Mechanism and Mesoscopic Characteristics of Indirectly Reinforced Gravelly Soil by a Geogrid

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1. Introduction

The reinforcing function of a geogrid works mainly through its interaction with the surrounding soil. The mechanical behavior of the geogrid-soil interface has been a hot topic. Previous research mainly focuses on the influence of macroscopic factors, such as overlying loads, the physical and chemical properties of soils, and the properties of the geogrid. However, there are difficulties in analyzing the mesoscopic fabric at the geogrid-soil interface and the evolution of its mechanical behavior during indoor pull-out tests from the mesoscopic aspect. The study of the effects of particle size and density on mixing behaviour in a ribbon mixer, which was proposed by Chandratilleke et al. [1], is used to investigate the effects of particle size and density on particle mixing in a laboratory-scale ribbon mixer. By using numerical simulation of wet particle flow in an intensive mixer, Zuo et al. [2] conducted the simulations of wet particle flow in an intensive mixer based on the three-dimensional discrete element method (DEM).

In recent years, extensive research on geogrid reinforcement has been conducted using the three-dimensional discrete element method. Tan et al. [3] simulated the axial loading test on a geogrid-encased stone column and the stone column was modeled using the discrete element method (DEM). To study the mechanical mechanism of geogrid-reinforced subgrades under transportation loading, Bhandari et al. [4] constructed a two-dimensional (2D) model for reinforced subgrades using the DEM and compared the results with unreinforced subgrades; it was found that the distribution of contact force chains of geogrid-reinforced subgrade was changed, which enhances the elastic modulus of the soil and reduces its plastic deformation. Ngoc et al. [5] presented a study of the interface of geogrid-reinforced sub-ballast through a series of large-scale direct shear tests and discrete element modeling, numerical modeling with the three-dimensional discrete element method (DEM) was used to study the shear behaviour of the interface of sub-ballast reinforced by geogrids. Abdi and Mirzaeifar [6] used the experimental and PIV evaluation of grain size and distribution on soil-geogrid interactions in the pull-out test. Gu et al. [7] used the discrete element method (DEM) to analyze the micromechanical behavior of an axially loaded geogrid-encased stone column installed in a clay bed, a three-dimensional DEM model was developed to simulate a partially encased stone column in the laboratory.
test under a plate loading condition. Li et al. [8] developed a series of geogrid-reinforced ballast models with different geogrid sizes and particular structures to reproduce the mechanical behavior of the geogrid under pull-out load and the rationality of the DEM model is verified by comparing the evolution law pull-out force measured by laboratory tests and numerical simulations under comparable conditions. Miao et al. [9] presented the pull-out behavior of a triangular geogrid embedded in a ballast under special consideration of the particle size based on the well-established constitutive models and particular configurations used in the discrete element method (DEM) simulation of the geogrid-stabilized ballast system.

In this study, based on experimental observations of the influencing zones of geogrid-reinforced gravelly soil, the Particle Flow Code 3D (PFC3D) program was used to simulate pull-out tests to analyze the macroscopic mechanical properties and mesoscopic characteristics of the geogrid-soil interface.

2. Gravellty Soil Modeling

The prototype soil sample has an average particle size $d_{50}$ of 9.5 mm with a maximum particle size of 16.00 mm, a coefficient of uniformity $C_u$ of 6.90, and a coefficient of curvature $C_c$ of 2.08. Yuanzheng et al. [10] noted that the strength and size of the soil particle should be considered in discrete element numerical calculations. Because of the limit of the computational capability and number of elements, the particle size and other model parameters can be reasonably adjusted in numerical calculations to obtain a numerical analysis result within the acceptable range of engineering error [11]. In this research, according to the test results of the prototype, the minimum particle size of the model was set to 1.0 mm. All soil particles with a diameter less than 1.0 mm were randomly replaced by particles with diameters in the range of 1 to 4.75 mm. Thus, the average particle size was 9.445 mm, and the maximum particle size, $C_{u}$, and $C_c$ were set to be 16.09, 3.25, and 0.99 mm, respectively (Figure 1).

Gravellty soil is a typical type of granular and cohesive soil, whose microscopic parameters (e.g., soil particle shape) have a large impact on its properties. The internal frictional behavior of gravelly soil is primarily determined by the friction and interlocking between two particles. Spherical particles in the PFC3D program contain fabric information and may rotate while interacting with each other, yielding relatively low shear strength. By contrast, the mechanical response of nonspherical particles is more closely to the actual situation [12]. Following the method of creating irregular particles in the DEM proposed by Ferellec and McDowell [13], two completely spherical particles were combined to form an ellipsoidal-like particle, and two main particles and two secondary particles were combined to form a tetrahedron-like particle, as shown in Figure 2.

The mesoscopic parameters of sandy soil particles in the model were calibrated by comparing the soil response in the numerical triaxial test and the laboratory test [14]. The confining pressure was applied by a servo mechanism. Axial loading was applied with the method of displacement controlling until the specimen failed. The specific mesoscopic parameters include particle density $\rho$: 1,650.0 kg/m$^3$; coefficient of friction $\mu$: 0.4; initial void ratio $n_0$: 0.16; normal contact stiffness $k_n$: $4 \times 10^5$ kN/m; shear contact stiffness $k_s$: $4 \times 10^5$ kN/m; and contact stiffness ratio: 1.0.

3. Geogrid Modeling

Geogrids have a spatial network structure with a certain thickness. The parallel connection model in the PFC3D can be used to simulate the extension force between two particles of cementing material. “Clumps” were used to combine particles of different sizes to simulate the true 3D shapes of nodes and longitudinal and transverse rib elements of a geogrid. The parallel connection model was applied to connect the nodes and longitudinal and transverse ribs of the geogrid to construct a complete geogrid model with a grid cell side length of 40 mm, which is consistent with that of the real geogrid (Figure 3). In the pull-out test, the pull-out force applied to the left-side longitudinal and transverse ribs transferred the normal tensile stress via the parallel connections formed between two particles of the geogrid.

The mesoscopic parameters of the geogrid were determined through the tensile test and trial-and-error approach. The selected mesoscopic parameters primarily reflected the physical and mechanical properties of the geogrid and its tensile response during the pull-out process: $\rho$: 1,000 kg/m$^3$, $\mu$: 0.4, the thickness of the transverse ribs of the geogrid: 2.4 mm, the thickness of the nodes of the geogrid (main particle size): 4.0 mm, the secondary particle size of the nodes: 2.4 mm, $k_n$: $4 \times 10^5$ kN/m, $k_s$: $4 \times 10^5$ kN/m, normal bond stiffness $K_n$: $1 \times 10^6$ kN/m$^2$, shear bond stiffness $K_s$: $1 \times 10^6$ kN/m$^2$, effective parallel bond modulus: $7 \times 10^5$ kN/m$^2$, and parallel bond stiffness ratio: $K_s$: 1.0.

4. Modeling and Analysis of the Pull-Out Test

The size of the loading box in the numerical pull-out test model is 250 mm in length, 200 mm in width, and 316 mm in height, which is the same as the YT140 pull-out tester for geosynthetics. Firstly, the $\mu$ between the soil particles and the geogrid was defined as zero, and the external walls were assumed to have no deformation. Secondly, a total of 316,804 soil particle elements were generated within the walls. Figure 4 shows the PFC3D geogrid pull-out test model. The loading rate was 2 mm/min.

4.1. Analysis of the Load-Displacement Curve of Pull-Out Test

Under the same test condition, the numerical pull-out tests were conducted under normal stress of 25, 50, 100, and 150 kPa. The reliability of the numerical model was examined by comparing the curves of the numerical model and those of the laboratory test, as shown in Figure 5.

It can be seen that all force-displacement curves exhibited the same patterns. Specifically, the pull-out force increased with the pull-out displacement and tended to
within a certain range above and below the geogrid. The peak areas of the influencing zones were observed (Figures 6–9). Besides the shear zones, two other peak areas near the geogrid were shear zones that manifested by movement, rolling, dislocation, and even plastic failure. As the pull-out displacement increased, two shear failure occurred on both sides of the geogrid were disturbed, which primarily showed an interlocking effect on the soil, and relative displacement occurred, the geogrid cells gradually underwent relative dislocations and rotation under the transfer and drive of the pull-out force on the geogrid. The soil particles within a certain range above and below the geogrid underwent rotational motions simultaneously. As the pull-out displacement increased from 0 to 6 mm, the soil particles at the protruding nodes and transverse ribs of the geogrid underwent significant displacements, and the displacements of the soil particles at the transverse ribs of the geogrid continuously increased.

4.2. Analysis of the Influencing Zone and Its Formation Mechanism. During the pull-out test, due to the change of the stress field, soil particles within a certain thickness range on both sides of the geogrid were disturbed, which primarily manifested by movement, rolling, dislocation, and even shear failure. As the pull-out displacement increased, two notable peak areas were observed on each side of the geogrid. The peak areas near the geogrid were shear zones (Figures 6–9). Besides the shear zones, two other peak areas (i.e., the peak areas of the influencing zones) were observed within a certain range above and below the geogrid. The width of the peak area was defined as the thickness of the influencing zone.

In the geogrid pull-out process, the shear zone and the influencing zone were not simultaneously formed. Both frictional action and interlocking action occurred at the geogrid-soil interface. The static friction between the soil and the geogrid played the primary role at the initial stage of the pull-out process, while there was no relative displacement occurred between the geogrid and the soil. When the relative displacement occurred, the geogrid-soil interface transitioned to dynamic friction, the geogrid cells gradually showed an interlocking effect on the soil, and relative dislocation occurred between the two soil particles. At the same time, the disturbance increased the strength of the soil. At this stage, the influencing zone appeared within a certain range above and below the geogrid. Subsequently, as the pull-out displacement increased, shear failure occurred on the geogrid-soil interface and shear zones were formed. When the pull-out displacement was relatively small at the initial stage of the pull-out test, the pull-out force had an insignificant impact on the porosity of the soil particles near the interface. When the displacement became large, the pull-out force and displacement of the geogrid had a large impact on the porosity of the soil particles near the interface, finally leading to a shear failure. In this process, the width of each influencing zone decreased to a certain extent, nearly before the shear zone. After the geogrid-soil interface underwent plastic failure, as the pull-out displacement continuously increased, the width of each influencing zone decreased to a certain extent. In actual engineering, after applying a geogrid, a certain extent of relative displacement will occur between the geogrid and the soil in the filling and roll compaction process, and the geogrid has an indirect reinforcing effect on the soil.

With the displacement field contour plots of soil particles under various vertical loads, the thickness of the contact surface was quantitatively analyzed. The thickness of each influencing zone was almost not influenced by the normal pressure, and the influencing zone above the geogrid was wider than that below the geogrid; this can be explained as follows: the direction of the normal force of soil below the geogrid and the pull-out resistance of the geogrid was both downward, and the ability of the soil particles below the geogrid balancing these two forces was less than those above the geogrid. The determined thicknesses of the influencing zones using the discrete element model are similar to the results obtained by Qiang et al. [15] using a PFC2D model, indicating that the thickness of the contact interface was 6–7 times that of the average soil particle size.

As shown in Figure 10, the evolution of the displacement vectors of soil particles with the pull-out displacement was analyzed; it can be seen that the soil particles near the geogrid underwent relative dislocations and rotation under the transfer and drive of the pull-out force on the geogrid. The soil particles within a certain range above and below the geogrid predominantly underwent horizontal, vertical, and rotational motions simultaneously. As the pull-out displacement increased from 0 to 6 mm, the soil particles within a certain range above and below the geogrid nearly only underwent relatively horizontal displacements along the geogrid length direction, while the displacements of the soil particles far from the geogrid were small. When the pull-out displacement of the geogrid exceeded 6 mm, the soil particles at the protruding nodes and transverse ribs of the geogrid underwent significant displacements, and the displacements of the soil particles at the transverse ribs of the geogrid continuously increased.

Figure 11 shows the morphology of the geogrid after the pull-out test, and it was analyzed that the geogrid was firstly deformed and then pulled out until the maximum displacement of 15 mm occurred at the first transverse rib within the pull-out box. In the pull-out process, the maximum deformation of the geogrid within the pull-out box was smaller than the pull-out displacement, which means the geogrid was both elongated and translated. The translation of the geogrid within the pull-out box was a process that gradually developed from the near pull-out end to the rear end of the entire geogrid. Moreover, the displacements of the transverse ribs of the geogrid were not initiated simultaneously, which means the transverse rib near the pull-out firstly underwent a displacement and was followed by the ribs behind this rib; this is because the geogrid had a certain ductility. At the initial stage of the pull-out test, the rear end of the geogrid almost did not deform; as the test processed, the further, a transverse rib from the first transverse rib was,
the smaller the deformation and force on the rib was. Evidently, in a geogrid reinforcement structure, the end-bearing resistance of the transverse ribs of the geogrid has an important role in the pull-out resistance composition [16].

4.3. Analysis of the Evolution of the Contact Force Chain of Soil Particles. The evolution of the contact forces in the particle system with pull-out displacements is shown in Figure 12, and it was revealed that the force chain was
initially evenly distributed within the pull-out box. However, as the pull-out displacement continuously increased, the connection forces between two soil particles were distributed due to the redistribution of the contact forces between two soil particles. As shown in Figure 12, the principal directions of the internal force chain within a
By observing the movement of the soil particles, it was found that a compacted zone appeared in the front part of the transverse ribs of the geogrid where the shear contraction occurred; at the same time, a void low-stress zone appeared, and shear dilation occurred in the rear part of the geogrid. This change of the force chain was eventually manifested by the reinforcing effect of the geogrid on the soil. With the continuous compressing action of the transverse ribs of the geogrid, a vector zone with a certain thickness of soil appeared at the entire interface, which is consistent with the stress distribution pattern near the certain range above and below the geogrid deflected as the test progressed.

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geogrid reinforcement determined by using the photoelastic analysis technique.

5. Conclusion

In this study, the characteristics of the interface between a geogrid and gravelly soil were investigated by a numerical pull-out test, and the influencing zones of the geogrid reinforcement were observed. The program PFC3D was employed to simulate the pull-out test to examine the mesoscopic characteristics of these influencing zones. The following conclusions can be drawn:

1. The calculation results obtained using the numerical geogrid-gravelly soil pull-out test and the laboratory test results exhibited the same patterns, demonstrating that the numerical method can qualitatively reflect the macroscopic and mesoscopic mechanical response patterns of the soil under the pull-out action of the geogrid.

2. Each side of the geogrid was characterised by a shear zone and an influencing zone, and the influencing zone appeared before the shear zone. The geogrid showed a certain indirect reinforcing effect on the soil within the influencing zones. The thickness of each influencing zone was almost not influenced by the normal pressure. Additionally, the widths of the influencing zones above and below the interface were different, and the influencing zone above the geogrid was wider than that below the geogrid.

3. From the mesoscopic aspect, it was revealed that in the geogrid-gravelly soil pull-out test, a stress concentration appeared at the front end of the first transverse rib of the geogrid, and the compression of the soil particles in front of each transverse rib of the geogrid by the transverse ribs caused a forward punching shear action and penetration of the soil. As the movement of the soil particles, shear contraction occurred in the front part of the transverse ribs of the geogrid, and shear dilation occurred in the rear part of the geogrid.

Data Availability

All the data included in this study are available upon request by contacting the corresponding author.

Disclosure

Code Availability. All codes included in this study are available upon request by contacting the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
Authors’ Contributions

JL, BW, and YLS performed the experiments, analyzed the data, and wrote the manuscript.

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