are used [32].

Existing research shows that there is little study on the combination of horizontal reinforcement sheets and vertical reinforcement cells as reinforcement in soils. The existing studies on 3D reinforcement have been focused on reinforcements made with galvanized iron, rubber, and Perspex [28, 29]. There is little research on geogrid as 3D reinforcement for soils. Considering this, this paper studies the effect of including both horizontal and vertical reinforcement on the behavior of a gravelly sand. Geogrid sheet and geogrid cells are used as horizontal and vertical reinforcement in 100 mm diameter and 200 mm in height soil specimens. Four reinforcement forms including the combination of horizontal reinforcement sheet and vertical reinforcement cell were adopted in the tests to study the effect of reinforcement arrangement and reinforcement layers on the behavior of the soils. The specimens were sheared under triaxial loading. The variations of axial and volumetric strains of the specimens with loading were monitored. A modified hyperbolic model is proposed to describe the softening strain behavior of the specimens after peak strength.

2. Materials and Methods

2.1. Materials Used in the Tests. The soil used in the tests is a well-graded gravelly sand bought from a commercial supplier in Liuzhou, China. The particle size distribution of the soil is shown in Figure 1. The coefficient of uniformity \((Cu)\) is 5.38 and the curvature coefficient \((Cc)\) is 1.16. According to the Unified Soil Classification System (USCS), the soil can be classified as well-graded sand with gravel (SW). The grains are mostly angular. The maximum and minimum dry bulk densities of the soil are 18.21 kN/m\(^3\) and 15.97 kN/m\(^3\), respectively. The specific gravity of the soil particles is 2.67. Biaxial HDPE geogrid with a mesh size of 20 mm \(\times\) 20 mm was used as the reinforced material. The properties of the geogrid are shown in Table 1.

The tests were performed on a universal cyclic triaxial loading system. The loading system has a maximum axial loading capacity of 10 kN. The maximum confining pressure and back pressure of the system are both 2 MPa.

2.2. Experimental Scheme and Procedure. To study the effect of reinforcing arrangement on reinforced soil behavior, three reinforcement schemes were used in the tests: one layer of geogrid square sheet (with a diagonal length of 100 mm as shown in Figure 2(a)), 70 mm diameter geogrid cell (Figure 2(b)), and the combination of geogrid cell and geogrid sheet (Figure 2(c)). To prepare a geogrid cell, a geogrid strip is rolled into a ring along the length direction so that two cells are overlapping. The overlapped ribs are tied with fine steel wire as shown in the figure. Compared with the method of bonding the overlapped mesh with epoxy resin [14], this method is simpler and closer to the common methods used in practice. In the combination reinforcement layout, there is no connection between the geogrid sheet and the geogrid cell. Four reinforcement schemes shown in Figure 3 are studied. In addition, one set of tests were performed on specimens with no reinforcement.

To prepare the specimens, the soils were oven-dried and compacted in 5 layers in a 100 mm inner diameter and 240 mm high split mold. A latex membrane is installed inside the split mold and placed onto the pedestal of the triaxial device. A porous stone disc was placed on top of the pedestal before raining soil into the split mold for compaction. According to the Code for Design of Railway Earth Structure (TB10001-2016), the compaction coefficient (the ratio of the density of the soil to its maximum density) of railway subgrade should be greater than 0.97, which gives a minimum relative density of 0.85 as used in the tests. To achieve this value, each layer is compacted with a wood tamper with 30 blows. Once a specimen is prepared, a porous stone disc is placed on the top surface of the soil column before fixing the specimen to the loading pad and removing the split mold. Considering the minimum relative density required in the standards, the effect of relative density is not studied in the tests. The specimens were saturated to the Skempton B value of 0.95 using the back pressure system in the triaxial cell. According to the Standard for Geotechnical Testing Method (GB/T50123-2019), for triaxial compression test on noncohesive coarse-grained soils, the shear rate should be 0.1%\(/\)min, so the specimens were sheared at the rate of 0.2 mm/min to reach an axial strain of 15%. Reinforced soil structures are normally high, for example, 20 m or higher [33]. Considering the stress
levels normally encountered, the confining pressures in the test were set at 50 kPa, 75 kPa, and 100 kPa.

### 3. Test Results

#### 3.1. Stress-Strain Curve Analysis

The stress-strain curves of the reinforced specimens follow the same trend as those of the unreinforced specimens, but with greater peak shear strength as shown in Figure 4. For the specimens reinforced with one layer of geogrid sheet and one geogrid cell, the shear behaviors are similar, which may be coincident. The specimens with combination 3D reinforcement have the greatest peak shear strength. This is because the embedding horizontal geogrid layer would restrain the forming of the shear band in the soil column and the geogrid cell would effectively increase the confining pressure to the soil particles [30]. The combination of both horizontal and the ring cell reinforcement would be much more effective than the use of either method alone. The reinforcing effect of geogrid and geogrid cell combination decreases as confining pressure increases. This is due to the fact that the contribution to confining effect from geogrid cell to soil movement reduces as confining pressure increases. With two layers of combined reinforcement, the reinforcement effect does not decrease much with the increase of confining pressure. This is because the double layer of geogrid sheet may have provided greater resistance to soil movement at higher confining pressures. The figure also shows that the elasticity modulus of the specimens does not change much with the inclusion of reinforcement. This is because the interaction between the geogrid and the soil is maximized when there is relative displacement between the soil and the reinforcements. At the early stage of the tests, the shear displacement is too small to activate the reinforcing effect; therefore, the shear behavior of the specimens is similar at lower strain levels. The strain level for the specimens to reach peak strength varies around 3%. This may suggest that the relative movement between soil particles still controls the strain at failure of the specimens.

Figure 4 shows that including one layer of geogrid sheet and one geogrid cell is almost similar in improving soil strength. The apparent cohesion (c) and the friction angle (φ) of the specimens are compared in Table 2. The results show that including one layer of geogrid sheet and a geogrid cell could double the apparent cohesion of the soil, but increase the friction angle by about 10%. By including one layer of combination reinforcement, greater effect can be seen in apparent cohesion improvement. When including 2 layers of combination reinforcements, both the friction angle and apparent cohesion of the soil can be improved, by about 20% and 300%, respectively. This indicates the effectiveness of multiple layers of combination reinforcement on soil strength improvement.

#### 3.2. Volumetric Strain Analysis

The relationship between the volumetric strain εv and the axial strain ε1 of the gravelly soil specimen with different reinforcement schemes under various confining pressures is shown in Figure 5. All the reinforced specimens exhibited great dilation behavior. The comparison shows that, with the inclusion of reinforcement, the volumetric strain of the soils could be reduced and the reduction of volumetric strain in the specimen with combination reinforcement is the greatest (about 30%). Again the ε1 and ε3 relationships of the specimens with one layer of geogrid sheet and with one geogrid cell are similar. The reduction of volumetric strain is the greatest in the specimen with two layers of combined reinforcement. Before reaching the peak strength, i.e., ε1 < 4%, the dilations of the specimens are very small (<3%).

### 4. Stress and Strain Relationship of Reinforced Gravelly Soil

Hyperbola models have been widely used to describe the strain development of sandy soils [34]. The model proposed by Duncan and Chang [35] is one of the popular models that require fewer parameters:

\[
\sigma_1 - \sigma_3 = \frac{\varepsilon_1}{a + b\varepsilon_1}
\]

The results of the triaxial tests are replotted in ε1/(σ1 - σ3) and ε1 space in Figure 6.

It is found that the relation of \(\varepsilon_1/(\sigma_1 - \sigma_3)\) and \(\varepsilon_1\) can be better described with a parabola function rather than a linear function:

\[
\sigma_1 - \sigma_3 = \frac{\varepsilon_1}{(a + b\varepsilon_1)^2}
\]

Meanwhile, the model describing contraction and dilatation phenomena proposed by Shen [36]:

\[
\varepsilon_v = \frac{\varepsilon_1 (d\varepsilon_1 + c)}{(e\varepsilon_1 + c)}
\]
Figure 2: Different forms of reinforcement: (a) geogrid sheet, (b) Geogrid cell, and (c) combination.

Figure 3: Arrangement of reinforcement schemes in the tests (dimensions are in mm): (a) geogrid sheet, (b) geogrid cell, (c) one layer of combination 3D reinforcement, and (d) two layers of combination 3D reinforcement.

Figure 4: Continued.
Figure 4: Deviatoric stress versus axial strain curves under different reinforcement forms. (a) $\sigma_3 = 50$ kPa, (b) $\sigma_3 = 75$ kPa, and (c) $\sigma_3 = 100$ kPa.

Table 2: Strength indices of the soil specimens: the apparent cohesion ($c$) and friction angle ($\phi$).

| Reinforcement scheme                              | $c$ (kPa) | $\phi$ (°) |
|---------------------------------------------------|-----------|------------|
| Unreinforced                                      | 15.9      | 44.5       |
| One layer of geogrid sheet                        | 29.6      | 48.8       |
| One geogrid cell                                  | 28.8      | 48.7       |
| One layer of geogrid composite                    | 53.9      | 46.4       |
| Two layers of geogrid composite                   | 59.9      | 53.4       |

Figure 5: Continued.
Figure 5: Volumetric strain and axial strain curves in different reinforced forms: (a) $\sigma_3 = 50$ kPa, (b) $\sigma_3 = 75$ kPa, and (c) $\sigma_3 = 100$ kPa.

Figure 6: Continued.
Figure 6: $\varepsilon_1/(\sigma_1 - \sigma_3) - \varepsilon_1$ curves of sand under different confining pressures: (a) $\sigma_3 = 50$ kPa, (b) $\sigma_3 = 75$ kPa, and (c) $\sigma_3 = 100$ kPa.

Figure 7: Continued.
Figure 7: Comparison of tested and modelled $\varepsilon_1/(\sigma_1 - \sigma_3)$ and $\varepsilon_1/\varepsilon_1$ relationship: (a) $\sigma_3 = 50$ kPa, (b) $\sigma_3 = 50$ kPa, (c) $\sigma_3 = 75$ kPa (d) $\sigma_3 = 75$ kPa, (e) $\sigma_3 = 100$ kPa, and (f) $\sigma_3 = 100$ kPa.
is modified to describe the volumetric strain-axial strain relationship during shearing:

\[ \varepsilon_v = \frac{\varepsilon_1 (d\varepsilon_1 - c)}{(e\varepsilon_1 + c)^2}. \]  \hspace{1cm} (4)

In the two equations, \(a\), \(b\), \(c\), \(d\), and \(e\) are fitting parameters obtained from \(\varepsilon_1/(\sigma_1 - \sigma_3)\) and \(\varepsilon_1\), and \(\varepsilon_1/\varepsilon_\gamma\) and \(\varepsilon_1\) curves, which can be done easily in Excel spreadsheet.

The variations of \(\varepsilon_1/(\sigma_1 - \sigma_3)\) with \(\varepsilon_1\), and \(\varepsilon_1\) with \(\varepsilon_\gamma\) of the specimens under the confining pressure of 75 kPa predicted using equations (2) and (4) are compared with the test results in Figure 7. The comparison shows that the proposed models can well capture the behavior of the soils, especially the postpeak softening strain behavior. This is different from the hardening behavior predicted with the Duncan–Chang model [35]. The data availability section is provided in Table 3. The model parameters used for the curves are shown in Table 3.

### 5. Conclusions

A number of triaxial shear tests have been performed on gravelly sand columns (100 mm diameter and 200 mm height) reinforced with geogrid sheet, geogrid cell, and combination of geogrid sheet and cell to study the effect of different reinforcing schemes on the behavior of the specimens. The stress-strain relationship and volumetric strain and axial strain relationship were monitored during the tests. It was found that reinforced specimens exhibit typical dilation shear behavior. Different reinforcing schemes have different effects on strength improvement. A modified Duncan–Chang model is proposed to describe the softening strain of the specimens after peak strength. The dilation of volumetric strain can be described with a modified Shen’s [34] model. Based on the limited number of tests on the reinforcement schemes used, it is found that

1. Including geogrid sheet, geogrid cell, or geogrid sheet and cell combination can improve both the friction angle and apparent cohesion of the soils. Including one layer of geogrid sheet or geogrid cell is similar in improving soil strength parameters. Including one layer of geogrid sheet and geogrid cell combination is more effective in improving apparent cohesion (by 235%) than improving friction angle (by 5%). Including two layers of combined layers of geogrid sheet and geogrid cell combination is effective in improving both apparent cohesion (by 300%) and friction angle (20%).

2. The relationship between \(\varepsilon_1/(\sigma_1 - \sigma_3)\) and \(\varepsilon_1\) can be better described with a parabola function rather than a linear function. The parabola function can well capture the softening strain behavior of the specimens after the peak strength.

### Data Availability

Since the experiment was completed with the support of Guangxi University of Science and Technology, the data used to support the results of this study can be obtained from the first author upon reasonable request via email: wjquan1999@163.com.

### Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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