14th World Congress in Computational Mechanics (WCCM)
ECCOMAS Congress 2020
19 – 24 July 2020, Paris, France
F. Chinesta, R. Abgrall, O. Allix and M. Kaliske (Eds)

THE SIMULATION OF ROCKFILL IN A CHARACTERISTRIC OF THREE- DIMENSIONAL STRENGTH

XUE-FENG LI[1,2] AND RUI-JIE LI[1,2,3]

[1]Solid Mechanics Institute, Ningxia University
No.489, Helanshan West Road, Xixia district, Yinchuan, Ningxia, P. R. China, 750021
lixuefeng1928@163.com

[2]School of Physics and Electronic-Electrical Engineering, Ningxia University
No.489, Helanshan West Road, Xixia District, Yinchuan, Ningxia, P. R. China, 750021
lixuefeng1928@163.com

[3]Highway Construction Authority of Ningxia Hui Nationality Autonomous Region
No.175, Beijing Middle Road, Jingfeng District, Yinchuan, Ningxia, P. R. China, 750011
lrj456@163.com

Key words: Rockfill, Three-Dimensional Strength Characteristic, Fabric, Anisotropy， Simulation.

Abstract. To study the three-dimensional strength characteristics of rockfill material under an anisotropic state, the anisotropic state variables were introduced into the Mohr-Coulomb failure criterion, and the failure criterion describing the three-dimensional strength of rockfill which was obtained in linear form in this paper. The anisotropic state variables were established with the fabric of rockfill particles. Based on the experimental results of a large triaxial consolidated drained test, fractal dimension theory was introduced to study the relationship between strength and deformation characteristics under different gradation and confining pressures. The experimental results and simulation have shown that: (1) The fractal theory can be used to quantitatively describe the rockfill particles crushing with all kinds of grades under different stress levels. (2) The fabric of rockfill particles was closely related to the three-dimensional strength characteristics. (3) The anisotropic state variables can describe the three-dimensional strength characteristics of rockfill well from a microscopic perspective.

1 INTRODUCTION

Rockfill was a common engineering material extensively used in hydraulic, railway, transportation, and other basic engineering construction. It showed different strength characteristics in the macroscopic affecting the stability of the structure. Therefore, the strength characteristics of rockfill materials have attracted the attention of the engineering and academic circles under different stress paths [1-2]. To study the strength characteristics of rockfill, many researchers carried a lot of large-scale triaxial test research. Studies have shown that void[3], stress level and density [4], confining pressure [5], particle crushing [6], gradation [7], coefficient of intermediate principal stress [8], and particle shape [9] are important factors influencing the strength and deformation of rockfill.

However, the anisotropic structures and characteristics of rockfill rarely participate in the in-depth study of microstructure. Considering that the fractal dimension provides a connection between the effect of microparticle size and the macroscopic strength, it can characterize the homogeneity of rock structures at different strengths and the uniformity of rocks on the microscopic scale [10]. Based on the author's work on the sand anisotropic damage criteria [11-13], this paper described the degree of anisotropy and establishes the rules of the anisotropic damage with the combination of micro characteristics and fabric of the rockfill materials.

2 FAILURE CRITERIA

This paper introduces the anisotropic state variable (Li et al. 2010) into the generalized Mohr-Coulomb failure criterion equation, and gives an anisotropic failure criterion in linear form as follows:

$$f = q - \left(1 + \varsigma A\right) M_f g\left(\theta_\sigma\right) p = 0 \tag{1}$$

where p is mean stress, $p = \sigma_{kk}/3$ and q is generalized deviatoric stress, $q = \sqrt{3(\sigma_{ij} - \delta_{ij} p)(\sigma_{ij} - \delta_{ij} p)/2}$. where δ_{ij} is Kronecker tensor. ς is weighting coefficient in Eq. (1). M_f is the peak failure stress ratio which was obtained for the triaxial compression test. $g\left(\theta_\sigma\right)$ is elliptic ridge function in the deviatoric plane (William and Warnke, 1975).

A is the anisotropic state variable. When the material fabric is isotropic, A is constantly equal to 0 and the strength criterion degrades to isotropic form, but when the fabric is anisotropic, the influence of anisotropic degree, the rotations on the principal stress axes, and other factors can be described on the strength of rockfills.

In Eq. (1), the anisotropic state variable should have the property of tensor invariant. It should be a scalar, so it can be defined as

$$A = \frac{\sigma_{ij}}{\sigma_m} F_{ij} - \left(\frac{\sigma_{ij}}{\sigma_m} F_{ij}\right)_0 = \frac{\sigma_{ij}}{\sigma_m} F_{ij} - A_0 \tag{2}$$

where A_0 are the reference point and the test point for determining the parameters of the failure criteria model. F_{ij} is the expression of the origin of particle arrangement fabric in Eq. (3) (Li and Wang et al, 2016).

$$F_{ij} = \begin{bmatrix} \dfrac{1 + a_1 + a_2 + a_1 a_2}{3 + a_1 + a_2 - a_1 a_2} & 0 & 0 \\ 0 & \dfrac{1 + a_1 - a_2 - a_1 a_2}{3 + a_1 + a_2 - a_1 a_2} & 0 \\ 0 & 0 & \dfrac{1 - a_1 + a_2 - a_1 a_2}{3 + a_1 + a_2 - a_1 a_2} \end{bmatrix} \tag{3}$$

where a_1 and a_2 are the orthotropic amplitude parameters, it is defined as

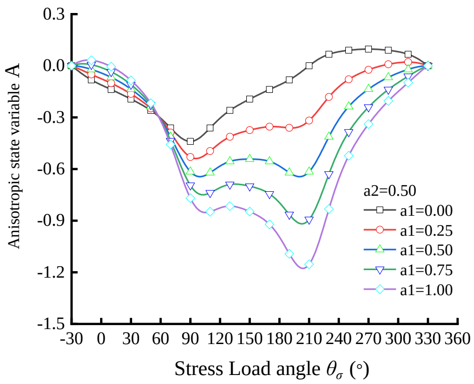
$$a_1 = \frac{1}{2N}\sqrt{\left(\sum_{k=1}^{2N}\left(\cos^2\left(\theta^{(k)}\right)\right) - \sin^2\left(\theta^{(k)}\right)\cos^2\left(\alpha^{(k)}\right)\right)^2 + \left(\sum_{k=1}^{2N}\sin\left(2\theta^{(k)}\right)\cos\left(\alpha^{(k)}\right)\right)^2} \quad a_2 = \frac{1}{2N}\sqrt{\left(\sum_{k=1}^{2N}\left(\cos^2\left(\theta^{(k)}\right)\right) - \sin^2\left(\theta^{(k)}\right)\sin^2\left(\alpha^{(k)}\right)\right)^2 + \left(\sum_{k=1}^{2N}\sin\left(2\theta^{(k)}\right)\sin\left(\alpha^{(k)}\right)\right)^2} \tag{4}$$

where a_1 and a_2 is two of the amplitude parameters on three orthogonal planes in the Cartesian coordinates respectively. Both of the amplitude parameters can be determinate according to the microscopic experiments. The data of the amplitude parameters range from 0 to 1 which describes the degree of anisotropy of materials on three sedimentary surfaces. θ^k is the KTH particle angle between the long axis orientation of the first particle and the corresponding coordinate axis. N is the total number of soil particles measurement. $\alpha^{(k)}$ is the KTH particle angle between the projection of the long axis of the first particle on the horizontal plane and the x_k-axis.

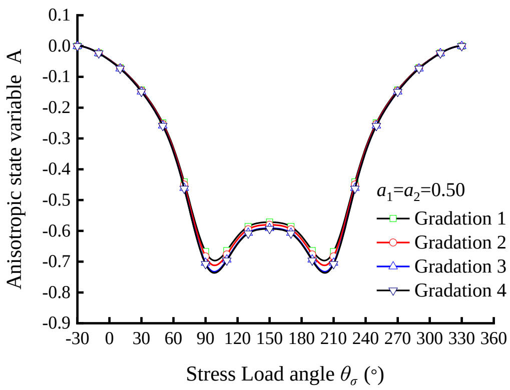
When the main directions of the fabric and the direction of σ_1、σ_2 and σ_3 are rotated respectively, the fabric in Eq. (4) is transformed as follow

$$F_{ij}^{'} = C_{ki}C_{lj}F_{kl} \tag{5}$$

where F_{ij} is the fabric tensor defined in Eq. (4) . C_{ij} is the transformation tensor formed by the cosine of the Angle between the fabric tensor and the direction of the principal stress. More details on the transformation were shown in reference [14].



(*a*) The law as the value change of a_1



(*b*) The law with the gradation changes

Figure 1: Relationship between the stress Lode angle and anisotropic state variables

The anisotropic state variable reflects the anisotropic degree of the material, and its size is related to the anisotropic amplitude and the stress condition. It shows the stress Lode angle variation law is related to anisotropic state variables in Fig.1.

3 EXPERIMENT VERIFICATION

3.1 Brief introduction to the rockfill test

The experiments adopt the shear test of isotropic consolidation drainage and conduct the triaxial consolidation drainage shear tests (CD) under different confining pressure increments, which refer to Li et al. 2016 [7]. At the same time, the experiments also carried out particle analysis on the samples after shearing. The particle density G_S is 2.77, the maximum particle size is 800 mm, the uneven coefficient C_u of the rockfill sample is 35.48, and the curvature coefficient C_c is 1.35. The parameters of test particle size are shown in table 1.

Table 1: Experimental parameters conditions and particle size

Serial number	Density	Confining pressure(kPa)	Particle mass percentage content (mm)/%					
			60	40	20	10	5	1.0
Gradation 1	0.6	300,600,1000,1500	100	75.7	44.3	22.9	11.0	3.0
Gradation 2	0.75	300,600,1000,1500	100	81.6	53.5	30.8	17.0	6.5
Gradation 3	0.90	300,600,1000,1500	100	85.4	60.8	39.4	24.0	9.5
Gradation 4	1.00	300,600,1000,1500	100	89.4	68.2	48.3	31.0	11.8

3.2 Strength test characteristic

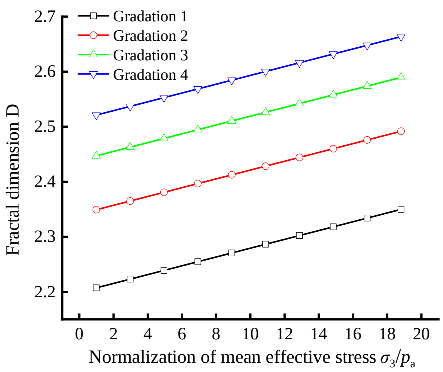
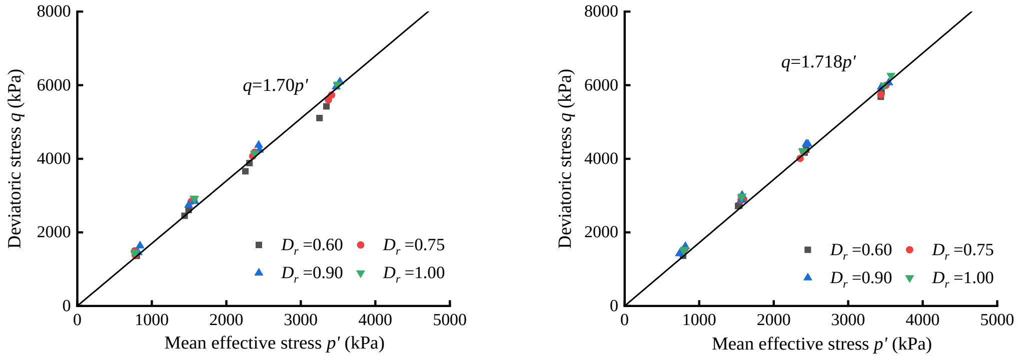


Figure 2: Relationship between gradation and fractal dimension

Considering that gradation of rockfill has a significant influence on its strength and deformation characteristics, the fractal theory is introduced in this paper for a quantitative description of rockfill gradation. The experimental results show that the larger the confining pressure, the more severe the crushing, the smaller the impact of the relative density on the particle crushing, the finer the gradation of the initial rockfill (that is the larger the initial fractal dimension D_0), the smaller the crushing degree. And it has a linear relationship between fractal dimension D and σ_3/P_a in Eq. (6)

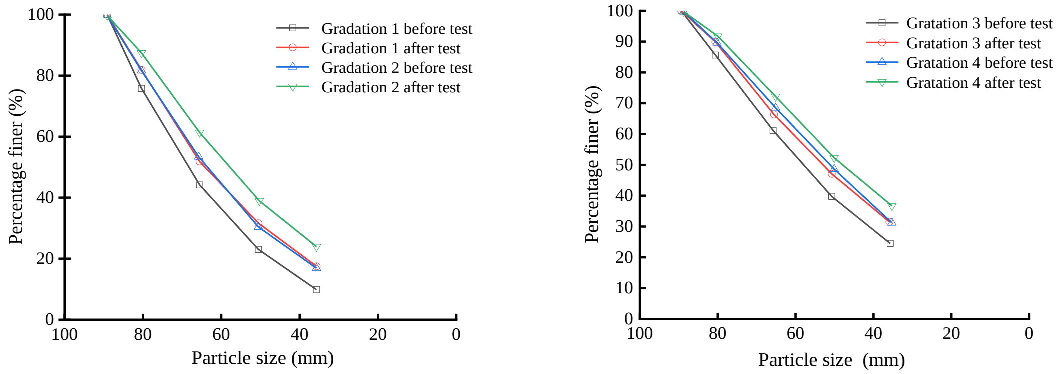
$$D = l + \kappa \frac{\sigma_3}{P_a} + \beta D_0 \tag{6}$$

Where l、 κ and β are model parameters. It can be calculated from experimental data. The diagram is shown in Fig 2.



(a) Sample 1 and Sample 2 (b) Sample 3 and Sample 4

Figure 3: The critical state point and trend line in the $p' \sim q$ plane



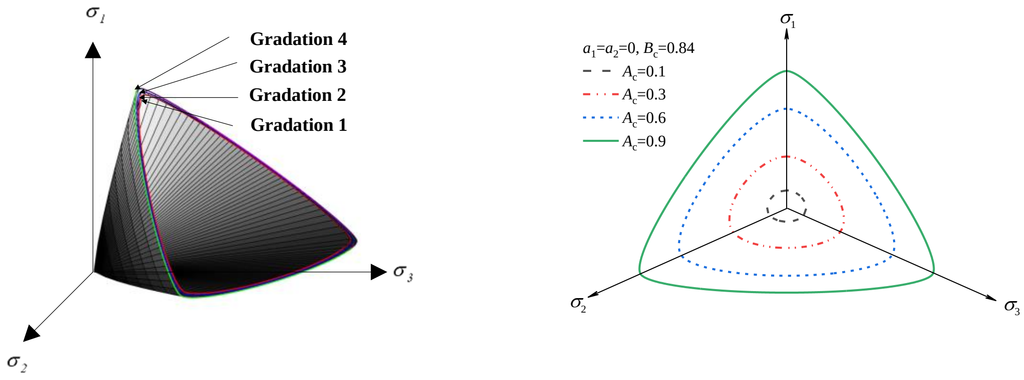
(a) Sample 1 and Sample 2 (b) Sample 3 and Sample 4

Figure 4: Comparison of particle breakage before and after the graded sample on CD tests

As can be seen from Fig.3, the critical state line of rockfill material is unique, and its critical state experimental point presents a linear change trend. It can be seen from Fig.4 that the initial gradation sample 1-4 showed significant particle breakage after the CD test. It was about 5%-7% higher than the original gradation in the particle size range from 40 mm to 80 mm. The mass percentage of particle size increases gradually and the overall trend is similar to the smaller particle size. The experimental results show that the strength of rockfill material is closely related to confining pressure and particle breakage. The results are consistent with the research results of Zhao [15].

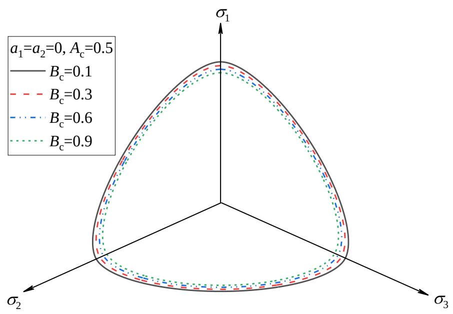
3.3 Three-dimensional strength characteristics

The simulation results and the failure surface are shown as follows. In Fig.5 (a), there is a function of the positive ratio between fractal dimension D_0 and A_c , and also A_c has a negative ratio with void ratio e. The yield surface expands with the increase of strength parameter A_c, it indirectly indicates that the higher the fractal dimension is, the finer the particle gradation is, the stronger the yield strength is. The smaller the void ratio, the denser the material arrangement, the stronger the yield strength. Fig.5 (b) and Fig.5 (c) show the change law of the strength failure plane with the strength parameters on π plane, respectively. It shows that the strength failure line is a curved triangle which is similar on π the plane. It has symmetry under the condition of the orthotropic amplitude parameter a_1 and a_2 equal.



(*a*) The failure surface of different gradation

(*b*) The failure surface with variation of strength parameters A_c



(*c*) The failure surface with variation of strength parameters B_c

Figure 5: Schematic of various failure surface with different strength parameters

4 CONCLUSIONS

- The anisotropic failure criterion of rockfill is established by combining macroscopic and mesoscopic theory. Anisotropic state variable of rockfill is newly defined to describe the influence of its microstructure characteristics that not only simplifies the failure criterion but also describes its strength characteristics. The experimental results show that the criterion can reflect the strength of rockfill with the change of microstructure.

- Based on the strength parameters represented by the fractal dimension and void ratio, it can better reflect the characteristics of the yield strength of rockfill changing with the microscopic characteristics. The three-dimensional strength of rockfill is related to the anisotropic state variables. It is more intuitive and easy to understand the relationship between the established state variables and the porosity and gradation of rockfill particles. The anisotropic amplitude increased with weaker yield strength and more obvious anisotropy. Specifically, the influence of anisotropic state variables is negatively correlated with yield strength.

5 ACKNOWLEDGEMENTS

This research was financially supported by the Key R&D Program of Ningxia Hui Autonomous Region Projects of International Cooperation and Exchanges (No. 2018DWHZ0084), Ningxia Science & Technology Innovation Leading Talent Project (No. KJT2019001), the National Nature Science Foundation of China (no. 51669027), and the National Key R&D Program of China (No. 2017YFC0504404). These supports are gratefully acknowledged.

REFERENCES

[1] Xu, M. and Hong, J.T. et al. DEM study on the effect of particle breakage on the macro- and micro-behavior of rockfill sheared along different stress paths. *Comput. Geotech.* (2017) **89**:113-127.

[2] Jia, Y.F. and Xu, B. et al. Particle breakage of rockfill material during triaxial tests under complex stress paths. *Int. J. Geomech.* (2019) **19**:04019124.

[3] Xu, W.W. and Shi, B.X. et al. Effects of porosity on strength and deformation of rockfill materials. *Chinese J. Geotech. Eng.* (2018) **40**:47-52.

[4] Cai, Z.Y. and Ding, S.Y. et al. Numerical simulation of strength and deformation characters of rockfill. *Chinese J. Rock Mechan. Eng.* (2009) **28**:1327-1334.

[5] Yang, G. and Yan, X. et al. Effect of particle shape and confining pressure on breakage and deformation of artificial rockfill. *Int. J. Geosynthetics and Ground Engineering* (2019) **5**: 15.

[6] Xu, Y.F. and Feng, X.B. et al. Fractal model for rockfill shear strength based on particle fragmentation. *Granul. Matter* (2015) **17**:753-761.

[7] Li, X.M. and Guan, Y.F. et al. Experimental studies on strength and deformation behaviors of rockfill materials considering particle gradation. *Hydro-Science Eng.* (2016) **4**:32-38.

[8] Guo, W.L. and Zhu, J.G. et al. Dilatancy equation for rockfill materials under three-dimensional stress conditions. *Int. J. Geomech.* (2019) **19**:04019027.

[9] Nie, Z.Z. and Zhu, Y.G. et al. Investigating the effects of Fourier-based particle shape on the shear behaviors of rockfill material via DEM. *Granul. Matter* (2019) **21**: 22.

[10] Huang, D.M. and Chang, X.K. et al. From rock microstructure to macromechanical properties based on fractal dimensions. *Adv. Mech. Eng.* (2019) **11**:1-13.
[11] Li, X.F. and Huang, M.S. et al. Failure criterion of anisotropic sand with the method of macro-mircro incorporation. *Chinese J. Rock Mechan. Eng.* (2010) **29**:1885-1892.
[12] Li, X.F. and Huang, M.S. et al. Quantitative description of microscopic fabric based on sand particle shapes. *China J. Highw. Transp.* (2016) **29**:29-36.
[13] Li, X.F. and Li, R.J. et al. Three-dimensional strength characteristic of rockfill. *China J. Highw. Transp.* (2020) **33**:54-62.
[14] Li, X.F. and Huang, M.S. et al. Failure properties of sand considering rotaion of principal stress axis with method of macro-meso incorporation. *Rock and Soil Mechanics* (2013) **34**:1923-1930.
[15] Zhao, F.X. and Chun, S.C. et al. Gradation evolution model based on particle breakage characteristics for rockfill materials. *Chinese J. Rock Mech. Eng.* (2019) **41**:1707-1714.