A Comprehensive Correlation Study of Structured Soils in Coastal Area of South China about Structural Characteristics

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Abstract: Granite residual soil is a common engineering material, and its mechanical properties are of great importance to engineering safety. This kind of soil presents obvious structural characteristics, and many researchers have emphasized the significance of its structural features. According to previous experiments, from a macroscopic perspective, many researchers have investigated the structural relationship between undisturbed and remolded soils, but few studies have considered it in the mesoscopic aspect. Adopting DEM (a mesomechanical simulation method), we can study how the structure affects the mechanical process between undisturbed and remolded soil. Therefore, this paper combines DEM with laboratory tests to study the structural characteristic correlation between undisturbed and remolded soil. The results indicate that a weak cohesion effect exists in undisturbed soil, and the damage of weak cohesion elements accompanies the failure process. Weak cohesion elements in undisturbed soil cause inhomogeneities in deformation, stress state, and damage accumulation, which ultimately causes differences in strength curves. This paper explains the mechanism of the structural effect on mechanical evolution from a mesomechanical perspective. The DEM simulation method proposed in this paper can be applied to structured soils and better guide engineering practice.

Keywords: residual soil; structural characteristic; DEM simulation; mesomechanical correlation

1. Introduction

The residual granite soil in the coastal area of South China is a common construction material. As an essential component of building foundations, highways, railway subgrades, and natural slopes in this area, its mechanical properties are of great importance to engineering practice [1]. According to previous research, residual granite soil presents a prominent structural characteristic. Quantitative characterization of this property can better guide engineering. Therefore, many studies have focused on this issue in geological materials (e.g., residual soil, bonded sand, calcium carbonate silt, soft clay, etc. [2–4]). One typically adopted research method is conducting laboratory tests of structured soils to establish the relationship between soil structure and constitutive features. Except for only studying the mechanical characteristics shown in lab experiments, we attempt to quantitatively describe the structural quality of granite residual soil from a mesomechanical perspective, which will provide insight and better guide engineering practice.

According to one of the typical views, the structural characteristic in residual soil is induced by weak bonds of grains in undisturbed soil [2]. Since 1968, when the critical
state framework of soil mechanics was proposed, research on the structural features of undisturbed soil and remolded soil has attracted much attention. In the earlier stage, Leroueil and Vaughan (1990) [4] conducted extensive studies on natural and artificial soils to explore their structural characteristics, and they indicated that the structural characteristics of these natural and artificial soils show similar laws in terms of strength and Young’s modulus [4]. A large number of studies on structured natural soils were also carried out during this period (including residual soil, soft clay and bonded sand, etc. [3]). In early studies, scholars placed emphasis on revealing the yield process of structured soil and qualitatively explained how the structure influences soils in constitutive models [2]. Considering a quantitative description, Xie and Qi [5] comprehensively considered the mechanical characteristics of undisturbed and remolded soil and presented several formulas to define the structural parameters. These studies provide significant insights into correlating structural characteristics in laboratory experiments [5]. Recently, the understanding of soil structure has been motivated by microdetection equipment, and many techniques have raised this research to a new level. It is well known that the structural characteristics of soil are closely related to its mesoscopic anisotropy and inhomogeneity. The discrete element method (DEM) is a powerful tool to study the mesomechanical behavior of discrete grain elements and the associated bonding effect related to their structural features and is widely used in rock and geotechnical fields [6–8]. An increasing number of researchers are successfully quantitatively studying the mechanical characteristics of soil through DEM. For example, Kang [9] correlated soil creep and pore characteristics by evaluating the creep process of different loose soils. Jang [10] quantitatively studied the influence of the mesofriction coefficient, Young’s modulus, and antirolling friction coefficient of soil by designing wheel–soil interface experiments with the assistance of DEM. Some constitutive studies of soil also focus on the DEM framework [11]. However, there is still a lack of research on the structural characteristics of soil with DEM.

In this paper, the macroscopic mechanical properties of the residual granite soil in the coastal area of South China are first studied with the triaxial drained compression test. Subsequently, in DEM, a quantitative study from the perspective of the bonding ratio is carried out. The results indicate that the structural correlation can be established according to lab tests and DEM analysis.

2. Contents and Methods

2.1. Laboratory Experiments

2.1.1. Preparation of Soils

The sample was obtained in situ from a construction foundation in Guangzhou. The ground surface is distributed with 2–4 m of common soil, and the lower part is the layer of residual granite soil. To obtain representative samples, we manually cut a soil block with a length of 30 cm during the excavation of the foundation pit. We wrapped it with a plastic cloth and sealed it with wax before transporting it to the laboratory. The geotechnical test results of the soil are listed in Table 1. According to X-ray diffraction mineral analysis, the soil contains 10.0% quartz, 72.0% kaolinite, 9.8% illite, 4.2% montmorillonite, and 4.0% hematite. Soil chemical analysis shows that the organic matter content of Guangzhou granite residual soil is close to 0, but it contains a large amount of free iron oxide and alumina. Previous studies have shown that the free oxide is a unique feature of residual granite soil. The free iron oxide and alumina are wrapped and filled to realize the bonded connection effect. When the soil is disturbed, the bonds are destroyed, and the strength decreases.

2.1.2. Testing Procedures

The testing apparatus used for this research is called ‘TSZ10 Automated Triaxial Instrument’. The maximum axial and lateral stresses that can be applied to the specimen are 3000 and 1500 kPa, respectively. The axial load was measured using a rigid load cell, which is sensitive to hydrostatic pressure (accuracy of 0.2 N). The back pressures
were measured by pressure transducers. Additionally, the upper and lower proximity transducers were adopted to measure the axial strain with an accuracy of 0.0005%.

Table 1. Physical and mechanical average parameters of granite residual soil.

| Depth (m) | Density ρ (g/cm³) | Water Content ω (%) | Dry Density ρ_d (g/cm³) | Void Ratio e | Plasticity Limit ω_p | Liquid Limit ω_L | Liquidity Index I_L | Plasticity Index I_P (%) | Compressive Index σ_1-2 (MPa) | Compressive Modulus E_s (MPa) |
|-----------|-------------------|---------------------|-------------------------|-------------|----------------------|------------------|---------------------|-------------------------|-----------------------------|-------------------------------|
| 8–10      | 1.79              | 32.2                | 1.30                    | 0.95        | 26.2                 | 43.3             | 0.35                | 17.1                    | 0.18                        | 10.8                          |

To evaluate the influence of structure on the mechanical behavior of granite residual soil, the high-pressure consolidation test and the triaxial drained compression test were adopted. Firstly, the soil block was cut with a ring knife with an inner diameter of 61.8 mm and a height of 20 mm to produce samples for the high-pressure consolidation test. Subsequently, the triaxial sample (40 mm × 80 mm) was obtained for the drained compression test. Then, we naturally air-dried the remaining soil and added water based on the original water content to prepare the remolded soil.

We used a triple consolidation instrument to carry out the high-pressure consolidation test. The test involved 8 loading levels (12.5, 25, 50, 100, 200, 400, 800, and 1600 kPa). Consolidation tests were performed with a strain rate of 0.001%/min. We derived the compression curves and calculated the compression factor based on the consolidation tests.

For the triaxial drained compression test, we adopted an automatic servo compression instrument. The testing procedures considered the details published by Lo Presti and Pallara et al. [12]. The four prepared undisturbed and remolded samples were consolidated at 100, 200, 300, and 400 kPa. The axial stress was increased to the abovementioned value with a strain rate of 0.01%/min. Meanwhile, the confining pressure was increased in order to keep the lateral displacement equal to zero. When the pore pressure was completely dissipated, the pressure was gradually applied and recorded loading data. The test was paused when the axial strain reached 15%.

2.2. DEM Simulation

2.2.1. Mesomodel in DEM

The purpose of laboratory tests is to analyze the structural influence on mechanical behavior from stress–strain curves, which are also macroscopic. Herein, DEM parameter calibration is required, and two kinds of mesocontact models are involved. One is termed the parallel bond model (PBM), which can describe the weak bond effect of soil structure, and the other is the linear contact model, which can simulate the expected motion of soil grains. The PBM is often used to simulate the bonds of rock and soil mass [13], and the failure process follows the Mohr–Coulomb criterion (when the local tensile or shear force exceeds the limit, the bonds will be broken). A linear contact model controls the sliding and motion after the failure of bonds [6].

2.2.2. Calibration of DEM Parameters

Because the mechanical properties of soil are complex, it is impossible to take every aspect into account when conducting simulations. Therefore, the calibration process in this paper considers the main mechanical parameters of soil (elastic modulus and peak strength) [14]. The mesoparameter calibration process was based on the laboratory test results. The parameter values of the DEM model were carefully calibrated by a gradual ‘trial-and-error’ process to better restore the real properties of the soil.

2.2.3. Test Procedures in DEM

Preparation of numerical samples: The size and grain radius of the DEM sample needed to first be determined. The size of the samples is 40 mm × 80 mm according to the lab test. The selection of grain radius requires some explanation. We adopted a common DEM
tool termed PFC, which is widely used in the DEM simulation process. The fundamental element in PFC is grain, and the grain size will affect the calculation accuracy. Ideally, a smaller radius of grain will result in a better simulation result. However, selection needs to consider the limited computing efficiency. According to previous research results, the grain size in the simulation process has a minor impact on the accuracy when $L/r$ (sample size to grain radius) >68 [15] or when the number of grains is greater than 15,000 [16]. Herein, we built the model with grains exceeding 20,000, which meets the accuracy requirements in 3D conditions.

Precompression: This step simulates the soil deposition process in nature. After this step, the assembly of discrete grains becomes compact, presenting a good contact forcing state that can be used for further testing.

Servo: To restore the confining pressure in laboratory tests, the applied force of the boundary was precisely controlled by the Fish code in the PFC, and the control process is shown in Figure 1. After the servo force was applied, the confining pressure of the sample was constant near the target stress. Before compression tests, the servo stress vector diagram was finished, as shown in Figure 2. It was found that the direction of the stress applied to the grains on the boundary points to the center coincided with the actual condition.

![Figure 1. Confinement servo process in DEM.](image-url)
Loading: The loading process was controlled by the side plates, and the loading rate was maintained at 0.001 m/s. Due to the small time step in the PFC, the loading speed could be approximately considered quasi-static loading, which was similar to the laboratory test.

3. Results and Discussion

3.1. Results of High-Pressure Consolidation Tests

The high-pressure consolidation curves of Guangzhou granite residual soil are shown in Figure 3. One can find that although the initial void ratio of undisturbed soil and remolded soil is the same, with the increasing loading stress, the compression curves of remolded soil are significantly lower than undisturbed soil. In addition, the deformation resistance of remolded soil is also weaker than undisturbed soil. It can be found that the compression line of undisturbed soil is curve-linear. When the consolidation pressure is less than 200 kPa, the soil deformation is small, and the curve is linearly dominated, but when the consolidation pressure is greater than 200 kPa, the slope of the curve increases rapidly, which coincides with the features of the typical structural soil. However, the slope of remolded soil is stable, indicating different mechanical properties compared with undisturbed soil.

In addition, the compression coefficient (characterizing the deformation property) and compressive modulus are derived through the consolidation test. According to the results, the compressive coefficient equals 0.18, and the compressive modulus equals 10.8 MPa in undisturbed soil. In remolded soil, the compressive coefficient equals 0.31, and the compressive modulus equals 6.15 Mpa. This indicates that the structural strength dissipates when the soil is sufficiently disturbed (remolded). Therefore, the compressive coefficient of the soil increases, and the compressive modulus decreases, which means that the soils' resistance to deformation is weakened.
Figure 3. High-pressure consolidation curves.

3.2. Results of Laboratory Compression Tests

From Figure 4, the stress–strain curves of undisturbed and remolded soil all present a strain-hardening effect. The difference is that the strength of undisturbed soil is significantly higher than remolded soil. With the effect of structure, the stress of undisturbed soil is considerably greater than remolded soil in the same strain. For example, when the confinement equals 300 kPa, the stress required for a 15% strain of undisturbed soil is 220 kPa, while it is only 190 kPa for remolded soil. In addition, the same conclusion can also be obtained when the strain is less than 5%. Similarly, under the same stress, the strain generated by undisturbed soil is significantly smaller than remolded soil, which is reflected in the stress–strain curves. The strain in the curve inflection point of undisturbed soil is greater than remolded soil. For example, when confinement equals 300 kPa and stress equals 100 kPa, the strain of undisturbed soil is 2%, while the strain of remolded soil is 3%. Further, the total and effective strength parameters are presented in Table 2, where one can find that the cohesion in undisturbed soil is greater than remolded soil.

Figure 4. Stress–strain curves of undisturbed and remolded soils.
Table 2. Calculated cohesion and shear resistance angles.

| Soil                | Total Strength Parameters | Effective Strength Parameters |
|---------------------|---------------------------|-------------------------------|
|                     | C/kPa        | $\phi^\circ$ | $C'/kPa$ | $\phi'^\circ$ |
| Undisturbed soil    | 34.7         | 10.5         | 40.0     | 14.3         |
| Remolded soil       | 21.1         | 11.8         | 23.3     | 16.6         |

3.3. Results of DEM Simulation

According to the laboratory test results, the structural difference between undisturbed soil and remolded soil is macroscopically reflected in the stress–strain curves. As mentioned above, residual soils are structurally characterized by weak inner bonds in undisturbed soils. This bond is destroyed in remolded soil. Therefore, in the numerical simulation, it is believed that an appropriate amount of bonding elements should be added to undisturbed soil to simulate the above-mentioned weak bond effect. Conversely, an utterly linear contact model is used in remolded soil to reflect the disturbing condition.

3.3.1. DEM Results of Undisturbed Soil

The DEM mesoparameters are calibrated through a ‘trial-and-error’ process in this paper. The purpose is to make the simulation results coincide with the laboratory tests. The stress–strain curves are shown in Figure 5. Despite extensive parameter calibration work, there are still some slight errors in these final curves for the reasons that the DEM tests are prepared in an ideal state, while the anisotropy, heterogeneity of the soil, and the stability of the machine servo will affect the shape of the curve in the actual process. Therefore, the rising stage and the plastic stage errors have a minor effect on the analysis process.

The numerical test is consistent with the control conditions of the laboratory test, and the loading is halted when the axial strain reaches 15%. The final state of this set of numerical tests is shown in Figure 6. The final deformation state of the test with a confining pressure of 100 kPa is different from other tests. The deformation of the test with a confining pressure of 100 kPa is uniform, showing both-side compaction accompanied by the waist expansion. The axial deformation of the end is larger than the middle part. The other three
sets of tests show a different deformation pattern: the waist is thin, and the end sides are swollen. Due to the structural effect (bonding element), the high confining pressure will amplify the local structural effect, resulting in nonuniform stress distribution and thus the emergence of the abovementioned deformation modes.

Figure 6. Loading results of undisturbed soils.

The statistical diagram of the contact force between grains in the spatial coordinates can be used to describe the stress concentration degree of soil. Figure 7 shows the stress statistics in the plastic stage. The column length and direction in the statistical graph represent different stress concentration states, and the longer column represents the higher the stress concentration degree. Since the force is obtained in the loading state, the direction of highly concentrated stress is mainly distributed in the vertical direction. Due to the weak bonding effect in undisturbed soil, the concentrated stress is not uniform. This nonuniformity is reflected in the stress statistics of 100–300 kPa. These stress states all show that the upper column is longer than the lower boundary. Therefore, we believe that the structural effect causes the nonuniform stress concentration.

Figure 7. Stress vector spatial statistical graph of undisturbed soils.

The numerical test in this paper simulates the structural characteristics of residual granite soil through PBM. During the loading process, the damage of the bonded elements can be captured with the assistance of DEM tests. The specific results are shown in Figure 8, where the disks distributed in the middle represent mesodamage. When the bond between grains is destroyed, it will be counted as disk-shaped mesoscale damage cracks. The damage figures are related to different strains (3%, 6%, 9%, 12%, 15%). The loading process of undisturbed soil shows the accumulation of damage in different stages. It can be found that the mesocrack development is uniform in the first three stages without local concentration. In the fourth and fifth stages, the overall crack spatial statistics are slightly denser at both ends than in the middle. Combined with the deformation figure in Figure 6 and the stress
concentration in Figure 7, it is believed that the weak bond effect of the residual granite soil eventually causes a nonuniform damage state and causes the final deformation difference.

Figure 8. Crack development in undisturbed soil under 300 kPa confinement.

The calibration process of undisturbed granite soil can restore the results of the laboratory test in the stress–strain curves. It can also reflect the structural deformation, stress concentration, and damage accumulation differences that cannot be reflected in the laboratory test. The calibration results are shown in Table 3.

Table 3. The calibration results of undisturbed soils.

| DEM Parameters | Tensile Strength $\sigma_t$/kPa | Cohesion Strength $c$/kPa | Friction Angle/° | Stiffness Ratio | Elastic Modulus/MPa | Frictional Coefficient $u$ | Damping $\beta$ | Width/mm | Height/mm | Mean Radius/mm |
|----------------|-------------------------------|--------------------------|------------------|-----------------|---------------------|--------------------------|----------------|-----------|------------|----------------|
| assignment     | 130                           | 130                      | 30               | 1.5             | 15                  | 0.05                     | 0.7            | 40        | 80         | 0.9            |

3.3.2. DEM Results of Remolded Soil

Similarly, this paper also calibrated remolded soil, and the stress–strain curves are shown in Figure 9. The final calibration curve error is still mainly reflected in the stress rising stage.

Figure 9. Stress–strain curves of remolded soil in DEM.
The final states of this set of numerical experiments are shown in Figure 10. Compared with undisturbed soil, it can be found that the deformations are more uniform, showing both-side compaction accompanied by the waist expansion. This is because the cohesive bonding force is not applied to remolded soil; hence, the weak cohesion effect caused by the structure is not reflected.

Figure 10. Final deformation of remolded soils.

The force vectors among contacts are also spatially calculated and shown in Figure 11. Due to the dissipation of weak bonds in remolded soil, the nonuniform distribution of highly concentrated stress has been significantly changed. For example, the concentration states at both ends are symmetrically distributed under 200–400 kPa confinements. However, at a lower confining pressure of 100 kPa, the stress shows asymmetry, which is caused by the low constraint on grains’ motion, while the high confining pressure will limit the flow of the grains. Therefore, we believe that remolded soil’s stress distribution and deformation are more uniform than undisturbed soil.

Figure 11. Stress vector spatial statistical graph of remolded soils.

The calibration process of the granite-re-molded soil can restore the mechanical properties shown in laboratory tests, which can be used to make correlations with undisturbed soil. The specific mesoparameter calibration results are shown in Table 4.
Table 4. Calibration results of remolded soils.

| DEM Parameters | Tensile Strength $σ_t$/MPa | Cohesion Strength $c$/kPa | Friction Angle/° | Stiffness Ratio | Elastic Modulus $E$/MPa | Frictional Coefficient $u$ | Damping $β$ | Width/mm | Height/mm | Mean Radius/mm |
|----------------|-----------------------------|---------------------------|------------------|-----------------|------------------------|--------------------------|------------|-----------|-----------|----------------|
| assignment     | 0                           | 0                         | 20               | 1.5             | 15                     | 0.05                     | 0.7        | 40        | 80        | 0.9            |

3.4. Structural Correlation of Undisturbed and Remolded Soils in Constitutive Relation

The empirical expression derived from the stress–strain curves is helpful in conveniently analyzing the constitutive relation. As demonstrated before, due to structural effects, Guangzhou granite residual soil presents different stress–strain relations. This section will provide a structural correlation analysis from the macro stress–strain aspect.

3.4.1. Constitutive Models of Remolded Soil

The stress–strain curves of remolded soil can be fitted with a hyperbola. By comparing the applicability of previous models, the Duncan–Chang model [17], which is widely used in soil engineering [18,19], is selected herein:

$$σ_1 − σ_3 = \frac{ε_σ}{a + bε_σ}$$

(1)

where $a$ and $b$ are the constant coefficients of the Duncan–Chang model. We fit the test results relying on Equation (1), and the derived parameters are shown in Table 5. The fitting results are shown in Figure 12.

Table 5. Parameters of Duncan–Chang model.

| Parameter | 100 kPa | 200 kPa | 300 kPa | 400 kPa |
|-----------|---------|---------|---------|---------|
| $a$       | 0.00012 | 0.00072 | 0.00043 | 0.00011 |
| $b$       | 0.03011 | 0.01433 | 0.01132 | 0.00998 |

Figure 12. Fitting results of remolded soil adopting the Duncan–Chang model.

From the fitted results, one can find that $a$ and $b$ increase with confinement, indicating a well correlation with confining pressures. In Figure 12, when $ε$ is less than 3.0%, the fitted
curves are slightly greater than the test results, but when ε reaches 3.0%, the fitting curves coincide well with the measured data. In general, the Duncan–Chang model can reflect the constitutive relation.

3.4.2. The Constitutive Models of Undisturbed Soil

We also utilize the Duncan–Chang model to fit test results of undisturbed soils and the fitted curves are shown in Figure 13a. Although the Duncan–Chang model can reasonably simulate the stress–strain relationships of remolded soils, it is not optimally suitable for undisturbed soils, especially in the initial stage. The fitted segment elastic modulus is also higher than the test data. We believe that the structural characteristics make contributions to the different constitutive relations, causing the worse fitting results of the Duncan–Chang model.

![Figure 13](image-url)

**Figure 13.** Comparison between test data and calculated results using different models. (a) Duncan–Chang model; (b) Shen model.
After a comprehensive comparison, the nonlinear model proposed by Shen [20] is selected to simulate remolded soil, which makes some nonlinear improvements compared to the Duncan–Chang model:

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

where \(a\), \(b\), and \(c\) are the constant coefficients of the Shen model, and this new model can better reflect structured soil.

According to Equation (2), we can fit the test results again and the calculated parameters are shown in Table 6. The corresponding fit results are shown in Figure 13b and Table 7, where one can find that the new fitting curves are much better than the original condition. The parameters of \(a\), \(b\), and \(c\) are reduced with the growth of confinements, indicating a better correlation with pressure. Therefore, we believe that the Shen model can better reflect the constitutive relations of undisturbed soil considering structural characteristics.

\[
\sigma_1 - \sigma_3 = \frac{\varepsilon_a (a + c\varepsilon_a)}{(a + b\varepsilon_a)^2} = \frac{\varepsilon_a}{(a + b\varepsilon_a)} (a + c\varepsilon_a) \tag{3}
\]

Table 6. Model parameter of Shen model.

| Parameter | 100 kPa | 200 kPa | 300 kPa | 400 kPa |
|-----------|---------|---------|---------|---------|
| \(a\)     | \(5.22 \times 10^{-5}\) | \(3.82 \times 10^{-5}\) | \(2.45 \times 10^{-5}\) | \(1.82 \times 10^{-5}\) |
| \(b\)     | 0.0032  | 0.0017  | 0.0012  | 0.0009  |
| \(c\)     | 0.0011  | 0.00074 | 0.00062 | 0.00034 |

Table 7. Coefficient of determination adopting two models.

| Model                  | Confinements/kPa | \(r^2\) |
|------------------------|------------------|---------|
| Duncan–Chang model     | 100              | 0.79413 |
|                        | 200              | 0.87513 |
|                        | 300              | 0.78969 |
|                        | 400              | 0.87311 |
|                        | 100              | 0.95275 |
| Shen model             | 200              | 0.99412 |
|                        | 300              | 0.98655 |
|                        | 400              | 0.99443 |

After the simple expansion of Equation (2), it is easy to discover the correlation between the Shen model and the Duncan–Chang model in Equation (3). Indeed, the left part of the expansion formula itself is the Duncan–Chang model. Therefore, the right part is the difference, which serves as a modification. Hence, the structural correlations between undisturbed and remolded soils are reflected in Equation (3). However, the constitutive correlation is constructed empirically, which can only explain the stress–strain difference. We want to further reveal the structural correlation from a mesomechanical perspective, which is demonstrated in Section 3.5.

3.5. Mesomechanical Structural Correlation between Undisturbed and Remolded Soil

The structural characteristics of undisturbed soil are caused by local clusters that can be simulated with PBM in DEM. From a typical view, when these bonded clusters are destroyed, the structural characteristics dissipate as well. Till now, we have revealed the structural correlation in the constitutive relationship. However, in this way, it is difficult to depict how the mesostructure affects the mechanical properties.

Therefore, we construct the numerical models according to stress–strain curves and distinguish undisturbed soil by adding bonded elements. Although we change some of the
remolded soil grains with bonded elements, a linear contact model still simulates the main body part. In this way, we can reflect the structural characteristics in a mesomechanical way. In Section 3.3, we demonstrated that the well-calibrated two kinds of soil model can restore laboratory results and reveal the bonding effect induced by anisotropy.

Herein, we quantitatively analyze the ratio of bonded elements to normal elements in undisturbed soil. In Figure 14, we present a remolded and undisturbed soil model in DEM, where the blue grains represent the main body structure, and the green clusters represent local bonded structures. We can also find the different contact states in two models, where the green portion of Figure 14c illustrates the PBM force, and the blue part represents the linear contact force.

Figure 14. Model and contact states of undisturbed and remolded soil. (a) Main body of remolded soil. (b) Bonded clusters and the main body of undisturbed soil. (c) Contact state of remolded soil. (d) Contact state of undisturbed soil.
Actually, before establishing the effective DEM models, we have carried out ‘trial-and-error’ adjustments many times. The PBM replacing process is completed by a random assignment method, which is closer to the natural state. The following steps accomplish the specific distribution method: (1) uniformly generating the model with a grain size between 0.9 and 1.2 mm spatially; (2) freely assigning a certain number of soil grains by random seeds and dividing them into two groups; (3) applying PBM to one of the groups to simulate the bonding effect.

Figure 15 shows the detailed constituting of two kinds of soils. According to the final calibration result, the mechanical differences between undisturbed and remolded soils are: (1) undisturbed soil contains 16.7% bonded elements, which can be destroyed under mechanical disturbance; (2) the bonded elements simulated by the PBM have a higher cohesion and internal friction angle. These structural characteristics eventually lead to the different simulation results reflected in the stress–strain curves. The detailed difference between the PBM and the linear model is depicted in Figure 16.

The PBM is a widespread model for simulating the bond effect. The bonds’ failure presents two different modes. For instance, tensile failure occurs when the local tension force exceeds $\sigma_t$, and shear failure appears when the local shear force exceeds the shear strength. After the failure, the linear model will control the grains’ motion, and the friction force is the remaining limitation. In the linear contact model, the force consists of linear elastic and viscous force ($f_c = f_l + f_d$). The value is determined by the normal ($k_n$) and shear ($k_s$) stiffness of springs. Dashpot produces a viscous force to simulate the kinetic energy dissipation, and the corresponded parameters are the critical damping ratio in the normal and shear directions ($\beta_n$ and $\beta_s$).
In Section 3.3, we revealed the overall structural correlation of remolded and undisturbed soil in constitutive models. We find that the main feature of the constitutive model was not altered, and similar analytical expressions can correlate mechanical differences. From the perspective of mesomechanics, this similarity is associated with the different elements shown in Figure 15. The blue part represents the basic structural characteristics of the soils, and the green part represents the bonded effect in undisturbed soil. This main body structure is regarded as the overall mechanical properties of the Duncan model, and the local bonded structures are believed to be the right part of the Shen model shown in Equation (3).

4. Conclusions

1. According to the experiments and simulations, the structural characteristic correlation between undisturbed and remolded soil was studied. The Duncan–Chang and Shen models were adopted to present the analytical correlation. Further, the DEM simulation interpreted the structural correlation considering the bonding effect.

2. The proposed method took laboratory tests and simulation results into account. The DEM simulation results complemented the mesoscale structural analysis. Particularly, we replaced 16.7% DEM grains with bonded elements to restore the laboratory results. The structural elements proved to produce more strength, extensive stress concentration, and the associated deformation.

3. We believe the Duncan–Chang model can reflect the stress–strain characteristics of remolded soil, and the Shen model can reflect undisturbed soil. The mesoscale difference can be simulated with different contact models in DEM. The comprehensive method can be adapted to guide engineering practice.
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