AN ASSESSMENT OF THE APPLICABILITY OF THE HOEK-BROWN FAILURE CRITERION TO JOINTED ROCK SLOPES BASED ON SYSTEMATIC NUMERICAL MODELLING

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ABSTRACT

The Hoek-Brown failure criterion (1980, 1983) and modified criterion (1992) as well as revised version (1994) is widely used for estimating rock mass strength properties in intensely fractured rock. The criterion suggests that mass strength is dependent primarily on lithological type, fracture spacing and intact rock strength relative to the in-situ stress level. The criterion is applicable to fractured rock masses where the potential for simple kinematical failure along individual discontinuities is not possible. The criterion makes no allowance for *degree of adversity* of jointing within the highly fractured mass.

This paper describes the results of numerical studies using UDEC in which shear behaviour within a slope of constant geometry has been assessed. Parameters such as fracture spacing, block size and intact rock strength have been kept constant in accordance with the classes of rock defined within the modified criterion. Discontinuity orientation has been varied systematically within the mass.

The results show that stability is highly dependant upon the relative discontinuity orientations within the rock mass even where kinematical sliding of wedges is not possible. A suggested modification of the criterion is proposed based on *degree of adversity* of jointing. Conclusions are drawn with respect to the available strengths for different rock mass qualities.

INTRODUCTION

The Hoek-Brown failure criterion (Hoek and Brown, 1980) and modified criterion (Hoek et al., 1992; Hoek, 1994) are widely used for estimating the strength of highly fractured rock masses which can be regarded as essentially isotropic. Hoek (1994) emphasises that the criterion should only be applied with extreme caution to rock mass containing few sets of joints and where the influence on behaviour of one set is likely to be dominant.

The general criterion as discussed in detail by Hoek (1994) takes the form:

$$\sigma'_1 = \sigma'_3 + \sigma_c \left[m_b \frac{\sigma'_3}{\sigma_c} + s \right]^a \tag{1}$$

where:
σ'_1 = major principal effective stress at failure,
σ'_3 = minor principal stress at failure, and
σ_c = uniaxial compressive strength of intact rock
m_b is a constant for the rock mass and corresponds approximately to the friction angle, ϕ within the linear Mohr-Coulomb criterion. It varies both with rock type (m_i component) and an index called the Geological Strength Index (GSI) which in turn is related directly to the rock mass classification ratings of Barton et al., (1974) and Bienawski (1976)

s and a are constants which depend upon the characteristics of the rock mass; s is analogous approximately to cohesive strength within the Mohr-Coulomb criterion and tends to zero for a very poor quality rock mass, reflecting the low tensile strength of such a weak rock mass.

For a given rock type (e.g. sandstone or granite) the parameters m_b , s and a vary, with structure (ranging from widely jointed and blocky to crushed) and with surface condition of discontinuities (very rough and unweathered to slickensided or clay infilled). Generally, the parameters s and m_b , in particular, reduce markedly with increasing number of discontinuity sets, increasing fracture frequency and lower shear strength of discontinuity surface. Within the various ratings, however, no allowance is made for *degree of adversity* of jointing; it is taken as a basic assumption for the Hoek-Brown criterion that joint orientations are "very favourable" as defined by Bienawski (1976).

In contrast to the Hoek-Brown criterion prediction of a reducing shear strength with increasing fracture frequency for an isotropic rock mass, Bandis et al. (1981) report that strength actually increased with reducing block size in physical model tests where the failure mechanism was dominated by sliding on adversely orientated sets of discontinuities. This was attributed to a reduced stiffness of the more closely jointed rock mass allowing more freedom for blocks to rotate thereby increasing the effective roughness component. Clearly these two situations of either no adverse discontinuities or behaviour dominated by sliding on adverse discontinuities are opposite ends of a spectrum of rock mass conditions. In many situations, whilst the fracture network does not permit failure by sliding along a single set of discontinuities, within the rock mass there are sets of impersistent, or non-daylighting discontinuities which are orientated so that sliding along these will contribute significantly to failure. The apparently contradictory conclusions of Bandis et al. (1981) and Hoek et al. (1992) regarding the trend for strength with decreasing block size causes something of a dilemma for geotechnical engineers.

THEORETICAL BACKGROUND

The Hoek-Brown failure criterion suggests that mass strength is dependent primarily on lithological type, fracture spacing and intact rock strength relative to the in-situ stress level. The criterion is applicable to fractured rock masses where the potential for simple kinematical failure along individual discontinuities is not possible. The criterion makes no allowance for *degree of adversity* of jointing within the highly fractured mass.

Some fundamental aspects of Hoek-Brown failure criterion have been widely studied. For example, improving understanding of the constants of Hoek-Brown failure criterion mainly from laboratory tests (Betournay et al., 1991). Using probabilistic stability analysis for variable rock slopes by Priest and Brown (1983) which described typical Hoek-Brown sliding failures. However, this research takes a close look at the consideration of geological and engineering aspects with the bigger scale numerical modelling to demonstrate the influence of *degree of adversity* of discontinuity orientation on jointed rock slopes stability by using Hoek-Brown failure criterion.

The general weakening influence of discontinuities on the available shear strength of the soil or rock mass is well established. Henkel and Skempton (1955) for example demonstrated that in fissured clays, analysis of slope stability on the basis of peak strength of the intact material will lead to a considerable overestimate of the Factor of Safety. It is also clear that where fractures are not randomly orientated, which is generally the case (see for example Pollard & Aydin, 1988), then strength will be anisotropic (Amadei, 1988). As the orientation of fractures vary with respect to the stress field, so the available strength will vary, in large part in response to changing freedom for different modes of deformation to develop (Reik & Zacas, 1978; Al-Harthi & Hencher, 1993).

The contribution of impersistent joints to rock slope stability was considered in detail by Einstein et al. (1983). Whilst it is clear that impersistent joints which are otherwise daylighting will result in mass strength lower than

that of intact rock the problem is not trivial theoretically and especially in practice where persistence is one on the most important yet difficult attributes of discontinuity geometry to ascertain in the field.
The problem of the influence of non daylighting discontinuities which have a component of dip in the direction of potential deformation was considered theoretically and analytically for discontinuities in soils by McGown et al. (1980). They allowed for strength reduction due to percentages of classes of discontinuities of particular orientations in their anisotropy ratio. The same principles might be expected to apply to rock masses. In particular, in rock slope, Hencher et al. (1996) have briefly described the principles of *degree of adversity* of discontinuity orientation to rock slope stability study contained physical models, numerical modelling and field case study.

In inclined rock masses, anisotropic rock mass strength depends upon inclined degree of rock mass and orientation of discontinuities (Amadei and Pan, 1992). And, rock mass strength reduction is with increasing the inclined degree of rock mass due to discontinuity shear strength decreasing. Therefore, it is necessity for understanding the influence of *degree of adversity* of discontinuity orientation (it is the inclination angle of discontinuities in two dimensions in the UDEC modelling) in jointed rock slopes.

This research is aimed at assessment of the applicability of the Hoek-Brown failure criterion to jointed rock slopes for investigating the influence of the presence of adversely orientated, yet persistent discontinuities to rock mass strength where sliding on single discontinuity surfaces is not a potential model of failure due to the geometry of the situation and the available shear resistance to sliding along the discontinuities based on a systematic numerical modelling. The influence of such discontinuity sets has been studied in detail by using UDEC modelling.

The research reported here to be investigated the fundamental mechanical processes involved rock slopes stability and apply Hoek-Brown failure criterion to the rock slopes. The rock slopes with different joint spacing and orientation were created and input parameters were defined with respect to Hoek-Brown failure criterion. The models were designed to investigate the influence of *degree of adversity* of discontinuity orientation in jointed rock slopes. Careful study of models have been used for analysing the stability of jointed rock slope according to Hoek-Brown failure criterion. This approach reported here will be helpful in jointed rock slopes design and understanding the strength characteristics of jointed rock masses by using Hoek-Brown failure criterion.

This paper describes the results of numerical studies using UDEC in which shear behaviour within a slope of constant geometry has been assessed. Parameters such as fracture spacing, block size and intact rock strength have been kept constant in accordance with the classes of rock defined within the modified criterion. Discontinuity orientation has been varied systematically within the mass.

UDEC SIMULATIONS

The distinct element method introduced by Cundall (1971) and developed within the software package, UDEC (Universal Distinct Element Code) is a powerful tool for performing strength and deformation analysis in blocky rock masses. The time stepping nature of the problem allows mechanisms of deformation to be studied for given fracture networks and geometries. The program has been used to predict deformations in real rock mass engineering situations with remarkable success (Barton et al., 1991).

In this research, UDEC version 1.83 (ITASCA, 1993) with two dimensions analysis is used. A series of UDEC models of idealised slopes were set up. Within each model the fracture networks of the rock mass were defined with the rock mass rating in terms of number of joint sets and block size kept constant together with parameters such as shear strength along discontinuities. Within each model of constant slope geometry the two factors which were varied discontinuity orientation and, to some extent persistence.

In UDEC modelling, Hoek-Brown failure criterion and constants were defined and input into each model. In this research Hoek-Brown failure criterion (1983) was used because of the limitation of the code. In fact, Hoek-Brown failure criterion has been developed in 1992 (Hoek et al., 1992) and 1994 (Hoek, 1994). And the difference between Hoek-Brown failure criterion (1980 and 1983) and (1992 and 1994) has been analysed by the authors by mathematical solution (will be described in the other paper).

However, in UDEC modelling, an equivalent non-linear continuous material is assumed that the rock mass behaves according to a non-linear constitutive law which the non-linear behaviour of a jointed rock mass can be represented by an elastic/plastic model. Therefore, the rock block model is assumed as elastic/plastic with Mohr-Coulomb failure criterion, the joint model is assumed as joint area contact elastic/plastic with Coulomb slip failure criterion. But the jointed rock mass strength is controlled by the Hoek-Brown failure criterion and constants (m, s and σ_c).

The jointed rock slopes with height 20 metres and angle 70 degrees were simulated. The rock mass under consideration contains two sets of discontinuities. A middle strong geological material (fair quality to good quality rock mass) with spacing from 0.4 to 2 metres was simulated in this research. Three different joint spacings (block sizes) were set up for different models with same discontinuity orientation to demonstrate the different deformations of jointed rock slopes with respect to Hoek-Brown strength criterion. Table 1 lists the geometrical models and input values for the UDEC modelling. In Table 1 the angle of joint is determined according to the coordinate system to be used by UDEC.

Plane strain loading conditions were assumed for the two-dimensional analysis. Gravitative loading is applied to the models. Horizontal stresses were assumed to be equal to half of vertical (gravitational) stresses. The jointed rock mass strength is defined by Hoek-Brown failure criterion with RMR = 44, m = 0.3, s = 0.0001 and σ_c = 50MPa. Table 2 lists the parameters and values to be defined and employed by the UDEC modelling for blocks, joints and Hoek-Brown constants.

TABLE 1

JOINT SPACING AND DISCONTINUITY ORIENTATION

Model	Joint Spacing (Block Size) (m)					
	2 (2x2)		1 (1x1)		0.4 (0.4x0.4)	
	Joint (angle)		Joint (angle)		Joint (angle)	
	Set 1	Set 2	Set 1	Set 2	Set 1	Set 2
1	175	85	175	85	175	85
2	170	80	170	80	170	80
3	165	75	165	75	165	75
4	160	70	160	70	160	70
5	155	65	155	65	155	65

TABLE 2

THE PARAMETERS AND VALUES OF MATERIAL PROPERTIES

	Parameter	Value
Block:		
	Density [kg/m^3]	2180
	Young's modulus [GPa]	22
	Poisson ratio	0.3
	Friction angle [degree]	35
	Cohesion [MPa]	0.5
	Dilation angle [degree]	5

	Tension [MPa]	0
Joint:		
	Friction angle [degree]	28
	Cohesion [MPa]	0
	Dilation angle [degree]	3
	Tension [MPa]	0
	Normal stiffness [GPa/m]	10
	Shear stiffness [GPa/m]	5
Hoek-Brown constants:		
	RMR	44
	m	0.3
	s	0.0001
	σ_c [MPa]	50

ANALYSIS OF THE RESULTS AND DISCUSSIONS

The UDEC simulation results are shown in Figures 1 to 3. Where Figure 1 shows the slope with 2m joint spacing (block size 2x2m) but different discontinuity orientations (represented by the joint set angles), Figure 2 shows the slope with 1m joint spacing (block size 1x1m) but different discontinuity orientations (represented by the joint set angles), Figure 3 shows the slope with 0.4m joint spacing (block size 0.4x0.4m) but different discontinuity orientations (represented by the joint set angles), which demonstrated the failure mechanisms relating to the *degree of adversity* of discontinuity orientation.

The failure mechanism of the slopes with the biggest joint spacing was toppling with different discontinuity orientations to be illustrated in Figure 1 (a) , (b), (c) and (d), (except Figure 1 (e) which was stable likely). It seems that these are not like Hoek-Brown failure despite the rock mass strength was defined by Hoek-Brown failure criterion. Obviously the failure shape of the slopes was influenced by the discontinuity orientation.

The slopes comprising of intermediate joint spacing (Figure 2) fail by sliding on the daylighting discontinuity set in all discontinuity orientations which demonstrated that discontinuity orientation is the controlling factor despite the rock mass strength was defined by Hoek-Brown failure criterion. Obviously the failure mechanism was influenced by the rock block sizes.

For the slopes with the smallest joint spacing (Figure 3), a shallow translational slide develops along a failure surface that bounds many blocks which is essentially a Hoek-Brown mass failure. These results from an aspect demonstrate the applicability of the Hoek-Brown failure criterion to jointed rock slopes.

However, from the results of the modelling, it is shown that the failure mechanism of the rock slopes is depended upon the different joint spacings (block sizes) and they proved the influence of *degree of adversity* of discontinuity orientation on the slope stability. For the same joint spacings (block sizes), the failure mechanism of the slopes is the same with the varied discontinuity orientation. Where the *degree of adversity* of discontinuity orientation need to be indicated for the slope stability (see Figure 1 (d) and (e); Figure 2 (d) and (e) and Figure 3 (d) and (e)). This results show that the toleration of dominated discontinuity orientation controls the failure mechanism of the slopes which demonstrated the influence of *degree of adversity* of discontinuity orientation on the slope stability.

For different joint spacings (block sizes), the failure mechanism is fully different for the same discontinuity orientation which is illustrated in Figure 1 (a), Figure 2 (a) and Figure 3 (a); Figure 1 (b), Figure 2 (b) and Figure 3 (b); ... and so on (also see Hencher et al., 1996). On the other hand, the smallest block size has the smallest horizontal displecement comparing Figures 1, 2 and 3 with the same discontinuity orientation which is coincident with the conclusions of Bandis et al. (1981). The results show that there are the influence of block size and discontinuity orientation under complex rock mass conditions which will be carefully considered when applying Hoek-Brown failure criterion to these rock slopes. With respect to different rock mass scale with different block sizes and joint spacing, applied Hoek-Brown failure criterion will be very carefully considered as described by Hoek (1994).

Furthermore, the modelling results show that there is a set of joints which dominated the failure mechanism (joint set 2 of Table 1), this can be seen from the failure shape of all models that the toppling, the sliding and the Hoek-Brown failure are approximately along the joint set 2. Therefore extreme caution will be given under the conditions of complex block sizes and discontinuity orientations of rock mass, where the *degree of adversity* of discontinuity orientation and Hoek-Brown failure criterion have to be carefully considered for jointed rock slope design and excavation.

CONCLUSIONS

An assessment of the applicability of the Hoek-Brown failure criterion to jointed rock slopes based on systematic numerical modelling has been carried out. The results show that stability is highly dependant upon the relative discontinuity orientations within the rock mass even where kinematical sliding of wedges is not possible. This results suggest that there is an influence range of discontinuity orientation which controls the failure mechanism of the rock slopes. Furthermore, different rock mass failure mechanisms which suggest that applied Hoek-Brown failure criterion to these rock slopes should be carefully considered with respect to the available strengths for different rock mass qualities.

It has been proposed that a modified Hoek-Brown failure criterion based on the *degree of adversity* of discontinuity orientation would be developed for estimating strength of highly fractured rock mass and the stability analysis of jointed rock slope. The studies on the influence of the *degree of adversity* of discontinuity orientation for suggested modification of the Hoek-Brown failure criterion are under progress.

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