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Modified criteria for sliding and non-sliding failure of anisotropic jointed rocks

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ABSTRACT

Modified failure criteria are proposed to estimate sliding and non-sliding strength of anisotropic rocks containing single or a set of parallel well-defined discontinuities. A newly modified form of Mohr–Coulomb relation is incorporated into two well-founded failure criteria namely Jaeger's criterion and Tien–Kuo criterion. Some input parameters of the proposed criteria may be indirectly determined using empirical correlations extracted from the literature. Consequently, the strength of anisotropic jointed rocks can be evaluated more easily and accurately compared with current failure criteria. Another advantage of the proposed criteria is that their use does not require any curve fitting procedure since the parameters can be estimated through the given relations. The concept of critical confining pressure is also assessed in more detail and an equation is proposed to predict the confining pressure above which discontinuity has no effect on the strength. In addition, laboratory tests are carried out to evaluate the theoretical results and it is shown that the proposed criteria are of acceptable accuracy and applicability.

1. Introduction

Reliable estimation of the strength and deformation characteristics of rock masses plays a crucial role in safe design of civil structures such as dams, bridge piers and tunnels. The term "rock mass" covers a broad spectrum of rock material from slightly fractured to heavily jointed masses. Due to several factors including existence of well-defined discontinuities and preferred fabric orientation, rock masses present anisotropic behavior and their mechanical properties become directional. In one particular case, presence of a through-going joint or a set of parallel joints results in transversely isotropic behavior which is graphically shown in the form of strength versus orientation angle curve (Fig. 1). Failure of such rocks is observable in two separate modes; first sliding mode happening when orientation angle ranges from say 20° to 50°, and second non-sliding mode where the orientation angle is either too sharp (around 0°–15°) or too flat (around 70°–90°) for sliding and thus failure of rock matrix takes place. Under higher confining pressures the sliding mode band narrows and eventually disappears. This implies that there is a critical confining pressure above which the jointed rock behaves as an isotopic medium regardless of joint orientation.

The strength of transversely isotropic rocks may be estimated theoretically or measured experimentally. Laboratory and field tests on jointed rocks are often laborious and expensive owing to the apparatuses required, sampling difficulties etc. On the other hand, current theoretical methods fail to predict the strength accurately at all joint configurations and confining pressures.

Jaeger [1] was probably the first who studied the problem of strength variations in transversely isotropic rocks. In the early works of Jaeger, however, the nonlinearity introduced into the strength due to variation of confining pressure was not taken into account. A modification to Jaeger's criterion was proposed by Duveau and Shao [2]. Tien and Kuo [3] adopted Jaeger's criterion for sliding mode and developed an analytical failure criterion for non-sliding mode by incorporating the theory of elasticity. In spite of its promising results, the method proposed by Tien and Kuo did not consider nonlinear effect of confining pressure on the strength anisotropy.

During past decades, many investigators have conducted laboratory tests in order to experimentally evaluate the strength of transversely isotropic rocks [4–10]. Einstein and Hirschfeld [11] and Yaji [12] conducted triaxial tests to study the effect of confining pressure as well as joint configuration on the strength and deformation properties of mainly artificial jointed rock specimens. Arora [13] carried out a comprehensive study on both intact and jointed specimens and proposed a parameter called joint factor (J_f) to represent the influence of joints on the strength reduction of jointed rock with respect to the intact rock under similar conditions. Ramamurthy and Arora [14] developed an empirical failure criterion for transversely isotropic rocks using the concept of joint factor. Although this failure criterion provides

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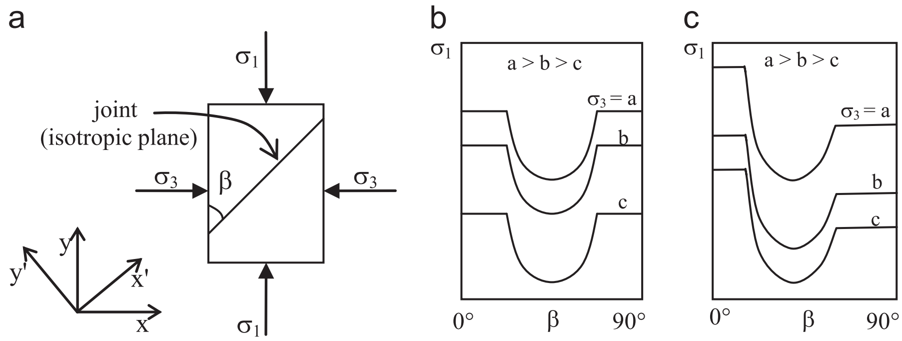

Fig. 1. (a) Anisotropic jointed specimen under conventional triaxial stresses. (b) Original Jaeger's criterion. (c) Modified Jaeger's criterion.

fairly accurate predictions, it requires considerable range of tests and curve fitting procedure and thus may be considered inadequate [3].

Hoek and Brown [15] categorized rocks into different classes such as purely intact, anisotropic with single plane of weakness and heavily jointed masses and presented their failure criterion for each class of rock. They discussed that any of these groups might be encountered in practical problems depending on the dimensions of the structure being considered. In particular, Hoek and Brown introduced a failure criterion for transversely isotropic rock containing single plane of weakness or a set of parallel joints. Recently, some researchers have proposed modifications to the original form of this criterion in order to make it directly applicable to transversely isotropic rocks [16,17]. However, these attempts only focused on inherently anisotropic rocks and did not cover the problem of induced anisotropy (as is the case for jointed rocks).

The effect of confining pressure on the strength of jointed rocks has been assessed by some researchers. Singh and Singh [18] proposed a modified Mohr–Coulomb failure criterion for anisotropic jointed rocks. They verified their proposed criterion by applying it to experimental data resulting from triaxial and polyaxial test results. They performed statistical back-analysis to obtain the value of critical confining pressure and concluded that this value is almost equal to uniaxial compressive strength of intact material. Singh and Singh, however, stated that their modified criterion has limitations particularly in the case of sliding failure mode. Ghazvinian and Hadei [19] investigated the behavior of artificially made anisotropic specimens with regard to the confining pressure and the joint inclinations. They conducted triaxial tests at different confining pressures and introduced anisotropy effect (A_e), a dimensionless parameter varying from zero to one. As A_e increases, the gap between the strength of the anisotropic and intact rock becomes wider. Conversely, as it decreases the strength of jointed specimen approaches that of intact rock; which implies that the effect of discontinuities is insignificant since the confining pressure has approached its critical value.

In the current study, a new failure criterion is proposed for transversely isotropic rocks. We first adopt Jaeger's criterion for sliding mode and Tien–Kuo criterion for non-sliding mode. Subsequently, by incorporating the modified Mohr–Coulomb criterion into these two criteria a new criterion is developed which is able to take account of confining pressure effects on the strength of jointed rock. Practical guidelines are then provided according to available literature to facilitate the use of proposed criterion. Triaxial tests are also carried out on anisotropic jointed specimens under different confining pressures to verify the efficiency and applicability of proposed method in predicting the strength of these types of rocks. In addition, a discussion is presented about the critical confining pressure in transversely isotropic rocks with through-going joints.

2. Jaeger's criterion

Jaeger [1] calculated the triaxial strength of anisotropic jointed rocks theoretically. He suggested the shear strength of joint surface to be expressed by the Mohr–Coulomb criterion as

$$\tau_j = c_j + \sigma_n \tan \phi_j \tag{1}$$

where the subscript j denotes the joint. Using principles of Mohr's stress transformation and calculating the shear and normal stresses acting on the joint surface (Fig. 1a) in terms of principal stresses (σ_1 and σ_3) and the joint orientation (β), Eq. (1) is reformulated as follows:

$$S_{1\ sliding} = (\sigma_1 - \sigma_3) = \frac{2(c_j + \sigma_3 \tan \phi_j)}{(1 - \tan \phi_j \tan \beta)\sin 2\beta} \tag{2}$$

For joint orientations close to 0°, Eq. (2) results in very high values of σ_1, and hence sliding on the joint surface is practically impossible. On the other hand, when orientation angle approaches 90°, the above equation gives negative (and thus meaningless) values for the compressive strength. In the original Jaeger's criterion, the strength of intact material is assumed as the upper limit for Eq. (2) (Fig. 1b). However, experimental observations have proved that the strength of jointed specimens in not necessarily the same when joint orientation approaches 0° and 90°. Therefore, a modification to Jaeger's criterion was introduced as shown in Fig. 1c. Furthermore, even when the sliding does not occur due to joint inclination, the strength still does not have a constant value. In other words, when the failure is controlled by the rock material, assumption of isotropic behaviour (Fig. 1b and c) is not realistic. Jaeger's criterion has another major shortcoming; it does not take account of the effect of confining pressure on the strength nonlinearity appropriately. Eq. (2) is a linear function of σ_3 which implies that the curvature of diagrams shown in Fig. 1 only shift upward as the confining pressure increases; while, these diagrams are logically expected to flatten at higher confining pressures and to show the reduction of joint effect. Fig. 2 depicts experimental data of specimens with sliding joint (β=25°) reported by Ramamurthy [14]. As is seen from this figure, despite of good agreement between predictions of Eq. (2) and measured strength data at lower confining pressures, Jaeger's criterion can not reflect the nonlinear trend which exists at sufficiently high confining pressures.

3. Tien–Kuo criterion

Tien and Kuo [3] presented an analytical failure criterion for strength of anisotropic rocks based on the concepts of theory of elasticity. They adopted Jaeger's criterion for sliding failure, however, stressed that the rock mass shows anisotropic behaviour when sliding on the joint is prevented. The axial strain (ε_{yy}) of the