Comparison of H-B and M-C Failure Criterion at Low Confinement and their Impact on the Prediction of Failure Zone Around an Underground Metal Mine

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Abstract. The accurate assessment of rock mass strength and the failure zone near the excavation is important for the rational design of underground structures. To predict the strength and behaviour of the rock mass during excavations, generally, the two most widely used failure criterion namely, linear Mohr-Coulomb and nonlinear Hoek-Brown criteria are used. However, the failure envelopes from the two criteria deviate much, especially, at low confinements. The main motive of this investigation is to understand the stress state around an opening. An underground copper mine of Hindustan Copper Limited (HCL) i.e., Khetri Copper mine in India was considered for this research where the host rock is quartzite schist. The mine is operated at a depth of around 475 m and the ore is extracted using the sublevel stopping method. From the finite element model, it was found that the stress state of the rock mass around the excavation mostly lies in the range between the direct tension and low value of confinements. This is the range where the H-B and M-C failure envelopes differ. The FEM modelling showed a different value of failure zone around the opening, 17.8 m from H-B compared to 8.0 m from the M-C criterion. This research suggested that for the quartzite rock investigated, the support requirements are more if the H-B failure criterion is considered instead of the M-C failure criterion.

1. Introduction

A failure envelope is needed to predict the failure zone of underground excavation and further estimate the support requirements. Failure envelopes are generally expressed in terms of the major principal compressive stress, that rocks can sustain for given values of intermediate and minor principal stresses. Though, the intermediate principal stress is usually ignored for the design in rock structures.

A typical failure envelope is shown in Figure 1. As shown in Figure 1, the initial stress state of rock before the excavation lie below the failure envelope. As the excavation progresses, different points around the excavation go through different stress paths [1]. If the final stress state of the rock lies above the failure envelope the rock is considered to be failed.

The two most widely used failure criterion are namely, linear Mohr-Coulomb (M-C) [2] and non-linear Hoek-Brown (H-B) [3] failure envelope. These two failure envelopes deviate much near the low confinement region ([4], [5]). Hence, to understand the stress state of rock and investigate the support requirements, finite element modelling (FEM) was done for the sublevel stope of Khetri Copper mine of Hindustan Copper Limited (HCL) in India. Using elastic analysis, the development of tensile zone around the opening and the stress path followed at different locations around the excavation was first analysed. Secondly, using the elastic-plastic analysis failure zone around the mine stope was determined and compared using both M-C and Hoek–Brown failure criteria.
2. Literature Review
2.1. Rock Mass Failure
Rock fails if applied stress exceeds its corresponding strength at that confinement. So, knowledge of the failure process is required for the successful design of any underground structures. And to know the behaviour of rock mass it is necessary to start with an intact rock sample, which involves studying the laboratory sample in uniaxial test, triaxial test, direct tension test and confined extension region [5]. Investigation of Figure 1 shows that most of the stress path for the rock mass is fundamentally unloading. And the direction of stress path is rotating. Also, rock experiences different stress condition in in-situ state and it fails when crosses the threshold limit.

2.2. Two-Dimensional Failure Criterion
2.2.1. Mohr-Coulomb Strength Criterion.
The linear M-C failure criterion was proposed by Coulomb in 1773. He suggested that developed shear stress is related to the angle of internal friction, cohesion and the applied normal stress [6]. Mohr proposed that shear failure takes place across a plane where shear stress is a function of normal stress.

\[ \tau = C + \sigma_n \tan \phi \] (1)

Where, \( \tau \) = Shear stress, \( c \) = Cohesion, \( \sigma_n \) = Normal stress, and a positive value is considered to be compressive, \( \Phi \) = Angle of internal friction.

The direction of the shear failure plane is \((45 + \Phi/2)\)^\circ.

In terms of major and minor principal stresses, the above Equation (1) can be written as

\[ \sigma_1 = \sigma_c + \sigma_3 \tan^2 \left( 45 + \frac{\phi}{2} \right) \] (2)

Where, \( \sigma_c \) = Uniaxial compressive strength (MPa) and \( \sigma_t \) = Uniaxial tensile strength (MPa)

\[ \sigma_c = \frac{2 c \cos \phi}{1 - \sin \phi} \] (3)

\[ \sigma_t = - \frac{2 c \cos \phi}{1 + \sin \phi} \] (4)
Equations 1 and 2 are both straight lines in the $\tau - \sigma_n$ and $\sigma_1 - \sigma_3$ planes. One of the limitations of the Mohr-Coulomb failure criterion is that it cannot predict the nonlinear response of rock mass. And this criterion may produce incorrect results if the failure mechanism is not shear.

2.2.2. Hoek-Brown Failure Criteria

The nonlinear H-B [3] failure criterion was first introduced in the early eighties. H-B (1980) found that the peak triaxial compressive strength of isotropic rock is related to confining stress based on the types of rock designated by $m_i$ and the relationship is given by Equation (5).

$$\sigma_1 = \sigma_3 + \sqrt{m_i \sigma_c \sigma_3 + s \sigma_c^2} \quad (5)$$

Where, $m_i$ and $s$ are the material constants, $s = 1$ for intact rock. Later, [3] a modified general equation for rock mass which given in Equation (6).

$$\sigma_1 = \sigma_3 + \sigma_{ci} \left( m_b \frac{\sigma_c}{\sigma_{ci}} + s \right)^a \quad (6)$$

$$m_b = m_i \exp \left[ \frac{GSI-100}{20-14D} \right] \quad (7)$$

$$s = \exp \left[ \frac{GSI-100}{9-3D} \right] \quad (8)$$

$$a = \frac{1}{2} + \frac{1}{6} \left( e^{-\frac{GSI}{15}} - e^{-\frac{20}{3}} \right) \quad (9)$$

Where, $D$ = Disturbance factor, it is varying from zero to one. Zero for intact rock and one for jointly rock mass and GSI is the Geological Strength Index.

3. Case Study: Khetri Copper Complex, Hindustan Copper Limited (HCL), India

A case study of Khetri Copper Complex, HCL was taken for numerical modelling and comparison of M-C and H-B failure envelopes at low confinement region. The mine is located in the Jhunjhunu district of Rajasthan in India. The orebody consists of a Chalcopyrite deposit which is surrounded by the formations of metamorphosed to quartzites, schists and phyllites. Sublevel stoping method of mining is practised at a depth of around 475 m for the production of ore with a daily and annual target of 5000T and 1.5 MT respectively. The plan and sections view of a typical sublevel stope at Khetri Copper mine is shown in Figure. The reserve of Khetri Copper Complex (KCC) is 39 MT at 0.94% of Cu [7]. The stress ratio near the KCC is around 2.3 [8]. The rock geomechanical properties were found using the RocData software [9] and it was used as an input material property for RS2 software [10]. Table 1 shows the average properties of the rock mass which was used for the modelling. The properties were used for backfilling the void is shown in table 2 [11].

| Parameters                        | Value         |
|-----------------------------------|---------------|
| Rock Type                         | Quartzite schist |
| Intact rock strength ($\sigma_c$) | 151 MPa       |
| Geological Strength Index (GSI)   | 71            |
| H-B constant (m_i, m_b, s and a)  | 15, 5.13, 0.035 and 0.51 |
| Young’s modulus                   | 36.4 GPa      |
| Poisson’s ratio ($\nu$)           | 0.14          |
| Rock mass tensile strength ($\sigma_t$) | -1.05 MPa |
| Cohesion                          | 11.7 MPa      |
| Angle of internal friction        | 40°           |
Table 2. Backfill material properties used for the FEM analysis [11].

| Parameters                  | Value       |
|-----------------------------|-------------|
| Modulus of Elasticity       | 300 MPa     |
| Poisson’s ratio (v)         | 0.2         |
| Density                     | 1800 Kg/m³  |
| Angle of internal friction  | 30º         |
| Cohesion                    | 0 MPa       |

Figure 2: Plan and sections view of a typical sublevel stope at Khetri Copper mine [7].

4. Finite Element Modelling
Section A-A of the Khetri Copper mine shown in Figure was modelled using the finite element modelling software RS2 for comparison of H-B and M-C failure criteria. The rock mass data obtained with RocData software are the input material properties used in created RS2 numerical model and the entire model geometry was excavated and backfilled in six stages. The width and height of excavation were 20.7m and 53.4m respectively. The vertical and horizontal state of stress used for the analysis were $\sigma_v = 12.9$ MPa and $\sigma_h = 29.67$ MPa.
5. Results

5.1. Elastic analysis
From the elastic analysis, it was found that the rock near the excavation was under a low confinement state of stress. To show the tensile zone around the excavation value of minor principal stress was customised between -10 MPa to 0 MPa which is shown in Figure . Whereas, Figure shows the stress state of the surrounding rock in $\sigma_1 - \sigma_3$ plane. This shows that the majority of data point lies in the low confining region. This plot was generated from the values of major and minor principal stress at stage 6 from elastic analysis in RS2 modelling.
5.2. Importance of Stress Path

As explained in Figure 1, the stress path for rock at a location around an underground opening is the curve it follows in $\sigma_1 - \sigma_3$ plane during the excavation stages. For this study to obtain the stress path for point P shown in Figure major and minor principal stress were extracted at the different stages. Figure shows that the stress state of point P is changing and goes through the low confinement region and follow a complex stress path. The initial and final stress state was (29.8 MPa, 12.9 MPa) and (8.8 MPa, 26.7 MPa) respectively.
5.3. Comparison of M-C and H-B criteria based on failure zone around the opening

The elastoplastic analysis was carried out for the determination of the failure zone near the opening based on M-C and H-B failure criteria using the material properties given in Table 1. Figure 6, indicates the failure zone at the low confinement region based on M-C and H-B failure criterion along with the symbol ‘X’ and ‘O’, which indicates that the rock fails in shear and tension at stage 4 respectively. The analysis shows that the depth of the failure zone near the excavation is 17.8 m and 8.0 m based on H-B and M-C failure criterion respectively. Hence, for the case analysed the support requirements are more if the H-B failure criterion is considered instead of the M-C failure criterion.

**Figure 6:** Stress path followed by point P, Figure 6, during the different stages of excavation.

**Figure 7:** Comparison of failure zone at low confinement region based on (a) Mohr-Coulomb (b) Hoek–Brown criteria, where the symbol ‘X’ and ‘O’ indicates the rock fails in shear and tension respectively.
6. Conclusion
Numerical analysis was used in this research to compare the M–C and H–B failure criteria at low confinement region using the case study of the Khetri Copper mine of Hindustan Copper Limited (HCL), India. The elastic and plastic analysis was carried out the determining the tensile zone and depth of failure zone around the excavation respectively. The following conclusions have been made from the above study.

- The stress state around the excavation goes through the complex stress path.
- The stress state around the excavation is at low confinement and can go to the tensile region.
- For the case analysed, the design of the support system using H–B required higher support compared to M–C. Because, the depth of the failure zone around an excavation is more in the case of H–B as compared to M–C failure criteria.
- The behaviour of rock in low confinement may be case dependent and must be investigated before designing the support system.

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