Comparison of Hock–Brown and Mohr–Coulomb criteria in the stability analysis of jointed rock slopes

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ABSTRACT: This paper presents the stability analysis at the right and left slopes of the road in Iran. Both field and laboratory studies were carried out. The field study included precise discontinuity surveys. Laboratory tests were carried out to determine Young's modulus, uniaxial compressive strength, unit weight and shear strength parameters of discontinuities. In this study numerical modeling were used for the right and left slopes of the road. Shear strength reduction analyses was carried out using Phase2 in the basis of Hock–Brown and Mohr–Coulomb criteria. According to results of numerical analysis, Strength Reduction Factor (SRF) of the right and left slopes are 1.37 and 1.46 for Hock–Brown criterion but 1.99 and 2.14 for Mohr–Coulomb criterion respectively. The obtained results present that application of Hock–Brown criterion yielded more reliable results in this situation and any rotational failure will not occur.

Keywords: Rock slope stability; Strength Reduction Factor; Hock–Brown criterion; Mohr–Coulomb criterion

INTRODUCTION

The slope stability of rocks is an important problem in geotechnical engineering. A great variety of numerical analyses such as finite element and distinct element methods are performed with development of many kinds of numerical programs on the geotechnical problems. A number of methods are being used for the assessment of slope stability (Crosta et al., 2003; Bhasin and Kaynia, 2004; Eberhardt et al., 2004).

Stability by strength reduction is a manner that the factor of safety is determined by weakening the soil or rock in stages in an elastic-plastic finite element analysis until the slope fails. The factor of safety is considered to be the factor by which the soil or rock strength needs to be reduced to reach failure (Dawson et al., 1999; Griffiths and Lane, 1999).

In the Strength Reduction approach, the soil or rock strength is dummy reduced, and so there is a need to redistribute the stresses. This can be done by the stress redistribution algorithm, and so this option can be indirectly used to do a strength reduction stability analysis.

The strength reduction factor (SRF) is defined as:

\[ SRF = \left( \frac{\tan \phi}{\phi} \right) = \left( \frac{c}{c_f} \right) \]

Where \( \phi \) and \( c \) are the effective stress strength parameters at failure, or the reduced strength. The strength reduction method usually uses the same SRF for all material and for all strength parameters, so that the stability factor reduces to one number in the end.

This paper proposes a simple and practical numerical procedure to evaluate the stability of rock slopes. The proposed model is regulated in a united manner to accommodate both the Mohr–Coulomb and generalized Hock–Brown criteria. In this model, all the strength parameters are assumed to be a function of deviatoric plastic strain and to decrease linearly to the residual values.

Site characterization

The study area is located in the trench of the road in Iran. The length of trench is 350 meter and it is dug in the gray carbonate rocks. Trenching has caused two rock slopes in the site, so that height of the right and left slopes is equal to 34 and 31 meters respectively, and their slope angle is equal to 72 degree. Trend of the trench is nearly
north–south and joints are the most basic structures that have subjected especially carbonate rocks and caused dense fracturing in these rocks.

**Material characteristics of carbonate rocks**

The physical and mechanical characteristics of the carbonate rocks were determined on obtained samples of boreholes and field tests on outcrops. The specific gravity of the carbonate rocks varies from 2.68 to 2.70.

The values of minimum and maximum UCS varies from 45 to 49 MPa, respectively, and the average value of 47 MPa. Therefore, according to ISRM (1981) the carbonate rocks proved to be weak rocks. In addition, based on Deere and Miller (1966) using the UCS, low strength were suggested for these rocks.

The average value for the rock material constant 
\( m_i \) was determined using Hoek and Brown (1988) failure criterion. The value of 
\( m_i \) for the crushed rocks was obtained equal to 12.

**Rock mass characteristics**

To acquire the carbonate rock masses characteristics, site investigations were carried out on the outcrops along the slopes and the core logs of few borehole drillings. The information obtained of these investigations will be used on the rock mass classification as indices.

The most important discontinuities in the site of project are joints and surface beddings. The scan-line surveys, spot measurements, and field observations according to ISRM (1981) were carried out on carbonate rocks along the trenches to determine the orientations, spacing, roughness, aperture, persistence, infilling and water condition of the fractures.

The whole fracture orientations in the studied area are shown in the equal area lower hemisphere stereographic projection in Figure 2. The points of maximum density led to identification of four main fracture sets (Dip/Dip Direction: 14/339, 79/231, 73/106, 77/314) (Figure 1).

![Figure 1. Equal area stereographic projection of the discontinuities measured in the carbonate rock masses](image)

The spacing of fractures ranges from 150 to 650 mm (moderate spacing, ISRM 1981) and the fracture surfaces are rough and slightly rough. The apertures of most fractures fall within very tight to open (<0.1–3 mm) categories (ISRM 1981). They are nearly continuous with about 1.2-8.5 m in length (medium persistence, ISRM 1981) and are often clean. The fracture surfaces are dominantly dry, stepped to planar and are fresh to slightly weathered (Figure 2).
The Rock Quality Designation (RQD) of the carbonate rock masses ranges between 23% and 34%. According to the RQD divisions proposed by Deere (1964), these rock masses set to poor class which indicates effects of the structures on the carbonate rocks strength.

**Mechanical properties of the carbonate rock masses**

The rock mass properties such as the rock mass strength ($\sigma_{cm}$), the rock mass deformation modulus ($Em$) and the rock mass constants ($mb$, $s$ and $a$) were calculated by the Rock-Lab program defined by Hoek et al. (2002). This program has been developed to provide a convenient means of solving and plotting the equations presented by Hoek et al. (2002).

In Rock-Lab program, both the rock mass strength and deformation modulus were calculated using equations of Hoek et al. (2002). The value of GSI was obtained from the last form of the quantitative GSI chart, which was proposed by Marinos and Hoek (2000).

In addition, the rock mass constants were estimated using equations of Geological Strength Index (GSI) (Hoek et al. 2002) together with the value of the carbonate rocks material constant ($mi$) (value in Table 1). Also, the value of disturbance factor (D) that depends on the amount of disturbance in the rock mass associated with the method of excavation, was considered equal to 8 for the carbonate rocks (Table 1), it means these rocks would be disturbed greatly during blasting.

Finally, the shear strength parameters of the rock mass ($C$ and $\phi$) for the crushed rock masses were obtained using the relationship between the Hoek-Brown and Mohr-Coulomb criteria (Hoek and Brown 1997) and are presented in Table 1. Furthermore, the stress – strain curves of the carbonate rocks are shown in Figure 3.

<table>
<thead>
<tr>
<th>GSI</th>
<th>$mi$</th>
<th>D</th>
<th>$mb$</th>
<th>s</th>
<th>a</th>
<th>$\sigma_{cm}$</th>
<th>$Em$</th>
<th>C</th>
<th>$\phi$</th>
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<td>45</td>
<td>12</td>
<td>8.00</td>
<td>0.454</td>
<td>0.0002</td>
<td>0.508</td>
<td>4.079</td>
<td>1585.41</td>
<td>0.250</td>
<td>42.03</td>
</tr>
</tbody>
</table>

**Analysis of slope stability**

One of the most important tasks in rock engineering is stability analysis of the rock slopes. The numerical method was employed for analysis of stability in the carbonate rock masses in trenches of the road.

Numerical analysis of rock slopes in the study area was accomplished using a two-dimensional hybrid element model, called Phase2 Finite Element Program (Rocscience 1999). The program is based on the finite element method including some geotechnical parameters. These geotechnical parameters are slope height, slope angle, uniaxial compressive strength, Poisson's ratio, unit weight of the rock, Geological strength index (GSI), Hoek-Brown parameters, deformation modulus of rock mass, friction angle, cohesion and situation of the joints and groundwater condition.
The Veneziano joint network model is used for numerical analysis (Figure 4) and this model is based on a Poisson line process. It adapts the Poisson process to generate joints of finite length (Dershowitz, 1985).

![Figure 3. Stress-strain curves for the carbonate rocks](image)

![Figure 4. Finite element mesh and the Veneziano joint network of the right and left slopes](image)

Shear strength reduction analyses was carried out using Phase2 in the basis of Hock–Brown and Mohr–Coulomb criteria for the right and left slopes and determined Strength Reduction Factor (SRF) for each slope. According to results of numerical analysis, Strength Reduction Factor (SRF) of the right and left slopes are 1.37 and 1.46 for Hock–Brown criterion but 1.99 and 2.14 for Mohr–Coulomb criterion respectively and any rotational failure will not occur (Figures 5 and 6). The obtained results present that application of Hock–Brown criterion yielded more reliable results in this situation.
CONCLUSIONS

This study is aimed at assessing the stability of the right and left slopes of the road in Iran. Based on the information collected in the field and laboratory, the slope stability was investigated. Shear strength reduction analyses was evaluated using Phase2 and determined Strength Reduction Factor (SRF) for the right and left slopes. The obtained results present that any rotational failure will not occur and application of Hock–Brown criterion yielded more reliable results in this situation. The Hock–Brown criterion allows the non-linear behaviour of the dilation angle with the shear displacement of rock blocks, but the dilation angle in the Mohr–Coulomb criterion is defined to be constant independent on the shear behaviour of rocks.

REFERENCES