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Study on breakage behaviour of original rockfill materials considering size effect on particle strength

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Abstract: In high rockfill dam, particle breakage is one of the main factors that lead to dam deformation. However, because of the large size of the rockfill particles, the breakage degree of the prototype rockfill materials is difficult to be measured directly through laboratory test. Therefore, the common practice is to reduce the size of the prototype gradation particle to less than 60 mm before the laboratory test can be carried out. However, due to the significant difference between the prototype and the test gradation, the parameters measured in the test are often quite different from the actual parameters of the prototype rockfill materials, thus affecting the in-depth study of the mechanical properties of the prototype rockfill materials. In this paper, a new method is proposed to describe the change of particle size distribution (PSD). Firstly, based on the theory of Weibull distribution of the particle strength and fractal crushing of the particle, the calculation of PSD change of the original rockfill materials is elaborated. Then, the relevant parameters are obtained by conducting the single-particle crushing test, and by comparing with the triaxial test, the rationality of parameter selection is verified. Moreover, the effects of the discrete degree of particle strength on the shape of the PSD is analysed. Finally, the relationship between the relative crushing parameters and stress state of the rockfill materials during loading is discussed.

Keywords: Weibull distribution; fractal crushing; prototype rockfill materials; single-particle strength

1 Introduction

In high earth rock dams, particle breakage phenomenon occurs frequently and significantly due to the relatively large stress. This phenomenon will lead to uneven settlement of the dam body, deteriorate the stress and deformation characteristics of the concrete face and the core wall, and endanger the safety of the dam impervious body[1].

The particle size of the prototype rockfill are generally as large as 800-1000 mm, thus, the diameter of the corresponding full-scale triaxial sample needs to be 4000 mm at least (Fig.1). Obviously, the current triaxial equipment is not available yet. Therefore, the traditional method is to reduce the size range of the prototype PSD to 0-60 mm, and then measure the crushing degree of the dam materials indirectly through the triaxial test[2-4]. However, the influence of size effect cannot be avoided since the grading of test materials is obtained from the reduced prototype PSD[5-8]. In addition, it is difficult to investigate the crushing characteristics of rock blocks on the particle scale due to the limitations of measurement means[9-11]. Moreover, the real-time PSD of rockfill materials cannot be accessed during the loading process.[12-14].

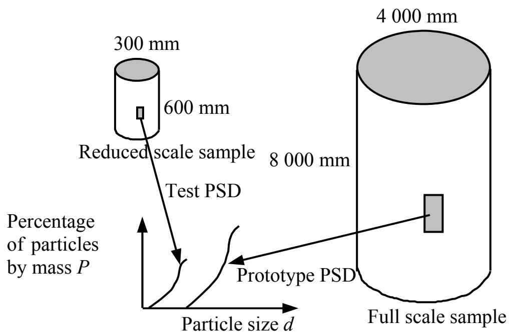

Fig.1 Schematic diagram of scaled sample and full-scale sample

To solve the above problems, in this paper, a method was first proposed to describe the grading evolution of prototype PSD directly on the full-size samples scale, and then, the relevant parameters were obtained through the triaxial test results of Gushui basalt rockfill materials, and the rationality of the model was verified by comparing the results with those of triaxial tests. At last, the influence of the particle strength dispersion degree on the prototype grading curves and the relationship between the crushing parameters and the stress state on the reduced and full sample scales were discussed, respectively.

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2 Evolution of prototype PSD

2.1 Probability statistics of the particle strength

In the single-particle strength test, the splitting stress of irregular rock block can be expressed by the following formula [15]:

$$\sigma_c = \frac{F}{d_0^2} \quad (1)$$

where F is the force corresponding to catastrophic facture; d_0 is the diameter of the rock block (the distance between two plates); σ_c is the tensile strength of the particle at failure.

Weibull[16] proposed that in the single particle strength test, the probability of the particle surviving under a certain stress obeys Weibull distribution, which can be expressed as follows:

$$P_s = \exp\left[-\left(\frac{\sigma_c}{\sigma_0}\right)^m\right] \quad (2)$$

where σ_0 is the characteristic stress, corresponding to the stress value when 37% ($P_s = e^{-1}$) of the total number of test particles survive(intersection points in Fig.2); m is the Weibull modulus, which reflects the variability of the particle strength. As is shown in Fig.2, m decreases with the increasing variability of the particle strength.

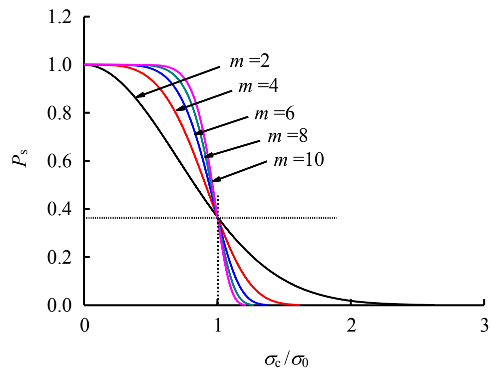


Fig.2 Weibull distributions of particle strength with different *m* value

2.2 Mechanism of particle facture

Nakata et al.[17-18] found that the splitting modes are distinct for particles of different lithologies when testing the particle strengths of two types of sands. However，the specific particle splitting modes were not proposed. McDowell et al.[19] simulated the gradation evolution of silica sands based on the particle flow program, assuming that a sphere particle is divided into 2-4 equal-sized spheres after crushing. This assumption is too simple, and severely deviates from the single grain strength test observations that a large rock generally splits into many small pieces of different sizes and shapes. And the irregular shapes of these small ones present geometric self-similarity. Therefore, fractal mathematics is suitable to describe this characteristics.

Tyler et al.[20] proposed that in three-dimensional space, the relationship between the mass percentage of soil particles and particle size can be expressed by the following formula:

$$P_{d<d_i} = \left(\frac{d_i}{d_{\max}}\right)^{3-D} \quad (3)$$

where d_i and $d_{\max}$ are the particle diameter and the maximum diameter of the sieve pore, respectively; D is the fractal dimension; $P_{d<d_i}$ is the mass proportion of particles whose diameters smaller than d_i .

2.3 Relationship between macro and micro force

Nakata et al.[17-18] proposed a simplified expression to build the relationship between the single particle stress and the load stress of the triaxial sample. After that, Chi et al.[9] suggested that this relationship could be modified for the rockfill materials (RFMs) as follows:

$$\sigma_c = q\eta\left(\sqrt[3]{\frac{(1+e)\pi}{6}}\right)^2 \quad (4)$$

where q is the deviatoric stress of triaxial sample; e is the void ratio; η is the particle shape correction parameter.

2.4 Particle size evolution model

Given that the stress state of the prototype dam material is difficult to measure directly, it is assumed in this paper that its stress state is consistent with the conventional triaxial test.

Before the loading of triaxial test, the mass of i-th particle group of the initial grading is $\boldsymbol{M}_{0i}$, $i = 1,2....9$, corresponding to the particle groups of 400-800、200-400、100-200、60-100、40-60、20-40、10-20、5-10 and 0-5 mm, respectively (According to *Code for coarse-grained soil tests for hydropower and water conservancy engineering* (DL/T 5356-2006)[21], the prototype dam material PSD is generally divided into 9 groups of different particle diameters).

When applying the axial loading to $q = q_1$, according to Equation (2) and Equation (4), the mass of the particles which do not split in the i-th particle group, $\boldsymbol{M}_{1i}$, can be determined as follows:

$$\boldsymbol{M}_{1i} = P_s \boldsymbol{M}_{0i} = \exp\left[-\left(\eta \cdot \frac{q_1}{\sigma_0}\left(\sqrt[3]{\frac{(1+e)\pi}{6}}\right)^2\right)^m\right] \cdot \boldsymbol{M}_{0i} \quad (5)$$

where $\boldsymbol{M}_{1i}$ is the mass of the surviving particles in the i-th particle group when the axial stress is q_1 . The mass of the crushing particles in i-th particle group is $\boldsymbol{M}_{0i} - \boldsymbol{M}_{1i}$.

For the mass of the crushing particles in i-th particle group, this mass can be distributed to each particle groups with finer particles according to fractal distribution. So the newly-generated mass of the i+1 and i+2 particle groups are determined as follows:

$$\boldsymbol{M}_{2(i+1)} = P_{(i+1)i}(\boldsymbol{M}_{0i} - \boldsymbol{M}_{1i}) \quad (6)$$

$$M_{2(i+2)} = P_{(i+2)i}(M_{0i} - M_{1i}) \tag{7}$$

Where $M_{2(i+1)}$ and $M_{2(i+2)}$ are the newly-generated mass of the i+1 and i+2 particle groups, respectively; $P_{(i+1)i}$ and $P_{(i+2)i}$ are the mass proportions of newly-generated particles in the i+1 and i+2 particle groups accounting for the mass of the crushing particles in the i-th particle group, respectively. These two proportions are determined using the following relationships:

$$P_{(i+1)i} = P_{(d_{i+2}<d<d_{i+1})} = \left(\frac{d_{i+1}}{d_i}\right)^{3-D} - \left(\frac{d_{i+2}}{d_i}\right)^{3-D} \tag{8}$$

$$P_{(i+2)i} = P_{(d_{i+3}<d<d_{i+2})} = \left(\frac{d_{i+2}}{d_i}\right)^{3-D} - \left(\frac{d_{i+3}}{d_i}\right)^{3-D} \tag{9}$$

where, d_i is the particle diameter and ranges from 0 to 800 mm, and $d_9 = 0$.

Therefore, the current newly-generated particle mass in each particle group when the axial stress is q_1, M_{3i}, could be calculated in the matrix form as follows:

$$M_{3i} = P_{m,n} \cdot (M_{0i} - M_{1i}) \quad (i=1\ldots9) \tag{10}$$

where m=i+1, n=i. And when m = n = 9, $P_{m,n}$ is given as

$$P_{m,n} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ P_{21} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ P_{31} & P_{32} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ P_{41} & P_{42} & P_{43} & 0 & 0 & 0 & 0 & 0 & 0 \\ P_{51} & P_{52} & P_{53} & P_{54} & 0 & 0 & 0 & 0 & 0 \\ P_{61} & P_{62} & P_{63} & P_{64} & P_{65} & 0 & 0 & 0 & 0 \\ P_{71} & P_{72} & P_{73} & P_{74} & P_{75} & P_{76} & 0 & 0 & 0 \\ P_{81} & P_{82} & P_{83} & P_{84} & P_{85} & P_{86} & P_{87} & 0 & 0 \\ P_{91} & P_{92} & P_{93} & P_{94} & P_{95} & P_{96} & P_{97} & P_{98} & 0 \end{bmatrix} \tag{11}$$

where $P_{m,n}$ is the fractal distribution matrix, determining how the crushing particles mass of each particle group are assigned to the particle groups with finer particles in each load step.

In this way, the updated particle mass of each particle group under the loading stress $q = q_1$, M_{4i}, can be expressed as

$$M_{4i} = M_{1i} + M_{3i} \quad (i=1\ldots9) \tag{12}$$

Once all the particles mass in each particle groups are determined, the prototype dam material PSD can be acquired at this stress state. Similar calculation process is repeated to get the updated PSD at the other axial stress q_1'.

3 Parameters of the model

Test materials were taken from the RFMs of the Gushui Concrete Faced Rockfill (CFR) Dam. The rock lithology is basalt with clear edges and corners. The maximum water absorption is 0.33%, and the uniaxial compressive strength is 83.5 MPa. In addition, the average relative density is 2.79, and the maximum particle size is 60 mm. The particle length-width ratio is 1.63. The PSD of rockfills before and after the scale reduction are shown in Fig.3 (in the Fig.3, σ_1 and σ_3 are the maximum and minimum principal stress, respectively). The test rockfills are divided into six particle groups, with the particle size ranges of 40-60, 20-40, 10-20, 5-10, 2-5 and 0-2 mm, respectively.

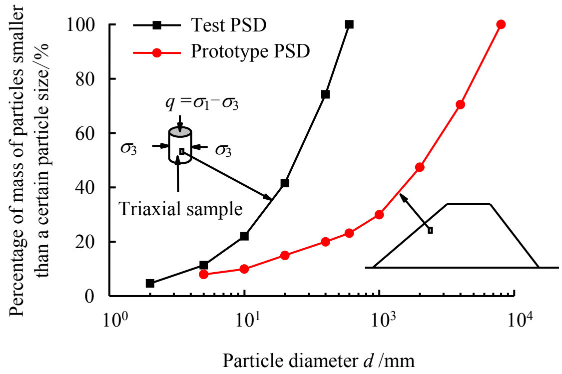
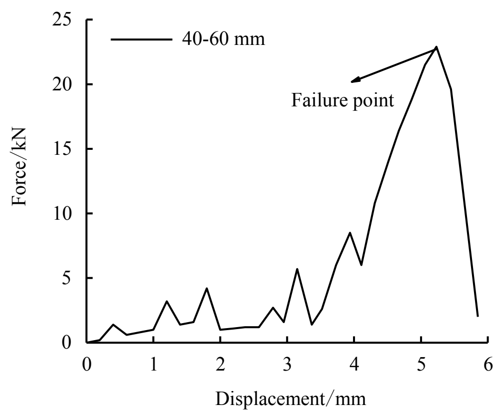


Fig.3 Test and prototype particle sized distributions (PSD) of rockfill materials

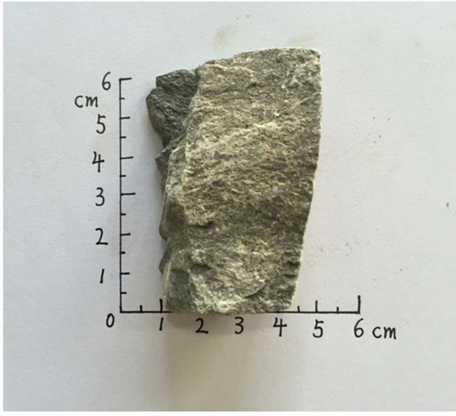
3.1 Single-particle crushing (SC) test

In the single-particle crushing test, 60 irregular rock blocks were first randomly selected from each particle group with the particle size larger than 2 mm to measure their corresponding particle crushing strengths (According to the code[21], the particles with size smaller than 2 mm are no longer subdivided, so the crushing of these small particles are no longer studied herein, and the particle strengths within 0-2 mm particle group do not need to be measured).

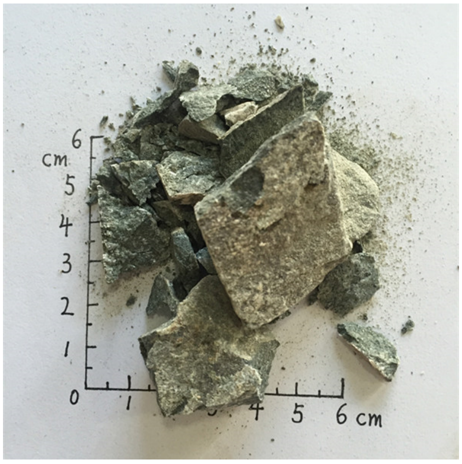
During the loading process, the upper and lower paralleled rigid plates moved toward with each other and compressed the rockfill particle until the particle crushed. At the initial compression stage, the corner of the stone was damaged, while the main body of the stone was crushed until the load exceeded the strength of the stone. Fig.4(a) gives the typical force-displacement curve. The stones sceneries before and after the test are shown in Fig.4(b) and 4(c), respectively. The total loading time was controlled within 60 s referenced to point loading test of rocks. After the crushing test, the sieve analysis were conducted on each particle group.



(a) Force-displacement curves



(b) The particle before the test



(c) The particle after the test

Fig.4 Typical force-displacement curve and photographs of rockfill materials before and after breakage

3.1.1 Parameters of Weibull distribution

After the single crushing tests for a particle group were implemented, the splitting stress σ_c of 60 random samples could be obtained from equation (1), and then the survival probability of the particle at $\sigma = \sigma_c$ in this particle group is:

$$P_s = \frac{N(\sigma \leqslant \sigma_c)}{N_a} \tag{13}$$

where $N(\sigma \leqslant \sigma_c)$ is the number of particles surviving at $\sigma \leqslant \sigma_c$; N_a is the total number of the particles tested ($N_a = 60$ in this paper).

Take the logarithm of two sides of formula (2), and then,

$$\ln\left[\ln\left(\frac{1}{P_s}\right)\right] = m\ln\sigma_c - m\ln\sigma_0 \tag{14}$$

Fig.5 shows the relationship between $\ln[\ln(1/P_s)]$ and $\ln\sigma_c$ for each tested particle group. The Weibull modulus m can be determined from the slopes of these curves, and the almost paralleled lines in Fig.5 implies that all the m values are close among each particle groups. This phenomenon is consistent with the results of McDowell[10]: m might be various for different types of rocks, but for the same type of rocks, the value of m is similar even if the rocks have different sizes.

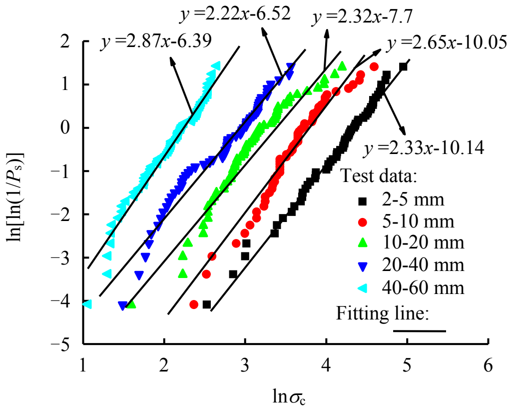


Fig.5 Weibull plots for each set of grains

3.1.2 Size-effect parameters on the characteristic strength

The characteristic stress σ_0 for each particle group could be obtained from the slopes and the intercepts of the curves in Fig.5. As shown in Fig.6, the characteristic stress σ_0 increases with the decrease of particle size d. The logarithms of both variables show a good linear relationship, which can be expressed by the following expression:

$$\sigma_0 = \lambda d^{-n/m} \tag{15}$$

where, λ and n are the constants for the same type of material, and their values can be obtained from the slope and intercept of the straight line in Fig.6.

For the McDowell's test[22], n = 3 for the four groups of Quiou sands was acquired. Nakata et al.[17-18] further found that the test results of quartz sand were consistent with the result of McDowell et al.. However, in the test of feldspar sand, the value of n is less than 3. The reason might be that the probability of critical fracture distribution is no longer geometrically self-similar, and the Weibull distribution is no longer applicable. The test results of this paper are consistent with those of feldspar sand.

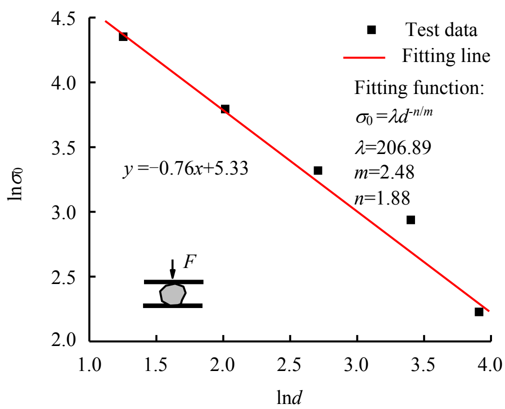


Fig.6 Relationship between characteristic strength and particle size

3.1.3 Fractal dimension of particle group

Fig.7 shows the PSDs of the tested five groups. Good linear relationships are shown in log-log coordinates, indicating that the crushed samples obey the fractal distribution well. The fractal dimensions of five groups ranges from 2.1 to 2.2. This narrow range suggests that the RFM particles with different sizes have the similar splitting model. So the mean value of these five fractal dimensions *D* is taken as the model parameter in this paper (shown in Table 1.)

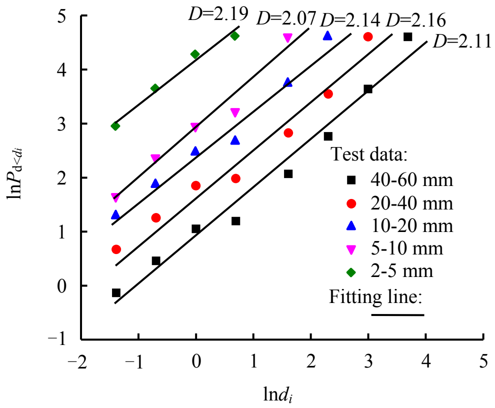


Fig.7 PSD curves for each set of grains after sieving

Table 1 Model parameters

λ	b	e_0	ρ_d /(g • cm^{-3})	m	n	D
206.9	−0.76	0.26	2.21	2.48	1.88	2.13

3.2 Large-triaxial compression tests

In order to verify the validity of the model, it is necessary to select several groups of grading curves measured in the real triaxial tests for comparison. The rockfill materials are split obviously under high confining pressure, so the PSDs of 9 samples under 3 confining pressures (including 1.0, 1.5 and 2.0 MPa) are chosen herein for verification. The corresponding axial pressures of the samples are shown in Table 2. Specific test process and test data can be referenced to this literature[22].

Table 2 Relative breakage parameters in loading process

σ_3 /MPa	σ_1 /MPa	Relative breakage index B_r		
		Test	Simulation	Prototype
1.0	5.754	0.026	0.025	0.004 3
1.0	5.724	0.021	0.021	0.004 3
1.0	4.159	0.011	0.013	0.001 8
1.5	7.803	0.031	0.028	0.007 3
1.5	7.788	0.025	0.023	0.007 3
1.5	5.282	0.013	0.015	0.002 6
2.0	9.855	0.031	0.029	0.007 3
2.0	9.450	0.024	0.023	0.007 2
2.0	6.007	0.013	0.014	0.002 6

4 Model parameters and test verification

The model parameters are summarized in Table 1, in which Weibull modulus *m* and fractal dimension *D* are the mean values of the results of five particle groups in the single particle strength test. The particle shape correction coefficient is set as 2.0. For the prototype grading materials, the characteristic strength parameters of 60-800 mm particles can be obtained from Equation (15).

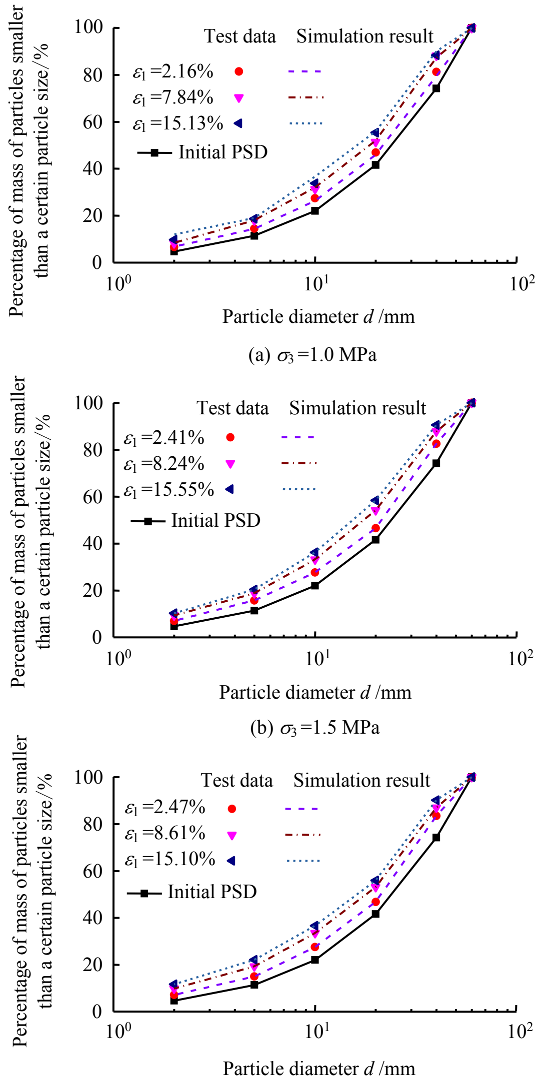


Fig.8 PSD evolutions of test rockfill during triaxial test with confining pressures of 1.0, 1.5 and 2.0 MPa

As is shown in Fig.8, the simulation results of grading evolution are close to the test results in the triaxial shear process under three confining pressures, which shows that the selected model parameters are reasonable. Under the same loading conditions, the PSD evolution of the full-scale prototype rockfill sample is simulated, and the results are shown in Fig.9. It can be seen that the particle breakage phenomenon is more serious with the increase of the load, especially for the 400-800 mm particle group, in which the number of particles is significantly reduced. During the evolution of grading curves, the shape of grading curves for test and prototype materials are also similar[23-26].

5 The influence of particle strength dispersion on the crushing of prototype rockfill materials

The PSDs of the prototype rockfill materials at the failure point are calculated for different Weibull modulus m, and the corresponding results are shown in Fig.10. It can be seen that the curve becomes more gentle with the decrease of m, and these four curves intersect at d =113 mm. In order to thoroughly study the relationship between the dispersion of particle strength and the crushing amount of particles in each particle group, the frequency curves of crushing mass content for each particle group are drawn in Fig.11. With d=309 mm as the boundary, the particle crushing amount increases with the increase of m for particles larger than 309 mm; while for the particles smaller than 309 mm, the particle crushing amount shows an opposite trends. This indicates that for larger particles, the greater the dispersion of particle strength is, the easier they are broken. However, for smaller particles, the greater the dispersion of particle strength is, the more difficult they are broken. In addition, with the decrease of particle size, the amount of broken particles reduces rapidly and converges to a stable value, implying that smaller particles are more difficult to break. This phenomenon is consistent with the research conclusions of McDowell[19].

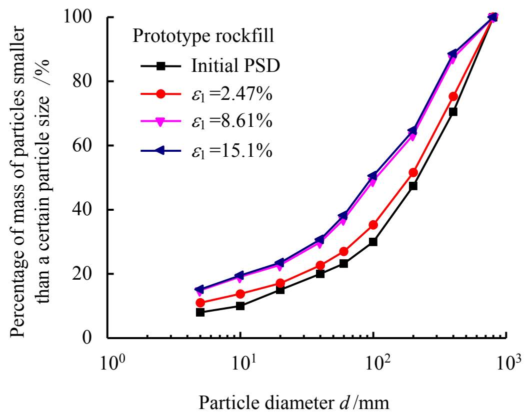


Fig.9 PSD evolution of prototype rockfill during triaxial test at confining pressure σ_3 =2.0 MPa

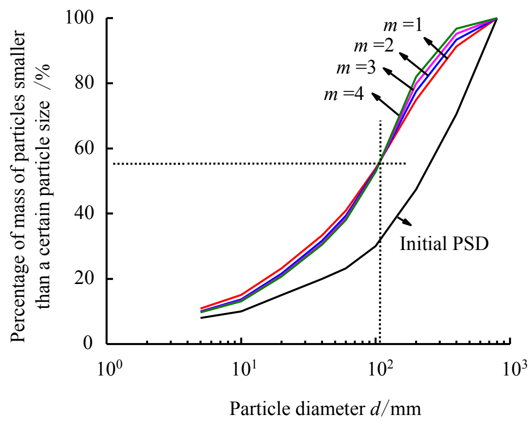


Fig.10 PSD curves with different *m* values

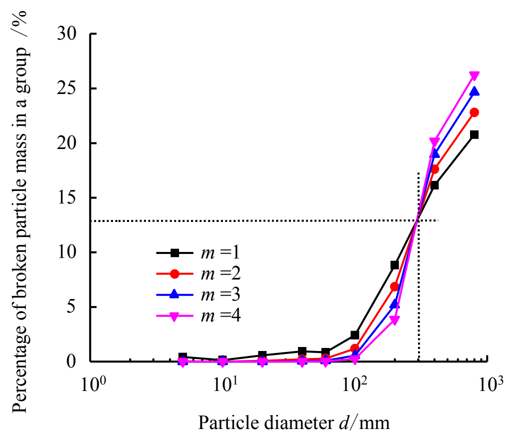


Fig.11 Percentage of broken particle mass of each particle group with different *m* values

6 Discussion on crushing parameters of prototype and test dam materials

In the research fileds of rockfill materials crushing, the relative crushing parameter, B_r, defined by Hardin[27], is generally used to quantify the particle crushing degree, which is defined as follows:

$$B_r = B_t / B_p \tag{16}$$

where B_r, B_p and B_t are the relative breakage index, the breakage potential and the total breakage potential, respectively. The value of B_t can be obtained through the area surrounded by grading curves before and after crushing and the minimum particle size line; B_p can be obtained through the area surrounded by initial grading curve and the minimum particle size line. Here, the minimum particle sizes of rockfill materials for prototype grading and test grading are 5mm and 2mm, respectively. And the larger the relative breakage index B_r is, the more seriously the rockfill materials crush.

The relationship between the relative breakage index B_r and stress could be expressed by the following equation[27]:

$$B_r = \frac{(\sigma_b / \sigma_r)^{n_b}}{1+(\sigma_b / \sigma_r)^{n_b}} \tag{17}$$

where σ_r is the anti-crushing capacity of soil, which is related to void ratio, particle properties and Mohr hardness; n_b is the fitting parameter; σ_b is the effective crushing stress. σ_b and σ_r could be expressed as[27]:

$$\sigma_b = \sigma_{n0}\left[1+9(\tau_0 / \sigma_{n0})^3\right] \tag{18}$$

$$\sigma_r = 800P_a(n_b - 0.3) \tag{19}$$

where σ_{n0} is the octahedral normal stress; P_a is the atmospheric pressure and τ_0 is the octahedral shear stress.

The calculated crushing parameters of prototype and test rockfill materials under different stress conditions are shown in Table 2. It can be seen that the calculated values for test rockfill materials are close to the measured values of real tests, indicating that the proposed model can reflect the crushing properties of rockfill materials. In addition, the calculated B_r of the prototype dam materials is one order of magnitude smaller than that of the test materials. The reason is that the prototype dam materials have more particle groups, leading to a larger B_p value and a smaller crushing parameters B_r. The values of B_r at the failure points under both confining pressures of 1.5 MPa and 2.0 MPa are close to each other, which suggests that the fracture state tends to be more stable under the high stress state, and also implies the existence of the ultimate grading curves.

According to the data in Table 2, Fig.12 gives the relationship between the relative crushing parameter B_r and the effective crushing stress σ_b for both types of materials in the logarithmic coordinate, where the fitting parameters n_b of test and prototype rockfill materials are 0.94 and 1.22, respectively. Both good linear relationships are seen between the crushing degree and the stress state for these two types of dam materials, which indicates that equation (19) can be applied to rockfill materials before and after the scale reduction.

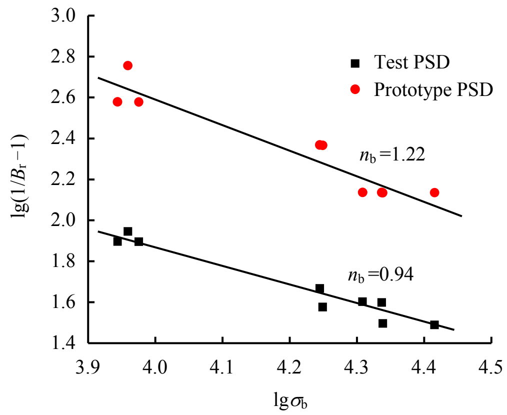


Fig.12 Relationships between effective breakage stress σ_b and relative breakage index B_r

7 Conclusions

This paper presents a method to describe the PSD evolution of the prototype rockfill directly based on the assumptions of particle failure probability and particle fractal crushing. The main conclusions are summarized as follows:

(1) The grading curves of prototype rockfill under different stress and dense states can be accessed directly by the proposed method from prototype PSD, avoiding the scale effect in the conventional test.

(2) The single-particle crushing test results show that the single particle strength of the Gushui basalt rockfill materials obeys the Weibull distribution well, and the splitting modes for all particle groups presents fractal distribution characteristics. The simulated grading curves are close to those of real triaxial test results, which indicates that the proposed model is reliable.

(3) The greater the dispersion of rockfill particle strength is, the more gentle the prototype grading curve at the failure point becomes. The smaller particles are more difficult to crush in the test, which is consistent with the result of triaxial test. During the loading process, the relationship between relative crushing parameter and the stress state for the prototype and test dam materials can be well quantified by the formula proposed by Hardin.

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