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Research Article

Grain Size Effect on the Mechanical Behavior of Cohesionless Coarse-Grained Soils with the Discrete Element Method

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Biaxial compression tests with the same specimen size and different maximum grain sizes were simulated for coarse-grained soils using the discrete element method to study the influence of grain size on the mechanical properties and force chain. The maximum grain sizes were 40, 20, 10, and 5 mm, respectively. The grading with self-similar fractal structure in mass is designed to ensure the same pore structure for soils. The shear strength increased with the increase in maximum grain size. Evident increase in shear strength and significant size effect were observed when the ratio of the specimen diameter to maximum grain size was less than five. The shear dilation of coarse-grained soils increases with the increase in maximum grain size. The contact force distribution was uniform when maximum grain size was small but tends to be uneven with the increase in maximum grain size, thereby causing the increase in shear strength by stable strong force chains. This finding demonstrates size effect on the mechanical properties and force chain of cohesionless coarse-grained soils under the biaxial compression condition.

1. Introduction

The size effect on cohesionless coarse-grained soils is an important topic in geotechnical engineering. Size effect, including sample and particle size effect, can be studied through tests and numerical simulations. A large number of test results for coarse-grained soils have been obtained. When the maximum grain size is large or the specimen size is small, the shear strength is high [1–7]. However, a few factors in laboratory tests, such as particle shape, gradation, uniformity, and particle breakage of soil, affect the test results [8–12]. The grading with the self-similar fractal structure in mass was used in triaxial compression tests to ensure the same pore characteristics for specimens with different maximum grain sizes and avoid the influence of grading [7]. However, the laboratory tests can only obtain a few macroscopic behaviors. With the increase in numerical simulation methods, the size effect of coarse-grained soils was simulated based on numerical tests, thereby controlling the error from the test material. Furthermore, the load transfer and fabric change in the deformation and failure process can be obtained, and the mechanism of size effect can be analyzed. Therefore, analyzing the size effect on coarse-grained soils using numerical tests is significant.

The discrete element method (DEM), which is an important method in numerical simulation, has been widely used to investigate coarse-grained soils since it was proposed by Cundall and Strack [13]. The size effect of coarse-grained soil is one of the main contents of DEM. Potyondy and Cundall [14] studied the influence of the ratio of specimen size to particle size on the elastic modulus and internal friction angle of the sample using particle flow code (PFC). The results showed that the mechanical parameters are later the same in the two-dimensional tests, whereas the parameters in the three-dimensional tests are related to the size. Matthew and Katalin [15] used the DEM to carry out the biaxial simulation tests for four cohesionless particle materials with different specimen sizes. Their results showed that sample shear strength reduces with the increase in specimen size. A series of triaxial compression tests were carried out on coarse-grained soil through PFC. The results demonstrated that the change in the ratio of specimen size to particle size has no evident influence on the shear strength of coarse-grained soils when the ratio is greater than 40 [16]. Rao and Chang [17] studied the influence of grain size on stress-strain-strength behaviors by using PFC^{2D} for soils with the maximum grain sizes of 60, 80, and 120 mm and the same ratios of specimen size to maximum particle size.

Scholars have attempted to explain the phenomenon of size effect in terms of its formation mechanism due to the complexity and uncertainty of the size effect of coarse-grained soils. Zhu et al. [12] believed that boundary constraints of the specimen can be attributed to the size effect. However, the specific action of the constraint on the formation of the size effect is not explained. Zhang and Hou [18] explained the size effect of granular materials due to the boundary constraint based on force chain theory. The contact force between the particles is evidently affected by the boundary when the specimen size is smaller than the characteristic length of the force chain.

The biaxial compression tests for cohesionless granular soils with different maximum grain sizes and self-similar fractal structures were performed based on the DEM to analyze the effect of maximum grain size on the mechanical properties and force chain of coarse-grained soils with the same specimen size. The mechanism of size effect of cohesionless coarse-grained soils was preliminarily discussed by the concept of the force chain.

2. Numerical Modeling of Biaxial Compression Tests

2.1. Introduction of Contact Stiffness Model. The linear contact stiffness model of PFC^{2D} was adopted in this paper [19]. In the contact plane, the contact force vector between two contact entities can be decomposed into normal and tangential components. The normal contact force component is the normal contact stiffness product and the overlap of particles and the normal unit vector of the contact surface, which can be written as follows [19]:

$$F_i^{\mathrm{n}} = k^{\mathrm{n}} U^{\mathrm{n}} n_i, \tag{1}$$

where F_i^{n} is the normal contact force component, k^{n} is the contact normal secant stiffness, U^{n} is the relative contact displacement in the normal direction, and n_i is the normal vector unit that defines the contact plane.

The shear force is computed in an incremental fashion. When the contact is formed, total shear force is initialized to zero. Each subsequent relative shear displacement increment leads to an increment of elastic shear force that is added to the current value, which can be written as follows [19]:

$$\Delta F_i^{\mathrm{s}} = -k^{\mathrm{s}} \Delta U_i^{\mathrm{s}}, \tag{2}$$

where ΔF_i^{s} is the shear contact force component, k^{s} is the shear stiffness, and ΔU_i^{s} is the relative contact displacement in the shear direction.

Based on the assumption that the stiffness of the two contacting entities acts in succession, the contact stiffness for the linear contact model is computed. The contact normal secant stiffness is given by the following equation:

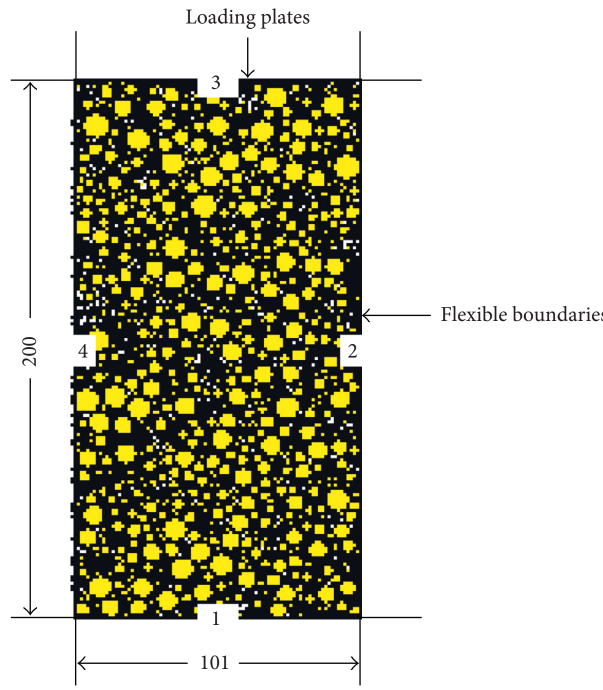

Figure 1: Biaxial compression test sample.

$$k^{\mathrm{n}} = \frac{k_{\mathrm{n}}^{[A]} k_{\mathrm{n}}^{[B]}}{k_{\mathrm{n}}^{[A]} + k_{\mathrm{n}}^{[B]}}. \tag{3}$$

The contact shear tangent stiffness is calculated as follows:

$$k^{\mathrm{s}} = \frac{k_{\mathrm{s}}^{[A]} k_{\mathrm{s}}^{[B]}}{k_{\mathrm{s}}^{[A]} + k_{\mathrm{s}}^{[B]}}, \tag{4}$$

where superscripts [A] and [B] denote the two particles in contact.

2.2. Specimen. Figure 1 shows the specimen of cohesionless coarse-grained soils with a diameter of 101 mm and a height of 200 mm. Among which, #1 and #3 walls were the lower and upper loading plates, respectively, and #2 and #4 were flexible boundaries, which can simulate the rubber membrane in triaxial tests.

The test soils with self-similar fractal structure in mass as used in the biaxial compression test were utilized to ensure the same pore characteristics for specimens with different maximum grain sizes. The grading was achieved as follows [20]:

$$\frac{M(d < d_i)}{M_{\mathrm{t}}} = \left(\frac{d_i}{d_{\max}}\right)^{3-D}, \tag{5}$$

where $M(d < d_i)$ is the mass of grains with the grain size d less than a certain grain size d_i, M_{t} is the gross mass of grains, $d_{\max}$ is the maximum grain size, and D is the fractal dimension.

Four different scaling methods were adopted to scaled rockfill materials. The results showed that the range of the

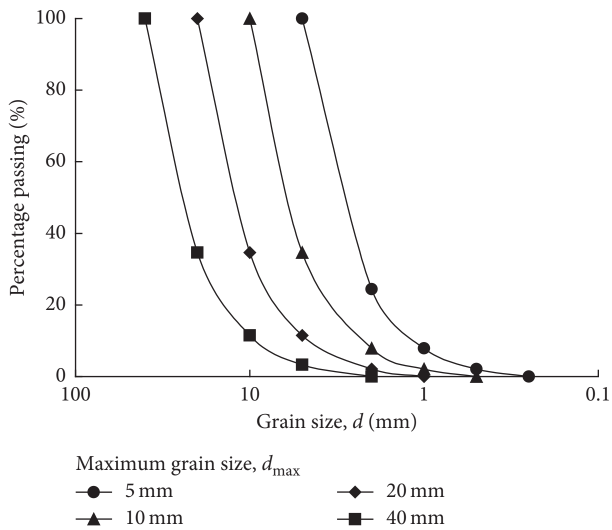

Figure 2: Distribution curves of grain sizes.

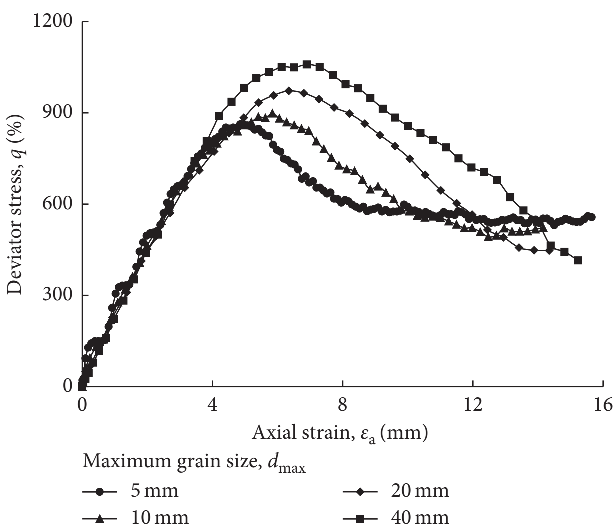

Figure 3: Behaviors of $q-\varepsilon_a$ (confining pressure of 300 kPa).

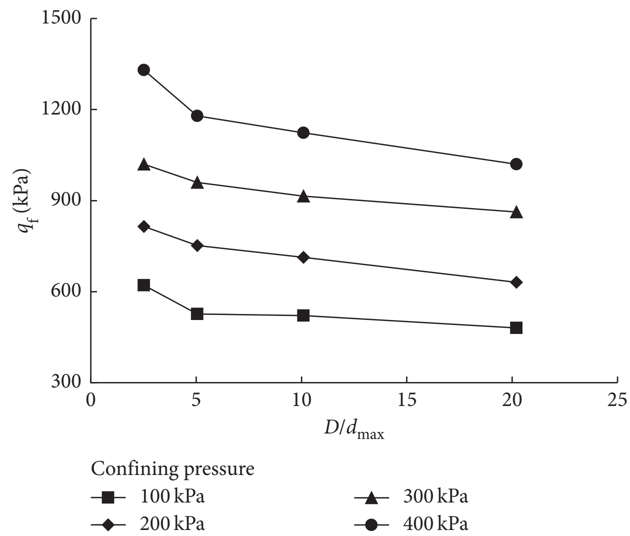

Figure 4: Behaviors of q_f-D/d_{max}.

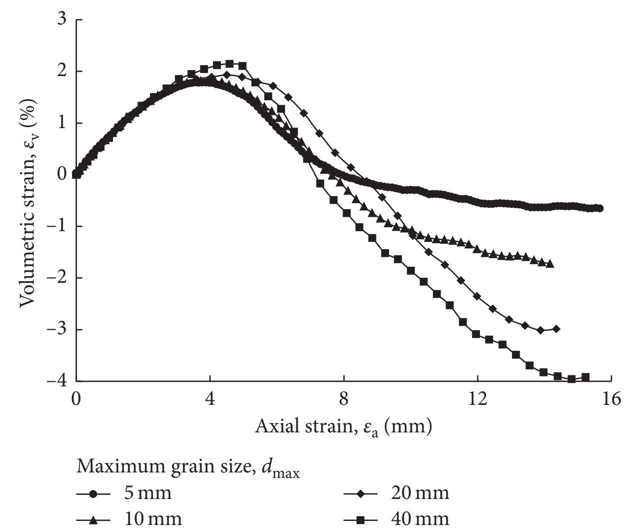

Figure 5: Behaviors of $\varepsilon_a-\varepsilon_v$ (confining pressure of 300 kPa).

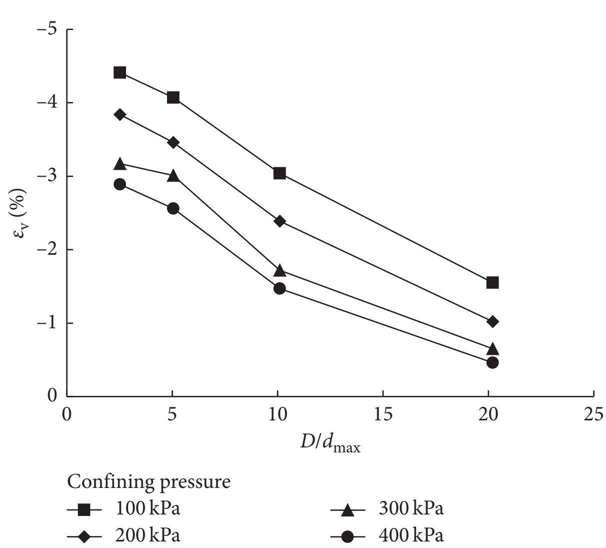

Figure 6: Behaviors of ε_v-D/d_{max}.

fractal dimension value is between 1.463 and 1.783 [21]. Therefore, D was set to 1.5 in the numerical tests. A total of four specimens with the similar grading were used in the numerical tests. The maximum grain size d_{max} was 5, 10, 20, and 40 mm, and the minimum grain size d_{min} was 0.25, 0.5, 1, and 2 mm, respectively. The particles of size less than d_{min} were dealt with the equivalent replacement method. The average grain size d_{50} was 3.1, 6.3, 12.6, and 25.2 mm, respectively. The coefficient of uniformity C_u and the coefficient of curvature of the specimens are 3.3 and 1.30, respectively. The graining curves are shown in Figure 2.

The confining pressures (σ_3) were 100, 200, 300, and 400 kPa. After consolidation, the confining pressure was maintained constant, and then, vertical pressure was applied.

2.3. Parameters. Thus far, the parameters used in DEM simulation cannot be directly obtained by laboratory tests because no definite relation exists between the mesostructure

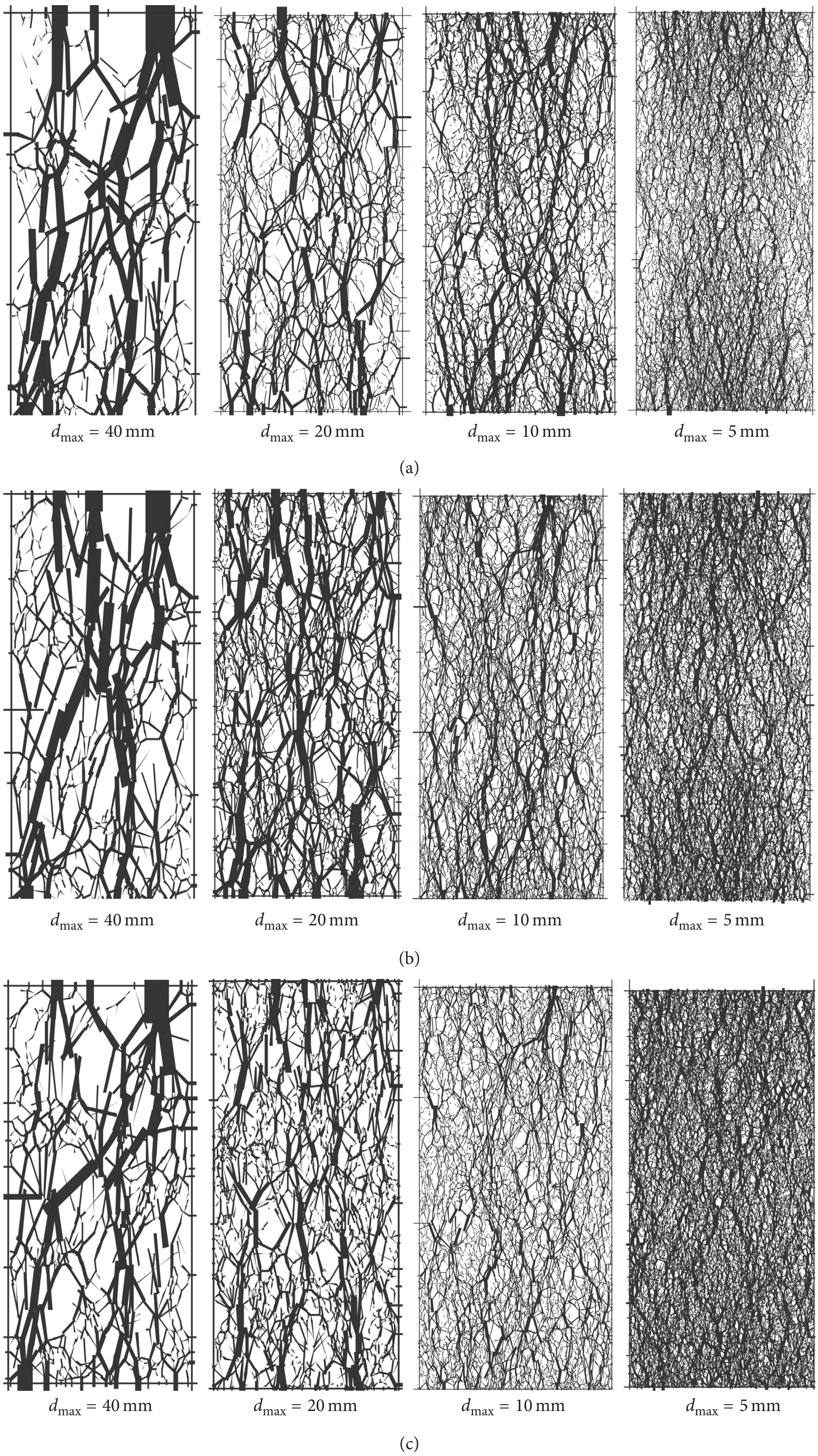

Figure 7: Continued.

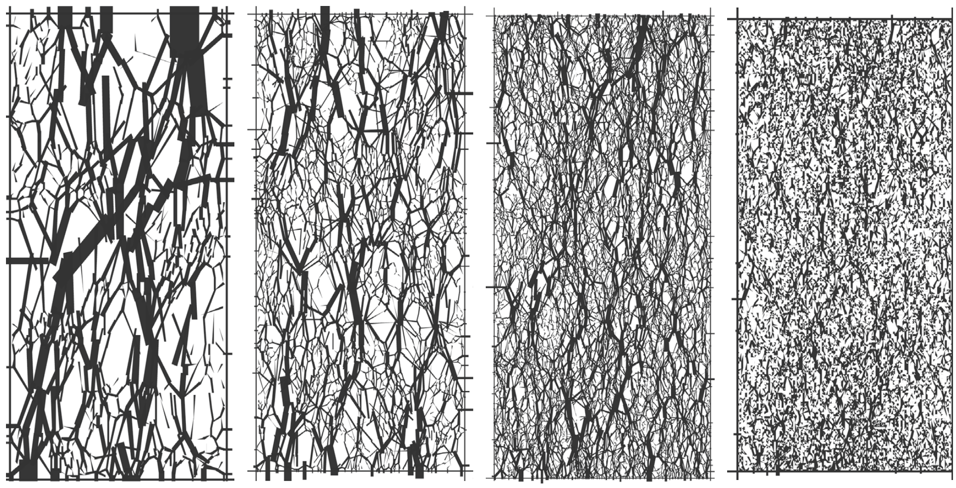

FIGURE 7: Force chain distribution of four different maximum particle sizes and four confining pressure conditions under peak stress state. (a) 100 kPa; (b) 200 kPa; (c) 300 kPa; (d) 400 kPa.

and macroparameters. The trial and error method is used to ensure that the numerical test results are in agreement with the laboratory test results. After repeated trial and error, the mesostructure parameters of biaxial numerical tests were obtained. The normal and tangential contact stiffness of the particles was 4×10^7 N/m, the normal and tangential contact stiffness of the wall was 2×10^8 and 0 N/m, respectively, the friction coefficient between particles was 2.4, the particle density was 2600 kg/m^3, the porosity of specimens was 0.15, and the loading rate was 0.3 m/s.

3. Results and Analyses

3.1. Size Effects on Strength. The deviator stress q-axial strain ε_a curves with different maximum grain sizes under the confining pressure of 300 kPa are shown in Figure 3. The curves under other confining pressures possess similar behaviors. The specimen was found to exhibit a strain softening behavior. The peak deviator stress is considered to be the failure deviator stress q_f. The $q_f - D/d_{max}$ curves are shown in Figure 4. The deviator stress q_f increases with the decrease in D/d_{max}, and the increasing tendencies of q_f are evident when $D/d_{max} \le 5$. This result is consistent with the laboratory test under the same conditions [7].

3.2. Size Effects on Deformation. The volumetric strain ε_v-axial strain ε_a curves with different maximum grain sizes under a confining pressure of 300 kPa are shown in Figure 5. The curves under other confining pressures have similar behaviors. The volume of the specimen contracts initially and then dilates and eventually reaches a steady state when the axial strain is up to 15%. The behaviors between the volumetric strain corresponding to the axial strain of 15% and D/d_{max} are shown in Figure 6. The shear dilatancy of cohesionless coarse-grained soils is evident with the decrease in D/d_{max}.

3.3. Size Effects on Force Chain. The mechanical properties of granular materials are determined by the force chain network formed by the mutual contact of particles [22–24]. The size effect mechanism of coarse-grained soils can be explained by the distribution and transfer law of contact force. Figure 7 is the force chain distribution of coarse-grained soils with different maximum particle sizes under the peak stress. As shown in Figure 7, "black" is denoted as the contact force which is larger than the average value, and its width is proportional to the contact force.

Figure 7 shows that the contact force is transferred mainly through the strong force chain. The strong force chain is mainly distributed along the direction of the major principal stress, and the weak force chain is distributed around the strong chain and acts as support. Both chains form a force chain network structure. With the increase in confining pressure, the lateral strong force chains gradually develop to support the axial strong force chains, and both chains form a stable force chain network. The macroscopic behavior indicates that when the confining pressure is high, the shear strength is also high, thus indirectly proving the rationality of the numerical simulation.

The breakage of the contact points causes the entire force chain to disintegrate and recombine. Maintaining stability is difficult when more particles exist on the force chain. In general, maintaining the stability of the force chain is difficult when its particle number exceeds five [25, 26]. When the maximum particle size is small, more particles exist in the sample, and the contact force is uniformly distributed; thus, forming the strong force chain is difficult. Therefore, the sliding and dislocation between particles easily occur, and the macroscopic behavior of particles shows that the soils have low shear strength. The increase in the maximum particle size results in evident sample boundary restraint. The contact force becomes uniform, and the stable strong chain becomes long due to the decrease in the particle number. Extending the strong force chains from one side of the sample to the other is easy, thereby forming a stable structure that is failure resistant. Macroscopically, the sample shows high shear strength and evident size effect.

4. Conclusion

The DEM simulation of biaxial compression tests for coarse-grained soils with different maximum grain sizes and self-similar fractal structures in mass was carried out. The effect of grain size on the mechanical properties and force chain of coarse-grained soils was also discussed. The main conclusions are as follows.

(1) The shear strength of coarse-grained soils increases with the increase in the maximum particle size. The shear strength of soils evidently increases when the ratio of the sample diameter to the maximum particle size is less than five.

(2) When the maximum particle size increases, the shear dilatancy of cohesionless coarse-grained soil also increases.

(3) When the maximum particle size is small, many particles exist in the sample, and the contact force distribution is uniform; thus, forming a strong force chain is difficult. When the maximum particle size increases, the particle number decreases, the contact force distribution of particles tends to be uneven, and the stable strong force chain increases the shear strength, thereby resulting in size effect.

Conflicts of Interest

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

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