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Research paper

A modified failure criterion for transversely isotropic rocks

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ABSTRACT

A modified failure criterion is proposed to determine the strength of transversely isotropic rocks. Mechanical properties of some metamorphic and sedimentary rocks including gneiss, slate, marble, schist, shale, sandstone and limestone, which show transversely isotropic behavior, were taken into consideration. Afterward, introduced triaxial rock strength criterion was modified for transversely isotropic rocks. Through modification process an index was obtained that can be considered as a strength reduction parameter due to rock strength anisotropy. Comparison of the parameter with previous anisotropy indexes in literature showed reasonable results for the studied rock samples. The modified criterion was compared to modified Hoek-Brown and Ramamurthy criteria for different transversely isotropic rocks. It can be concluded that the modified failure criterion proposed in this study can be used for predicting the strength of transversely isotropic rocks.

1. Introduction

The existing experimental evidence (Donath, 1964; Hoek, 1964; McLamore and Gray, 1967; Horino and Ellickson, 1970; Kwasniewski, 1993; Ramamurthy, 1993; Nasseri et al., 2003; Colak and Unlu, 2004; Karakul et al., 2010) indicates that most of sedimentary and metamorphic rocks, such as shale, slate, gneiss, schist and marble display a strong anisotropy of strength. Rocks flow and recrystallize under new tectonic stresses and form weak foliation planes. These planes of weakness (i.e. schistosity and foliation) affect the strength and deformational behaviors of rocks with orientation of applied stresses. Hence, these types of rocks usually exhibit some preferred orientation of fabric or possess distinct bedding planes, which result in transversely isotropic behavior on the macro-scale. Lo et al. (1986) stated that transversely isotropic behaviors of rocks such as elasticity, electrical conductivity and permeability are related to the both matrix and pore space distributions.

Although many attempts have been made in the past to describe the strength anisotropy of transversely isotropic rocks, no general methodology has emerged yet. The first attempt seems to be Jaeger's single weakness plane theory (Jaeger, 1960), where two independent failure modes, i.e., failure along the discontinuity and failure through intact material, were assumed to exist. The idealized distribution of triaxial strength predicted by Jaeger's theory is similar to that of planes in Fig. 1a. Throughout the paper, inclination angle β is the angle between direction of major principal stress and weakness plane. For those rocks displaying a discrete fabric (i.e., multiple weakness planes), the experimental results have shown that the strength varies continuously with β (Fig. 1b).

In order to reproduce the gradual variation of the strength, Jaeger (1960) postulated that the cohesion of rock material, within the plane inclined with respect to the weakness plane, was not constant but varied depending on the angle of inclination, whereas the friction angle was considered as constant. More recently, Hoek and Brown (1980) assumed that the strength parameters m and s in their well-known failure criterion are not constant but varied depending on the direction of weakness plane. However, although

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Abbreviations

β	Weakness plane orientation in relation to major loading direction
φ	Friction angle of rock
C	Cohesive strength of rock
R_c	Degree of strength anisotropy
E	Young's modulus
$E_{\max}$, $E_{\min}$	Maximum and minimum values of Young's modulus
UCS	Uniaxial Compressive Strength
$\sigma_{c\beta}$, σ_{cj}	UCS with anisotropy direction of β
A, D	Rock constants
$\beta_{\min}$	Minimum angle of anisotropy
$\sigma_{c(90)}$	UCS perpendicular to the weakness plane
$\sigma_{c(\min)}$	Minimum value of UCS commonly in a weakness plane
K_β	Strength anisotropy parameter for different orientation of weakness plane, β
m_i	Rock constant
σ_1, σ_3	Maximum and minimum principal stresses
A, B	Rock constants
r	Strength reduction factor
σ_{ci}	UCS of intact rock
α	Strength reduction parameter in the proposed criterion
$\sigma_{c\beta-pr}$	UCS predicted by modified criterion
$\sigma_{c\beta-lab}$	UCS from laboratory testing
α_j, B_j	Parameters in the Ramamurthy criterion as functions of anisotropy orientation j (in relation to major stress direction similar to β)
RMSE	Root mean square error
σ_i^t, σ_i^p	Tested and predicted values of σ_1 for the ith data

the values of m and s are selected based on the orientation of weakness planes, it should be noted that the formulation remains isotropic, so that it is doubtful whether the orientation of failure plane predicted by this approach is realistic. Another drawback of this approach, as well as the earlier one by Jaeger (1960), is the requirement that the dip direction of weakness planes should coincide with the direction of minor principal stress. Saroglou and Tsiambaos (2008) modified the Hoek-Brown criterion by testing some metamorphic rocks from Greece, and demonstrated that m and s are independent of anisotropy direction. In general, however, Jaeger (1960) and Hoek and Brown's works are of importance in that they showed that the failure criterion can be modified to take into account the anisotropy in strength properties. While the applicability of Hoek and Brown (H–B) approach is restricted, Nova (1980) extended the discussion on anisotropy to the true triaxial stress conditions. Amadei and Savage (1989) also analyzed the transversely isotropic strength of jointed rock having a single set of weakness planes in three-dimensional (3D) conditions. In that work, the intact rock strength is described by the H–B criterion, whereas the joint strength is modeled by the Coulomb criterion with zero cohesion. Although the variation of material properties with orientation was not directly considered, the authors showed that the strength of the jointed rock depends on the direction of weakness planes and the intermediate principal stress.

A large number of research papers were documented on strength anisotropy of rocks. For instance, Nasseri et al. (1996 and 1997) investigated the anisotropy on gneiss and schist. Ramamurthy et al. (1988, 1993) assessed the anisotropy of phyllites. Al-Harthi (1998) concentrated on the behavior of sandstones and Attewell and Sandford (1974) worked on shale and slate. Pomeroy et al. (1971) evaluated the strength anisotropy of coal. Allirote and Boehler (1970) focused on strength anisotropy of diatomite while Elmo and Stead (2010) assessed rock pillar anisotropy of limestone and Wardle and Gerrard (1972) studied on the strength

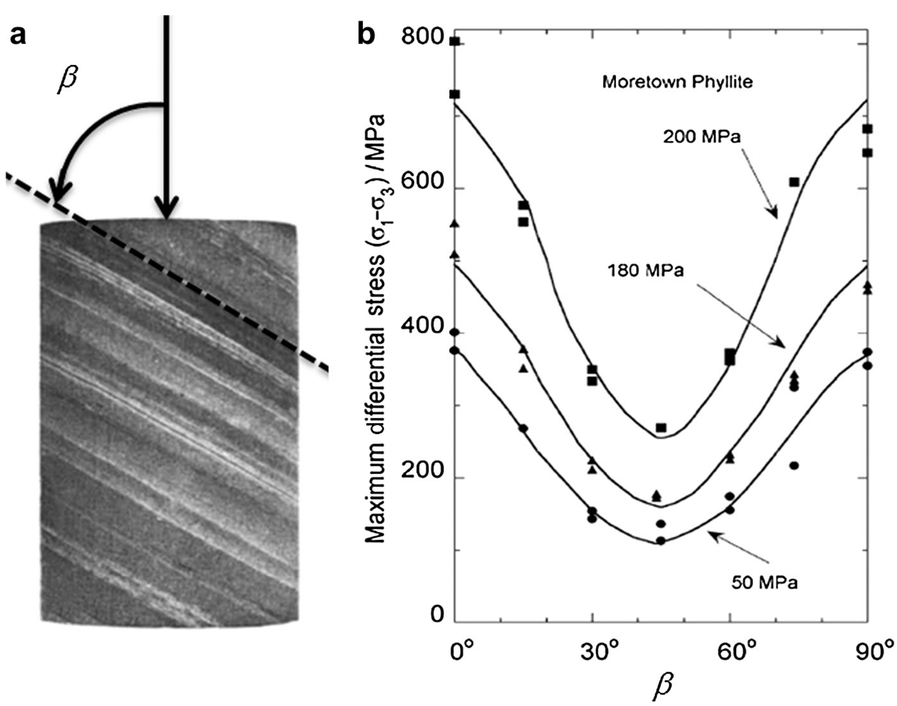

Figure 1. (a) Angle of weakness plane measured from major loading direction, (b) variation of differential stress at failure condition of triaxial compression test with respect to plane of weakness (after McLamore and Gray, 1967).