Research and Development Journal
Volume 26 Issue 4 October-December 2015
Received 2 April 2015 Accepted 11 November 2015

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

LABORATORY ASSESSMENT OF COMPRESSIVE STRENGTH OF JOINTED ROCKS UNDER CONFINEMENTS

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ABSTRACT

Triaxial compressive strength tests have been performed to determine strength of rock mass model with multiple joint sets and joint frequencies under confining pressures up to 12 MPa. The predictive capability of some commonly used strength criteria is assessed. The cubical sandstone specimens with nominal dimensions of 60×60×60 mm^3 and 80×80×80 mm^3 are compressed to failure using a true triaxial load frame. The joints are simulated by saw-cut surfaces to obtain joint frequencies ranging from 13 to 67 joint per meter. Results indicate that the larger numbers of the joint frequencies and joint sets show the lower strengths. This is true for all confining pressures. The increase of the rock mass model strength with the confining pressure tends to be non-linear, particularly for the three joint sets specimens. For single joint set specimens, the strength of the specimens with joints normal to σ_1 axis always yields greater strength than those with joints parallel to σ_1 axis. Hoek-Brown, Sheorey, Yudhbir and Ramamurthy-Arora strength criteria give equally good correlation with the test results, showing R^2 greater than 0.9. The parameter s of the Hoek-Brown criterion is highly sensitive to the joint frequency while parameter m tends to be insensitive to the joint frequency.

KEYWORDS: Triaxial Compression, Rock Mass, Strength Criteria, Hoek-Brown Criterion

1. Introduction

The reliable strength estimation of jointed rock mass is necessary to develop safe and economical designs for slopes, foundations and underground excavations. Rock mass is an inhomogeneous and anisotropic material with complex behavior, which contains random planes of discontinuities. Several researchers have proposed rock mass strength criteria based on laboratory testing [1-5], case studies [6] and numerical analyses [7] to determine the effects of joint frequency, joint orientation and joint set number on rock mass strengths. It has been found that compressive strength of rock mass decreases with increasing joint frequency [1] and joint set number [8]. The effect of joint on strength depends on the orientation. The lower strengths are obtained when the joint planes make angles between 30°-40° with the major principal stress [1,2,9]. The existing strength criteria for rock mass have been verified by comparing with the actual in-situ conditions [10]. Even though several rock mass strength criteria have been proposed, verification of their accuracy and limitations under large confinements has rarely been attempted.

The objective of this study is to perform triaxial compressive strength tests on rock specimens with single and multiple joint sets under large confinements. The failure criteria proposed by Hoek and Brown [11], Sheorey et al. [6], Yudhbir et al. [12] and Ramamurthy and Arora [1] are used to compare with the test results to evaluate their predictability. The tests are performed on cubical shaped specimens with simulated joints under various frequencies and joint set numbers. Via statistical analyses the most suitable rock mass strength criteria are identified.

2. Sample Preparation

The rock specimens used in this study are Phra Wihan sandstone. They are classified as fine-grained quartz sandstones with highly uniform texture and density [13]. Cubic specimens with nominal dimensions of 60×60×60 mm^3 80×80×80 mm^3 are prepared. Artificial joints are made of saw-cut surfaces. Up to 80 specimens are prepared with two different joint conditions: single joint set and three mutually perpendicular joint sets with joints frequencies from 13 to 67 joints per set. The single joint set specimens are subjected to the test with joints parallel and normal to the maximum principal axis. The three test conditions with joint arrangements with responded to the principal direction are shown in Table1. These cases are briefly summarized below.

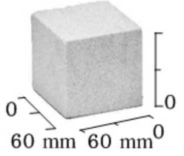
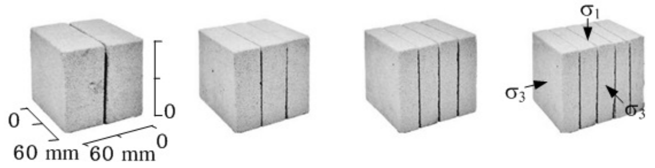
Case 1: One joint set specimens with four joint frequencies are prepared to study the effect of joint frequency when the joints are parallel to the major principal axis. There are 1, 2, 3 and 4 joints for each set (equivalent to 17 to 67 joints per meter).

Case 2: Similar to Case 1, separate set of one joint set specimens are prepared to assess the effect of joint frequency when the joints are perpendicular to the major principal axis.

Case 3: Specimens with three mutually perpendicular joint sets are prepared to study the effects of joint set numbers and joint frequencies. There are 1, 2, 3, 4 and 5 joints for each set (equivalent to 13 to 63 joints per meter).

All cases are tested under confining pressures ranging from 1 to 12 MPa. The triaxial compressive strengths of intact block specimens of sandstone are also determined.

Table 1 Specimens prepared for triaxial compression test with one and three joint sets, joint frequencies equivalent from13 to 67 joints/m

Cases	Specimens
Intact	
1 One joint set parallel to the major principal axis	
2 One joint set normal to the major principal axis	
3 Three mutually perpendicular joint sets	

3. Test Procedure

A true triaxial load frame [14] is used to apply axial stress (σ_1) and constant confining pressures (σ_3) to the intact and jointed rock mass model. Before testing these specimens are wrapped with plastic film. Neoprene sheets are placed in all interfaces between the loading platens and specimen surfaces to minimize the friction. The axial stress is applied along the axial (vertical) direction of the specimen. The constant confining pressures (σ_2=σ_3) range from 0, 1, 3, 5, 7 to 12 MPa. After installing the jointed rock specimen into the load frame, six hydraulic cells apply loads to obtain the pre-defined magnitude of the uniform confining and axial stresses on the specimen. The test is started by increasing the axial stress (major principal stress) at a constant rate of 0.1 MPa/s using the hydraulic pump. The specimen deformations are monitored by displacement transducers along the three loading directions and are used to calculate the principal strains during loading. The readings are recorded until failure. Photograph is taken of the post-test specimens and the modes of failure are identified. All tests are conducted under ambient temperature.

4. Test Results

Figure 1 shows the stress-strain curves of three mutually perpendicular joint sets specimens. The stress-strain curves show linear behavior, under all confining pressures and joint frequencies. The effect of the joint frequency on the rock model is reflected as the reduction of stresses and increment of strains at failure. Post-test specimens show two types of failure mode: extensile splitting mode and crushing mode.

(1) Extensile splitting mode involves tensile fractures which are parallel to the major principal stress direction. The main mechanism of failure is the extensile failure through the intact pieces and pre-existing joints of the specimen.

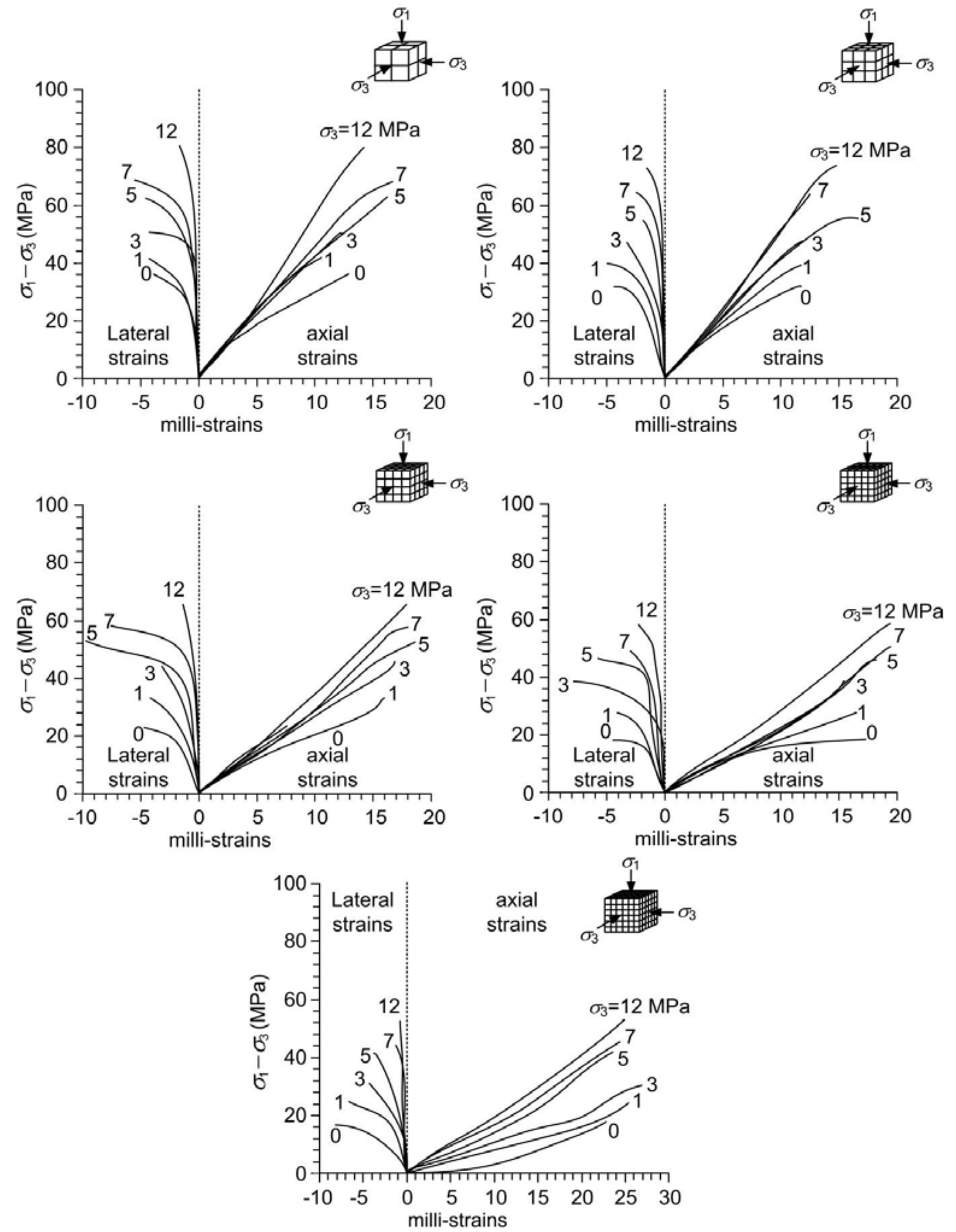


Figure 1 Examples of axial and lateral strains measured from various confining pressures for specimens with three mutually perpendicular joint sets. The numbers of joints are 1, 2, 3, 4 and 5 joints for each set

It occurs in specimens with single joint sets (Cases 1 and 2). The specimens under high confining pressures show larger number of minute cracks.

(2) Crushing mode: This mode of failure shows combination of minute cracks, tensile fractures, crushed pieces and rock powder. There was always a combination of more than one mechanism. This failure mode is found in specimens with multiple joint sets (Case 3). The crushing mode is found in specimens under high joint frequency and confining pressures.

Figure 2 shows the major principal stresses at failure as a function of confining pressure. The larger numbers of the joint frequencies show the lower strength of rock mass model. The increase of the rock strength with the confining pressure tends to be non-linear, particularly for the three joint sets specimens. For single joint set specimens, the strength of rock mass models with joint normal to σ_1 always yields greater strength than those with joint parallel to σ_1 axis. The drop of strength due to joint frequency increase for the three joint set specimens tends to be more rapid than those of the single joint set specimens.

5. Strength Criteria

Four strength criteria that are commonly used to determine rock mass strength are compared against the triaxial strength data obtained from three mutually perpendicular joint sets specimens. These include the Hoek-Brown [11], Sheorey [6], Yudhbir [12] and Ramamurthy-Arora criteria [1]. Exhaustive reviews of these criteria have been given elsewhere [10,15], and hence will not be repeated here. They are all formulated in the terms of σ_1 and σ_3. The predictive capability of these strength criteria is determined and compared using the coefficient of correlation (R^2) as an indicator. The higher R^2 value indicates the better predictability of the criterion. Governing equations of these strength criteria used in the regression and constants calculated for strength criteria are shown in Table 2. All criteria can provide good correlation with the test data, with R^2 greater than 0.9. Figure 3 compares the test data with curve fits of the strength criteria in the terms of σ_1 as a function of σ_3 at failure. Figure 4 shows the decrease of parameters *m* and *s* of Hoek-Brown criterion as the joint frequency increases. The parameters *m* and *s* of one joint set specimen are greater than those of the three joint set specimens. The uniaxial compressive strengths of rock mass models predicted by Shoerey and Ramamurthy-Arora strength criteria are shown in Figure 5. The results indicate that the uniaxial compressive strength decreases with increasing joint frequency.

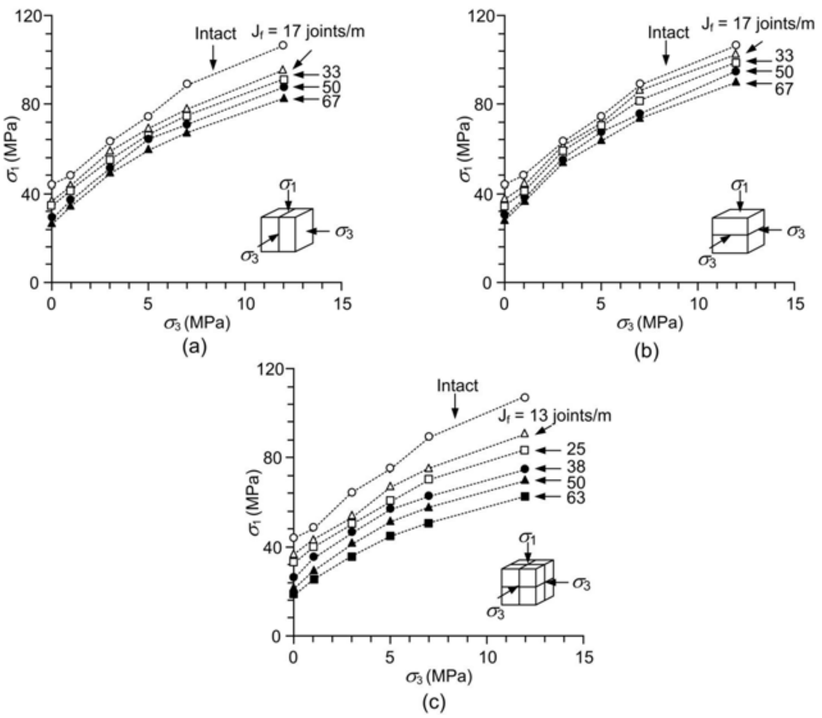
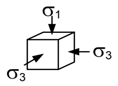
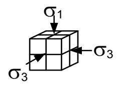
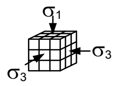
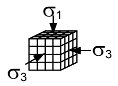
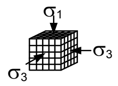
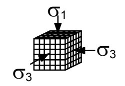


Figure 2 Major principal stresses at failure as a function of confining pressure for case 1 (a), 2 (b) and 3 (c)

Table 2 Strength criteria and their constants calibrated from the test data

Specimens	Parameters						
Hoek–Brown (1980) $\sigma_1 = \sigma_3 + (m\sigma_c\sigma_3 + s\sigma_c^2)^a$	m	14.10	11.30	9.22	7.89	6.03	4.83
	s	1.0	0.7	0.5	0.4	0.3	0.2
	R^2	0.992	0.969	0.984	0.971	0.979	0.986
Sheorey et al. (1989) $\sigma_1 = \sigma_{cm}(1+\sigma_3/\sigma_{tm})^{bm}$	σ_{cm}	41.8	35.8	31.0	26.5	22.9	19.6
	σ_{tm}	2.6	2.1	1.8	1.4	1.2	1.0
	b_m	0.54	0.51	0.48	0.47	0.46	0.45
	R^2	0.991	0.986	0.988	0.991	0.992	0.997
Yudhbir et al. (1983) $\sigma_1/\sigma_c = A + B(\sigma_3/\sigma_c)^\alpha$	A	0.97	0.82	0.70	0.59	0.50	0.43
	B	4.04	3.64	3.31	2.98	2.71	2.44
	α	0.79	0.76	0.72	0.70	0.68	0.65
	R^2	0.986	0.984	0.986	0.987	0.989	0.993
Ramamurthy–Arora (1994) $(\sigma_1 - \sigma_3)/\sigma_3 = B(\sigma_{cm}/\sigma_3)^\alpha$	σ_{cm}	43.3	37.4	32.3	27.5	24.0	20.7
	B	3.19	3.15	3.13	3.08	3.00	2.90
	α	0.69	0.69	0.69	0.69	0.69	0.69
	R^2	0.989	0.973	0.979	0.980	0.997	0.995

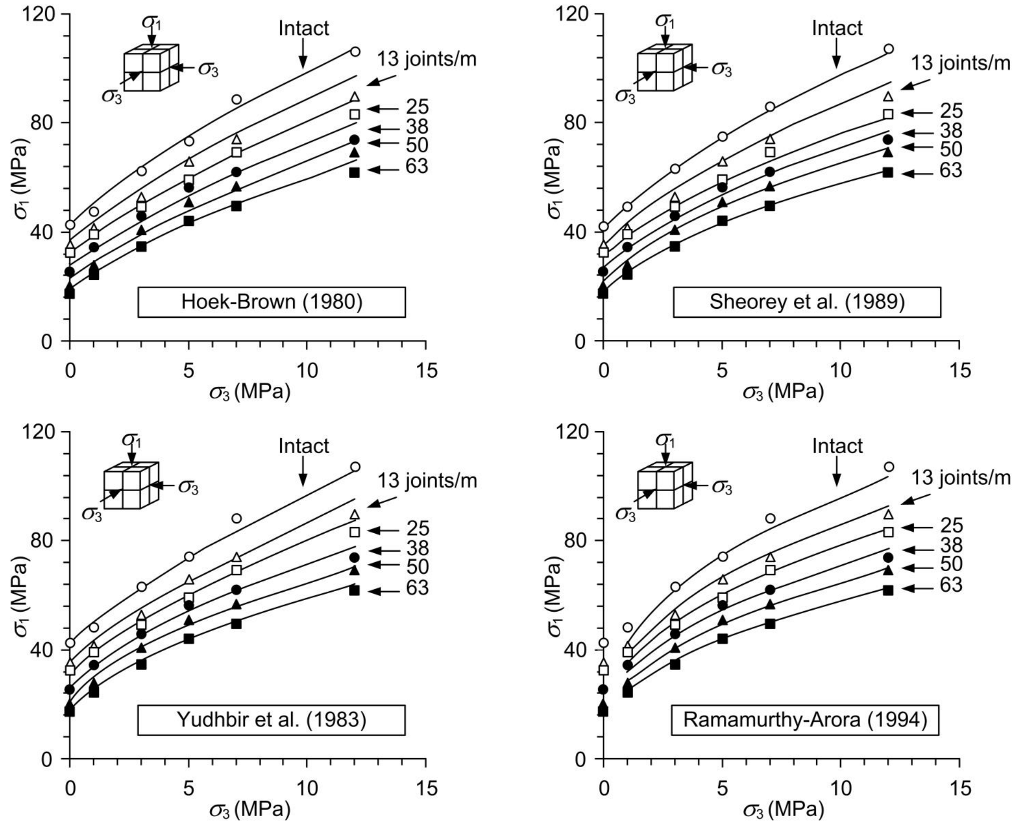


Figure 3 Test data (points) and curve fits of four strength criteria

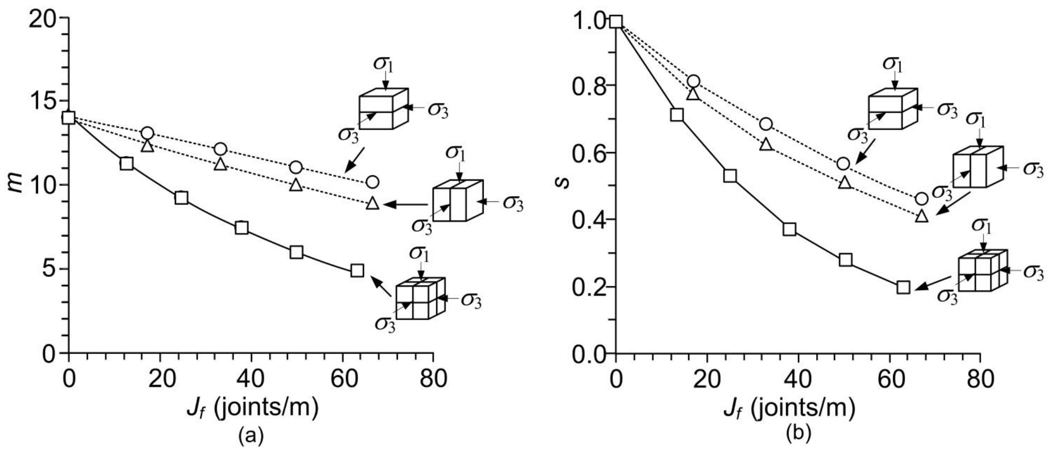


Figure 4 Hoek-Brown parameters m and s as a function of joint frequency

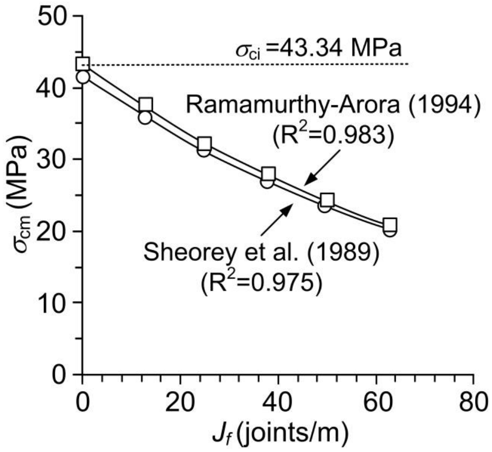


Figure 5 Uniaxial compressive strengths of rock mass model (σ_{cm}) with three joint sets, σ_{cm} calculated from Sheorey and Ramamurthy-Arora criteria as a function of joint frequency

6. Discussions and Conclusions

The triaxial compressive strength decreases with increasing joint frequency. These generally agree with the experimental observations by Ramamurthy and Arora [1] on jointed specimens of plaster of Paris. For single joint set specimens here the strength of rock mass models with joint normal to σ_1 always yields greater strength than those with joint parallel to σ_1 axis. These agree with experimental observations by Colak and Unlu [2], Saroglou and Tsiambaos [3], Goshtasbi et al. [9] and Nasseri et al. [16]. The drop of strengths for the three joint set specimens tends to be more rapid than those of the single joint set specimens. One important finding from the study is that the decrease of rock mass strength as the joint frequency increases tends to be equally act throughout the ranges of confining pressures used here (1-12 MPa).

All strength criteria used here give a good estimation of the specimen compressive strengths. The Hoek-Brown criterion can effectively describe the effect of joint frequency on the strength results. The parameter *s* decreases rapidly with increasing joint frequency while parameters *m* tend to be insensitive with the joint frequency, ranging between 4.83 and 14.10. The parameters *m* and *s* of the one joint set specimens are higher than those of the three joint set specimens. This suggests that decreasing of joint set numbers will increase the rock mass strength. The uniaxial compressive strength of rock mass model

(σ_{cm}) decreases with increasing joint frequency, which agrees reasonably well with the σ_{cm} calculated from Sheorey and Ramamurthy-Arora criteria. It is recognized that the joints studied here are simulated from smooth saw-cut surfaces. The strengths of the rock mass model for all cases obtained here, therefore, represent the lower bound of the strengths of actual rock mass where most fractures are rough. In addition the applied major principal stresses performed here are always normal or parallel to the joint planes. It is expected that the rock mass model strengths would be lower if the applied stress makes oblique angles with the joint planes, as evidenced by the test results given by Ramamurthy and Arora [1], Colak and Unlu [2] and Goshtasbi et al. [9].

Acknowledgements

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.

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