Practical estimation of veinlets shear strength properties in hypogene rock mass

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ABSTRACT: Structures present in rock masses have a significant importance on strength and deformation of the rock mass that govern the rock mass' performance in underground mining. Although important progress has been made in these last decades, data on their geomechanical properties is still limited. Furthermore, the majority of studies on joints characterization are connected to rock slopes, open structures and / or with soft infilling material, and low confinement stress conditions; while in underground hypogene rock mass, minor structures are generally sealed, with fillings not necessarily categorized as soft, and variable magnitude and orientation of the major stresses defined by the mining excavations sequences. This paper presents a practical approach to estimate the veinlets shear strength properties on hypogene rock mass based on rock mechanics tests results and Barton Bandis criterion, corresponding mainly to sealed veinlets with fillings with higher strength than those usually found in open pit mining.

Keywords: Veinlet's strength properties, rock mass characterization, Barton Bandis criterion.

1 INTRODUCTION

All rock masses contain discontinuities such as veinlets, bedding planes, joints, shear zones and geological faults. At shallow depth (low confining stress) potential failure of the intact rock material is minimal and the behavior of the rock mass would be controlled by joints, shear zones and faults. On the other hand, under high stress condition, minor structures are sealed with different infilling materials that control the rock mass behavior. In deeper mines, the challenge is to characterize a hypogene rock mass, defined by welded veinlets with infills having different strengths.

The presence of infillings can have a very significant impact on the strength of defects. The effect of infilling on shear strength will depend on both the thickness and the mechanical properties of the infilling material. It is important that infillings are well identified, and appropriate strength parameters are estimated to be used for underground stability analysis and design. This veinlets characterization will impact in fragmentation, galleries and drifts stability and caveability among others.

The aim of this paper is to present a practical approach to estimate the veinlets shear strength properties of hypogene rock mass based on rock mechanics tests results and Barton Bandis criterion. The approach is mainly applied to sealed veinlets with infilling material with higher strength than those usually can be found in open pit mining. This work has been developed to be implemented on hypogene environment in underground excavations, high stress conditions and cannot be used in a weathered and jointed rock mass.

2 HYPOGENE ROCK MASS

The primary rock mass of a Porphyry Copper Systems can be defined as a large volume of a hydrothermally altered lithology intersected by a dense stockwork of mineralized cemented veins with a persistence from centimetric to metric scale and thickness from less than 1mm up to few centimetres with the majority of veins having less than 2mm of thickness as shown in Figure 1a.

This rock mass can be emplaced in a hypabyssal environment, and it is still located at depth, hence it is a fresh, unweathered and impermeable rock mass; from the geomechanical point of view it is characterised by higher intact rock strength and absence of open joints. The geomechanical behaviour is mostly controlled by two main features:

- Type and intensity of the hydrothermal alteration that is controlling the intact rock strength, i.e., the silicification can increase the rock strength, potassic alteration is associated with high strength, whereas argillic alteration decreases the rock strength.
- Orientation and mineral infill of cemented veins. Most of the geomechanical instabilities in mining operations are structurally controlled and would be influenced by the orientation of the intersection between structure and excavation and the strength of the mineral infill, i.e., quartz filled veins will be strengthening the rock mass, whereas gypsum or sericitic infill would be downgrading the rock mass strength. Figure 1 shows some typical examples of different infilling materials.

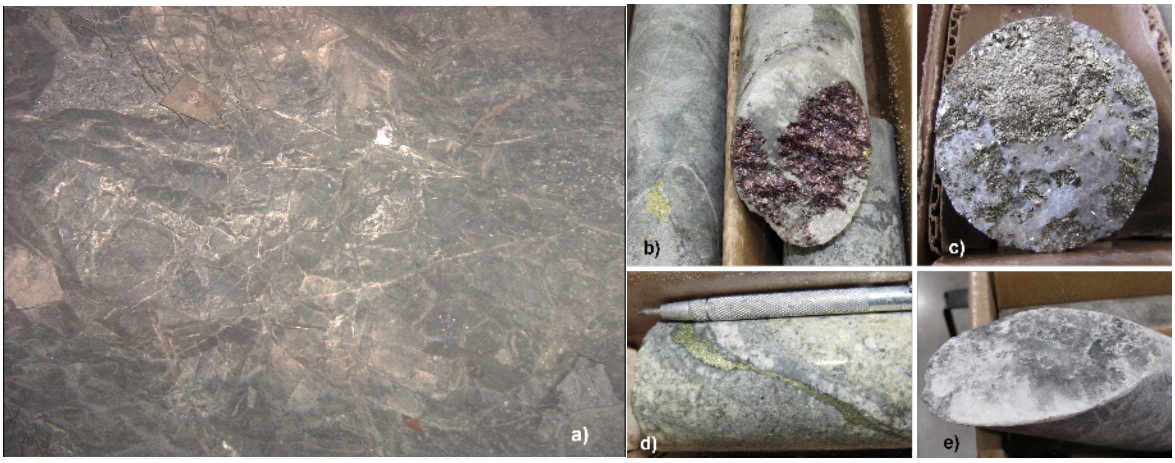


Figure 1. Primary rock mass and typical examples of cemented and open cemented veinlets with several infilling minerals. a) Stockwork that mainly shows anhydrite veinlets, with very weak or no halo alteration (spacing between bolts is close to 1 m). b) Bornite-anhydrite-chalcopyrite infilling materials, c) Pyrite-anhydrite infilling materials, d) Chalcopyrite cemented veinlets and e) Anhydrite infilling materials (modified from Russo et al. 2020).

3 VEINLETS SHEAR STRENGTH ESTIMATION

It should also be noted that although the Mohr-Coulomb criterion is the most commonly used in practice, it ignores the non-linearity of the shear strength failure envelope. There are several examples of non linear envelope definition (see Ladanyi & Archambault 1970, Barton 1973, 1976, 1980, 1987, 1985, Barton & Choubey 1977, Barton & Bandis 1993, Huang et al. 1993, Bobet & Einstein 1998, Vásárhelyi & Bobet 2000, Wang et al, 2003, Asadollahi & Tonon 2010, Sanei et al, 2015 among others). To be valid, the shear strength parameters should be tested for a range of normal stresses corresponding to the field condition. For this reason, special care must be taken when considering the “typical” values reported in the geotechnical literature, because if these values have been determined for a range of normal stresses different from the case being studied, they might be not applicable. In this regard, it must be noted that many of the “typical” values mentioned in the geotechnical literature correspond to open structures or structures with soft/weak fillings under low normal stresses. Though these “typical” values may be useful in the case of open pit design, they may not be applicable to the case of underground mining, where the confining stresses are substantially larger than in the case of open pit slopes.

To assess the shear strength of cemented joints or veinlets present in a primary rock mass, the following methodology is recommended based on triaxial tests and geotechncial characterization:

(a) A scale ranging from 5 to 10 cm can be considered, and results from a series of triaxial and UCS tests for which failure of the sample took place along pre-existing veinlets (Type D failure according to Russo & Hormazabal, 2006) can be examined. The Goodman’s approach (1989) can be applied for these triaxial tests. According to this method, principal stresses obtained by failures occurring along pre-existing veins during triaxial tests can be used to calculate the normal stress σ_n and shear stress τ acting along the discontinuity from the values of σ_3 and σ_1 given by the triaxial tests (see Figure 2).

(b) Joint Condition Strength (JCS) and Joint Roughness Condition (JRC) indexes can be obtained from geotechnical core logging. Normally, JCS varies in ranges going from 80 MPa to 250 MPa and JRC index varies between 5 and 20. The basic friction angle (ϕ_b) for the infilling material can be reasonably assumed between 25 and 35°.

(c) In agreement with (a) and (b), shear strength can be assessed according to the Barton-Bandis criterion as:

$$\tau_{max} = \sigma_n \tan\left(JRC \cdot \log\left(\frac{JCS}{\sigma_n}\right) + \phi_r\right) \qquad (1)$$

Equation (1) allows to define the envelope strength, which is valid at a scale of 5 to 10 cm and does not consider the scale effect (see Figure 3).

(d) Grouping results according to in-filling material with similar mechanical behaviour were appropriate for shear strength assessment. Furthermore, evaluated in-filling corresponds to highly frequent structural sets. This approach allows the veinlet envelope to be adjusted to consider the cohesion according to the infilling material, so that the strength at a scale of 5 to 10 cm is given by:

$$\tau_{max} = \sigma_n \tan\left(JRC \cdot \log\left(\frac{JCS}{\sigma_n}\right) + \phi_r\right) + c \qquad (2)$$

Equation (2) allows to define the envelope strength for different infilling materials, which is valid at a scale of 5 to 10 cm.

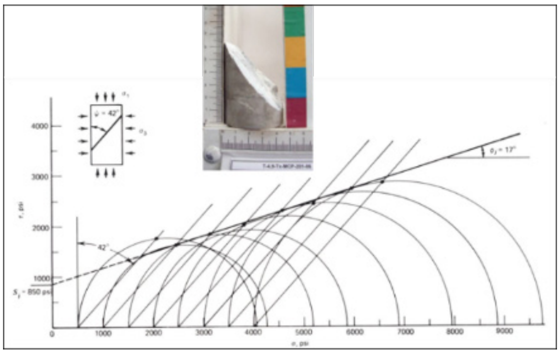


Figure 2. Use of triaxial compression tests to define the shear strength of veins or other defects with infilling materials (modified from Goodman, 1989).

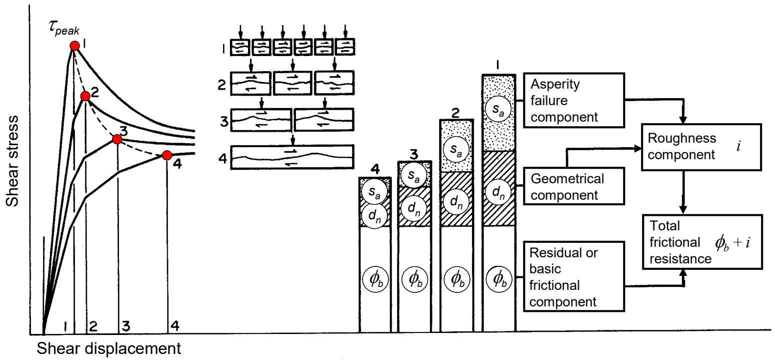


Figure 3. Summary of scale effects over shear strength components of non-planar defects. ϕ_b is the basic friction angle, d_n is the peak dilation angle, S_a are surface asperities, and i is the roughness angle (modified from Barton, 1980).

(e) To take into account the scale effect, "drift scale" veinlets are considered as those that have trace lengths ranging from 5 to 10 m, and "larger scale" veinlets as those with trace lengths ranging from 50 to 100 m, assuming that the scale effect of the different parameters that define the shear strength can be treated independently, as follows:

- Considering the above in terms of the JCS index scale effect. The upscaling equation is shown in (3):

$$JCS_n = JCS_o \left(\frac{L}{L_o}\right)^{-0.03JCSo} \tag{3}$$

- Considering the above in terms of the JRC index scale effect. The upscaling equation is shown in (4):

$$JRC_n = JRC_o \left(\frac{L}{L_o}\right)^{-0.02JRCo} \tag{4}$$

- There is not much background information regarding the cohesion scale effect for veinlets with strong in-filling material, but according to Karzulovic et al 2001, to assume a decrease in cohesion in approximately 50% when going from testing areas of approximately 25 cm^2 to areas of approximately 450 cm^2, as a first approximation, the suggestion is that this scale effect could be evaluated as:

$$c_L = c_{L_o} \left(\frac{L}{L_o}\right)^{-0.5} \tag{5}$$

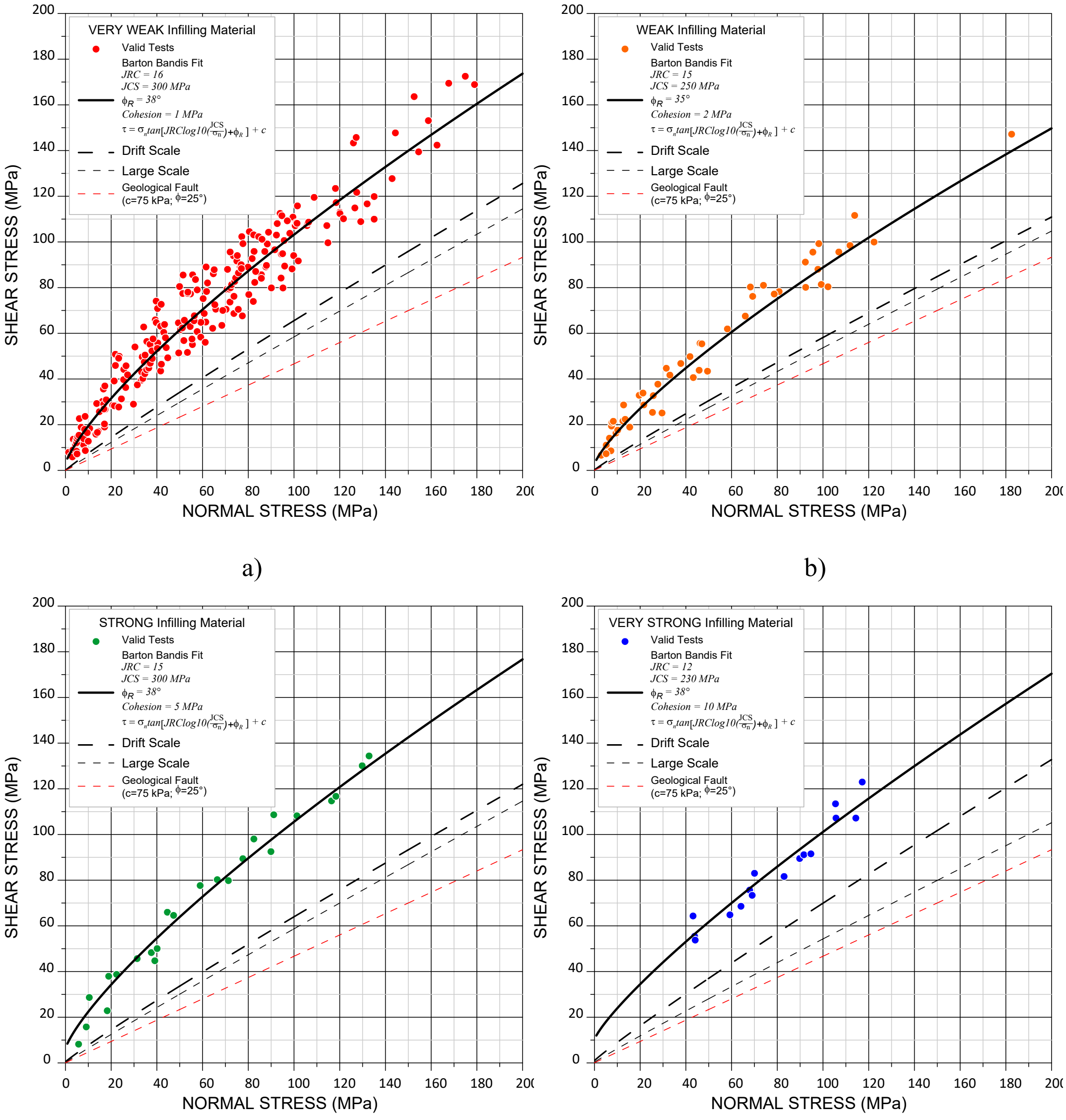
where c_L is the cohesion for an L trace length, and c_{Lo} is the cohesion measured for a trace length of length L_o.

(f) Based on all of the above, the shear strength envelopes of veinlets with very strong infilling materials (quartz among others) to very weak infilling materials (carbonate and gypsum among others) can be considered. Figure 4 shows an application of real tests using this approach.

4 CONCLUSIONS AND FINAL COMMENTS

The methodology presented is a practical approach based on well known methodologies to estimate the veinlets shear strength properties on hypogene rock mass under high stress conditions. The strength envelopes derived using this methodology can be applied for stability analysis in a medium to high confining stress condition. For a low confining stress (σ_3 < 1 MPa) analysis (i.e. wedge analysis among others) this methodology can be applied using engineering judgement and comparing resulting values with direct shear tests results.

This approach can be improved by logging veinlet thickness that can be one of the factors affecting the variability on the tests results presented in this work.



a)

b)

c)

d)

Figure 4. Shear strength envelopes of veinlets. a) Very Weak infilling material (mainly Gypsum, Calcite, Carbonate), b) Weak infilling material (mainly Chalcopyrite, Ahnydrite, Bornite), c) Strong infilling material (mainly Pyrite, Magnetite), d) Very Strong infilling material (mainly Quartz). Note: Drift-scale = 10m, Large-scale = 100m. Also is included as a reference the envelope for a geological fault (cohesion of 75 kPa and friction angle of 25°).

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REFERENCES

Asadollahi P. and Tonon, F. (2010): Constitutive model for rock fractures: revisiting Barton's empirical model. Engineering Geology, vol. 113, pp. 11-32.

Barton, N. (1973): Review of a new shear strength criterion for rock joints. Eng. Geol. 7:287-332.

Barton, N. (1976): The shear strength of rock and rock joints. Int. J. Rock. Mech. MIN. Sci. 13:255-279.

Barton, N. (1980): Estimation of in situ joint properties, Nasliden Mine, Applications of Rock mechanics to Cut-and-fill Mining, Lulea, Sweden, IMM, London.

Barton, N. (1995): The influence of joint properties in modeling jointed rock masses, Proc. 8th ISRM Congress, Tokyo, Japan, Vol. 3, A. A. Balkema.

Barton, N. (1987): Discontinuities, Chapter 5, GROUND ENGINEER'S REFERENCE BOOK, de F. G. Bell (editor), Butterworths, London.

Barton, N. & Choubey, V. (1977): The shear strength of rock joints in theory and practice. Rock Mech, Vol. 10.

Barton, N. & Bandis, S. (1993): Some effects of scale on the shear strength of joints: Int. J. Rock Mech. Min. Sci. 6 Geomech. Absr. Vol. 17, pp. 69-73.

Bobet, A., Einstein, H.H. (1998). Fracture coalescence in rock-type materials under uniaxial and biaxial compression. Int. Rock Mech. Min.; vol. 7: 863–888.

Goodman R E (1989) Introduction to rock mechanics Second Edition (Wiley New York).

Huang, X., Haimson, B.C. Plesha, M.E. and Qiu, X (1993): An investigation of the mechanics of rock joints – part I: laboratory investigation. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, vol. 30, pages 257-269.

Karzulovic, A., Brzovic, A., Pereira, J., Marambio, F., Russo, A, & Cavieres, P. (2001): Propiedades Geomecánicas de las Estructuras del Macizo Rocoso Primario de Mina El Teniente. XII Simposium de Ingeniería en Minas, Departamento de Ingeniería en Minas. USACH.

Ladanyi, B. & and Archambault, G. (1970): Simulation of the shear behavior of a jointed rock mass. Proceedings, 11th, Symposium on Rock Mechanics (AIME), pp. 105-125.

Sanei, M. Faramarzi, L. Fahimifar, A. Goli, S. Mehinrad, A. and Rahmati, A. (2015): Shear strength of discontinuities in Sedimentary rock masses based on direct shear tests. International Journal of Rock Mechanics and Mining Sciences, vol. 75, pages 119-131.

Russo A and Hormazabal E (2016): A methodology to select valid results from lab tests to estimate properties of intact rock with microdefects Proceedings of the 50th US Rock Mechanics/Geomechanics Symposium. Houston, Texas. June 2016 (American Rock Mechanics Association. ARMA).

Russo A, Vela I and Hormazabal E (2020): Quantification of the intact geological strength index for rock masses in hypogene environment Proceedings of MassMin 2020, Eight International Conference on Mass Mining. Santiago, Chile. December 9–11, 2020.

Vásárhelyi & Bobet A. (2000). Modeling of crack initiation, propagation and coalescence in uniaxial compression. Rock mechanics and Rock Engineering. Vol. 33: 119 –139.

Wang, J.G., Ichikawa, Y and Leung, C.F (2003). A constitutive model for rock interfaces and joints. Int. J. Rock. Mech. MIN. Sci. 40:41-53.