Modelling brittle rock mass behaviour in deep underground excavations

Giuseppe Cammarata
Seequent, The Bentley Subsurface Company, Milan, Italy

Davide Elmo
University of British Columbia, NBK Institute of Mining Engineering, Vancouver, Canada

Sandro Brasile
Seequent, The Bentley Subsurface Company, Delft, The Netherlands

ABSTRACT: Thorough knowledge of brittle phenomena around underground excavations is of paramount importance for predicting the extension and shape of the failed zone and assisting in assessing adequate support and reinforcement systems. This behaviour is difficult to capture in conventional continuum modelling approaches, requiring the development of advanced constitutive models. A continuum constitutive approach based on the Hoek-Brown failure criterion and enhanced by introducing a softening rule to replicate the brittle behaviour of rock masses and associated failure due to dilatating sharing has been recently proposed. In this paper, this new Hoek-Brown with Softening model is adopted to predict the progressive brittle failure of the Lac du Bonnet granite at the Underground Research Laboratory Mine-by test tunnel. The results confirm the capability of the constitutive approach to replicate the brittle behaviour associated with strain localization.

Keywords: Brittle rock failure, Continuum numerical models, Hoek-Brown with Softening, Mine-by test tunnel, Deep underground excavations.

1 INTRODUCTION

In the last few decades, due to the increasing need for both deep underground constructions (e.g., railway tunnels, repositories for nuclear waste and large powerhouse caverns) and deep mine operations, there has been growing interest in studying the behaviour of rock at high in-situ stress conditions where brittle failure leads to spalling and rock bursting. Observations of rock fracturing in underground excavation boundaries have shown that brittle failure is due to advancing slabbing with the growth of surface-parallel fractures during the first phase of the degradation phenomena. Shear failure is then experienced during the final stages of this brittle rock damage.

Numerical modelling using both continuum, discontinuum and hybrid modelling approaches have provided important contributions to the simulation of brittle behaviour and has proved to be extremely challenging. In particular, this behaviour is difficult to capture in conventional continuum modelling approaches (e.g., Martin et al. 1999) and this has led to the development of advanced constitutive laws for use in continuum models (e.g., Hajiabdolmajid 2001 and Diederichs 2007).

Moreover, considering the tendency of rock masses to dilate is particularly important for brittle rocks, the adoption of more advanced constitutive approaches in combination with variable dilation models (e.g., Alejano & Alonso 2005; Zhao & Cai 2010 and Walton & Diederichs 2015) has highlighted the significant impact of dilation on brittle failure around excavation (e.g., Zhao et al. 2010 and Walton et al. 2014).

Within this context, the Hoek-Brown with Softening (HBS) model has been recently proposed and implemented in the finite element (FE) code PLAXIS. This paper focuses on the simulation of brittle failure in the form of spalling and slabbing for excavation in very good quality and massive rock masses at a high depth. A summary of the main features of the HBS model is first addressed (details of its formulation are reported in Marinelli et al. (2019) and Plaxis (2023)). The validation of this enhanced continuum constitutive approach against field observations and modelling results for the Underground Research Laboratory (URL) Mine-by test tunnel is reported to illustrate the ability to replicate the extent of brittle failure around a deep underground excavation in a massive rock mass.

2 HOEK-BROWN WITH SOFTENING MODEL

In the HBS model, the generalized representation of the Hoek-Brown (HB) yield criterion envelope proposed by Jiang (2017) is adopted. The constitutive framework is enriched by implementing a hyperbolic softening rule to consider material degradation in the post-peak regime, a non-associated plastic flow, a tension cut-off, and a viscous regularization technique to restore the objectivity of the numerical solution.

The rock mass strength decrease is represented through a hyperbolic decay of the material properties (HB parameters m_b and s) by considering the following hardening rule:

$$\begin{Bmatrix} m_b \\ s \end{Bmatrix} = \begin{Bmatrix} m_{bi} - \left(\dfrac{m_{bi} - m_{br}}{B_m - \varepsilon_{eq}^{p}}\right)\varepsilon_{eq}^{p} \\ s_i - \left(\dfrac{s_i - s_r}{B_s - \varepsilon_{eq}^{p}}\right)\varepsilon_{eq}^{p} \end{Bmatrix} \tag{1}$$

where subscripts i and r refer to the initial and residual values of the corresponding variable, whilst ε^{p}_{eq} is the equivalent plastic strain representing the cumulated value of deviatoric plastic strain.

To provide a reliable development of volumetric strain in the post-peak region, HBS accounts for a nonlinear trend of dilation angle ψ which is controlled through the same hyperbolic evolution used for the HB parameters:

$$m_{\psi} = m_{\psi i} - \left(\frac{m_{\psi i} - m_{\psi r}}{B_{\psi} - \varepsilon_{eq}^{p}}\right)\varepsilon_{eq}^{p} \tag{2}$$

where the variable m_{ψ}, which introduces a non-associated plastic flow in the plastic potential, relates the dilation angle ψ with the HB parameters.

Parameters B_m and B_s in equation (1) govern the rate of softening resulting from the deviatoric shearing, while parameter B_{ψ} in equation (2) prescribes the rate of dilation after initial yielding.

To consider a tensile strength cut-off function, the value of the mean stress p representing the tensile limit of the HB envelope is reduced through the parameter α, which ranges between 0 (nil tensile strength) and 1 (no cut-off).

In the brittle/dilatant regime, the development of localized shear bands strongly affects the mesh-objectivity of the response (Pijaudier-Cabot & Bazant 1987). Therefore, to restore mesh-objectivity due to strain localization, a viscoplastic regularization is considered based on Perzyna's over-stress theory (Perzyna 1966). To this end, a fluidity parameter γ in conjunction with a temporal gradient is introduced, defining, therefore, an internal scale length controlling the shear band thickness (Sluys 1994).

3 MODELLING BRITTLE FAILURE WITH HBS MODEL

The reliability of the HBS model for simulating failure mechanisms with dilatant shear bands has been investigated through FE computations (Zalamea et al. 2020 and Cammarata et al. 2023).

To demonstrate its potential to model very-good-quality and massive rock masses at a high depth where severe in-situ stress conditions occur, HBS model is here employed for simulating brittle failure in the form of spalling and slabbing at the URL Mine-by test tunnel (e.g., Martin et al. 1997).

3.1 The Mine-by tunnel experiment

The Mine-by tunnel experiment at the URL in Pinawa (MB, Canada) consisted of a 3.5-m-diameter circular tunnel mined at a depth of 420 m below the surface in massive Lac du Bonnet granite, which representative material properties are reported in Table 1.

Table 1. Properties of Lac du Bonnet granite associated with the URL Mine-by tunnel excavation.

Parameters	Symbol	Unit	Value
Young's modulus	E	GPa	60
Poisson's ratio	ν	-	0.2
Uniaxial compressive strength	σ_{ci}	MPa	224
Intact rock tensile strength	σ_{ti}	MPa	7
Geological Strength Index	GSI	-	90
HB constant	m_i	-	28.11
Disturbance factor	D	-	0

The comprehensive in-situ and laboratory testing campaign (e.g., Martin 1997) intended to investigate brittle failure for the assessment of safe and stable conditions for a deep repository for nuclear waste in a very high-quality rock mass with low permeability. The in-situ stress at this location was characterized by maximum principal stress of 60 MPa inclined at 11° to the horizontal and minimum and intermediate principal stresses of 11 and 45 MPa, respectively.

A multiple-stage process of progressive spalling damage, leading to the formation of V-shaped notches at the roof and floor of the tunnel, was observed, with a maximum spalling depth of about 50 cm. Parameters adopted for numerical analyses (e.g., Hajiabdolmajid 2002 and Zhao et al. 2010) were defined based on material properties available from the extensive investigation (Table 1).

3.2 Numerical modelling using HBS model

Numerical analyses have been carried out to prove the capability of HBS to simulate the depth of brittle failure at the Mine-by tunnel. To accurately predict the progressive spalling damage associated with high in-situ stress conditions, a sufficiently fine mesh along the tunnel boundaries is required due to the large stress changes occurring in the elements surrounding the excavations. Therefore, a mesh composed of about 27000 6-noded triangular elements has been adopted (Figure 1).

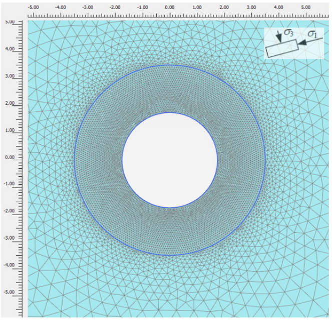

Figure 1. Mine-by test tunnel PLAXIS model: zoomed-in FE mesh.

The field stress in the model has been entered consistently with the magnitude of the in-situ stress reported in the previous section, which considers the actual rotation of 11° of the principal stresses in the cross-section of the tunnel.

The HBS material parameters adopted for the numerical modelling are listed in Table 2, with stiffness parameters consistent with those reported in Table 1. The selection of the other parameters reported in Table 2 requires additional considerations which are detailed in what follows.

Table 2. Rock mass parameters of Lac du Bonnet granite for HBS constitutive model.

Parameters	Symbol	Unit	Value
Young's modulus	E	GPa	60
Poisson's ratio	ν	-	0.2
Intact rock compressive strength	σ_{ci}	MPa	160
Tensile strength reduction factor	α	-	0.2
Geological Strength Index	GSI	-	90
Intact rock HB parameter	m_i	-	15
Disturbance factor	D	-	0
Residual HB parameters	(m_{br} / s_r)	-	1.1 / 0.0003
Rate of softening parameters	$(B_m = B_s)$	-	0.0001
Peak/residual dilation parameter	$(m_{\psi i} / m_{\psi r})$	-	8 / 0
Rate of dilation parameter	$(B_{\psi i})$	-	0.01
Fluidity	γ	d^{-1}	10

The strength parameters in Table 1 refer to the peak strength conditions. However, experience in case studies shows that the stress level at which the spalling damage initiates around a tunnel is lower than peak strength (e.g., Martin et al. 1999) and more in agreement with crack initiation stress level.

This aspect is considered in the selection of strength parameters for the HBS model (Table 2). The HB envelopes plotted in Figure 2a define the boundaries for the fracturing process for the Lac du Bonnet granite (Hoek and Martin, 2014). In Figure 2a the measured in situ stress is denoted by point A, while point B represents the stress after excavation, which is about 160 MPa. These roof and floor stresses fall just above the curve corresponding to strain localization. Therefore, they can be adopted as a representative value for the compressive strength (σ_{ci}) along with a corresponding value of 15 for the parameter m_i, suitable for characterizing the concerning HB envelope.

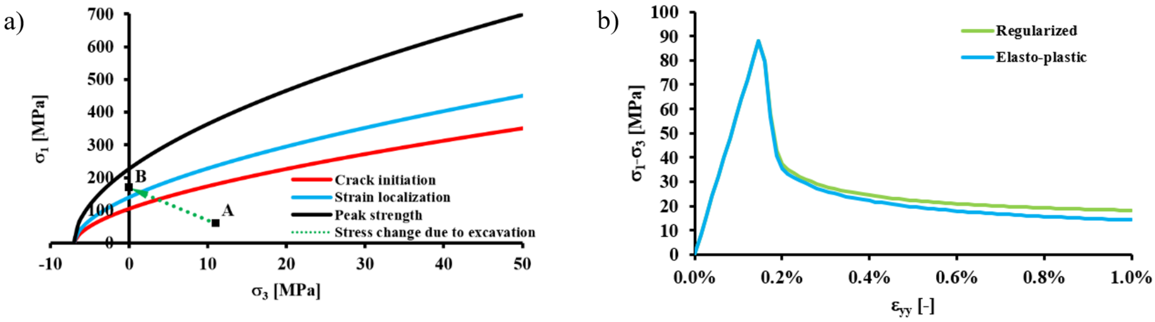

Figure 2. Material behaviour: a) strength envelopes for Lac du Bonnet granite. The changes in the stresses in the rock surrounding the tunnel are also shown as points A and B in this plot (after Hoek and Martin, 2014); b) Stress-strain curve evolution from the peak to the corresponding residual stress and effect of the fluidity γ on the HBS model behaviour: viscoplastic (regularized) versus elastoplastic model for γ value equal to $5d^{-1}$.

Similar considerations have been applied to the definition of the reduction factor α set up consistently with the intact rock tensile strength obtained from laboratory tests (Table. 1).

For the rock mass, the residual strength parameters have been estimated from a residual GSI value of about 30 GSI, following the approach suggested by Cai et al. (2007).

To set up the parameters controlling the rate of softening (defining the strain level range for peak/residual strength transition), the softening evolution has been calibrated based on the stress-strain responses reported in the literature (e.g., Hajiabdolmajid et al. 2002 and Zhao et al. 2010).

As depicted in Figure 2b, a value of γ equal to 5 d^{-1} provides a reasonably close match between viscoplastic and elastoplastic responses at the material point level. Thus, this property value has been adopted to provide a regularization effect for the strain localization in the numerical model.

The dilation angle model parameters ($m_{\psi i}$, $m_{\psi r}$ and B_{ψ}) have been calibrated based on the model adopted by Zhao et al. (2010), where reported dilation angle curves varying with confinement stress showed decreasing peak mobilized values from 60° to 35° and residual dilation angle lower than 15°.

The results of the numerical analysis reported in Figure 3a show that the predicted failed zone matches the in-situ measurements (e.g., Martin 1997) and numerical modelling with both continuum (e.g., Hajiabdolmajid et al. 2002 and Zhao et al. 2010 and discontinuum/hybrid approaches (e.g., Hamdi, 2015) in terms of V-shaped notches and extent of the damage zone.

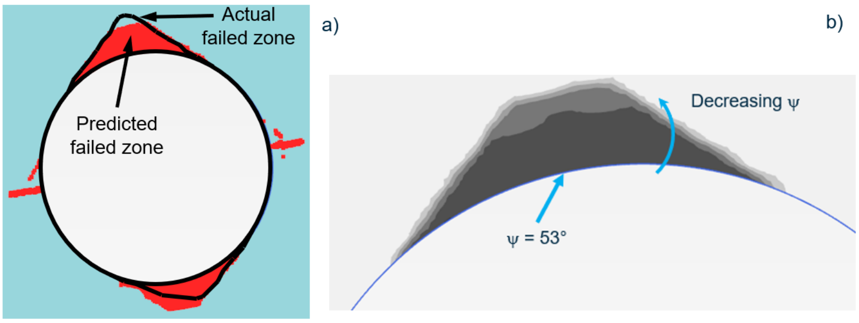

Figure 3. Prediction of the failed zone with HBS: a) V-shaped notches at the roof and floor of the tunnel and extent of the damage zone; b) dilation angle model parameter (m_{ψ}) distribution within the spalled zone.

Figure 3b shows the distribution of the dilation angle in the failure zone: the dilation angle changes within the failure zone where variations in terms of plastic strain and stress confinement conditions are expected when the tunnel is excavated. A decrease from its largest value near the excavation boundary moving away from the excavation surface is depicted. The same value of the dilatant angle in all elastic and plastic zones would be plotted if a constant dilation angle model had been adopted.

4 CONCLUSIONS

Progressive brittle failure around excavation is challenging to be represented in continuum modelling approaches. The HBS model adopted in this paper implicitly captures this phenomenon by introducing a hyperbolic decay of the post-peak response along with a nonlinear dilation model and a viscous regularization technique to mitigate the mesh-dependency of the computed results due to the propagation of strain localization phenomena. This constitutive model, whose parameters can be easily calibrated on available test results, has been validated against data from the URL Mine-by tunnel and the following remarks can be drawn:

- HBS can capture the brittle behaviour around underground excavations in massive rock masses subjected to very high-stress levels by accurately predicting the extent of the damaged zone and, in turn, allowing for an optimization of the excavation geometry and the support and reinforcement requirements, of paramount importance to the designer.
- HBS offers a nonlinear dilation model that describes the variability of the dilation angle with confinement stress and strain. It is thus capable of replicating the nonlinear mechanical behaviour of rocks near the excavation boundary.
- By implementing a viscous regularization technique, HBS mitigates the mesh-dependency of the numerical solution due to the strain localization characterizing the brittle failure process, thus overcoming the general difficulty of capturing this behaviour with continuum models (e.g., Walton et al., 2014).

These considerations emphasize the capabilities of the HBS to provide an augmented constitutive platform to assess the brittle failure risk, thus opening the avenue to more reliable design strategies for underground excavations.

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