Research Article

Numerical Simulation Study on Compression Characteristics of Gravelly Soil Mixture Based on Soft Servo Method

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Because of complex mechanical properties and deformation mechanism, gravel soil mixture is an important medium of concern in the field of geotechnical engineering. Based on the continuous-discontinuous coupling algorithm formed by the structure shell elements and the particle discrete element method (PFC3D), the soft servo loading of the sample is realized, and the typical triaxial compression test data are used to calibrate mesoscale parameters. Furthermore, the numerical tests under different rock contents and confining pressure are carried out. The change rule of shear strength of mixed medium is discussed. It shows that the continuous-discontinuous coupling algorithm achieves a good effect in reflecting the deformation process. Under the mechanism of the flexible servo, the failure mode of the sample takes on drum-failure mode, and the internal of the damaged sample forms an obvious asymmetric X-shaped shear band. With the increase of stone content, the internal friction angle and cohesive force distribution of the sample have certain discreteness, but on the whole, the internal friction angle and cohesive force increase with the increase of stone content. The results can provide a reference for the parameter determination of mixed mediums such as gravel soil.

1. Introduction

Gravel soil mixed strata are generally formed by Quaternary alluvial deposits and ice water deposits, which are widely distributed in riverbeds, floodplains, and low terraces; generally derived from the diluvium of the Quaternary alluvium; and formed by the outwash deposits. It is characterized by large layer thickness, rich groundwater content, high flow rate, and large permeability coefficient and close to or in direct contact with the surface water. Typical gravelly soil is commonly used in engineering, which is shown in Figure 1. Gravelly soil is a common filling material in subgrade and dam engineering. Due to the complex mechanical behavior and great randomness of deformation, the study of gravelly soil has become a focus, especially the study of the complex interaction and the cooperation deformation mechanism between gravel and soil, which is widely concerned by the geotechnical community.

According to the physical and mechanical properties of the mixed medium, scholars mainly use a large- and medium-sized triaxial compressor, shearing instrument, and in situ push-shear test instruments to analyze its water content, strength characteristics, compressibility, permeability, and particle composition [1–5]. Through the direct shear test, it is found that the influence of gravel size on the shear strength of miscellaneous fill is greater than that of gravel content and arrangement direction [6, 7]. Through the large-scale direct shear test, the empirical formula is established to predict the shear strength of miscellaneous fill with 0%-50% stone content [8, 9]. With the development of computer software, scholars analyze the mechanical properties of miscellaneous fill from the microerspective by numerical simulation method; the influence of rock content, water content, density, gravel shape, and other factors on the strength characteristics of miscellaneous fill was studied; and the corresponding prediction model is established to

FIGURE 1: General gravelly soil in situ: (a) overview of a project; (b) gravel-soil mixture in a local steep slope; (c) the second spot of gravel-soil mixture.

predict the strength parameters of miscellaneous fill [10–13]. A discrete element biaxial test was used to study the effect of different lateral loading methods on the macromechanical properties and microstructure evolution of miscellaneous fill [14]. Biaxial test and direct shear test of the mixed medium are simulated by two-dimensional particle flow, and influence rule of rock content, shape, and roughness of block stone on friction angle and cohesion in miscellaneous fill was analyzed [15].

In recent years, with the development of discontinuous numerical simulation methods, numerical test technology based on discrete elements plays an important role in the research of soil-gravel mixture. Compared with physical experiments, the numerical experiments based on the discrete element method are less expensive and repeatable and also have tremendous advantages in the abovementioned research on microparticle size. Although some scholars have used discrete elements to simulate large-scale triaxial tests of soil-rock mixtures, there is a big flaw in the simulation: the current discrete element triaxial test simulation is through the lateral cylindrical rigid wall servo which is used to load the sample under confining pressure. Since the rigid wall does not deform, the lateral free deformation of the sample will be limited during the confining pressure loading process. On the contrary, the specimens are loaded under confining pressure by rubber film on the outside of the specimens in the indoor triaxial test, which allows free lateral deformation of the specimens. Therefore, the flexible loading characteristics of rubber film on confining pressure in the indoor triaxial test cannot be reasonably simulated by using the rigid cylindrical wall in the discrete element. Furthermore, under the axial load, the soil-rock mixture containing complex nonuniform media will undergo extremely nonuniform deformation, and the use of rigid wall loading confining pressure will affect the deformation and failure of the soil-rock mixture. At present, some scholars attempt to simulate the flexible loading characteristics of rubber film on confining pressure in laboratory tests by using sectional composite wall [16, 17] and flexible bonded granular film instead of cylindrical wall and have achieved good simulation results in application.

In this paper, a discrete element numerical model of the gravel-soil mixture is established based on three-dimensional

laser scanning technology and random construction method. Combining with the flexible shell unit servo method of continuous-discontinuous coupling algorithm, triaxial compression tests are carried out for gravel-soil mixture with different stone contents under different confining pressures. The failure characteristics of samples under flexible servo conditions, the variation rule of rubbing angle, and cohesion with increasing stone content are analyzed.

2. Principle of Soft Servo Construction Method for Gravel Soil

Shell element is a common kind of structural element in geotechnical continuous numerical simulation, such as the FLAC3D method. In these methods, each shell-type structural element is defined by its geometric and material properties. A shell-type element is assumed to be a triangle of uniform thickness lying between three nodal points. An arbitrarily curved structural shell can be modeled as a faceted surface composed of a collection of shell-type elements. Each shell-type element behaves as an isotropic or anisotropic, linearly elastic material with no failure limit. However, one can introduce a plastic-hinge line (across which a discontinuity in rotation may develop) along the edges between shell-type elements, using the same double-node procedure as applied to beams. Each shell-type element provides a different means of interacting with the grid. The structural response of the shell is controlled by the finite element assigned to the element. Because these are all thin-shell finite elements, shell-type elements are suitable for modeling thin-shell structures in which the displacements caused by transverse-shearing deformations can be neglected.

Each shell-type element has its local coordinate system as is shown in Figure 2. This system is used to specify applied pressure loading. A separate material coordinate system is used to specify orthotropic material properties, and a surface coordinate system (providing a continuous description of the shell midsurface spanning adjacent shell-type elements) is used to recover stresses. The shell-type element coordinate system is defined by the locations of its three nodal points, labeled 1, 2, and 3 in Figure 2. The shell-type element coordinate system is defined such that

- (1) the shell-type element lies in the xy -plane
- (2) the x -axis is directed from node 1 to node 2
- (3) the z -axis is normal to the element plane and positive on the “outside” of the shell surface. (The two sides of each shell-type element are designated as outside and inside.)

The material constitutive behavior may be isotropic, orthotropic, or anisotropic. Thus, one property must be specified. It is assumed that the material properties are homogeneous over the shell-type element (i.e., they do not vary with position) and that the shell thickness is constant. A description of the material properties follows.

The shell-type elements model general shell behavior as a superposition of membrane and bending actions via the five

FIGURE 2: Schematic diagram of the shell element coordinate system: (a) shell elements attached to the surface of the solid zones; (b) local coordinate system definition of a shell element.

3-noded triangular finite elements described in shell finite elements. The material properties of the finite elements that model membrane and bending actions are described by the material-rigidity matrices.

$$\begin{aligned} [\mathbf{D}_m] &= \int_{-t/2}^{+t/2} [\mathbf{E}_m] dz = t[\mathbf{E}_m], \\ [\mathbf{D}_b] &= \int_{-t/2}^{+t/2} [\mathbf{E}_b] z^2 dz = \frac{t^3}{12} [\mathbf{E}_b], \end{aligned} \quad (1)$$

respectively, where t is the shell thickness, $[\mathbf{E}_m]$ and $[\mathbf{E}_b]$ are material-stiffness matrices that relate stresses to strains via the constitutive relations:

$$\{\sigma_m\} = \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = [\mathbf{E}_m] \{\varepsilon\} = \begin{bmatrix} c_{11}^m & c_{12}^m & c_{13}^m \\ & c_{22}^m & c_{23}^m \\ \text{sym} & & c_{33}^m \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix}, \quad (2)$$

$$\{\sigma_b\} = \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}_b = [\mathbf{E}_b] \{\varepsilon\} = \begin{bmatrix} c_{11}^b & c_{12}^b & c_{13}^b \\ & c_{22}^b & c_{23}^b \\ \text{sym} & & c_{33}^b \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix}. \quad (3)$$

The material-rigidity matrices are used to form the finite element stiffness matrices and to recover stress resultants.

The stresses in (2) are obtained from the stress resultants by

$$\begin{aligned} \{\sigma_m\} &= \frac{1}{t} \begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix}, \\ \{\sigma_b\} &= \frac{12}{t^3} \begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix} z. \end{aligned} \quad (4)$$

For isotropic material properties, only E , ν , and t must be specified. For orthotropic and anisotropic material properties, the material directions and t must be specified. For most cases, $[E = E_m = E_b]$. However, when modeling equivalent or transformed orthotropic shells (with elastic properties equal to the average properties of components of the original shell) and controlling the membrane and bending rigidities independently, it is necessary to set $[E_m \neq E_b]$.

To make the soil particles and gravel particles of discrete media interact with the continuous shell element, the method based on boundary control particles is used. The wall element in the PFC must be coordinated with the shell element, so specify the wall element that is consistent with the coordinate point of the shell element. The contact force of the internal particles is transmitted to the node of the wall unit according to the equivalent method, and the node of the wall is attached to the node of the shell unit, so the two move synchronously, and the flexible material parameters of the shell are transferred to the internal particles to achieve the effect of flexible servo.

According to the above principle, the shell unit will receive the external force transmitted by the particle system and deform. After trial calculation, the thickness of all shell units is set at 0.15 m, the modulus is set at 5.0 MPa, and Poisson's ratio is set at 0.0 in this paper.

(a)

(b)

(c)

FIGURE 3: Schematic diagram of a three-dimensional laser scanner and typical gravel particles: (a) laser scanner; (b) oval particles; (c) cubic particles.

(a)

(b)

(c)

(d)

FIGURE 4: Schematic diagram of gravel soil numerical model construction: (a) empty model; (b) gravel particles; (c) soil particles; (d) complete model.

3. Realization Method of Numerical Model of Sand and Pebble Mixture

3.1. Construction Method of Gravel Skeleton Particles. 3D laser scanning technology is an advanced fully automatic high-precision stereo scanning technology. It uses the geometric relationship of triangles to determine the distance. Firstly, the scanner emits laser light to the surface of the object and uses the CCD camera at the other end of the baseline to receive the reflected signal of the object and record the angle between the incident light and the reflected light. Knowing the baseline length between the laser light source and the CCD, the distance between the scanner and the object can be deduced from the geometric relationship of the triangle, as shown in Figure 3. Delaunay triangle mesh is generated by the method based on volume division, surface division, surface projection, etc. Graphic scanning accuracy has an important influence on the analysis of soil-rock mixture particles. To accurately obtain the real three-dimensional geometric data of the soil-rock mixture particles, the three-dimensional laser scanner HandyScan 700™ is used in this paper, as shown in Figure 3. The scanner emits 7 crossed laser lines with a measurement speed of 480,000 (times/sec) and an accuracy of 0.030 (mm). The laser beam determines the geometric value through the relative position of the white coordinate point on the black disk and the surface point coordinate of the earth-rock mixture particles in Figure 3(a). The coordinate data is collected and transmitted to the computer. At the same time, the particle surface point coordinates are recorded to directly form the particle three-dimensional graphics. Because the distribution of gravel particles inside the gravel-soil mixture is extremely complex and highly random, a random structure model that conforms to the statistical law is generally established in the numerical model. In this paper, the 3D laser scanner is used to scan and model the gravel particles to establish a model library. Then, using the model library as a benchmark, randomize the gravel particles to get more 3D models of gravel particles.

3.2. Numerical Model Generation Steps. A cylinder with a diameter of 32 cm and a height of 65 mm is used to speed up the calculation of the initial model of the discrete element. The diameter of the soil particles is distributed between 5 mm and 10 mm, the diameter of the gravel particles is distributed between 20 mm and 60 mm, and the porosity of the initial model is 0.3.

The establishment of a discrete element model of gravel soil mixture based on the generated flexible shell includes the following three steps:

- (1) Firstly, a standard three-dimensional sample size is generated from the shell unit. The sample size in this paper is set as the standard sample size with a diameter of 32 cm and a height of 65 cm. The generated standard shell model is emptied to prepare for the placement of gravel and soil particles
- (2) Secondly, randomly scanned gravel particles are put into the model according to the stone content of the

FIGURE 5: Comparison of laboratory triaxial test results and numerical simulation results of gravel soil mixture.

TABLE 1: Mesoscopic parameters of the discrete element model of gravel soil mixture.

Contact type	emod (Pa)	kratio	Friction coefficient
Stone-stone	2e10	1.0	1.0
Soil-stone	20e8	1.5	0.25
Soil-soil	10e8	2.5	0.20
Shell	5e6	0.0	0.0

FIGURE 6: Schematic diagram of specimen compression characteristics.

test to control the porosity and reserve space for the input of soil particles

- (3) Thirdly, the right amount of soil particles between 5 mm and 10 mm are put into the model to fill the remaining space and to keep a demand gravel content. To make the model compact, the wall servo system is used to reach a stable state to obtain a complete gravel soil mixed model, as shown in Figure 4

FIGURE 7: Comparison of failure modes at 15% strain (500 kPa): (a) deformed particles; (b) particle displacement; (c) profile of the displacement; (d) experiment result.

3.3. Calibration of Particle System Parameters. Compared with the results of the indoor triaxial test, it can be seen from Figure 5 that the stress-strain curve obtained by the numerical simulation agrees well with the results of the indoor test, and the mesoscale obtained by the calibration can be observed. And the calibrated parameters as are shown in Table 1 can be used for subsequent experimental research. At the same time, the numerically simulated sample failure form is in good agreement with the laboratory test sample destruction form.

During the triaxial compression of the numerical sample, the failure mode is divided into six processes according to strain magnitude. The cross-sectional diagram is shown in

Figure 6. (1) At the beginning of compression, the particles in the middle of the sample did not produce displacement. Asymmetrical displacement occurs at the end, indicating that the specimen is still in the compaction stage at the beginning, and the stress increases linearly with strain. (2) As the sample is further compressed, there is a tendency to swell on both sides, the compressed area on the upper and lower ends is further increased, and the linear relationship between stress and strain remains. (3) The stress reaches the peak value and does not increase anymore. The gravel particles at both ends of the sample have a significant displacement, indicating that after the peak value, the gravel particles act as the main pressure bearer, and the bulging phenomenon on both

FIGURE 8: Comparison of soft and rigid servo effects.

FIGURE 9: Three-dimensional fabric diagram: (a) statistics of contact force direction and magnitude; (b) tangential contact force distribution; (c) normal contact force distribution.

FIGURE 10: Statistical distribution of normal contact force between particles in gravel soil mixture under different strains.

sides tends to be obvious. (4) The strain of the sample continues to increase, the stress shows a fluctuating state but no longer increases, the two ends of the sample are further compacted, the bulging phenomenon on both sides is obvious, and X-shaped shear bands begin to appear inside the sample. (5) The sample is further compressed, the compaction phenomenon at both ends is further intensified, the soil particles are squeezed by the gravel particles, and a certain displacement occurs, and the X-shaped shear band formed inside tends to be obvious. (6) The bulging phenomenon of the sample is obvious, the X-shaped shear band is obvious, and the sample is damaged.

When the strain reaches 15%, the failure form of the numerical model test specimen and that of the indoor test specimen are compared as shown in Figure 7. The X-shaped shear band inside the sample is obvious, indicating that the mesoparameters of the discrete element model are reasonable and subsequent experiments can be carried out.

4. The Influence of Soft and Rigid Servos on the Test Curve

The rigid servo refers to the synchronous deformation of the nodes on the boundary wall [18], while the flexible servo

refers to the continuous adjustment of the nodes on the wall with loading [19], and the adjustment is controlled by the force of the shell structural unit. Due to the different action mechanisms of soft servo and rigid servo, it affects the macromechanical parameters reflected by the stress-strain curve obtained by the compression test. The triaxial compression tests of soft servo and rigid servo under different confining pressures are compared.

The stress-strain effects under soft and rigid servos are compared in Figure 8. In the numerical experiment, the discrete element models with the same gravel contents are placed in the empty models of flexible and rigid servos. Under the same mesoparameter conditions, only the servo system is changed. The triaxial compression test was carried out under the confining pressures of 300 kPa, 500 kPa, and 800 kPa. It can be seen that the stress-strain curve of the sample under soft servo conditions is more in line with the indoor test curve and under the rigid servo conditions. Before the stress reaches the peak value, the sample is not much different from the result of the soft servo, but after the stress of the sample reaches the peak value, the continuous decrease of the stress exhibited by the rigid servo is quite different from the result of the indoor test. The simulation is more in line with the requirements.

FIGURE 11: Statistical distribution of tangential contact force between particles in gravel soil mixture under different strains.

5. Analysis of Numerical Simulation Results Based on Soft Servo Control

Using the mesoparameters of the gravel soil mixture calibrated and using the principle of shell soft servo loading, the numerical models of different gravel contents were established, respectively, and the triaxial compression tests under the confining pressures of 300 kPa, 500 kPa, and 800 kPa were carried out. The numerical simulation results are analyzed as follows.

5.1. Microstructure Analysis of the Contact Force between Gravel Soil Particles. Generally, only macroparameters such as stress and strain can be obtained in the laboratory test. It is difficult to get the distribution rule of microparameters such as normal and tangential forces among particles in the sample. The distribution of micromechanical characteristics is very important to reflect the failure rule of the sample. To study the contact between gravel particles and soil particles in the process of compression failure of gravel soil mixture, the conditions of 60% stone content and 500 kPa confining pressure are researched, the contact forces between particles in the sample under different axial strains are counted, and all contact forces are recorded [20–24]. After

FIGURE 12: Stress-strain curve of gravel soil mixture with different stone contents.

FIGURE 13: Relationship between shear strength parameters and stone content of gravel soil mixture: (a) relationship between friction angle and stone content; (b) relationship between cohesion and friction angle.

obtaining the three-dimensional fabric information between particles, the contact force is superimposed in the circumferential direction, as shown in Figure 9. After the three-dimensional fabric force is superposed in the circular direction, the contact force distribution on the plane is obtained as is shown in Figure 10, and the statistical distribution diagram of the normal direction between particles is shown in Figure 10. The results show that in the initial stage (strain = 0), the specimen is in the initial consolidation state, the stress is in the isotropic state, and the distribution of contact force is approximately circular. After that, with the increase of axial strain, the distribution of normal contact force between particles in the specimen changes obviously. The distribution of contact force gradually increases with the increase of strain. After the stress reaches the peak value, the statistical value of contact force does not increase, which is consistent with the result of the stress-strain curve. The statistical diagram of tangential contact force drawn is shown in Figure 11; at the initial stage, the specimen is in the initial consolidation state; at this time, there is almost no shear in the specimen, and the size of tangential contact force between particles is almost zero. After that, with the increasing of axial strain, the specimen is in the shear state, and the tangential contact force between particles is in a petal-like distribution, and after the stress of the specimen reaches the peak value, the statistics of tangential contact force is no longer available largely.

5.2. The Influence of Different Rock Content on Compression Properties. The triaxial compression tests under different confining pressures have been carried out for the numerical models with 30%, 45%, and 60% stone content. The stress-strain curves obtained are shown in Figure 12. The result shows that (1) for the samples with the same stone content, the peak stress increases with the increase of confining pressure, and the axial strain corresponding to the peak stress increases accordingly, and (2) for the samples with different stone contents, under the same confining pressure, the peak

stress increases with the increase of stone content, and the axial strain corresponding to the peak stress also increases. The test results show that with the increase of confining pressure and stone content, the strength and deformation resistance of gravel soil mixture are improved correspondingly.

After a triaxial compression test on samples with different stone contents under the same confining pressure, the Mohr-Coulomb strength formula is used to determine shear strength as follows:

$$\tau = \sigma \tan \varphi + c. \quad (5)$$

After geometric transformation, it can get

$$\sin \varphi = \frac{(\sigma_1 - \sigma_3)/2}{c \cdot \cot \varphi + (\sigma_1 + \sigma_3)/2}. \quad (6)$$

After simplification, we can get

$$\begin{aligned} \sigma_1 &= A + B\sigma_3, \\ A &= \frac{2c \cdot \cos \varphi}{1 - \sin \varphi}, \\ B &= \frac{1 + \sin \varphi}{1 - \sin \varphi}. \end{aligned} \quad (7)$$

The values of A and B can be obtained by linear regression of several groups of experimental data. The cohesion c and friction angle can be obtained by the values of A and B according to the following formula:

$$\begin{aligned} \varphi &= \arcsin \frac{B - 1}{B + 1}, \\ c &= \frac{A(1 - \sin \varphi)}{2 \cos \varphi}. \end{aligned} \quad (8)$$

As shown in Figure 13, the results of multiple sets of

numerical tests are calculated, and the samples with the same stone content show certain discreteness in the results of friction angle and cohesion due to the randomness of gravel particles inside. But on the whole, the internal friction angle of the gravel soil mixture increases linearly with the increase of the stone content, and the cohesion also increases with the increase of the stone content. However, the discreteness of the data is obvious. It is considered that with the increase of the stone content, the contact between gravel particles increases, which further increases the cohesion of the sample.

6. Conclusion

The three-dimensional laser scanning and randomization method are used to establish the discrete element gravel soil mixed model with different stone contents. Under the flexible servo mechanism, the compression tests are carried out on the samples with different confining pressures and different stone contents. The mechanical properties and deformation and failure rules of the gravel soil mixture are analyzed. The following conclusions can be drawn:

- (1) Compared with the experimental results under the condition of rigid servo and flexible servo, the results of flexible servo are more consistent with the results of the indoor test. After the stress reaches the peak value, the stress cannot keep a stable state with the increase of strain with the rigid servo system while the soft servo system can, so the flexible servo mechanism is more suitable for gravel-soil mixed medium
- (2) The strength and resistance to deformation of gravelly soil mixture increase with the increase of rock content and confining pressure. Although the internal friction angle and cohesion of gravel soil mixture show certain discreteness, and the discreteness of cohesion is greater than that of internal friction angle, generally speaking, the internal friction angle of gravel soil mixture increases linearly with the increase of rock content, and the cohesion also increases nonlinearly with the increase of rock content
- (3) Under the flexible servo mechanism, the gravel soil mixture specimen is finally bulging failure, and an asymmetric X-shaped shear band is formed after failure. The failure pattern and the size and distribution pattern of the internal shear band of the gravel soil mixture specimen are affected by the gravel content and also related to the confining pressure

Data Availability

Data is available on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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