Introduction to Suggested Methods for Failure Criteria

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Accurate assessment of rock strength is necessary for the rational design of underground structures, for the evaluation of wellbore stability, for the determination of in situ stresses (e.g., hydraulic fracturing, borehole breakouts, drilling-induced cracks), and as part of geophysical research such as faulting and earthquake mechanics. In engineering fields, the stress condition by which ultimate strength is reached is referred to as the “failure criterion”. Failure criteria are often expressed in terms of the major principal compressive stress σ_1 that rocks can sustain for given values of the other two principal stresses, σ_2 and σ_3 . In its most general form, this can be expressed as $\sigma_1 = f_1(\sigma_2, \sigma_3)$ or $f_2(\sigma_1, \sigma_2, \sigma_3) = 0$ (Scholz 1990) where f_1 or f_2 are functions that vary with the selected criterion and can be determined theoretically, empirically or from laboratory tests (in some failure criteria, the effect of σ_2 is not considered and in that case the functions f_1 or f_2 are independent of σ_2). The convention used is positive for compression, and it is implied that failure is expressed in terms of effective stresses; correspondingly, expressions such as $f_2(\sigma_1, \sigma_2, \sigma_3) = 0$ and $f_2(\sigma'_1, \sigma'_2, \sigma'_3) = 0$ are used interchangeably.

Laboratory experiments should be aimed at characterizing deformation and strength behavior under stress conditions simulating those encountered in situ. However, most laboratory tests are conducted on cylindrical

specimens subjected to uniform confining pressure. Such conventional triaxial tests simulate only a special field condition where intermediate and minor principal stresses, σ_2 and σ_3 , are equal. Triaxial tests have been widely used for the study of mechanical characteristics of rocks because of equipment simplicity and convenient specimen preparation and testing procedures. The underlying assumption is that the intermediate principal stress has negligible effect on rock strength.

A growing number of in situ stress measurements at shallow to intermediate depths has shown that rock stresses are almost always anisotropic, i.e., $\sigma_1 \neq \sigma_2 \neq \sigma_3$ (Haimson 1978; McGarr and Gay 1978; Brace and Kohlstedt 1980). Additional evidence based on borehole breakout dimensions in crystalline rocks (Vernik and Zoback 1992) and on calculations for the critical mud weight necessary to maintain wellbore stability (Ewy 1998) unequivocally show that rock failure criteria should account for the effect on the strength of the intermediate principal stress.

The first extensive true triaxial compressive tests in rocks, in which $\sigma_1 \neq \sigma_2 \neq \sigma_3$, were conducted by Mogi (1971). He subjected Dunham dolomite and other rocks to different intermediate principal compressive stresses for the same minor principal stress, and then raised the major principal stress to failure. Mogi demonstrated experimentally that for the rocks tested, strength was a function of σ_2 in a manner similar to that predicted theoretically by Wiebols and Cook (1968). Although Wiebols and Cook and Mogi demonstrated independently that the intermediate principal stress has a major effect on rock strength, their work has been largely ignored for over 20 years. Recently, the interest in the true triaxial strength of rocks has been rekindled in part by the need to employ appropriate failure criteria for the design of structures in rock under complex

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loading. Haimson and Chang (2000) and Chang and Haimson (2000) designed and built a true triaxial testing apparatus and conducted an exhaustive series of tests on Westerly granite (Rhode Island, USA) and on KTB amphibolite (Germany). Their results largely confirmed those obtained by Mogi (1971). Additional true triaxial testing also supported previous findings regarding the effect of the intermediate principal stress on the compressive strength of Long Valley, California, hornfels and metapelite, a Korean rhyolite, and several Taiwanese sandstones and siltstones (Chang and Haimson 2005, 2007; Oku et al. 2007; Haimson and Rudnicki 2010).

Following a keynote lecture by Professor Haimson on “A three-dimensional strength criterion based on true triaxial testing of rocks” at the SinoRock 2009 Symposium in Hong Kong, Professors Hudson and Ulusay, President of ISRM and President of the ISRM Commission on Testing Methods, respectively, approached him regarding the need to standardize the different failure criteria used in practice and make the ISRM members aware of new developments. As a result, a new working group on “Suggested Methods for Failure Criteria” was established, co-chaired by Bezalel Haimson and Antonio Bobet. The co-chairs invited seven internationally known rock mechanics experts to join the working group. They all accepted the challenge. Their names are listed in the following table.

The working group agreed to prepare suggested methods for the most known failure criteria applied to rock and to make recommendations about when each criterion may be applied, highlighting wherever possible the extent to which the effect of the intermediate principal stress is accounted for. The scope of work is restricted to isotropic and homogeneous rock without discontinuities. Failure criteria of rock mass were left for later consideration. Suggested methods were completed for the following failure criteria:

Criterion	Working group members
Mohr–Coulomb	J. Labuz and A. Zang
Hoek–Brown	E. Eberhardt
3D Hoek–Brown	S. Priest
Drucker–Prager	L. Alejano and A. Bobet
Lade and modified Lade	S. Fontoura
Based on true triaxial testing	Ch. Chang and B. Haimson

In preparing each suggested method, the Jaeger and Cook (1979) notation was followed to the extent possible.

The publication of these suggested methods is an attempt to standardize the use of failure criteria in rock mechanics practice enabling the practitioner to employ the most appropriate criterion for the project at hand.

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