3D DEM simulation of initial anisotropy in dredger fill soft soil

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Abstract. The initial anisotropy has a significant effect on the mechanical properties of the soft soil. Based on the initial anisotropy of the particles, the mechanical characteristics are analysed from a microscopic view, and the micro-macro relationship of the soil is established. According to the particle morphology of soft soil, the discrete element method is used to construct the flaky particle clusters, and seven sets of samples with different initial deposition angles are established for consolidation and undrained triaxial simulation tests. The results show that the strength of the sample decreases first and then increases with the increase of the deposition angle. When the deposition angle is 0°, the flaky particles mostly appear in a nearly horizontal suspension, and the sample has the largest shear strength. The distribution of the contact force chain formed by the particles in the shearing process is also related to the deposition angle. Different deposition angles form displacement fields of different shapes. When the deposition angles are 45° and 60°, there are obvious deformation displacement bands. At the same time, the initial deposition angle affects the particle coordination number. The higher the sample strength corresponding to the lowest average coordination number of particles. The contact normal anisotropy coefficient is related to the strain hardening and strain softening characteristics in the shearing process. The increase in the contact normal anisotropy coefficient shows the characteristics of hardening, and the smaller the contact normal anisotropy coefficient shows the characteristics of softening.

1. Introduction
As one of the developed areas in China, the coastal areas of China have a vast sea area, but a small land area. In order to solve the problem of lack of land area, reclamation of land from the sea has become an effective way, and dredger fill is widely used as a material in the project of reclamation of land from the sea in coastal areas. Dredging soft soil is a kind of soil formed by dredging the river and sea silt to the shore and gradually depositing it. Compared with ordinary sand materials, dredger fill has the characteristics of abundant material sources, convenient transportation, and economical price[1].
Due to the under-consolidated state of hydraulic fill soft soil, it has the characteristics of high water content, high void ratio, high compressibility, low strength, and certain structural properties[2, 3]. The soft soil is disturbed during the process of hydraulic fill. The internal structure undergoes a new deposition process from disorder to order, and the structural strength is also reshaped from scratch. The formation of the soft soil structure of the dredger fill leads to anisotropy of the soil, which affects the strength, deformation, and permeability of the soil. These properties are issues of concern in engineering construction, and a mature theory has not yet been formed. In particular, the vertical deformation of dredger-filled soft soil is long-term creep, which is easy to induce settlement disasters. It is necessary to start the study of anisotropy by the structure of sedimentary dredger-filled soft soil.

For the research on the anisotropy of soft soils, more scholars start from experiments and explore the laws of anisotropy. This includes the use of laboratory tests to study the strength, deformation and penetration of anisotropic soft soils. Ochiai and Lade [4] study the influence of different deposition angles and various stress paths on the anisotropy of sand. The test results show that when the stress path is the same, the strain corresponding to the peak stress is the smallest and the largest when the deposition angle is 90° and 0°, respectively. Gao and Lou [5] used indoor special-shaped cross plate shear tests to study the anisotropy of undrained shear strength of Shanghai soft clay. The study showed that when the total stress is zero, as the angle between the failure surface and the horizontal increases, the greater the undrained shear strength. Yu [6] studied the permeability anisotropy of remolded kaolin by triaxial apparatus, indicating that the permeability anisotropy of remolded kaolin was caused by the difference between the pore area of vertical section and that of horizontal section.

The above scholars mostly use the method of indoor test to study the anisotropy of soft soil, but the method of indoor test has certain shortcomings, such as disturbance to the soil during the test, and each test sample cannot be guaranteed the consistency of its internal structure. Anisotropy is divided into initial anisotropy and induced anisotropy. The initial anisotropy is the change in mechanical properties of the soft soil in the dredger fill engineering, due to various reasons that lead to the different arrangement of soil particles in different directions. When sampling in the project, for the dredger fill formed by natural sedimentation, the soils sampled from different angles form initial anisotropy. Studying the initial anisotropy formed by different sampling angles has important guiding significance for engineering sampling of dredger fill. Due to the limitation of laboratory test methods, the use of laboratory tests to study soils with specific deposition angles is less. With the development of computer technology and the deepening of numerical simulation research, more and more scholars used numerical simulation to study the initial anisotropy.

Hosseininia [7] simulated the initial anisotropy of sand with convex polygons through a biaxial numerical simulation test, and found that the initial anisotropy of particles has a significant effect on the shear strength and swelling properties of the specimen. Mirghasem [8] used the discrete element model to simulate the direct shear test of elliptical sand particles, and studied the effect of the initial elongation of the particles on the macroscopic and micro mechanical behavior. The results show that the initial anisotropy influences the fabric anisotropy, contact normal force, contact shear force. Jiang [9] randomly generated elliptical particles with the same aspect ratio with initial anisotropy through the discrete element program, and studied the effects of initial anisotropy on the contact normal, contact force and other micro mechanical characteristics under monotonic and cyclic shear tests. Jiang et al. [10] studied the influence of the positioning and arrangement characteristics of sand on the initial anisotropy through a biaxial test based on a self-compiled discrete element program. Zhang et al. [11] established a biaxial test model of sand through PFC, and analyzed the original anisotropy of sand from the perspective of the microscopic long-axis orientation of particles and the average coordination number. Qian et al. [12]quantitatively studied the macro-mechanical and microscopic characteristics of the initial anisotropy of coarse-grained materials from the perspective of fabric tensor by constructing irregular-shaped coarse-grained materials. The above scholars have carried out initial anisotropy research, mostly focusing on coarse grains such as sand or conducting two-dimensional simulation tests, and seldom using flake particles to develop three-dimensional simulation tests.
Therefore, this paper uses the PFC3D as a research method to construct flake particles and prepare samples with different deposition angles to simulate the triaxial test under a specific confining pressure. Through the triaxial test, the macro-mechanical characteristics of the flaky particles in the shearing process are analyzed and the meso-mechanical mechanism is explored.

2. DEM Simulations
With the different of sand particles, which are spherical or ellipsoidal. The particles of soft soil are flakes, which can be seen from the SEM image of 2000 times. Combined with the research on soft soil particles [13], flaky particles with an aspect ratio of 2:1 are constructed, as shown in Figure 1.

![Figure 1 Construction of flake particles](image)

2.1. Micro-parameter selection
The macroscopic mechanical properties of soil are affected by two factors: one is the differences in mechanical properties caused by internal factors such as the particle composition, particle shape, and internal spatial structure of the soil; the other is the differences in macro-mechanics caused by external factors such as pressure, stress path, and loading method. Coulomb's law mentions that the shear force of clay is determined by the friction angle and cohesion. The value of these two physical parameters depends on the internal factors of the soil including the composition of the particles, the shape of the particles, and the spatial structure, which are irrelevant to the external factors. In the PFC numerical simulation, due to the difference of particle materials and sizes, the microcosmic parameters in the PFC program are often not consistent with the actual friction angle and cohesion of the soil. In order to simulate more accurately, it is necessary to select appropriate microcosmic parameters of PFC to conform the actual soft soil.

Based on the related research of existing scholars, the selected meso-parameters are shown in Table 1.

| Meso-parameters               | Value       |
|-------------------------------|-------------|
| Particle density $\rho$ / $kgm^{-3}$ | 2500        |
| Contact modulus $E$ / $Pa$     | $1\times10^5$ |
| Stiffness ratio $n$           | 1.0         |
| Coefficient friction $\mu$    | 0.5         |
| Normal bond strength $F_n$ / $Pa$ | $1\times10^{-2}$ |
| Shear bond strength $F_s$ / $Pa$ | $1\times10^{-2}$ |
| Initial porosity $e_0$        | 0.53        |

2.2. Sample preparation
In order to make this simulation more realistic, the model sample is set to be cylindrical, with a height of 100 mm and a diameter of 50 mm, as shown in Figure 3. Two upper and lower plane rigid walls are set up, which are used for vertical loading; a cylindrical rigid wall is set around for loading confining pressure, and the confining pressure is set to 100 kPa. Use the history command to record the model information when the strain is 15%. There are seven sets of samples of the natural deposition, and the
corresponding deposition angle $\alpha$ is 0°, 15°, 30°, 45°, 60°, 75°, 90° to the deposition direction, as shown in Figure 2.

![Figure 2](image)

The triaxial test model and seven deposition samples at different angles

3. Analysis of results

3.1. Macroscopic responses of different deposition angle

The results of the triaxial shear test are shown in Figure 3. It can be seen from Figure 3: (1) The angle of deposition has a significant influence on the relationship between stress and strain. As the initial deposition angle increases, the strength of the soil undergoes a process of decreasing and then increasing. In the later stage of loading, when the initial deposition angle is 0°-45°, the specimen exhibits strain hardening characteristics; at 60°-90°, the specimen exhibits strain softening characteristics, with significant peak strength and residual strength. (3) When the deposition angle is 0°, the sample exhibits the greatest strength. This is because when the deposition angle is 0°, the particles are naturally deposited under the condition of their own weight in a relatively stable state. Affected by the deviatoric stress, the particles are squeezed together and the strength is the highest. When the deposition angle changes, the particles are inclined to the horizontal plane. When shearing occurs, it is easier to slide between the particles and the strength of the sample is reduced.

![Figure 3](image)

Figure 3 Seven sets of stress-strain relationships with different deposition angles

Figure 4 shows the change of the 15% strain stress with the initial deposition angle. As shown in the figure, the peak strength of every initial deposition angle can be further compared. The initial anisotropy of the soft soil sample has a significant impact on its macroscopic responses. It can be seen from the
fitting curve in Figure 6 that the lowest point of the peak strength is between 45° and 60°, which is because the deposition direction is closer to the failure surface and the horizontal deposition plane. When the deposition angle is $45°+2/\phi$.

Figure 4 The change of peak stress with deposition angle

3.2. Change of contact force chain

In PFC, the force between the particles is characterized by the contact force. When the particles contact with the particle or the wall, a contact force is generated and a contact force chain is formed. As shown in Figure 5, it represents the distribution of the contact force chain at different deposition angles with strain at 10%, 15%, and 20%. The blue one indicates the smaller contact force, the red one indicates the greater contact force. When the deposition angle is from 0° to 60°, with the continuous increase of axial strain, the proportion of green, yellow, and red contact force chain is continuously increasing, and the chains are continuously becoming thicker. With the contact force between the particles on the microscopic level is constantly increasing, the stress of the specimen on the macroscopic level increases with strain, showing the characteristics of strain hardening. When the deposition angle is 60° to 90°, number of darker color contact force chains tend to decrease, indicating that the contact force of the particles has decreased. Correspondingly the macroscopic characteristic is that the stress decreases with the increase of strain, showing the characteristic of strain softening. With the change of the deposition angle, the change of the microscopic contact force chain is consistent with the macroscopic stress and strain. (2) Variation law of contact force chain at different deposition angles. Samples with different deposition angles with an axial strain of 15% are selected for comparison. Through comparison, it can be found that from 0° to 45°, the proportion of green, yellow, and red chains gradually decreases, and the number of blue power chains continues to increase. From 60° to 90°, the blue force chains continue to increase, but at the same time the number of green force chains also increases. The change of the number of strong contact force chains with the deposition angle is consistent with the macroscopic stress value. (3) As shown in the figure, the contact force chain has a certain direction, and the direction of most of the contact force chain is consistent with the direction of the deposition angle. This shows that the difference of the deposition angle will affect the direction of the contact force chain.
(a) Deposition angle is 0°

(b) Deposition angle is 30°

(c) Deposition angle is 45°

(d) Deposition angle is 60°
3.3. Displacement field

Figure 6 is a partial enlarged figure of the displacement with the deposition angles of 0°, 30°, 45°, 60° and 90° when the strain is 15%. When the strain is 15%, the displacement distribution field of each deposition angle shows some common characteristics. The displacement of the top and bottom is larger, and the displacement of the middle is smaller. The middle part with small displacement can be divided into middle area and both sides area. The displacement of the particles in the middle area shows inward contraction, the displacement of the particles in the two sides shows outward expansion. The sample shows expansion characteristics as a whole. There are also differences in the displacement field shape in the middle formed by different deposition angles, which is caused by the initial anisotropy of the particles. When the deposition angle is 45° and 60°, the displacement field shape is "trapezoid", and there is an obvious displacement band. This is because when the deposition angle is 45° and 60°, it is closer to the angle of the failure surface, and therefore it is easy to form such an inclined displacement band.
Figure 6  Five groups of deposition angle displacement field distribution and local displacement field amplification. The arrow in the figure indicates the direction of particle displacement

3.4. Coordination number

The coordination number $C_n$ of the particle is one of the indicators to measure anisotropy[13], which is calculated by the average contact number of each particle. The coordination number $C_n$ is given by:

$$C_n = \frac{2N_c}{N_p}$$

where $N_c$ is the number of activated contacts between particles, and $N_p$ is the total number of contacts between particles. Figure 7 shows the relationship between the coordination number of each deposition angle and the axial strain. The deposition angle is from 0° to 45°, and the coordination number increases with the increase of strain; when the deposition angle is from 60° to 90°, the coordination number decreases with the increase of strain. The change rule of coordination number with strain is opposite to the relationship between stress and strain. When the deposition angle is 0°-45°, the coordination number increases with the increase of deposition angle; when the deposition angle is 60°-90°, the coordination number decreases with the increase of deposition angle.
Figure 7 The relationship between the coordination number and the strain

3.5. Contact normal anisotropy coefficient

The fabric tensor based on the contact normal is a widely used index to measure the anisotropy of micro-particle structure, and it is usually expressed as a second-order tensor [14]. The second-order tensor is defined as follows:

$$\phi_{ij} = \frac{1}{N \cdot N_c} \sum_{n \in N_c} n^i n^j$$

(2)

where $N$ is the total number of particles, $N_c$ is the total number of contacts, and $n$ denotes the unit vector along the normal direction of the contact. The direction distribution of the contact normal $\phi_{ij}$ can be approximately described by the following distribution function:

$$E(\theta) = \frac{1}{2\pi} \left[ 1 + a_{ij} n_i n_j \right]$$

$$a_{ij} = 4 \left( \phi_{ij} - \frac{1}{2} \delta_{ij} \right)$$

(3)

In the equation, $E(\theta)$ is the distribution function of the contact normal, and $\delta_{ij}$ is the Kronecker delta. $a_{ij}$ is a second-order tensor that characterizes fabric anisotropy. Using the second invariant of the deviatoric stress tensor of this tensor can represent the degree of critical fabric anisotropy [15]. It is expressed by the contact normal anisotropy coefficient $C_c$, which is defined by:

$$C_c = \sqrt{3 a_{ij} a_{ij}} / 2$$

(5)

Figure 8 shows the change of contact normal anisotropy coefficient with axial strain. When the deposition angle is 0°, 15°, and 30°, the contact normal anisotropy coefficient first increases and then decreases, and then gradually converges at the same point; When the deposition angle is 45°, 60°, 75° and 90°, the contact normal anisotropy coefficient decreases with the progress of loading. When the deposition angle is 45°, the reduction of the contact normal anisotropy coefficient is small, almost linear; when the deposition angle is 60° and 75°, the contact normal anisotropy coefficient decreases greatly in the early stage of loading, and then tends to flatten; when the deposition angle is 90°, the contact normal anisotropy coefficient decreases linearly. When the particles are subjected to external force, first adjust the contact force to resist the external force. If the contact force is not enough to resist the external force, adjust the contact system to resist the external force, resulting in the change of the contact normal.
anisotropy coefficient[16, 17]. When the deposition angle is 0°-30°, the contact system is adjusted between the particles to increase the contact normal anisotropy coefficient, so that hardening characteristics appear in the later stage of loading; when the deposition angle is 60°-90°, the anisotropy coefficient is reduced, and the later shows the characteristics of strain softening. The contact normal anisotropy coefficient is closely related to the macroscopic mechanical strength of the specimen.

Figure 8 The variation of contact anisotropy coefficient $C_C$ with axial strain

4. Conclusion
In this paper, a three-dimensional DEM is used to explore the initial anisotropy of different deposition angle in flaky particles by taking triaxial simulation tests. A number of novel observations were identified from the results:

(1) The initial anisotropy has a significant impact on the macro-mechanical properties of soft soils. As the initial deposition angle increases, the strength first decreases and then increases, with the lowest strength between 45° and 60°.

(2) By micro analysis, the macroscopic responses of soft soil are affected by the contact force chain and particle displacement. The direction distribution of the contact force chain has a greater relationship with the initial deposition angle; different deposition angles form different displacement fields, and obvious displacement bands are formed at 45° and 60°.

(3) The initial anisotropy strength of different deposition angles has an inverse relationship with the coordination number of the particles, and the strength of the soil sample does not increase with the increase of the coordination number of the particles.

(4) The contact normal anisotropy coefficient is closely related to the strength of soft soil. During the shearing process, the soil sample adjusts the strength of the soil by adjusting the contact normal distribution. When the contact anisotropy coefficient increases, the stress-strain curve presents the characteristic of hardening, and when the contact anisotropy coefficient decreases, the soil sample presents the characteristic of strain softening.

Acknowledgments
This research is supported by the National Natural Science Foundation of China (Grant Nos.41877228, 41877229), Guangdong Basic and Applied Basic Research Foundation (2018B030311066 and 2019A1515010554), Science and Technology of Guangzhou City, China (Grant No.201904010136), China Postdoctoral Science Foundation (2019M663241) and Fundamental Research Funds for the Central Universities (20lgpy39).
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