The state-dependent dilatancy properties of rockfills considering the influence of gradation

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Abstract: The stress dilatancy theory has been succeeded in demonstrating the deformation properties of clay. However, the deformation behaviors of rockfills are related to the stress and its initial state, so the stress dilatancy theory cannot apply to the rockfills directly. We take the state-dependent dilatancy theory of sand as a reference, design a series of large-scale triaxial shear tests on rockfill specimens with different gradations and densities under different confining pressures, and study the shear deformation characteristics of rockfills. According to the test results, the mathematical expression of the volume strain and deviatoric strain is established, which can reflect the contractive and expansive deformation behaviors. Then, ignoring the elastic deformation of rockfills and differentiating the mathematical equation of volume strain and deviatoric strain, the relationship of dilatancy rate and deviatoric strain can be obtained approximately. Finally, we analyze the influence of gradation, density and confining pressure on the dilatancy rate, and propose the general expression of the state-dependent dilatancy of rockfills.

Introduction

Dilatancy is an important behavior of the granular materials, referring to the volume change during shearing process. In general, dilatancy is the volume expansion, contraction is the volume compression. In the triaxial space, the dilatancy d is defined as the ratio of the plastic volume strain increment to the plastic deviatoric strain increment [1, 2]: $d = \mathrm{d}e_{\mathrm{v}}^{\mathrm{p}} / \mathrm{d}e_{\mathrm{q}}^{\mathrm{p}}$, where $\mathrm{d}e_{\mathrm{v}} = \mathrm{d}e_1 + 2\mathrm{d}e_3$, $\mathrm{d}e_{\mathrm{q}} = 2(\mathrm{d}e_1 - \mathrm{d}e_3)/3$, and the superscript 'p' stands for 'plastic'. Rowe's stress dilatancy theory [3] has been widely used for many clay models, such as cam-clay model, modified cam-clay model, etc. Because the dilatancy defined in the theory is only related to the stress, but independent of the material initial state, the stress dilatancy theory has some limitation for the description of coarse granular soils [4].

The limitation of stress dilatancy theory has been recognized in recent years, many researchers have tried to tackle this issue. Li [5, 6] and Dafalias [5] proposed a general form of the state-dependent dilatancy for sand, which can be expressed as $d = f(h, e, Q, C)$, where d is dilatancy rate, η is stress ratio, e is void ratio, C denotes collectively material parameter constants, and Q denotes other internal variables that may affect the dilatancy behavior.

The behaviors of rockfills [7-9] are similar to the sand's. It also has some special characteristics, for big particle, high strength, small deformation, well penetration and stability, particle breakage, and so on. The dilatancy theory of rockfills is the basis for establishing unified modeling framework. So far, few investigations have been made on the state-dependent dilatancy theory of rockfills. In this paper, refering to the state-dependent dilatancy theory of sand, we design a series of experimental research and theory analysis, and propose the state-dependent dilatancy theory of rockfills which can improve the dilatancy theory of geotechnical materials.

Laboratory Tests

Materials

In the present work, Hekoucun reservoir dam rockfill material in China was prepared for testing, selecting the maximum particle size as 60 mm. The particle of this material is angular with a particle size between 5 mm and 60 mm, while when the particle size is less than 5 mm, the material consists of subangular particles. Particle size, strength, shape, void ratio, wetting, gradation, stress path [10], and stress condition are important factors which influence the strength and stress-strain properties of rockfills. The test scheme (Table 1) is adopted to study the dilatancy behaviors of rockfills in different gradations (Fig. 1), densities and confining pressures.

Table 1 Large-scale triaxial test scheme

Gradation	Relative density D_r	Initial confining pressure [MPa]
1	0.60, 0.75, 0.90, 1.00	0.3, 0.6, 1.0, 1.5
2	0.60, 0.75, 0.90, 1.00	0.3, 0.6, 1.0, 1.5
3	0.60, 0.75, 0.90, 1.00	0.3, 0.6, 1.0, 1.5
4	0.60, 0.75, 0.90, 1.00	0.3, 0.6, 1.0, 1.5

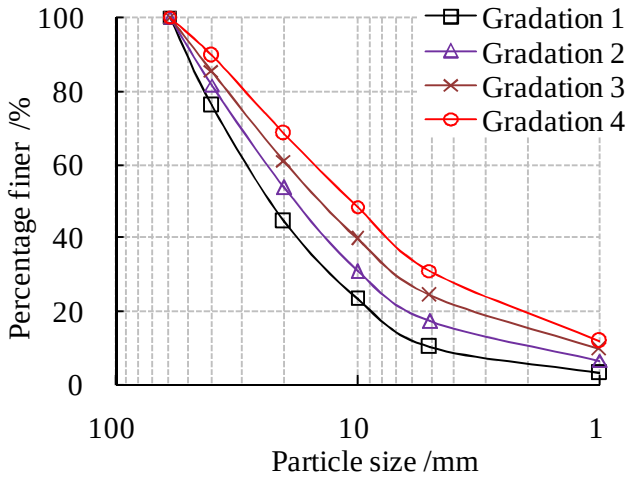


Fig. 1 Particle size distribution of rockfills in the large-scale triaxial test

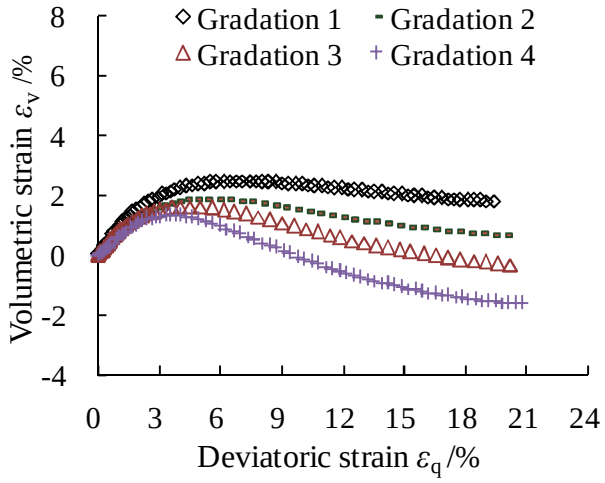
Triaxial compression test

Large-scale triaxial compression equipment is used for testing the rockfills. The specimen diameter is 300 mm; its height is 700 mm. The maximum testing particle size is 60 mm, so the ratio of the maximum particle size to the specimen diameter is 0.2. The sample is prepared in a split mold without water. According to one designed gradation, all the sample components are mixed with different particle size. The mixed material is divided into five equal parts for compacting in the split mold. The sample is saturated by water saturation method, and then it is consolidated by the designed initial confining pressure. When consolidation of the sample is stable, it is sheared under draining condition with the constant axial strain rate of 2 mm/min. The shearing process continued until the axial strain up to 20%.

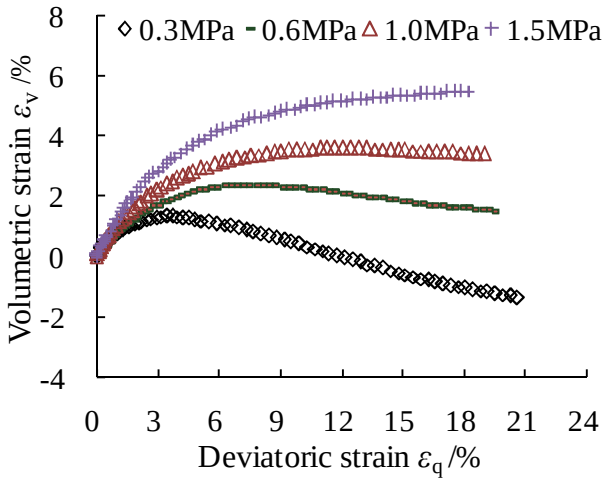
Test results

Gradation, density and confining pressure have great influence on the volumetric strain behaviors of rockfills. Figs. 2(a)~(c) show the test results of rockfills on the relationship between the volumetric strain e_v and deviatoric strain e_q. The test results of different gradation samples in Fig. 2(a) are conducted when the confining pressure is 1.0 MPa and the relative density is 0.90. Take the gradation 4 sample as an example, it has more fine particles and the volumetric expansion is more obvious. The test results of gradation 1 sample in Fig. 2(b) are conducted under different confining pressures when the relative density is 0.75. When the confining pressure is 1.5 MPa, the volumetric strain becomes contraction; in contrast, when the confining pressure is 0.3 MPa, the volumetric strain becomes

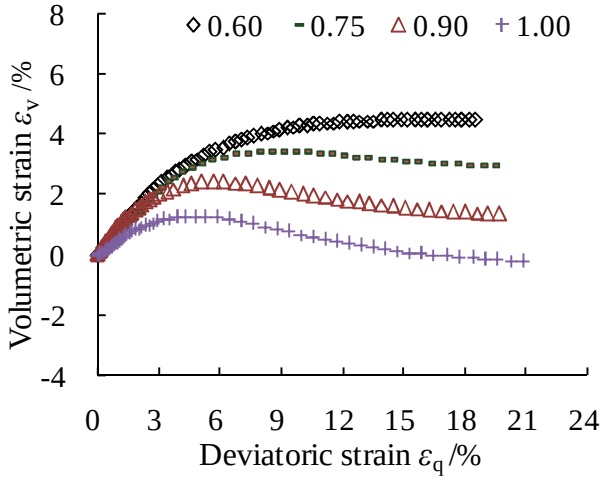
expansion. So the larger confining pressure results in more particle breakage. In Fig. 2(c), the test results of gradation 3 samples are obtained under different densities when the confining pressure is 1.5 MPa. Obviously, the much denser of the rockfill sample, the more volumetric expansion.



(a) s_3=1.0MPa , D_r=0.90



(b) Gradation 1, D_r=0.75



(c) Gradation 3, s_3=1.5MPa

Fig. 2 Volumetric strain versus deviatoric strain

Dilatancy

Based on the definition of dilatancy *d*, in order to properly formulate a state-dependent dilatancy function for rockfills, it is important to investigate the volume changing rule among the whole shearing process. From analyzing the triaxial experimental results, the relationship between the volumetric strain and deviatoric strain can be expresses as:

$$e_v = f\left(e_q\right) = A + B\ln\left(1+e_q\right) + C\frac{e_q}{1+e_q} + De^{-e_q}, \tag{1}$$

where e_v is the volumetric strain; e_q is the deviatoric strain; *A*, *B*, *C*, *D* are material parameters, they are constants under the condition of certain gradation, density and pressure. The parameters' value based on the above test results are listed in Tables 2~4.

Table 2 The values of rockfill material parameters (s_3=1.0MPa , D_r=0.90)

Parameter	Gradation 1	Gradation 2	Gradation 3	Gradation 4
A	-2.67	1.38	1.53	1.10
B	-0.83	-0.52	-1.19	-2.21
C	7.56	1.24	2.19	4.35
D	1.92	-1.90	-2.00	-1.90

Table 3 The values of rockfill material parameters (Gradation 1, D_r=0.75)

Parameter	0.3[MPa]	0.6[MPa]	1.0[MPa]	1.5[MPa]
A	-4.65	-5.30	-5.27	-2.76
B	-2.83	-1.22	-0.16	1.33
C	12.82	11.34	9.96	4.84
D	3.82	4.60	4.68	2.39

Table 4 The values of rockfill material parameters (Gradation 3, s_3=1.5MPa)

Parameter	0.60	0.75	0.90	1.00
A	-5.94	-2.36	1.07	1.08
B	0.58	0.25	-0.43	-0.82
C	9.50	5.33	1.99	1.53
D	5.17	1.75	-1.49	-1.55

Rockfills is a kind of coarse granular materials. The elastic deformation is very small, so the elastic volumetric strain and elastic deviatoric strain could be ignored. For Eq. 1, differentiating the volumetric strain and deviatoric strain, which is dilatancy rate *d* approximately, as

$$d=\frac{\mathrm{d}e_{\mathrm{v}}^{\mathrm{p}}}{\mathrm{d}e_{\mathrm{q}}^{\mathrm{p}}}\approx\frac{\mathrm{d}e_{\mathrm{v}}}{\mathrm{d}e_{\mathrm{q}}}=\frac{\mathrm{d}f}{\mathrm{d}e_{\mathrm{q}}}=\frac{B}{1+e_{\mathrm{q}}}+\frac{C}{\left(1+e_{\mathrm{q}}\right)^{2}}-De^{-e_{\mathrm{q}}}, \tag{2}$$

where *d* is dilatancy rate; e_{v} is the whole volumetric strain; e_{q} is the whole deviatoric strain; $e_{\mathrm{v}}^{\mathrm{p}}$ is the plastic volumetric strain; $e_{\mathrm{q}}^{\mathrm{p}}$ is the plastic deviatoric strain; *B*, *C*, *D* are material constants, they are given in Tables 2~4 correspondingly.

Eq. 2 describes the dilatancy changing rule. Figs.3 (a) ~(c) show the relationship between the dilatancy rate *d* and deviatoric strain e_{q} directly. When the dilatancy rate *d* less than 0, the sample is expansive during shearing process; otherwise, when *d* larger than 0, it is contractive. In Fig. 3(a), the gradation 4 sample has more fine particles; *d* is much less than 0 and the dilatancy is more obvious. Fig. 3(b) shows that, the confining pressure is 1.5 MPa, *d* is not less than 0; in contrast, when the confining pressure is 0.3 MPa, *d* is less than 0, so smaller confining pressure results in more dilatancy. In Fig. 3(c), the rockfill sample is much denser, the dilatancy is more obvious.

According to the above experimental results and analysis, the general form of the state-dependent dilatancy for rockfills can be expressed as

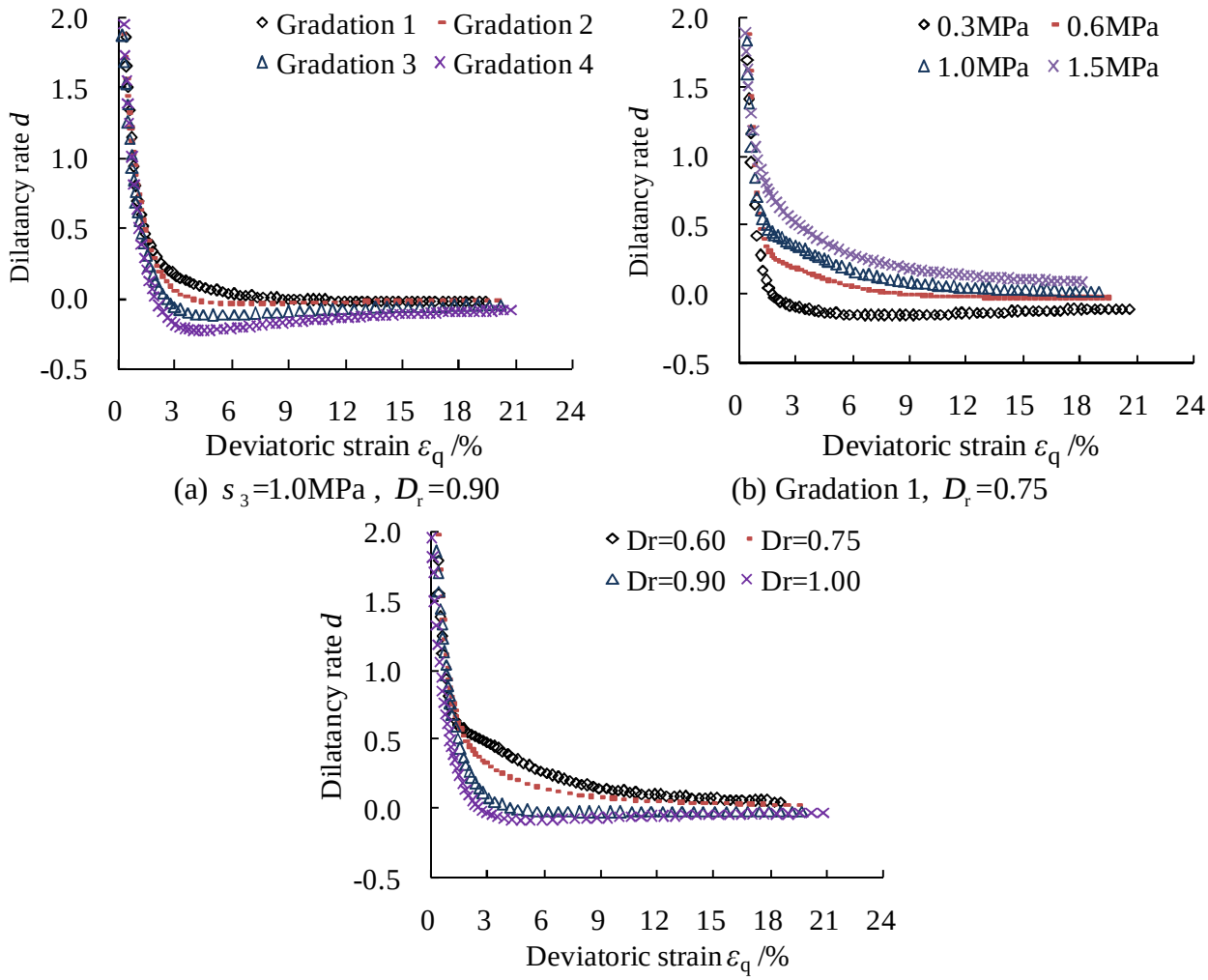
$$d=f(l\ ,\ \mathrm{e}\ ,\ h\ ,\ \Omega), \tag{3}$$

$$h=q/p', \tag{4}$$

where λ is the gradation parameter; e is the void ratio; η is the stress ratio, q is the deviatoric stress, p' is the effective mean normal stress, Ω denotes other internal factors that may affect the deformation behaviors of rockfills.

Conclusions

The volumetric strain and dilatancy behaviors of Hekoucun reservoir dam rockfills are studied by large-scale triaxial shearing tests under the condition of different gradations, densities and confining pressures. The test results directly reflect that the influences of gradation, density and pressure are very important to the deformation properties of rockfills. Furthermore, the mathematical function about the volumetric strain and deviatoric strain is established, and the dilatancy rate changing with deviatoric strain can be obtained by one approximate assumption and differentiating. Then, the general expression of rockfills is proposed depending on the stress level, gradation and density. The specific expression of the state-dependent dilatancy for rockfills needs further research.



(a) s_3=1.0MPa , D_r=0.90

(b) Gradation 1, D_r=0.75

(c) Gradation 3, s_3=1.5MPa

Fig. 3 Dilatancy rate versus deviatoric strain

Acknowledgments

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