The Correct Way to use the Hoek-Brown Strength Criterion for Slope Stability Analysis on the Example of Vals (Tyrol/Austria)

Mariella Illeditsch
pi Geotechnik ZT GmbH, Vienna, Austria

Alexander Preh
Research Centre of Engineering Geology, Institute of Geotechnics, Vienna University of Technology, Vienna, Austria

Johann Thomas Sausgruber
Agriculture, Forestry, Regions and Water Management, Federal Ministry Republic of Austria, Innsbruck, Austria

ABSTRACT: The Hoek-Brown (HB) strength criterion is increasingly used to investigate the stability of slopes. However, it is still partly unclear how this should be implemented for slopes in a correct way. There are two ways to use the HB strength criterion. On the one hand, the HB parameters can be converted into equivalent Mohr-Coulomb (MC) parameters by estimating a suitable range of minor principal stresses. The result is a linear failure envelope. On the other hand, the nonlinear HB failure envelope can be applied directly by calculating apparent MC parameters for each point of the HB failure envelope. The result is a nonlinear failure envelope. Equivalent MC model parameters are usually used in numerical model calculations. However, this approach has some disadvantages. On the example of Vals, where a rock fall of about 117,000 m³ occurred in December 2017, a new method for using apparent MC parameters is presented.

Keywords: Rock Slope, Hoek-Brown Criterion, Stability Analysis, Strength Reduction Method, Continuum Mechanics, Equivalent Mohr-Coulomb Parameters.

1 INTRODUCTION

In Vals (Tyrol/Austria), a rock fall with a detachment volume of around 117,000 m³ occurred on December 24th, 2017. It destroyed parts of the Vals state road L230 and just missed nearby houses. Mapping and measurements by the Austrian Torrent and Avalanche Control (TAC) after the incident indicate a potentially unstable slope area (Figure 1). This needed to be investigated to predict a possible detachment process and volume in the future.

A numerical analysis of the valley flank was performed. Laboratory test results from the nearby Brenner Base Tunnel Materialversuchsanstalt_Strass (2014) are available. The tunnel is not far from the Vals valley flank and explores the same geological rock unit. Therefore, the test results are representative for the Vals valley flank. These results and the mapping data (GSI, joint structure) from the TAC are the basis for the numerical analysis.

A continuum or a discontinuum approach may be chosen for the stability analysis. We initially used the Discrete Element Method DEM (3DEC) for a discontinuum mechanical limit equilibrium study. This failed due to the model size, which required too long computation time or severe simplifications.

(a) (b) (c)

Figure 1. (a) Existing scarp and tension crack (red line); (b) tension crack at the top of the potentially unstable area; and (c) FLAC3D model of the Vals valley flank; red: outline of observed moving area.

So, we used the finite-difference continuum-mechanics program FLAC3D (Itasca Consulting Group) for our stability analysis.

2 GEOLOGICAL SETTINGS

The valley flanks of Vals are composed of rocks of the Bündner Schist group. The rock group includes graphitic phyllites, calcareous phyllites, calcareous quartzite bearing schists and marbles, which originally represent flyschoid metasediments of Mesozoic age (Frisch, 1978). During the Alpine orogeny, these sediments underwent strong multiphase ductile to brittle deformation as a result of stacking of thrust sheets (Lammerer & Weger (1998) and Schmid et al. (2013)) accompanied by metamorphism, leading to greenschist facies (Frank et al., 1987) and Tertiary exhumation in the orogen (Selverstone (1988) and Fügenschuh et al. (1997)).

Figure 2. Outcrop, representative for strongly folded and jointed rock mass of Bündner Schists in the valley of Vals: S—schistosity (magenta), 2—conjugate discontinuities (yellow), 3—fault plane (red).

In terms of tectonic history, the main structural features affecting rock mass properties and failure are (Figure 2): (1) the persistent but folded rock schistosity (s) dipping 30° to the NW; (2) NNW–SSE to N–S striking; and (3) ENE–WSW to E–W striking, steeply inclined joints, and faults. The discontinuity sets (2) and (3) are related to ductile–brittle deformation in the context with Brenner normal fault (Fügenschuh et al., 1997). The discontinuities mentioned are very persistent.

From a geological point of view, the existing rock mass is inhomogeneous and anisotropic. Soft rocks such as phyllites are intercalated with hard rocks of calcareous to quartzite-bearing schists and marbles. Hence, the uniaxial strength varies from less than 25 MPa to more than 100 MPa.

On the larger scale, these anisotropic conditions remain the same with depth, so that one can speak of ‘homogeneous anisotropy’. To overcome this anisotropy, a continuum mechanical approach was assigned. The rock mass outcrops are described by applying the GSI chart for flysch sediments (Marinos & Hoek, 2000). According to that, the rock mass in Vals represents a GSI in the range between 32 and 36.

3 METHOD

A limit equilibrium study was conducted to assess the stability of the valley flank after the 2017 event and to verify the potentially unstable area (Figure 1). This was done in two ways, using (1) equivalent strength parameters and (2) apparent (‘local’) strength parameters.

FLAC3D provides the possibility to calculate safety factors by applying the Strength Reduction Method SRM (Dawson et al., 1999). In this process, the shear strength of the material is gradually reduced to bring the slope to a state of limit equilibrium. The limit equilibrium can be determined using the Mohr-Coulomb (MC) or the Hoek-Brown (HB) criterion.

(1) Using the MC criterion, (equivalent) strength parameters c and φ are assumed to be constant for the considered homogenous region. The equivalent MC envelope is one straight line for the entire homogenous region. It cannot fit the HB curve equally well at all depths (i.e., for all σ_3). For lower and higher σ_3 ranges, the equivalent MC parameters may overestimate the ultimate shear strength compared to the HB curve.

(2) Using the HB criterion, apparent MC parameters (c_c and φ_c) are determined for each individual numerical zone (with variable σ_3). Thus, they are to be considered as ‘local’ parameters, i.e., they are different in each zone, depending on σ_3 (Figure 3).

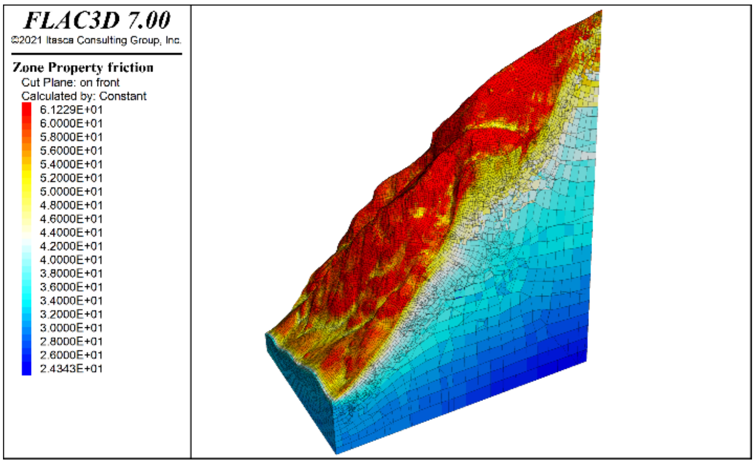


Figure 3. Contour plot of the apparent (local) friction angle [deg], determined for each zone according to the minor principal normal stress σ_3.

The advantage of ‘local’ over equivalent MC parameters has already been demonstrated in the literature. Li et al. (2007) investigated the accuracy of using equivalent MC parameters to estimate the factor of safety. Especially for steep slopes, using equivalent MC parameters leads to poor estimates of safety factors and poor predictions of detachment volumes. The problem lies in the required estimation of a suitable range for minor principal stresses (σ_3) over the ‘slope height’ (i.e., the vertical distance from the ground surface to the shear plane).

Therefore, the HB criterion was used to determine the limit equilibrium with the SRM. However, the SRM with HB material requires a local approximation with the MC criterion (apparent MC parameters). The factor of safety calculated in this way cannot be directly used to calculate the HB parameters for the limit equilibrium state.

The SRM leads to a model with different MC parameters in each numerical zone (Figure 3). It does not lead to the same HB parameters for the whole model. However, they are required for prediction calculations. The challenge is to find those HB parameters that lead to the different apparent MC parameters, as shown in Figure 3. In other words, the challenge is to find the HB parameters of the HB envelope for the limit equilibrium state derived by SRM.

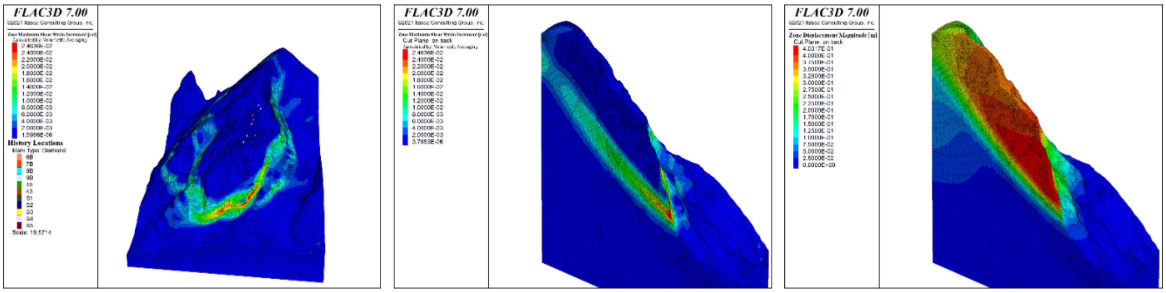
This is achieved by adjusting the geological strength index GSI and/or the disturbance Factor D. Adjustment of these parameters is plausible based on the following considerations: (1) Based on the statement in Hoek's GSI chart (Marinos & Hoek, 2000), it is more realistic to consider a range of GSI rather than a single value; and (2) Since the rock mass can be assumed to have been disturbed by past slope movements, the disturbance factor may be increased.

The laboratory parameters m_i = 12, σ_{ci} = 45.8 MPa, and E_i = 30 GPa are kept constant.

Since this is an approximation, the derived values of GSI and D should be optimized. To calibrate our model, we performed a concordance check according to Mergili et al. (2017). For a detailed description of the procedure, please refer to Illeditsch et al. (2022).

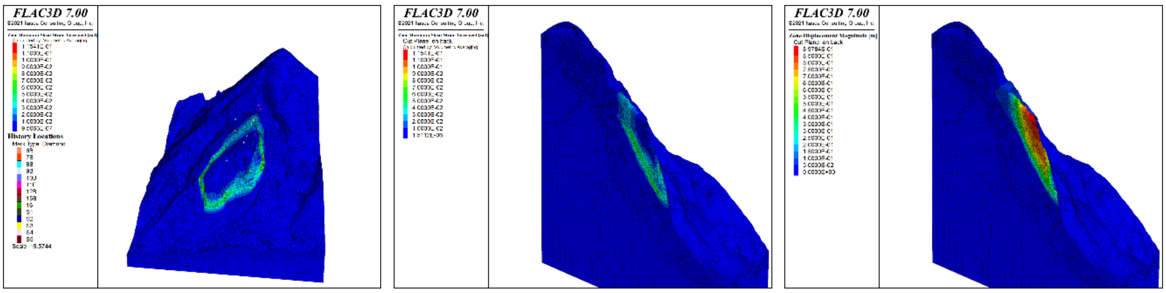
4 RESULTS OF THE STABILITY ANALYSIS

For the stability analysis with (1) equivalent strength parameters, the 'slope height' was estimated to be 80 m with respect to a possible slope movement. The factor of safety of the analysis with equivalent MC parameters at 80 m is 1.47 (Figure 4).



(a) (b) (c)

Figure 4. Model with (1) equivalent MC parameters (h = 80 m), FoS = 1.47: (a) contour plot of the shear strain increment; (b) section of the shear zone; and (c) section of the moving area (displacement magnitude).



(a) (b) (c)

Figure 5. Model with (2) apparent MC parameters, FoS = 1.21, GSI = 34, D = 0.35: (a) contour plot of the shear strain increment; (b) section of the shear zone; and (c) section of the moving area (displacement mag.).

We also investigated how different 'slope heights' for calculating the (1) equivalent MC parameters affect the calculation results. The results of Li et al. (2007) were confirmed by our calculations: the models show too large unstable areas, which are not observed in nature (compare with Figure 1), and too high safety factors.

The stability analysis with the HB material model and (2) apparent MC parameters resulted in a safety factor of 1.21. However, the safety factor calculated in this way cannot be used directly to calculate the HB parameters for the limit equilibrium state. To find the HB parameters of the HB envelope for the limit equilibrium state, we adjusted the disturbance factor D from 0 to 0.37 (with a remaining GSI of 34). Calibration of the GSI and D via concordance check (Mergili et al., 2017) yielded 34 and 0.35, respectively. The calibrated strength parameters were used to predict displacements when the factor of safety was just below 1 (state of limit equilibrium, Figure 5).

A continuous shear band is formed in both models. Both models show the failure mechanism slope creep (Poisel & Preh, 2004), i.e., the continuous decrease of displacements with depth. Based on the extent and depth of the shear band in Figure 4, the movement can be classified as deep-seated landslide. The volume of the calculated detachment (based on the shear band) in the model with (1) equivalent MC parameters (Figure 4) is about 6.000.000 m³, compared to about 470.000 m³ in the model with (2) apparent MC parameters (Figure 5).

5 DISCUSSION

The structural failure of the Vals valley flank in 2017 was a wedge failure. In such a case, the question arises whether a stability assessment using continuum mechanical (smeared) methods is appropriate. From a geological point of view, the Vals rock mass is inhomogeneous and anisotropic. For this reason, a discontinuum mechanical calculation (DEM with 3DEC) was initially applied. In the case of the Vals valley flank, however, a DEM calculation is not feasible or only feasible with strong simplifications. The extension and anisotropy of the rock face require an increase in the joint spacing or a combination of joint orientations (Figure 6).

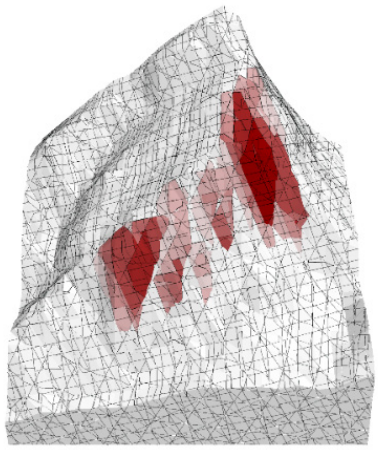


Figure 6. 3DEC simplified rigid block model with displacements ≥ 1m (red). (Preh et al., 2022)

On a larger scale, these heterogeneous and anisotropic conditions remain the same with depth. Therefore, we can speak of 'homogeneous conditions' at the slope scale.

In continuum mechanical models, it is state of the art to describe heterogeneous rock masses such as flysch using the HB criterion (Marinos & Hoek, 2000). The manipulation of both GSI and D is plausible. It is more realistic to consider a range of the GSI rather than a single value. In addition, we can assume that the rock mass was disturbed by stress relief after the Würm glaciation followed by initial slope movements. GSI and D are also excellent for calibrating models.

In our discontinuum mechanical and continuum mechanical calculations, the models each consist of a homogeneous region (e.g., same joint spacing/material properties throughout the model). It was not possible to back-calculate the 2017 event using the homogeneous models. Therefore, we can assume that the event was caused by a local weak zone or a water-bearing layer within the rock mass. However, such conditions could not be mapped in the scarp area.

Our investigations show that a linear material model such as that of MC is poorly suited to represent both the brittle fracture behavior of rock at lower and the ductile behavior at higher lateral stresses σ_3. The same problem exists when converting HB parameters to equivalent MC parameters. A linear failure envelope is therefore a poor approximation to natural conditions. The HB criterion with its curved failure envelope is more appropriate. On the other hand, the HB criterion requires the GSI to be determined by field mapping. In addition, the HB criterion is poorly suited for limit equilibrium studies because the SRM cannot be applied directly. In numerical models, this weakness is addressed by introducing the apparent MC parameters. The challenge is to convert the apparent MC parameters back to HB parameters. The presented method shows a feasible way to do this.

6 CONCLUSIONS

The presented method eliminates the difficulty of estimating a suitable range for minor principal stresses (σ_3) using the 'slope height'.

For the present stability analysis, it was not possible to back-calculate the 2017 structural wedge failure using the HB criterion. However, it was possible to verify the area currently most at risk of failure based on field mapping. This was not possible using equivalent MC parameters, only apparent MC parameters. Using equivalent MC parameters results in a failure mechanism that is not observed in nature, and a higher factor of safety!

Numerical methods provide safety factors using the SRM, which so far can be applied only to MC parameters, but not to HB parameters. The presented method for calculating HB parameters from the distribution of different apparent MC parameters in each zone by manipulating GSI and D is a promising approach. This enables true limit equilibrium studies and prognostic calculations using the HB criterion with continuum mechanical numerical methods.

REFERENCES

Dawson, E. M., Roth, W., & Drescher, A. (1999). Slope Stability Analysis by Strength Reduction. *Géotechnique, 49* (6), 835-840.

Frank, W., Höck, V., & Miller, C. (1987). Metamorphic and tectonic history of the central Tauern Window. In H. W. Flügel & P. Faupl (Eds.), *Geodynamics of the Eastern Alps* (pp. 34-54). Deuticke.

Frisch, W. (1978). Gradierte Serien am Tauernwestende - Zentralanstalt für Meteorologie und Geodynamik. *Geologischer Tiefbau der Ostalpen, 230*, 23-24.

Fügenschuh, B., Seward, D., & Mancktelow, N. S. (1997). Exhumation in a convergent orogen: the Western Tauern Window. *Terra Nova 9* (5-6), 213-217.

Illeditsch, M., Preh, A., & Sausgruber, J. T. (2022). Challenges Assessing Rock Slope Stability Using the Strength Reduction Method with the Hoek-Brown Criterion on the Example of Vals (Tyrol/Austria). *MDPI Geosciences* (Special Issue). https://doi.org/https://doi.org/10.3390/geosciences12070255

Lammerer, B., & Weger, M. (1998). Footwall uplift in an orgencic wedge: the Tauern Window in the Eastern Alps of Europe. *Tectonophysics, 285 (3-4)*, 213-230.

Li, A. J., Merifield, R. S., & Lyamin, A. V. (2007). Stability charts for rock slopes based on the Hoek–Brown failure criterion. *International Journal of Rock Mechanics & Mining Sciences, 45*, 689-700.

Marinos, P., & Hoek, E. (2000). GSI – a geologically friendly tool for rock mass strength estimation. GeoEng 2000, Melbourne.

Materialversuchsanstalt_Strass. (2014). *Laborversuchsergebnisse BBT*.

Mergili, M., Fischer, J. T., Krenn, J., & Pudasaini, S. P. (2017). r.avaflow v1, an advanced open-source computational framework for the propagation and interaction of two-phase mass flows. *Geoscientific Model Development, 10* (2). https://doi.org/10.5194/gmd-10-553-2017

Poisel, R., & Preh, A. (2004). Rock slope initial failure mechanisms and their mechanical models. *Felsbau, 22*, 40-45.

Preh, A., Illeditsch, M., & Sausgruber, J. T. (2022). Diskrete vs. verschmierte Modellierung von Felswänden oder wo sind die Anwendungsgrenzen des HB-Kriteriums. 51. Geomechanik-Kolloquium Tagungsbeiträge, TU Bergakademie Freiberg.

Schmid, S. M., Scharf, A., Handy, M. R., & Rosenberg, C. L. (2013). The Tauern Window (Eastern Alps, Austria): a new tectonic map, with cross-sections and a tectonometamorphic synthesis. *Swiss Journal Geoscience, 106*, 1-32.

Selverstone, J. (1988). Evidence for east-west crustal extension in the Eastern Alps: implications for the unroofing history of the Tauern Window. *Tectonics, 7* (1), 87-105.