วิศวกรรมสารฉบับวิจัยและพัฒนา
Engineering Journal of Research and Development

วิศวกรรมสถานแห่งประเทศไทย ในพระบรมราชูปถัมภ์
The Engineering Institute of Thailand under H.M. The King's Patronage

ปีที่ 31 ฉบับที่ 3 กรกฎาคม-กันยายน 2563
Volume 31 Issue 3 July-September 2020

Received 18 June 2019
Revised 8 August 2019
Accepted 3 October 2019 Physical Sciences

STRENGTHS OF ROCK MASS MODELS WITH ROUGH FRACTURES UNDER LARGE CONFINEMENTS

Kiattisak Seepun[1], Thanittha Thongprapha[2] and Kittitep Fuenkajorn[3*]

[1]Student, Geomechanics Research Unit, Suranaree University of Technology, Thailand

[2]Instructor, Geomechanics Research Unit, Suranaree University of Technology, Thailand

[3]Professor, Geomechanics Research Unit, Suranaree University of Technology, Thailand

*Corresponding author: kittitep@sut.ac.th

บทคัดย่อ

งานวิจัยนี้ได้ทำการทดสอบกำลังกดของแบบจำลองมวลหินขนาดเล็กที่มีจำนวนชุดรอยแตกและความถี่ของรอยแตกต่างกันภายใต้ความดันล้อมรอบสูงถึง 12 เมกะปาสคาล แบบจำลองมีขนาด 55×55×55 ลูกบาศก์มิลลิเมตร ที่จำลองด้วยการกดในแนวเส้นและทดสอบโดยใช้เครื่องกดในหลายแกน ตัวอย่างแบบจำลองมีความถี่ของรอยแตกผันแปรจาก 36 ถึง 54 รอยแตกต่อ 1 เมตร ผลที่ได้ระบุว่าเกณฑ์การแตกของ Hoek และ Brown ที่มีค่าคงที่เพียง 2 ตัว (m และ s) สามารถอธิบายการแตกของแบบจำลองมวลหินได้ดีทัดเทียมกับเกณฑ์การแตกของ Sheorey Yudhbir และ Ramamurthy-Arora ที่มีค่าคงที่ 3 ตัว ค่าคงที่ m และ s ลดลงเมื่อความถี่ของรอยแตกเพิ่มขึ้น ผลกระทบของความถี่ของรอยแตกต่อกำลังกดมีค่าสูงขึ้นเมื่อความดันล้อมรอบเพิ่มขึ้น

ABSTRACT

Triaxial compressive strength tests are performed to determine strength of small-scale rock mass models with different joint sets and frequencies under confining pressure up to 12 MPa. Sandstone specimens (55×55×55 mm^3) with joint sets simulated by tension-induced fractures are loaded to failure using a polyaxial load frame. The specimens have joint frequencies ranging from 36 to 54 joints per meter. Hoek-Brown criterion with two material parameters (m and s) can describe the rock mass strengths as well as the criteria of Sheorey, Yudhbir and Ramamurthy-Arora which have three material parameters. The parameter s decreases with increasing joint frequency, while parameter m is less sensitive to the joint frequency. The effects of joint frequencies on the rock mass compressive strengths tend to increase with confining pressure.

KEYWORDS: Triaxial compression, Joint frequency, Strength criterion, Rock mass.

1. Introduction

Several empirical criteria have been proposed to describe strength of rock mass. They are developed based on laboratory testing [1-5], case studies [6-7], and numerical simulations [8] to determine the effects of joint frequency, orientation and joint set number on rock mass strengths. It has been found that rock mass strength decreases with increasing joint frequency [9] and joint set number [10]. The joint orientation also affects the rock mass strength. Even though several rock mass strength criteria have been proposed, verification of their predictability under large confinements has rarely been attempted, particularly for rock mass with multiple joint sets.

The objective of this study is to perform triaxial compressive strength tests on sandstone specimens with single and multiple joint sets under confining stresses up to 12 MPa. The joints are simulated by tension-induced fractures with frequencies ranging from 36 to 54 joints per meter. Some commonly used strength and deformability criteria are applied to the test results to evaluate their validity. The effects of joint frequency, joint set number and confining stress on the strengths of the small-scale rock mass models are determined.

2. Sample preparation

The rock specimens are prepared from Phra Wihan sandstone. They are fine-grained quartz sandstones with highly uniform texture and density [11]. The specimens have nominal dimensions of 55×55×55 mm^3. Artificial joints are made by tension-inducing method. Up to 55 specimens are prepared with three different joint conditions: single joint set, two joint sets and three-mutually perpendicular joint sets. The joint frequencies and orientations with respect to the applied loads are shown in Table 1. They are briefly described below.

For Case I, one-joint set specimens are prepared to study the effects of joint frequency and major principal stress direction on the strength of rock specimens. Two sets of the specimens are prepared with joints parallel and normal to the major principal axis. There are 1 and 2 joints for each set. Each set has equal spacing.

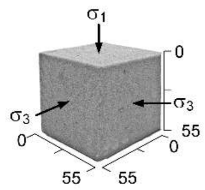
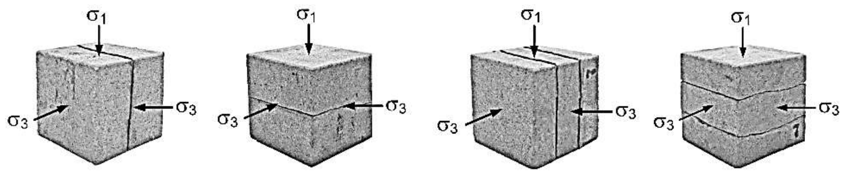
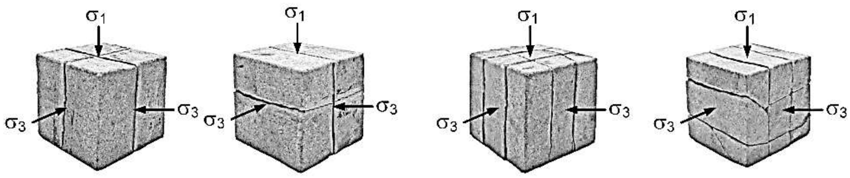
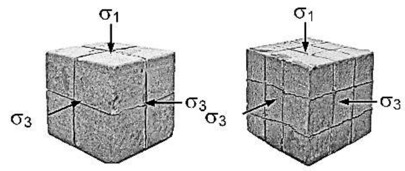
Case II, two-joint set specimens are prepared to assess the effect of joint frequency when the joints are parallel and normal to the major principal axis.

For Case III, specimens with three-mutually perpendicular joint sets are prepared to study the effects of joint set number and joint frequency. There are 1 and 2 joints for each set.

3. Test method

A polyaxial load frame [12] is used to apply axial stress (σ_1) and constant confining pressures (σ_3) to the intact and jointed rock specimens. This device is developed to test rock specimens with soft to medium strengths under polyaxial stress states. The specimens are oven-dried before testing. Neoprene sheets are placed at all interfaces between the loading platens and specimen surfaces to minimize the friction. The constant confining (lateral) stresses range from 0, 3, 5, 7 to 12 MPa. First the specimen is subjected to the pre-defined confining stresses. The axial stress is then increased at a constant rate of 0.1 MPa/s using an electric hydraulic pump. The specimen deformations are monitored along the three loading directions. They are used to calculate the principal strains during loading. The readings are recorded until failure occurs. The failure is defined by the drop of the applied axial stress. Photographs are taken of the post-test specimens. The modes of failure are examined.

Table 1 Specimens prepared for triaxial compression test with one, two and three joint sets, joint frequencies equivalent to 36 and 54 joints/m.

Cases	Specimens
Intact	
I One joint set	
II Two joint sets	
III Three mutually perpendicular joint sets	

4. Test results

Figure 1 shows examples of stress-strain relations in terms of the differential stress as a function of strain for Cases I and III. The effect of joint frequency on the rock specimens can be observed by the reduction of failure stresses and the increase of the failure strains. The effects of the confining stresses on the strength of the specimens can be observed from the σ_1 -σ_3 diagrams for all cases, as shown in Figure 2. The relations between σ_1 and σ_3 at failure tend to be non-linear for the intact sandstone and for the specimens with all joint frequencies. The specimens with higher joint frequencies (J_f) show lower strengths than those with lower joint frequencies. The effect of joint frequency on the strength tends to be greater for the specimens with joint parallel to σ_1 (Figures 2a and 2c), as compared to those with joints normal to σ_1 (Figures 2b and 2d). For example for the specimens with joint parallel to σ_1 (Figure 2a), the strengths of the specimens with 54 joints/m decreases by about 14% from the intact strength. Under this joint frequency the specimen strengths for specimens with joint normal to σ_1 (Figure 2b) decrease by about 18%. The effects of joint frequency are greatest for the three-joint set specimens (Case III, Figure 2e). The strengths of specimens containing three joint sets with 54 joints per meter drop by nearly 26% from the intact strength.

The single joint set specimens with joints normal to σ_1 (Figures 2b and 2d) show higher strength than those with joints parallel to σ_1 (Figures 2a and 2c). The strength discrepancies are primarily due to the fact that for cases I and III, σ_1 direction is parallel to tall sandstone blocks that form the rock mass models. The height-to-width ratios of these plates are relatively high (varying from 2 to 3, depending on the joint frequencies). Under axial loading each plate can laterally dilate (toward the thinner sides), and hence the extensile fractures can be induced in vertical or nearly vertical directions. The pre-existing joints also help the induced extensile fractures to propagate through the specimen models. The induced fractures can propagate more easily for the specimens with higher joint frequency, as compared to those with lower joint frequencies. This explains why the strengths of specimens with joint parallel to σ_1 decrease with increasing joint frequency. Under large confinement the lateral dilation of the sandstone plates toward the pre-existing joints becomes more difficult, and hence some shear fractures are induced across the specimen models.

For the specimens with σ_1 normal to joint planes, the specimens cannot dilate easily under loading, and therefore the compressive shear fractures are predominant. As a result the strengths of specimens with joint normal to σ_1 tend to be greater than those with joint parallel to σ_1. These shear fractures for specimens with joint normal to σ_1 can propagate easier for the

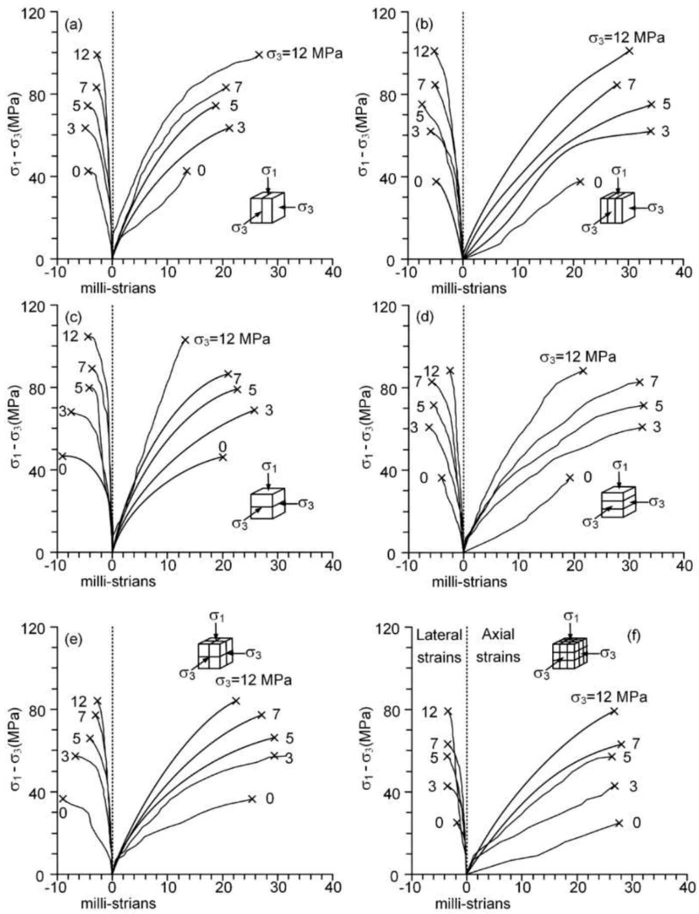


Figure 1 Examples of axial and lateral strains measured from various confining pressures for case I (a, b, c, d) and case III (e, f). The numbers of joint are 1 and 2 joints for each set

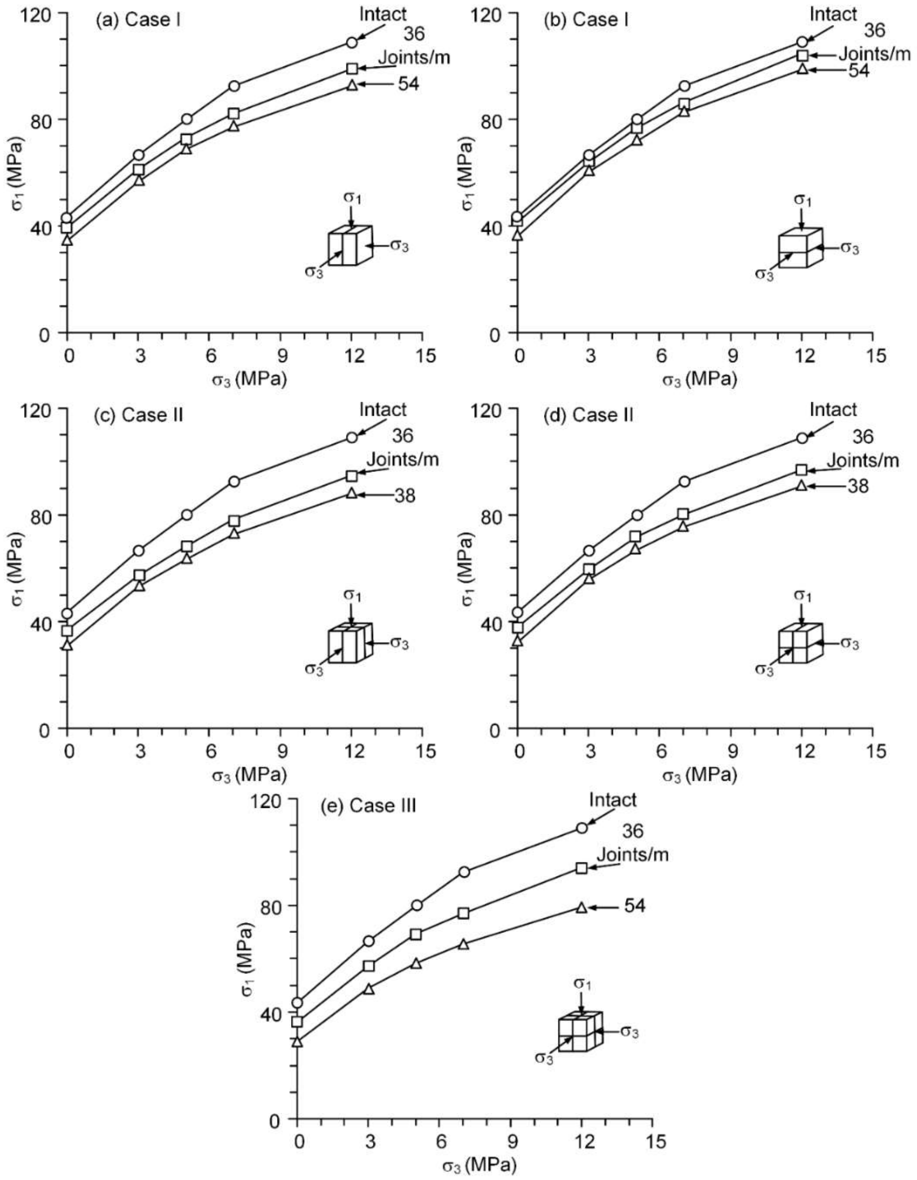


Figure 2 Major principal stress at failure as a function of confining pressure for case I, II and III

specimens with higher joint frequencies and under lower confining stresses, as compared to those with lower joint frequencies and higher confining stresses. Under the same joint frequency the strengths of Case III specimens are lower than those of Cases I and II because each sandstone block has an additional free face to dilate (i.e., there are two mutually perpendicular joint sets parallel to σ_1 direction)

5. Strength criteria

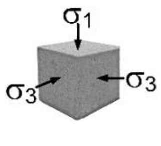
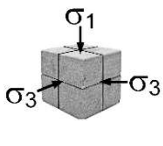
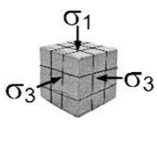
Four widely used strength criteria are compared against the test results obtained from the three-mutually perpendicular joint set specimens. These include the Hoek-Brown [1], Sheorey [6], Yudhbir [13] and Ramamurthy-Arora [9] criteria. Exhaustive reviews of these criteria have been given elsewhere [1, 14-15], and hence their detail derivation will not be presented here.

Statistical analyses are performed using the SPSS code [16] to fit the test results with the criteria above. The predictive capability of these criteria is determined and compared using the coefficient of correlation (R^2) as an indicator. The material constants and coefficients of correlation calculated for these criteria are summarized in Table 2. All criteria provide good correlation with the test data, with R^2 greater than 0.9. Figure 3 compares the test results with the curve fits in the terms of σ_1 as a function of σ_3 at failure. Note that these four strength criteria are not truly applicable for the one joint set specimens because their rock mass models are not isotropic. As a result, the one joint set test results are not fitted with these strength criteria.

6. Discussions and conclusions

Series of triaxial compression tests have been performed to determine strength of small-scale rock mass models with single and multiple joint sets and joint frequencies under large confinements. It is found that the compressive strengths decrease with increasing joint frequency. This agrees with the experimental observations by Ramamurthy and Arora [9] on jointed specimens of plaster of Paris. For one-joint set specimens tested here the strengths of rock specimens with joints normal to σ_1 axis are always greater than those with joints parallel to σ_1 axis. This agrees with experimental observations by Colak and Unlu [7], Saroglou and Tsiambaos [18] and Goshtasbi, et al. [19]. The decrease of rock mass strengths as the joint frequency increases tends to act equally throughout the range of confining stresses used here (3-12 MPa).

Table 2 Strength criteria and their constants calibrated from test data of Case III

Strength criteria	Parameters	Joint frequencies (joints/m)		
		Intact 	36 	54 
Hoek-Brown (1980) $\sigma_1 = \sigma_3 + (m\ \sigma_c\ \sigma_3 + s\sigma_c^2)^{1/2}$	m	14.10	10.10	8.20
	s	1.00	0.68	0.51
	R^2	0.977	0.978	0.979
Sheorey et al. (1989) $\sigma_1 = \sigma_{cm}(1 + \sigma_3/\sigma_{tm})^{bm}$	σ_{cm}	43.00	34.40	30.00
	σ_{tm}	2.60	2.30	2.10
	b_m	0.55	0.55	0.55
	R^2	0.996	0.997	0.996
Yudhbir et al. (1993) $\sigma_1/\sigma_c = A + B(\sigma_3/\sigma_c)^{\alpha}$	A	0.97	0.79	0.70
	B	4.15	3.43	3.07
	α	0.73	0.73	0.73
	R^2	0.988	0.982	0.978
Ramamurthy and Arora (1994) $(\sigma_1 - \sigma_3)/\sigma_3 = \beta(\sigma_{cm}/\sigma_3)^{\alpha}$	σ_{cm}	43.40	35.80	31.50
	β	1.10	1.05	1.00
	α	0.70	0.70	0.70
	R^2	0.988	0.979	0.976

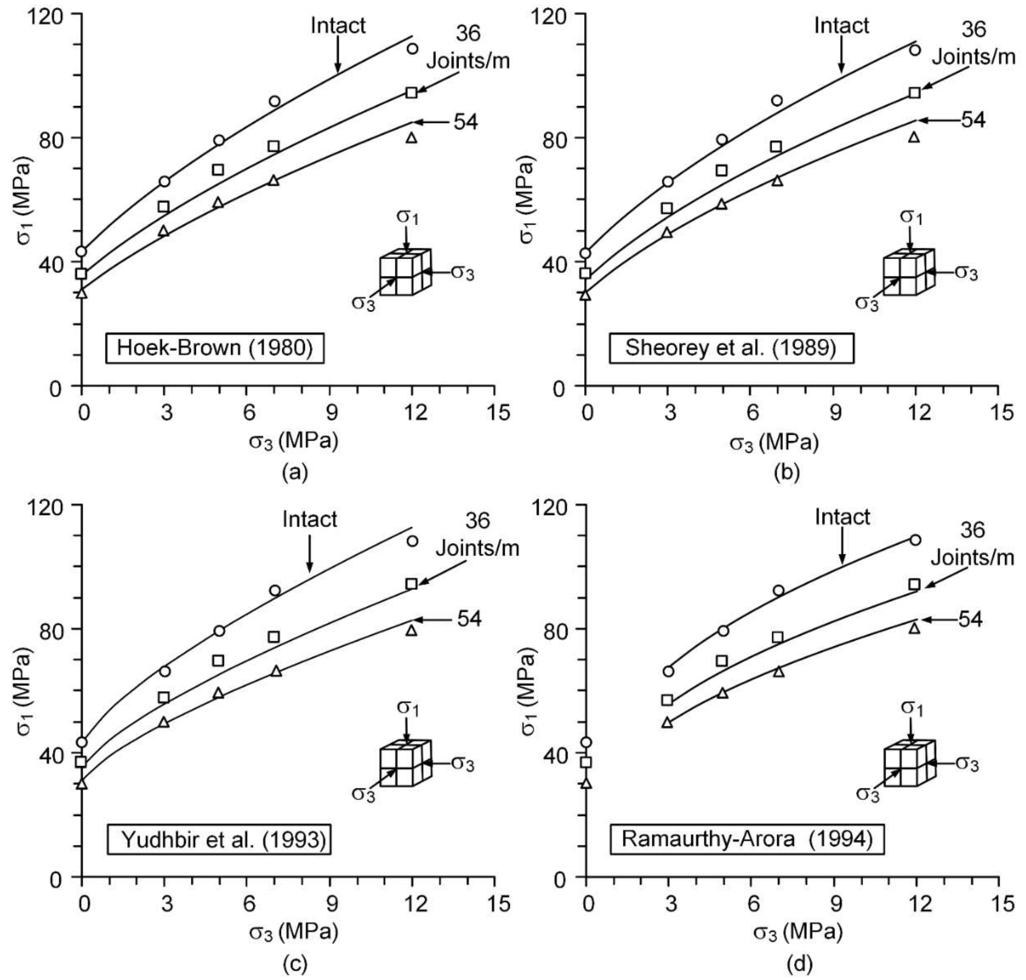


Figure 3 Test data (point) and curve fits of four strength criteria

All strength criteria used here can well predict the strengths of the rock mass specimens under the confining stresses up to 12 MPa. The Hoek-Brown criterion with only two constants (m and s) can describe the rock mass strengths as well as the three parameters criteria. The parameter s decreases rapidly with increasing joint frequency while parameters m tend to be insensitive to the joint frequency. The parameters m and s of the intact and two-joint set specimens are higher than those of the three-joint set specimens. This suggests that decreasing joint set numbers will increase the rock mass strength. Figure 4 compares Hoek-Brown parameters (m and s values) and Yudhbir parameters obtained here with those of Thaweeboon, et al. [20] and Thaweeboon and Fuenkajorn [21], who performed similar test on the sandstone model with smooth saw-cut surfaces. It is clear that under the same joint frequcies, the rough joints (tested here) show higher m and s values and higher A and B values than those of the smooth joints of Thaweeboon, et al. [20] and Thaweeboon and Fuenkajorn [21] experiments.

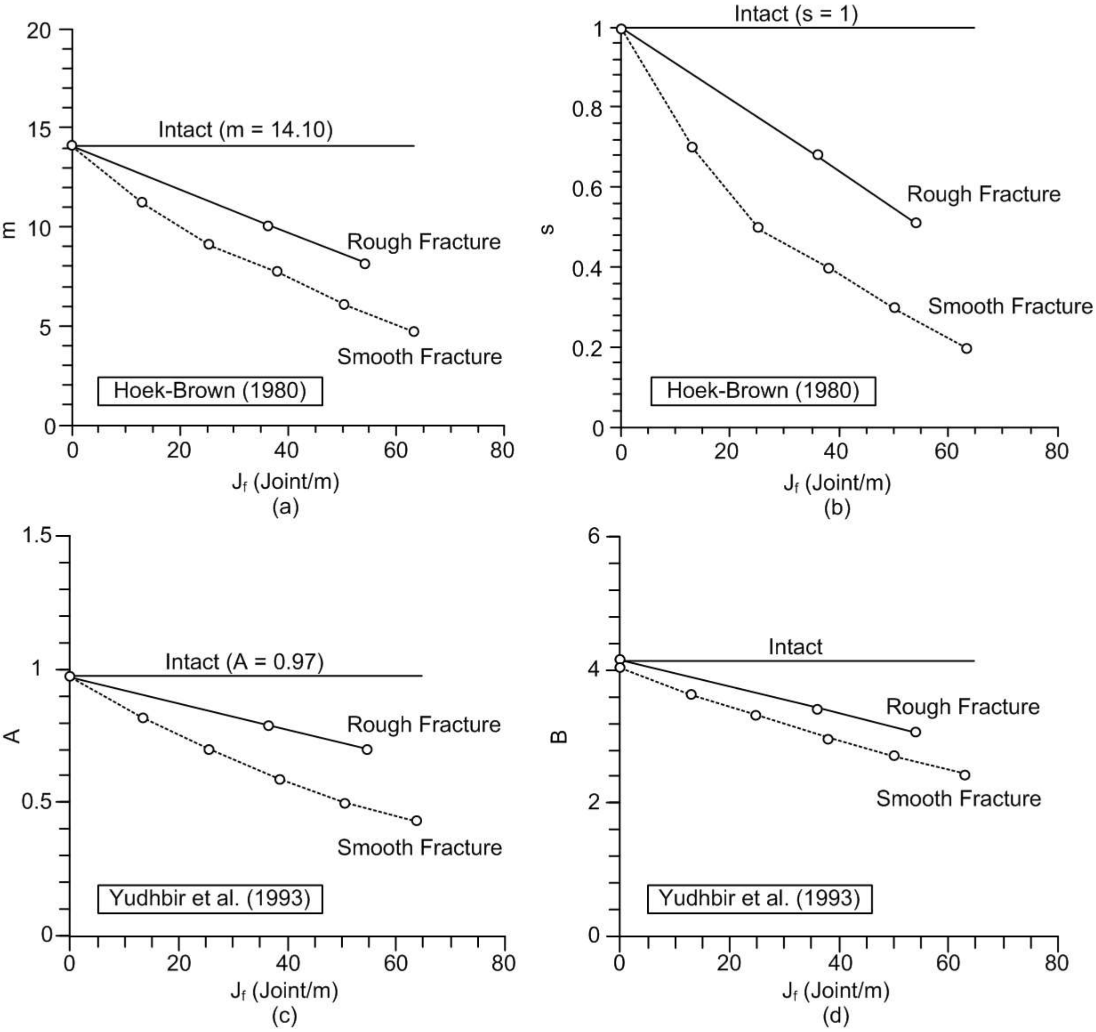


Figure 4 Hoek–Brown parameters m (a) and s (b) and Yudhbir et al parameter A (c) and B (d) comparing the model with tension-induced fractures (solid lines) with those of smooth fractures of Thaweeboon, et al. [20] and Thaweeboon and Fuenkajorn [21]

Acknowledgment

This study is funded by Suranaree University of Technology and by the Higher Education Promotion and National Research University of Thailand. Permission to publish this paper is gratefully acknowledged.

References

[1] Hoek, E. and Brown, E.T. Empirical strength criterion for rock masses. *J, Geotech. Eng.*, 1980, 160 (GT9), pp. 1013-1035.

[2] Saroglou, H. and Tsiambaos, G. A modified Hoek-Brown failure criterion for anisotropic intact rock, *Int. J. Rock Mech. Min. Sci.*, 2008, 45 (2), pp. 223-234.

[3] Singh, M. and Singh, B. Modified Mohr-Coulomb criterion for non-linear triaxial and polyaxial strength of jointed rocks, *Int. J. Rock Mech. Min. Sci.*, 2012, 51, pp. 43-52.

[4] Rafiai, H. New empirical polyaxial criterion for rock strength, *Int. J. Rock Mech. Min. Sci.*, 2011, 48 (6), pp. 922-931.

[5] Kulatilake, P.H.S., Park, J., and Malama, B. A new rock mass failure criterion for biaxial loading conditions, *Geotech. Geol. Eng.*, 2006, 24, pp. 871-888.

[6] Sheorey, P.R., Biswas, A.K., and Choubey, V.D. An empirical failure criterion for rocks and joint rock masses, *Eng. Geol.*, 1989, 26 (2), pp. 141-159.

[7] Cai, M., Kaiser, P.K., Uno, H., Tasaka, Y., and Minami, M. Estimation of rock mass deformation modulus and strength of jointed hard rock masses using the GSI system, *Int. J. Rock Mech. Min. Sci.*, 2004, 41 (1), pp. 3-19.

[8] Halakatevakis, N., and Sofianos, A.I. Strength of a blocky rock mass based on an extended plane of weakness theory, *Int. J. Rock Mech. Min. Sci.*, 2010, 47, pp. 568-582.

[9] Ramamurthy, T., and Arora, V.K. Strength predictions for jointed rocks in confined and unconfined states, *Int. J. Rock Mech. Min. Sci.*, 1994, 31 (1), pp.9-22.

[10] Yang, Z.Y., Chen, J.M., and Huang, T.H. Effect of joint sets on the strength and deformation of rock mass models, *Int. J. Rock Mech. Min. Sci.*, 1998, 35 (1), pp. 75-84.

[11] Boonsenerk, M. and Sonpiron, K. Correlation of tertialy rocks in northeast, Thailand, In: *Stratigraphy and Tectonic Evolution of Southeast Asia and the South Pacific*, 1997, pp. 656-661.

[12] Fuenkajorn, K., Sriapai, T., and Samsri, P. Effects of loading rate on strength and deformability of Maha Sarakham salt, *Eng. Geol.*, 2012, 135-136, pp. 10-23.

[13] Yudhbir, Y., Lemanza, W., and Prinzl, F. An empirical failure criterion for rock masses, In: *5th ISRM Congress*, Melbourne, Australia, 10-15 April 1983, pp. 1-8.

[14] Sheorey, P.R., *Empirical Rock Failure Criterion*, A.A.Balkema, Rotterdam, 1997.

[15] Hoek, E., Carranza-Torres, C., and Corkum, B. Hoek-Brown failure criterion-2002 edition, In: *5th North American Rock Mechanics Symposium*, Toronto, 2002, pp. 267-273.

[16] Colin, D.G., and Paul, R.K. *IBM SPSS statistics 19 made simple*, Psychology Press, New York, 2012.

[17] Colak, K., and Unlu, T. Effect of transverse anisotropy on the Hoek-Brown strength parameter 'mi' for intact rocks, *Int. J. Rock Mech. Min. Sci.*, 2004, 41 (6), pp. 1045-1052.

[18] Saroglou, H., and Tsiambaos, G. A modified Hoek-Brown failure criterion for anisotropic intact rock, *Int. J. Rock Mech. Min. Sci.*, 2008, 45 (2), pp. 223-234.

[19] Goshtasbi, K., Ahmadi, M., and Seyedi, J. Anisotropic strength behavior of slates in the Sirjan-Sanandaj zone, *J. S. Afr. Inst. Min. Metall.*, 2006, 106, pp. 71-76.

[20] Thaweeboom, S., Dasri, R., Sartkaew, S., and Fuenkajorn, K. Strength and deformabiliy of small-scale rock mass models under large confinements, *Bull. Eng. Geo. Environ.*, 2017, 76 (3), pp. 1129-1141.

[21] Thaweeboon, S and Fuenkajorn, K. Laboratory assessment of compressive strength of jointed rocks under confinements. *Research and Development Journal*, 2015, 26 (4), pp. 7-14.