Spatial modeling of rock strength heterogeneity and anisotropy using Universal Discontinuity index (UDi)

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ABSTRACT: Rock strength anisotropy and heterogeneity are two key properties of various types of rocks. Discontinuities are the most significant factor on the anisotropic and heterogeneous behavior of rock mass strength. In this study, Universal Discontinuity index (UDi) applied to spatial modeling of the anisotropic and heterogeneous behavior of rock mass due to presence of discontinuities around a tunnel for the prediction of the geometry of over-excavation. UDi is based on the state of the art of the rock mass characterization systems and rock failure criteria. More precisely, UDi combines the quantitative and measurable parameters of the discontinuity network including volumetric discontinuity intensity (P32), the orientation of the discontinuities, vectorial based criteria of Warburton for kinematic rock block failure, and Mohr-Columb criteria for shear failure analysis. The results of this are validated through comparison with observed over-excavation at field data.

Keywords: Rock strength anisotropy and heterogeneity, Universal Discontinuity index, rock block failure, shear failure, over-excavation.

1 INTRODUCTION

Rock strength heterogeneity and anisotropy are the most important mechanical properties of rock mass. The presence of discontinuities causes rock masses to be largely heterogeneous and anisotropic, and inelastic (Jing & Stephenson, 2007), as they behave quite differently from the corresponding intact matrix. Therefore, the role of discontinuities on the heterogeneous and anisotropic behavior rock mass, and their spatial variation should be investigated as part of safety assessments for any rock engineering project.

Several approaches have been developed to evaluate of the strength and deformability of excavated fractured rock masses, which can be categorized into direct and indirect approaches. The direct approaches are based small scale laboratory tests and large-scale in situ tests. While small scale test cannot represent the discontinuities within jointed rock masses in the field, the large-scale in situ tests are performed to measure mechanical properties of fractured rock masses, but this approach is time consuming and expensive. In the indirect approach, analytical solution, back analysis, rock block theory, and numerical simulations are used. Based on field measurements during and/or after construction, back analysis can be used to estimate the mechanical behavior of fractured rock mass (Cai et al. 2007). However, back analysis cannot be used to provide valuable design input parameters in the feasibility study stage. Block theory (Goodman and Shi, 1985) and vector analysis (Warburton, 1981) are widely used for assessment of block failure analysis around underground excavation. Numerical simulation has been used as an alternative approach, which allows to capture the complicated behavior of fracture systems and capture interactions between fractures and intact rock (Wang et al., 2020, Hekmatnejad et al., 2022). Empirical rock mass classifications have been widely used to estimate rock mass quality (Bieniawski 1973; Palmstrøm 1995; Barton 1974). There are several rock mass classification systems including the Rock Mass Rating (RMR) system (Bieniawski, 1973), the Q-System (Barton et al., 1974), the Rock Mass index (RMi) (Palmstrom, 1995), and the Geological Strength Index (GSI) system (Hoek and Brown, 1997). All these rock mass classification systems are qualitative or semi-quantitative, subjective and with no unit. Moreover, they do not consider the mutual interactions between stress field and discontinuities. Therefore, the assumption of estimating the strength of a structurally complex fractured rock mass using a single index is still debated. However, they provide valuable information related to the quality of the rock mass.

In this study it is considered to evaluate the spatial variation of the rock strength and its anisotropy using Universal Discontinuity index (UDi) presented by Hekmatnejad et al., (2022). In the formulation of UDi, it is assumed that that the discontinuity parameters, in-situ stress field and their mutual interactions are the most influential causative factor on a wide variety of discontinuous rock mass behaviors. The UDi is based on well-defined discrete fracture network parameters, in-situ stress field, and the mechanical law of frictional sliding equilibrium for rock material. The results of the study verified with the spatial variation of the observed over-excavations around a tunnel.

2 UNIVERSAL DISCONTINUITY INDEX (UDi)

The Equation shows the formula of Universal Discontinuity index for geo-mechanical engineering designs:

$$\mathbf{UDi} = P_{32}\ (m^{-1}) \times [1 + w_1 C.V_{\text{tot-ver}} + w_2\ (N_{AF}/N_{TF}) + w_3(C.V._{\text{ tot-}\sigma 1})] \qquad (1)$$

Where,

- **UDi** is the Universal Discontinuity Index.
- **P_{32}** is the total volumetric fracture intensity (the mean area of fractures per unit volume of rock mass m^{-1}).
- **C.V. $_{\text{tot-ver}}$** is the relative total circular variance which measures the degree of dispersion of discontinuity orientations from the vertical direction.
- **C.V. $_{\text{tot-}\sigma 1}$** is the total circular variance with respect to the direction of a vector which forms an angle of $45^{\circ} + \varphi_w/2$ with maximum principal stress.
- **N_{AF}** is the number of shear active fractures according to frictional Coulomb failure criteria.
    - **N_{TF}** is the total number of fractures within rock mass.
- w1, w2 and w3 are the weighting factors depending on rock engineering design.

It is worth to mention that the value of UDi can be calculated for a discrete fracture network by replacing the area of each single fracture instead of P32 in Equation 1. In addition, the calculation of the circular variance would be more straightforward (See Hekmatnejad et al., 2021) as the complete geometry of the discontinuities is available. The values of the Universal Discontinuity index are minimal in case of optimally oriented discontinuities for tensile failure mechanism, as the tensile strength of the fractured rock mass compared to the compressional strength of rock is relatively unimportant. Figure 1 shows workflow to estimate the UDi.

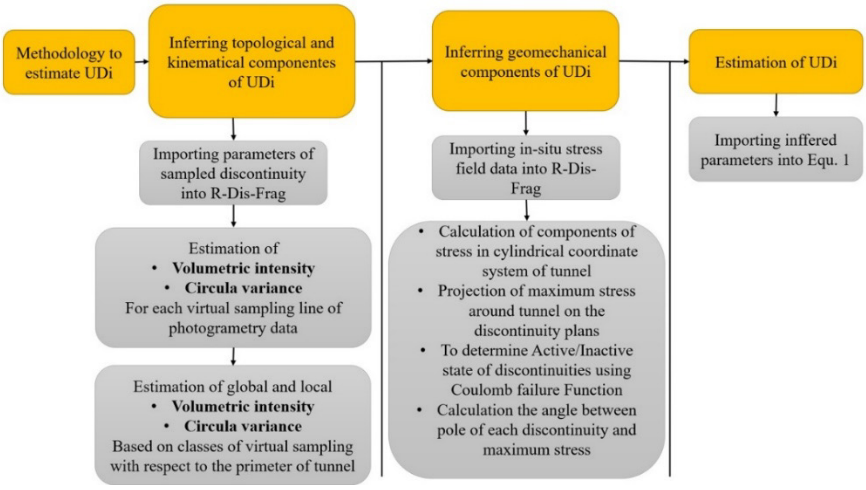


Figure 1. The flowchart to calculate UDi.

It is considered to implement UDi to assess the geometry of the over-excavation around a tunnel of El Teniente mine, Chile. The data was obtained by applying a 3D digital photogrammetry (DTM) system, which makes it possible to characterize discontinuities and over-excavation in the tunnels in 3D (Berzovic and Leon, 2018). The geometrical characterization includes information on the location (X, Y and Z coordinates), diameter and orientation. It is studied 52 sections of a tunnel with a total number of 3452 discontinuities distributed along a 252 meters length of a horizontal excavation. To estimate the parameters of UDi, it is used a 1D virtual sampling technique which permits to estimate volumetric fracture intensity (P32), circular variance, and to calculate effective normal stress and shear stress in the plane of discontinuities and, relative circular variance with respect to the direction of maximum principal stress (see Figure 2). A regular rectangular grid is considered, with 33 cm spacing to sample all tunnel faces to ensure sample representativeness and validity for statistical inference. Since virtual sampling does not impose additional cost, denser networks can be used for sampling. There boreholes can be grouped into 9 classes with respect to the perimeter of a tunnel for local estimation of the UDi. These configuration permits to consider the relative variation between the discontinuities and variable stress field around a tunnel. The average value of each set of boreholes represents the value of UDi for that location. The values of in situ stress and their orientation are shown in Table 1. Assuming the homogenous rock material, considering reverse stress regime which does not coincide with tunnel axis, the maximum stress concentration will occur at right top corner of a tunnel. Figure 3A show the Boxplot of the UDi around a tunnel. According to Figure 3A the most over/excavation will occurred at top, left top corner and left wall of a tunnel. These results are in contradiction with continuum mechanics, but they are generally in accordance with the observed over excavation along a tunnel Figure 3B. This apparent contradiction can be explained by the mutual variation of the tensor of stress and discontinuities around a tunnel which impose the anisotropy and heterogeneity of rock strength.

Table 1. the in-situ stress measurements obtained along the tunnel.

S1 (MPa)	**S2** (MPa)	**S3** (MPa)	**Az1 °**	**Az2 °**	**Az3 °**	**Dip1 °**	**Dip2 °**	**Dip3 °**
59.2	45.3	30.3	135.7	225.0	260.8	5.3	-7.4	80.9
59.1	45.2	30.5	135.4	224.8	262.5	5.5	-7.2	81.0
60.0	45.2	30.5	135.5	224.8	265.1	5.7	-6.9	81.0

Figure 4 shows variation of the components of UDi around a tunnel. This Figure provide insight about the dominant failure modes for each part of a tunnel. The highest values of the P32 corresponds to the top, left top and left wall of a tunnel Figure 4A. According to Figure 4B the probability of the kinematic failure reaches to maximum at left top corner of a tunnel, however, the shear failure mechanism at wall reaches to its minimum value and maximum at walls and top of a tunnel, respectively (Figure 4C). Figure 4D shows the variance of the relative angles between principal components of stress around the tunnel and the pole of discontinuities from 60°.

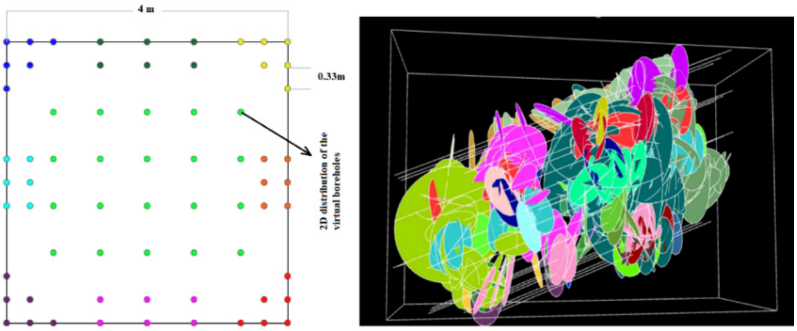
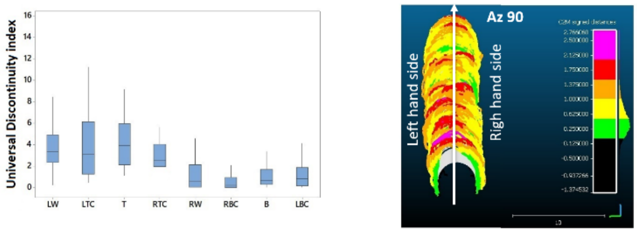


Figure 2. Left: 2D view of the distribution of virtual boreholes in tunnel face. Right: 3D view of the virtual boreholes.



(A)

(B)

Figure 3. A) boxplot of the values of UDi for each position of a tunnel perimeter, B) The mapped over excavation along a tunnel.

Figure 5A shows the variation of the UDi and over-excavation along a tunnel. It is observable that in general the are a good agreement between variational trend of both variables. This confirms that the UDi can be used an index to assess the likelihood and severity of the over-excavation.

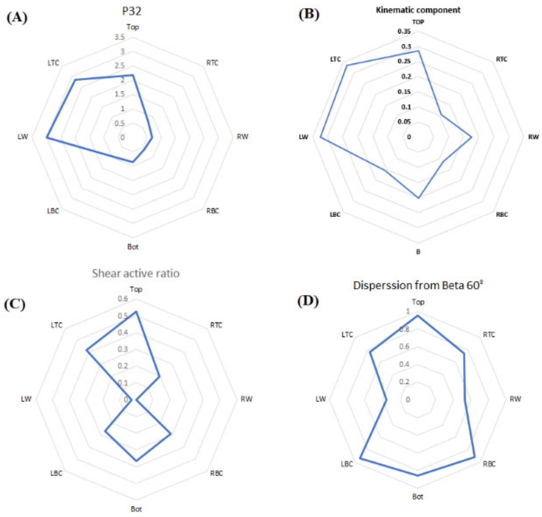


Figure 4. The variations of each factor of UDi with respect to a tunnel perimeter.

To verify the applicability of the UDi, we compared the results of the UDi for each tunnel section, against a RMi for corresponding sections. As one can see there is a strong reverse relationship between these two parameters (See figure 5B). This can be explained through highly negative correlation between P32, rock block volume and RMi as shown in Figure 5C and 5D.

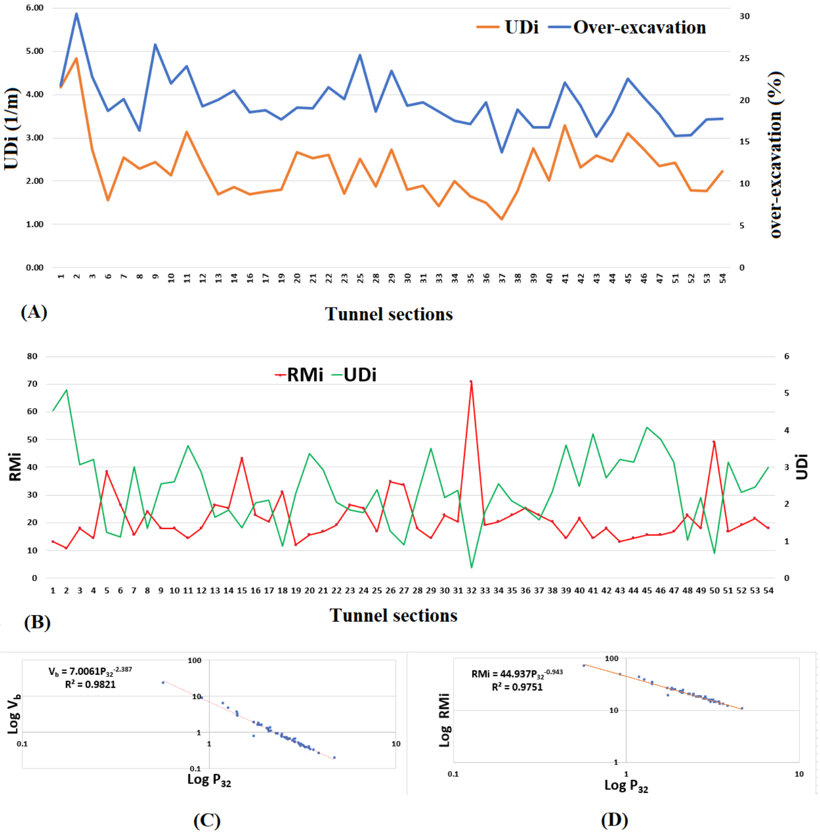


Figure 5. A) The values of the UDi and Over-excavation for each section of a tunnel. B) The relation between the UDi and RMi. C) The scatter plot of the volume of the rock blocks vs. P32. D) The scatter plot of the P32 vs. RMi.

3 DISCUSSION

The calculation results of UDi shows that the UDi is applicable to predict the geometry of over excavations. The consideration of anisotropy and heterogeneity of rock strength for engineering problem with directional features is necessary. In this case the obtained variation of the values of the UDi represent the rock strength anisotropy and inhomogeneity along tunnel advance. The directional UDi with respect to perimeter of the tunnel are obtained to improve the determination of the rock strength anisotropy and inhomogeneity, even at smaller scale, and to enhance the accuracy and efficiency of the prediction of over-excavation. We can determine the UDi in many different directions, such as the directions selected in this study. For the study object of the rock masses in the tunnel excavation of the new El Teniente mine, over-excavation is a crucial engineering problem. Over-excavation occurs in multiple directions, therefore the presentation of a fast and robust approach based on available data than can capture the directional nature of over-excavation phenomenon is primordial. Moreover, the UDi can be considered for the characterization of the rock mass at very specific rock engineering design.

4 CONCLUSION

The main conclusions are presented as follows:

The UDi rating system contains degree of a damage and its interaction with stress field, and the failure criteria, provide information of the heterogeneity and anisotropy of fracture rock mass.

- The heterogeneous and anisotropic nature of rock mass strength is due to the mutual interaction of the discontinuities and stress field.
- The variational geometry of the over-excavation resulted by the interactions between the discontinuities and in situ stress field, captured using UDi system.
- Based on the in-situ stress field of a Tunnel of New El Teniente mine, the maximum expected over-excavation focuses on the top and right top corner of the tunnel. However, in practice the maximum and most frequent over-excavation occurs at top, left top corner and left wall of the tunnel. It is essential that to consider these discontinuities, their interaction with induced stress filed around tunnel and their propensity to trigger kinematic and shear failure be taken into consideration during tunnel construction.
- To study the role of the discontinuities on the heterogeneity and anisotropy of rock strength, we analyzed the geometry of over-excavation of 54 sequences of a tunnel. The P32 is the most significant parameter one the heterogenous and the orientation of the discontinuities with respect to direction of maximum principal stress, and their kinematic states is the important on the anisotropic nature of rock mass strength.

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