Analysis of Mechanical response of Granular Buried Ditch under high-fill foundation

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Abstract. High-fill foundations can solve the problem of land shortage in mountainous cities. In high ground stress and water immersion environment, stress concentration will lead to gravel particle breakage in drainage blind ditch, and the drainage blind ditch exists a risk of drainage failure, which will bring great harm to high-fill foundation. In this paper, model tests and PFC simulation were carried out to analyze the mechanical response of gravel particles in drainage blind ditch under high ground stress and water immersion. Firstly, large-scale triaxial shear tests were carried out to explore the effects of confining pressures, dry-wet conditions and initial void ratios on breakage and mechanical characteristics of gravel particles. The stress-strain curve of gravel particles was studied and the influence of variation of gravel graduation and particle crush rate on peak strength and dilatancy were analyzed. Then, the single particle breakage model under high pressure was established and the influence of immersion was considered in numerical simulation. The crushing test of gravel particles was carried out and the impact of particle breakage on mechanical characteristics was studied. The results show that the stress-strain curve of gravel particles has a behavior of strain hardening. Particle breakage has a significant impact on the strength and dilatancy of gravel particle. The gravel particle breakage rate is approximately linear with confining pressure and initial void ratio. Immersion of the gravel particle increased the volumetric strain, weakened the dilatancy and increased the gravel particle breakage rate.

1. Introduction
High-fill foundations can solve the problem of land shortage in mountainous cities. In collapsible loess areas, the bottom drainage system plays a vital role in high-fill foundations, and the reduction of drainage system efficiency will bring great harm to the project itself. Gravel drainage blind ditch is a commonly used drainage system, which has the advantages of low cost and easy construction. However, the gravel drainage blind ditch exists a risk of drainage failure caused by particle breakage in high ground stress and water immersion environment, which will bring a great harm to high-fill foundation. Huang [1] found that particle breakage will change the grain size distribution and the density of gravel soil, thereby affecting the mechanical characteristics of coarse-grained soil. Particle breakage impaired the dilatancy behavior of the gravel soil to become a more contractive soil, significantly influencing the shearing, dilatancy and drainage behavior of soil [2]. Since the phenomenon of particle breakage under high stress level was first mentioned by Terzaghi and Peck [3], a large number of studies have been carried out regarding influence of particle breakage on soil behavior (4-15). There are many factors affecting particle breakage, such as particle size and shape, gradation, relative density, force and boundary conditions. Gao [16] found that particle breakage increases with the increase of confining pressure and particle size, resulting in the decrease of shear strength of materials. Particle breakage will occur at a low stress level due to the large particle size and more particle corners, especially for coarse-grained soil such as gravel soils [17].

Gravel drainage blind ditch in high-fill foundations are often in high ground stress and water immersion environment. At present, there are few studies in the mechanical response of gravel particles in drainage blind ditch under high ground stress and water immersion. Thus, in this paper, large-scale triaxial shear tests and PFC 3D numerical simulation were carried out to analyze the mechanical response of gravel particles in drainage blind ditch. Firstly, the effects of confining pressures, dry-wet conditions and initial void ratios on breakage and mechanical characteristics of gravel particles were explored. Then, the single particle breakage model under high pressure was established and the influence of immersion was considered in numerical simulation. The crushing test of gravel particles was carried out to study the impact of particle breakage on mechanical characteristics. The results show that the stress-strain curve of gravel particles has a strain hardening behavior. Particle breakage has a significant impact on the strength and dilatancy of gravel particle. The gravel particle breakage rate is approximately linear with confining pressure and initial void ratio. Immersion of the gravel particle increased the volumetric strain, weakened the dilatancy and increased the gravel particle breakage rate.

2. Large scale triaxial test

2.1. Experimental equipment

Large scale triaxial shear tests were performed on gravel particles in Yan'an New District high-fill foundations using the apparatus shown in Figure 1. This apparatus has a maximum load capacity of 1000 kN and a maximum confining pressure of 2 MPa. The specimen diameter was 300 mm and the height was 600 mm.
The materials used in the large scale triaxial tests were taken from the bottom drainage system of the high-fill foundation in Yan’an New District. The gravel soil particles were mainly composed of sandstone, slate and the percentage of grain size were shown in Table 1. The gravel soil particles used in the test was uniform with continuous grain size, and the coefficient of uniformity $C_u$ was 2.06, $C_c$ was 1.05.

| Grain size /mm | Percentage /% |
|----------------|---------------|
| <5             | 0.41          |
| 5-10           | 0.55          |
| 10-20          | 2.42          |
| 20-30          | 12.71         |
| 30-40          | 30.49         |
| 40-50          | 39.46         |
| 50-60          | 13.95         |

The large scale triaxial shear tests were divided into 10 groups to study the mechanical properties and particle breakage law of gravel soil under different confining pressures, dry-wet states and different initial pores. As shown in Table 2, there were 6 groups of specimens in the air-dried state and 4 groups of specimens in the saturated state.

| Specimen moisture state | Initial void ratio e0 | Confining pressure /kPa |
|-------------------------|-----------------------|--------------------------|
| air-dried state         | 0.793                 | 100                      |
| air-dried state         | 0.793                 | 200                      |
| air-dried state         | 0.793                 | 400                      |
| air-dried state         | 0.793                 | 600                      |
| air-dried state         | 0.765                 | 400                      |
| air-dried state         | 0.738                 | 400                      |
| saturated state         | 0.793                 | 100                      |
| saturated state         | 0.793                 | 200                      |
| saturated state         | 0.793                 | 400                      |
| saturated state         | 0.793                 | 600                      |

During the loading process, the specimen was consolidated under different confining pressure, and the shear stage was carried out after the excess pore water pressure was dissipated. The strain-controlled method was employed in the shear stage, and the shear rate of the specimen is 0.3 % axial strain per minute until the specimen axial strain reached 15 %. After the loading process, the sieve test was carried out and the variation of grain size percentage was counted to calculated the particle breakage rate of specimens.
2.2. Relationship of stress-strain curve

The confining pressure has a significant impact on the triaxial test results. As shown in Figure 2, the axial strain under the peak stress increases significantly with the increase of confining pressure when the confining pressure is 100kPa and 200kPa, and the strain softening was not occurred. The peak strength was not reached when the confining pressure is 400kPa and 600kPa, showing obvious strain hardening behavior. With the increase of confining pressure, the dilatancy of the specimen weakened, and gradually changed from dilatancy to shear shrinkage. Besides, dry-wet conditions of specimens have a great impact on mechanical characteristics of gravel particles. After immersion saturation, the strength and the initial tangent modulus of the specimen were decreased while the volume strain of the specimen and the axial strain reaching the peak strength were increased. The gravel particle in drainage blind ditch were more likely to break in the saturated environment. As the initial void ratio decreased, the strength of the specimen was increased and the volume strain was decreased.
(c) The relationship between deviatoric stress \( q \) and axial strain \( \varepsilon_1 \) of air-dried specimens with different initial void ratios.

(d) The relationship between volume strain \( \varepsilon_v \) and axial strain \( \varepsilon_1 \) of air-dried specimens with different initial void ratios.

**Figure 2.** Deviatoric stress-axial strain-volume strain relationship of different specimens.

2.3. Porosity in shear stage

Since the critical state void ratio was discussed by Casagrande [18] and critical state soil mechanics was proposed by Roscoe [19], a large number of studies have been conducted concerning the characteristics of the critical state locus (CSL) in \( e - lgp' \) plane [20-27]. The relationship curve between void ratio and average effective stress in shear stage of large scale triaxial test was shown in Figure 3 and the void ratio are calculated by \( e = e_0 - (1 + e_0)e_v \). The void ratio with axial strain of 15 % was taken as the void ratio of the critical state for the specimen not reaching the critical state. The reference critical state line in Figure 3 is a straight line when the particle breakage was not considered. Due to the occurrence of particle breakage, the relationship curve of specimen reaching the critical state is a curve rather than a straight line.

![Figure 3](image-url)

(a) Air-dried specimen \( e - lgp' \) relationship curve

(b) Saturated specimen \( e - lgp' \) relationship curve

**Figure 3.** \( e - lgp' \) relationship curve of specimen.

The concept of reference critical state line in \( e - lgp' \) plane [28] was employed to establish the expression of void ratio vary with average effective stress. The critical state line for particle breakage can be expressed as follows:

\[
e_{cr} = e_{r0} - \Delta e
\]

(1)

where \( e_{cr} \) denotes void ratio of critical state line considering particle breakage; \( e_{r0} \) denotes pore ratio corresponding to reference critical state line; \( \Delta e \) denotes variation of void ratio due to particle breakage, corresponding to the degree of particle breakage and stress level. The reference equation of critical state line \( e_{r0} \) is as follows:

\[
e_{r0} = e_{a0} - \lambda_{a0} lgp' (p'/p_a)
\]

(2)

where \( p' \) denotes average effective stress, \( p_a \) is an atmospheric pressure; \( e_{a0} \) denotes the void ratio when the average effective stress \( p' \) is equal to \( p_a \); \( \lambda \) denotes slope of reference critical state line, which can be determined by triaxial tests.

\[
\Delta e = f(B,p')
\]

(3)
where $B$ denotes the degree of particle breakage, corresponding to the degree of stress level. Therefore, $\Delta e$ can be simplified as the function of average effective stress $p'$

$$\Delta e = \xi(\sigma_3/p_a) \lg (p'/\sigma_3)$$

(4)

Take equation (4) into equation (1), analytical formulas of void ratio and average effective stress in shear stage of large triaxial test are established as follows:

$$e = e_{0a} - \lambda \lg \left( \frac{\sigma_3}{p_a} \right) - \xi(\sigma_3/p_a) \lg \left( \frac{p'}{\sigma_3} \right)$$

(5)

where $\xi$ is particle breakage parameter, demonstrating the decrease of void ratio caused by gravel particle breakage. Parameters of air-dried specimen and saturated specimen can be obtained by the analysis of test data. Parameters of air-dried specimen are $e_{0a} = 0.793$, $\lambda = 0.041$, $\xi = 2.92 \times 10^{-2}$ while parameters of saturated specimen are $e_{0a} = 0.791$, $\lambda = 0.092$, $\xi = 7.25 \times 10^{-2}$. The comparison between experiment and calculated value of air-dried specimen are shown in Figure 4 and the calculation results of equation (5) are in good agreement with the triaxial test data.

![Comparison between experiment and calculated value of air-dried specimen](image1)

(a) Comparison between experiment and calculated value of air-dried specimen

![Comparison between experiment and calculated value of saturated specimen](image2)

(b) Comparison between experiment and calculated value of saturated specimen

**Figure 4.** Comparison between experiment and calculated value.

### 2.4. Particle breakage in shear stage

The specimen variation of grain size is shown in Figure 5. Gravel particle breakage was more likely to occur in high ground stress environment. As the confining pressure increased, the content of grain size 40-60mm was significantly decreased while the content of grain size 2-5mm and 5-10mm were significantly increased. The specimen will be broken to produce particles with grain size less than 2 mm in the shear stage that did not exist before the test. As the initial void ratio increased, the particles were more likely to be broken, and the degree of particle breakage became larger.
The index $\text{ct}$ suggested by Marsal [29] was employed to describe the degree of particle breakage, and the calculation equation was adopted as follows:

$$\text{ct} = \frac{t}{f} = t - f$$  \hspace{1cm} (6)

where $t$ denotes the percentage of grain size before the test; $f$ denotes the percentage of grain size after the test. As shown in Figure 6, particle breakage rate increased after immersion saturation of the specimen, and the particle breakage rate was approximately linear with confining pressure. Gravel particle breakage was more likely to occur in high ground stress and immersion saturation environment. Moreover, particle breakage rate decreases with the increase of initial void ratio and is approximately linear with initial void ratio.
3. PFC 3D numerical simulation

To carry out a large number of large-scale triaxial shear tests is not convenient due to the large size of gravel particles and numerical simulation can make up for the shortcomings of large scale triaxial shear tests. Large deformation or even particle breakage is prone to occur at high stress level for the gravel particles. The discrete element method (DEM) based on Newton's second law and force-displacement relationship proposed by Cundall [30] was used to carry out further numerical analysis. In this paper, fragment substitution model was employed to simulate the particle breakage of gravel soil, which can detect the variation of void ratio and particle gradation in specimen during the triaxial shear stage. Fragment substitution model is based on a certain crushing criterion and a number of small particles are generated to replace the original particles when particles meet the crushing criterion. The crushing criterion is to set a threshold and the gravel particle breaks when the stress state of the particle reaches the threshold condition. Octahedral shear stress [31] was employed as the criterion for particle breakage, and the tensile stress obtained from the compression test of single particle was employed as the criterion threshold. The crushing criterion used in this paper is octahedral shear stress $q$, which can reflect the particle crushing law under complex contact conditions.

$$ q = \frac{1}{2} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2]^{\frac{1}{2}} $$

where $\sigma_1$, $\sigma_2$, $\sigma_3$ are average principal stress of particles respectively, the average principal stress of particles extracted from PFC 3D is adopted as follows:

$$ \sigma_{ij}^e = \frac{1}{n} \sum_{n} (x_{ij}^{(o)} - x_{ij}^{(c,\phi)}) F_j^{(c,\phi)} $$

Figure 6. Relationship between particle breakage rate and confining pressure, initial void ratio.
where $V$ is the particle volume, $x_i^{(c)}$ is the particle contact position, $x_i^{(p)}$ is the particle position, $F_i^{(c,p)}$ is the contact force, $n_c$ is the contact number. According to the compression test of single particle [32], the single particle strength satisfied the Weibull distribution.

$$q_0 \propto d^{-\frac{3}{m}}$$  \hspace{1cm} (9)

where $q_0$ is the strength of particles, $d$ is the grain size, $m$ is weibull modulus. In order to simulate the shape of gravel particles, a cluster unit composed of two spherical particles [33] was adopted and the centers of the two spherical particles that make up the cluster unit were connected to the surface of another sphere.

**Figure 7.** Cluster unit composed of two spherical particles.

The particle breakage diagram of cluster unit was shown in Figure 8. The original particle cluster was replaced by two smaller particle clusters with the same shape when the particle cluster satisfies the crushing criterion. The long axis direction of the two newly generated particle clusters is parallel to each other, and the connection between the centroids is parallel to the original particle clusters. The position of the newly generated particle cluster is limited by the long axis size of the original particle cluster and the rotation of random angles can occur around the long axis of the original particle cluster.

**Figure 8.** Clump splitting diagram.

Hertz nonlinear contact model was adopted in the contact between particle clusters, and the loading process of the specimen is similar to the triaxial test. Firstly, the specimen was consolidated to the target confining pressure and then the upper wall moves for loading with
the speed of 0.1m/s. The PFC 3D model of the specimen were shown in Figure 9, where the red particles were the newly broken particles in the loading process.

![PFC 3D model of the specimen.](image)

(a) specimen before loading  (b) specimen after loading

**Figure 9.** PFC 3D model of the specimen.

Due to the confining pressure range of the large-scale triaxial shear tests is 100 kPa-600 kPa, the relevant attribute parameters in the PFC 3D model are selected by calibrating the stress-strain relationship of the air-dried specimen in the laboratory test under the confining pressure of 400 kPa, so that the model parameters can reflect the mechanical properties of specimen under low and high confining pressures. Parameters of PFC 3D model are shown in Table 3.

**Table 3.** Parameters of numerical test model.

| Model and contact attributes | Value |
|-----------------------------|-------|
| Loading rate (m/s)          | 0.1   |
| Normal stiffness of wall $k_s$ (N/m) | $1\times10^{12}$ |
| Friction coefficient of wall $\mu_w$ | 0 |
| Spherical density (kg/m$^3$) | 2600 |
| Shear modulus (N/m)         | $1\times10^9$ |
| Poisson ratio $\nu$         | 0.35  |
| Coefficient of friction $\mu$ | 0.8  |
| 37% strength $q_0$(MPa)     | $2.2\times10^6$ |
| Weibull modulus $m$         | 4.3   |
| Diameter $d_0$ (m)         | 0.04  |

The numerical simulation results of gravel particles with different confining pressures under air-dried state are selected for analysis. The numerical simulation not considering particle breakage during the loading process were carried out to further analyze the influence of particle breakage on the mechanical properties of particle clusters. The comparison of the numerical simulation results of particle breakage and non-particle breakage was shown in
Figure 10. Gravel particle breakage was more likely to occur under high confining pressure. As shown in Figure 10 (a), the decrease of deviatoric stress caused by particle breakage was more significant with the increase of confining pressure. Particle breakage impaired the dilatancy behavior of the gravel soil to become a more contractive soil, significantly influencing the peak strength of soils. Gravel particle breakage was more likely to occur in water immersion environment. As shown in Figure 10 (b), particle breakage significantly increased the volumetric strain. Thus, in high ground stress and water immersion environment, drainage blind ditch exists a large risk of drainage failure caused by gravel particle breakage.

Figure 10. The comparison of the numerical simulation results of particle breakage and non-particle breakage.

4. Conclusion
The effects of different confining pressures, dry-wet conditions and different initial void ratios on the crushing law and mechanical properties of gravel particles were studied through large-scale triaxial shear tests and PFC 3D numerical simulation. The stress-strain characteristics of gravel soil, gradation variation caused by particle breakage, and the influence of particle breakage on peak strength and dilatancy are discussed. The main conclusions are as follows:
(1) The stress-strain curve of gravel soil presented a behavior of strain-hardening. With the increase of confining pressure, the dilatancy of the specimen weakened, and gradually changed from dilatancy to shear shrinkage.

(2) Dry-wet conditions of specimens have a great impact on mechanical characteristics of gravel particles. After immersion saturation, the strength and the initial tangent modulus of the specimen were decreased while the volume strain of the specimen and the axial strain reaching the peak strength were increased.

(3) As the initial void ratio decreased, the strength of the specimen was increased and the volume strain was decreased. The analytical formula of void ratio $e$ and average effective stress $p'$ was established as follows:

$$e = e_0 - \lambda \log \left( \frac{\sigma_3}{p_a} \right) - \xi \left( \frac{\sigma_3}{p_a} \right) \log \left( \frac{p'}{\sigma_3} \right)$$ (5)

(4) The particle breakage rate is approximately linear with confining pressure, initial void ratio, and the water saturation increased the particle breakage rate. Gravel particle breakage was more likely to occur in high ground stress and immersion saturation environment.

(5) Particle breakage significantly weakened the dilatancy and reduced the peak strength of gravel soils. With the increase of confining pressure, particle breakage was more likely to occur and the decrease of deviatoric stress was more significant. In high ground stress and water immersion environment, drainage blind ditch exists a large risk of drainage failure caused by gravel particle breakage.

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