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Indicator kriging applied to RMR geomechanical modelling in a Pb-Zn deposit case study

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Abstract

The opening of a mining enterprise requires knowledge of the geomechanical characteristics of the mineral deposit, which will be worked according to the use of parameters of stability and/or resistance of the material, as well as the discontinuities present in the rock. In this study, the Rock Mass Rating methodology was used to propose a geomechanical model in a lead and zinc deposit hosted in the sedimentary rocks of Camaquã Basin, Brazil. A geological model was created using the analysis of 50 drill holes with their geological descriptions, grouped into five lithological units, from base to top: rhythmite, lower sandstone, conglomerate, upper sandstone, and ore. The samples were regularized in composites of three meters in length, and then categorized into the five classes of the RMR system. Classes were estimated for each lithological unit using indicator kriging to obtain a model with the probability of each estimated block belonging to each RMR class, and thus the predominant class probabilities of each block. While it was possible to observe a predominance of class II (good rock) in the conglomerate, lower sandstone and ore, in the upper sandstone and rhythmite class III predominates (fair rock), and a few blocks were classified in class IV (poor rock) and V (very poor rock). Although the geomechanical model demonstrates the quality of the rock mass in general, being indispensable to more detailed studies, it is believed that the model allows greater safety in the classification of the rock mass and later use for slope stability and pit design.

keywords: geomechanical model; indicator kriging; Rock Mass Rating.

1. Introduction

Mineral deposits are characterized by complexity, uncertainty and heterogeneity resulting from the complex geological processes that acted during its formation and evolution (Chen *et al.*, 2017). In the early stages of a mining project, sometimes even before proving the project pre-feasibility, it is necessary to make decisions, such as the mining method to be used for ore extraction. Drilling investigations and *in situ* tests in the exploratory phase provide important information from specific sampling sites. The spatial distribution of these data becomes a useful tool in the reproduction of the variability of ore grades, lithologies and geomechanics quality in order to assist the decision-making process.

1.1 Geomechanical classification systems

There are several systems of geomechanical rock mass classification (Barton *et al.*, 1974; Bieniawski, 1973; Bieniawski, 1989; Wickham *et al.*, 1972), that use parameters of stability and/or resistance of the material, as well as rock discontinuities characteristics. The purpose of these classification methods is to group geotechnical elements into classes that present a similar behavior in order to assist future operational and design processes.

The Rock Mass Rating (Bieniawski, 1973; Bieniawski, 1989) is one of the most widely used systems to estimate the quality of rock masses in mining projects. Over the years, the method has been optimized for applications in different areas and has undergone significant changes in the assessments assigned to different parameters (Bieniawski, 2011;

Celada *et al.*, 2014). Since the project is still in pre-feasibility phase, with only drill hole database information; the version suggested by Bieniawski (1989) was used in the present study. The classification is based on the attribution of weights to the six key parameters that the author considered most important for the behavior of rock masses: (i) uniaxial compressive strength of rocks; (ii) Rock Quality Designation;(iii) joint and bedding spacing; (iv) joint condition; (v) groundwater condition; and (vi) orientation of discontinuities with respect to the opening axis.

1.2 Estimation method

Geostatistics is a science that assumes that the values of regionalized variables are spatially correlated (Isaaks & Srivastava, 1989) and is widely used to obtain value estimates at non-sampled sites. The geostatistical techniques attempt to extract the structural characteristics of the regionalized phenomenon, that is, a correlation function that describes the direction in which the values of the variable are correlated (Huijbregts, 1975). Ordinary Kriging (Matheron, 1963) is the basic estimation method used, but it has several other variations that may be better to use according to the mineral deposit characteristics, or the variable that needs to be estimated. Indicator Kriging (Journel, 1983) stands out among nonlinear methods, and its application is indicated for categorical variables such as the RMR classes. The focus of the IK method is the definition of areas with a greater or lesser probability that a given event will occur, rather than the estimation of the value of the variable, such as Simple and Ordinary Kriging (Oliveira, 2008).

The estimated model contributes to the knowledge of the spatial variation of the geomechanical characteristics, which can help, for example, to design the future slope dimensions according to the different local characteristics (Lana *et al.*, 2010; Madani *et al.*, 2018; Maninoni, 2003; Pereira *et al.,* 2017).

2. Case study

The study area presents approximately 1300 meters in N-S direction and 400 meters in L-W direction located in the southernmost portion of Rio Grande do Sul state, Brazil. The mineral deposit analyzed is inserted in sedimentary rocks of the Camaquã Basin and is constituted basically of medium to coarse sandstone, with occurrence of fine sandstone. The base of the sedimentary sequence of the study area includes rhythm and sandstone packages. At the top of the sequence, clast-supported polymictic conglomerates occur. Locally, these rocks are affected by hydrothermal alteration, with breccias in some points (Fabrício *et al.*, 2017).

3. Materials and methods

The database is consisted of 50 drill holes with lithological description of samples every 3 meters in length. The average spacing between the holes is approximately 100 m and the average depth is 240 m. The arrangement of the holes is shown in Figure 1.

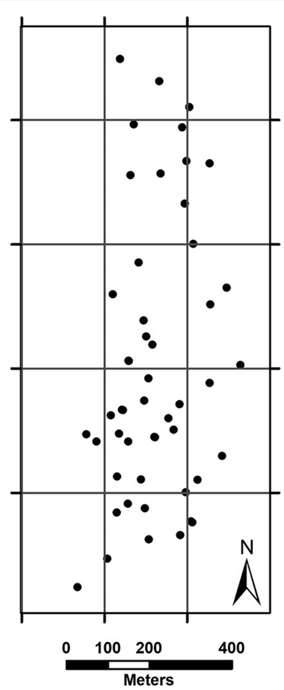

Figure 1 - Location map of drill holes. For information confidentiality request, the coordinates of the area are not displayed in the map.

3.1 Classification parameters

The first step was to perform the calculation of the RMR index for each sample of the database. The RMR index was calculated accordingly to the methodology proposed by Bieniawski (1989), where tables with the weights assigned to the key parameters of the rock are used: (i) uniaxial compressive strength of rocks; (ii) Rock Quality Designation; (iii) joint and bedding spacing; (iv) joint condition; (v) groundwater condition; and (vi) orientation of discontinuities with respect to the opening axis.

3.1.1 Uniaxial compressive strength of rocks

The rock material has the capacity to bear a load up to a certain limit, after which it loses resistance causing its rupture. The rupture value is the limit of the rock resistance and it is this value that is used as reference in geomechanical projects (Vallejo, 2002). The determination of uniaxial compressive strength of intact rock limit was performed with the Point Load Test (Ulusay & Hudson, 1985). The method consists of compressing a rock sample between two conical tips of carbide, which cause the material to rupture. To perform the test, the methodology proposed by the International Society for Rock Mechanics (ISRM) was used.

3.1.2 Rock Quality Designation index (RQD)

Another important parameter to be considered is the RQD, which is a measure of the quality of rock core taken from a borehole (Deere, 1964; Deere & Deere, 1988) and presents the degree of jointing or fracture in a rock mass in percentage. It is defined as the sum of the lengths greater or equal to 10 cm of rock recovered divided by total core run length.

3.1.3 Discontinuity characteristics

The discontinuity spacing parameter refers to the distance between adjacent discontinuities. In this study, the mean spacing between the discontinuities was used, which was determined by dividing the total core run length by the number of discontinuities in the core run.

In the discontinuity condition analysis, the discontinuity length (persistence), separation (aperture), roughness, infilling (gouge), and weathering are considered. In the RMR classification, there are two alternatives for this parameter: one is used if it has more detail of these characteristics, and the other one is used if it has general characteristics about the condition of the discontinuities. In the present study, the second option was applied.

In the parameter of presence of water, all the holes received the score relative to the presence of "interstitial water" because either there is no large amount of water or it occurs in small proportions.

Since there was no more detailed information of the project, the discontinuity orientation parameter was considered as "very unfavourable" utilized for tunnels and mines.

After the determination of the parameters above, the RMR value for each analysed drilling hole interval was calculated for all the drill holes samples.

3.2 Geological model

The geological modelling was performed in the Micromine® software, using the lithological description of 50 drill holes, where five lithologic units were defined, from base to top: lower sandstone, rhythmite, conglomerate, upper sandstone, and ore (Figure 2).

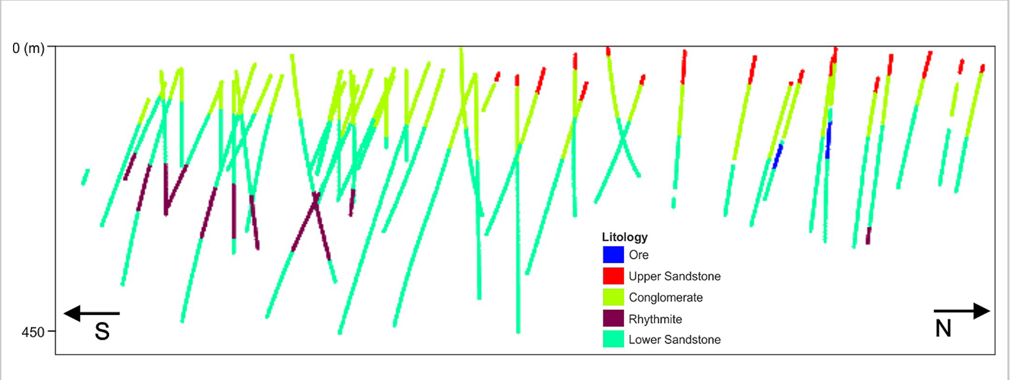

Figure 2 - Profile view of the drilling holes and their lithology.

With the imported database, the area was divided into sections with W-E directions, in which the outlines of each rock unit were delimited. The next step was the interpolation of the sections to create the 3D model.

3.3 RMR estimation

Using regular size samples and their RMR values, five categorical variables were created in the database, each one corresponding to an RMR class, and then these classes were coded as 0 or 1indicators, where 0 means that the sample does not belong to the class, and 1 means that the sample belongs to it. The Indicator Kriging approach permits direct estimate of the uncertainty distribution of these categorical variables, where the expected value of the indicator variable is the stationary prior to the probability of the RMR class at an unsampled location (Huijbregts, 1975; Journel, 1983; Deutsch & Journel, 1998).

Variographic analysis of the indicators was performed to identify the anisotropic direction. For that, eighteen possible directions were tested, with a 10° variation between them. In this step all the samples were used, without division by lithology. Among the classes, there was identified a sub-horizontal preferential direction of 10° (approximately N-S). The parameters used in the variography and estimation are summarized in Table 1.

Table 1 - Parameters used in the variogram, variographic model and during kriging.

VARIOGRAM PARAMETERS		MODEL PARAMETERS		KRIGING PARAMETERS	
Number of lags	40	Structures	1	Max range	120
Lag separation	25	Nugget effect	0.1	Medium range	60
Lag tolerance	12.5	Contribution	10.15	Min range	30
Bandwidth	12.5	Sill	0.25	Azimuth	10°
Angular tolerance	10°	Variographic model	Exponential	Dip	0°

A grid with 25 x 25 x 3 m cells was created, and classes were estimated for each lithological unit using a minimum of 3 and a maximum of 12 data for each estimated value. It is worth noting that for the estimation, only data from the same lithology were used; for example, within the conglomerate lithology, only the Classes I, II, III, IV and V samples that belong to the conglomerate were estimated. As a result, each estimated block had a value between 0 and 1, which corresponds to the probability of belonging to the given class. In the next step, the geomechanical model was constructed with the highest probability class of each block (Figure 3).

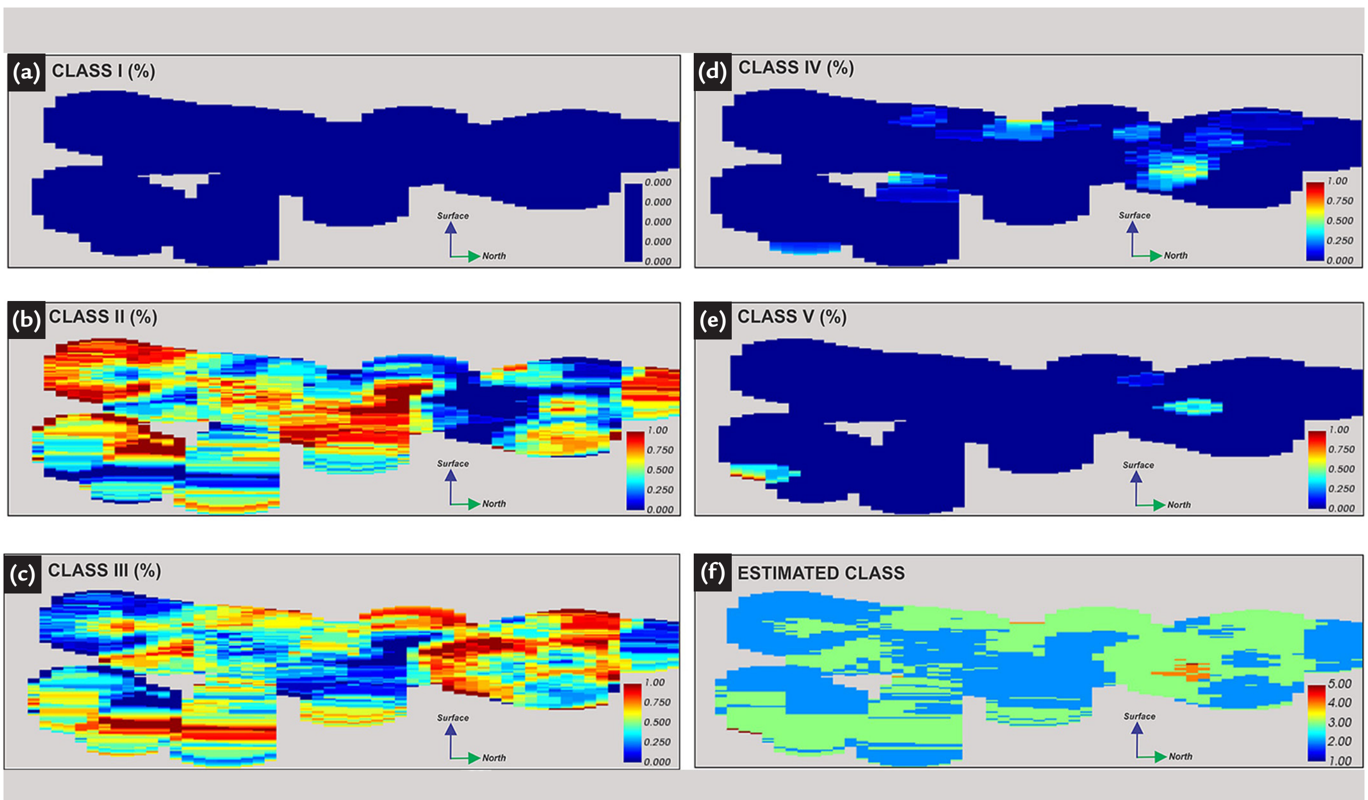

Figure 3 - Section of the geomechanical model with the probability in percentage of each block belong to one of the classes: (a) zero probability of belonging to Class I; (b) probability between 0 and 1 of belonging to class II; (c) probability between 0 and 1 of belonging to Class III; (d) probability between 0 and 1 of belonging to Class IV; (e) probability between 0 and 1 of belonging to Class V; (f) estimated final class resulting from the class most likely to occur in each block.

4. Results and discussion

4.1 Geomechanical model

Figure 4 shows the estimated model where a comparative analysis of the distribution of classes by lithology allowed to observe that a predominance of rock mass Class II occurs in the lower sandstone and in the ore. In the rhythmite, conglomerate and upper sandstone, the predominance of rock mass Class III occurs. Also, Classes IV and V (lower RMR values, poor and extremely poor rock mass) are preferably located in the more superficial portions of the holes, and consequently, the estimated blocks have the same tendency. This behaviour can be explained by the intemperate action, which interferes in the quality of the rock mass. However, other variables, such as sandstone composition (detrital and diagenetic) and textured aspects (granulometry and sedimentary structures) may considerably interfere in rock resistance. No block was classified as Class I (very good rock mass). Because the quality of the rocks is not particularly good, the importance of the block model for the safety slope dimensioning is evident.

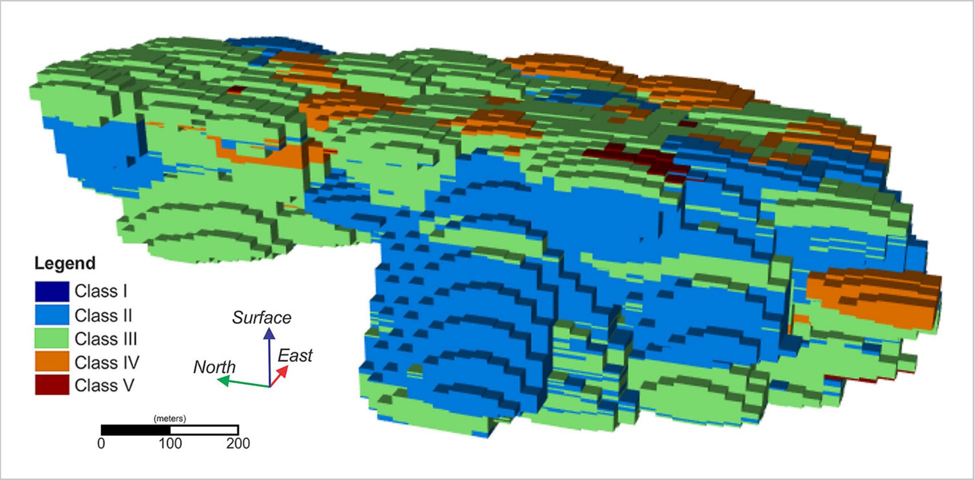

Figure 4 - Final 3D geomechanical model, with the distribution of the estimated RMR classes.

4.2 Model validation

In order to verify if the estimated models were satisfactory, showing coherence with reality, some methods were used to validate the results. First, visual validation was performed, comparing the estimated blocks with the neighbourhood samples (Figure 5). As there was predominance of Class III in the geomechanical model, the visual validation was focused on this class. Figure 5 shows the drill holes and estimated blocks with their respective ranges and RMR values. Note that the blocks that were estimated as Class III are close to the samples with RMR values between 60 and 41 that is, the Class III RMR interval, which is expected because of the greater importance these samples will have during the estimation of the blocks of that region.

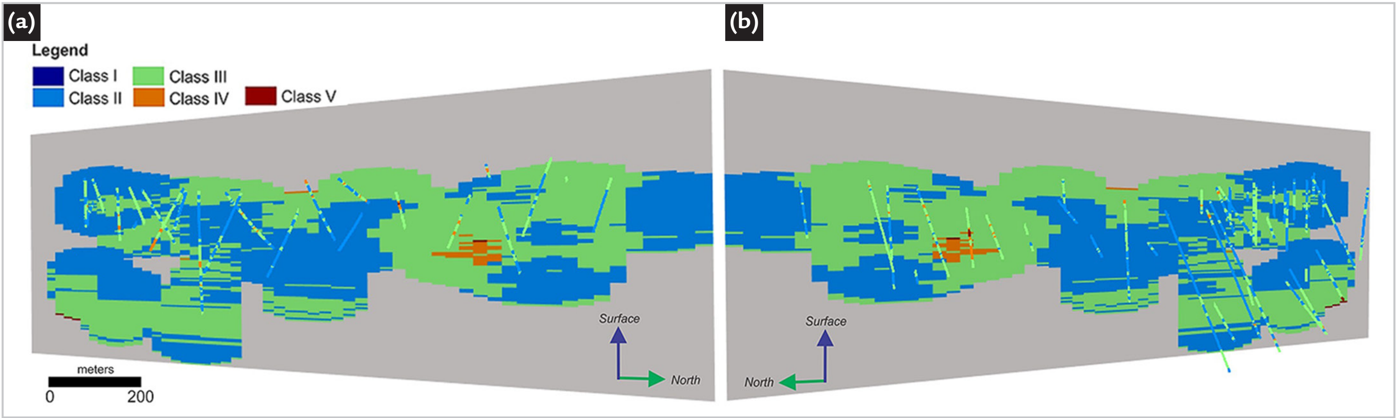

Figure 5 - Sections of the 3D block model and drill holes showing the visual validation performed.
For example, it is possible to observe the blocks that present RMR Class II and III were defined due to the presence of samples with Class II and III.

The second validation method used was the comparison of the proportion of classes in the samples and in the estimated blocks. Two graphics were utilized (Figures 6 and 7), one containing the percentage of blocks

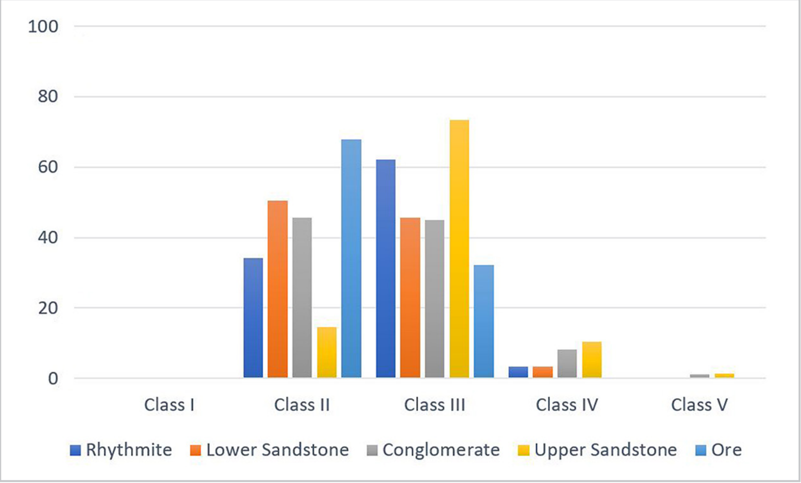

Figure 6 - Percentage of samples in each class by lithology.

estimated in each class within the determined lithologies, and the second containing the RMR percentage of the drill holes in each class by lithology. Analysing both images, we can notice the predominance of both blocks in Class III, as well as RMR values in the same class, which, according to the geomechanical model, is coherent.

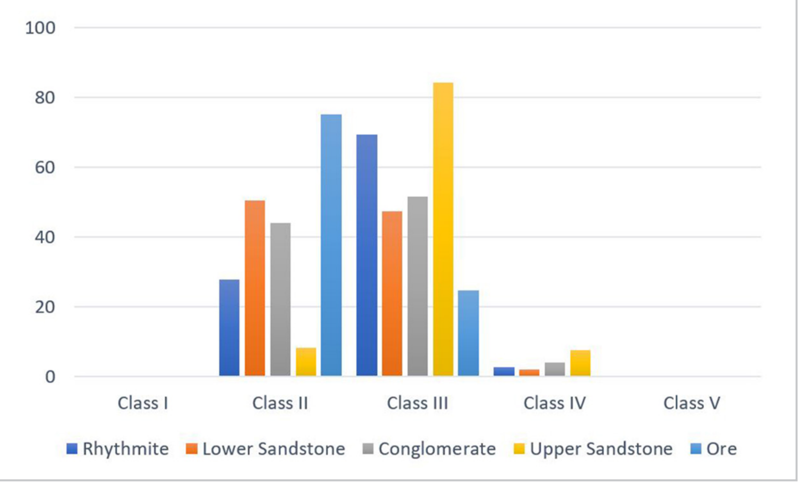

Figure 7 - Percentage of blocks estimated in each class by lithology.

5. Conclusions

The model allows greater safety in the classification of the massif and later use for slope stability and open pit design. Although the geomechanical model demonstrates the quality of the rock mass in general, more detailed studies are indispensable. An alternative to improve the results would be the use of another classification system for comparison, such as the GSI System (Barton *et al.,* 1974), which uses a representative of block size, shear strength, and effective tension to predict the quality of the mass and the need for support.

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References

BARTON, N. R.; LIEN, R.; LUNDE, J. Engineering classification of rock masses for the design of tunnel support. ***Rock Mech.***, v. 6, n. 4, p.189-239, 1974.

BIENIAWSKI, Z. T. Engineering classification of jointed rock masses. ***Trans. S. Afr. Inst. Civ. Eng.***, v. 15, p. 335-344, 1973.

BIENIAWSKI, Z. T. ***Engineering Rock Mass Classification***. New York: John Wiley & Sons, 1989.

BIENIAWSKI, Z. T. Errors in the application of the geomechanical classifications and their correction. ***Ingeopres, Actualidad Técnica de Ingeniería Civil, Minería, Geología y Medio Ambiente***, Madrid, n. 208, p. 10–21, 2011. (Conferencia magistral Adif–Geocontrol.)

CELADA, B.; TARDÁGUILA, I.; VARONA, P.; RODRÍGUEZ, A.; BIENIAWSKI, Z. T. Innovating tunnel design by an improved experience based RMR system. *In*: WORLD TUNNEL CONGRESS, 9–15 May 2014, Foz do Iguaçu, Brazil. ***Proceedings*** […]. Englewood, NJ: WTC, 2014. p. 9.

CHEN, J.; LI, X.; ZHU, H. Geostatistical method for inferring RMR ahead of tunnel face excavation using dynamically exposed geological information. ***Engineering Geology***, v. 228, p. 214-223, 2017.

DEERE, D. U. Technical description of rock cores for engineering purposes. ***Rock Mechanics and Engineering Geology***, v. 1, p. 17-22, 1964.

DEERE, D. U.; DEERE, D. W. The Rock Quality Designation (RQD) index in practice. In: KIRKALDIE, L. (ed.). ***Rock classification systems for engineering purposes***. [S. l.]: ASTM, 1988. p. 91-101.

DEUTSCH, C. V.; JOURNEL, A. G. ***GSLIB***: geostatistical software library and user's guide. New York: Oxford University Press, 1998.

FABRÍCIO, J. F.; ABICHEQUER, L. A.; SOUZA, L. E., OLIVEIRA NETO, R.; GONÇALVES, I. G. Análise e interpretação de parâmetros de qualidade de maciço para proposição de modelo geomecânico. ***Revista Monografias Ambientais***, v. 14, p. 62-79, 2017.

HUIJBREGTS, C. J. ***Regionalized variables and quantitative analysis of spatial data, in display and analysis of spatial data***. New York: John Wiley & Sons, 1975. p. 38-53.

ISAAKS, E. H.; SRIVASTAVA, R. M. ***An introduction to applied geostatistics***. New York: Oxford University Press, 1989.

JOURNEL, A. G. Nonparametric estimation of spatial distributions. ***Journal of the International Association for Mathematical Geology***, v. 15. n. 3, p. 445-468, 1983.

LANA, M. S.; CABRAL, I. E.; GRIPP, A. H.; GRIPP, M. F. A. Estimation of potential failure risks in a mine slope using indicator kriging, ***Numerical and Analytical Methods in Geomechanics***, v. 34, n. 16, p. 125-1742, 2010.

MADANI, N.; YAGIZ, S.; ADOKO, A. C. Spatial mapping of the rock quality designation using multi-gaussian kriging method. ***Minerals***, v. 8, n. 11, p. 530, 2018.

MARINONI, O. Improving geological models using a combined ordinary-indicator kriging approach. ***Engineering Geology***, v. 69, n. 1-2, p. 37-45, 2003.

MATHERON, G. Principles of geostatistics. ***Economic Geology***, v. 58, p. 1246-1266, 1963.

OLIVEIRA, S. B. ***Estudos geoestatísticos aplicados a um depósito magmático de Ni-Cu***. 2008. 94 f. Dissertação (Mestrado em Geociências – Recursos Minerais e Hidrogeologia) – Instituto de geociências, Universidade de São Paulo, São Paulo, 2008.

PEREIRA, P. E. C.; RABELO, M. N.; RIBEIRO, C. C.; DINIZ-PINTO, H. S. Geological modeling by an indicator kriging approach applied to a limestone deposit in Indiara city – Goiás. ***REM - International Engineering Journal***, v. 70, n. 3, p. 331-337, 2017.

SUGGESTED method for determining point load strength. In: ULUSAY, R.; HUDSON, J. A. (ed.) ***The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 1974-2006***. Turkey: ISRM, 1985. p. 53-60.

VALLEJO, L. I. ***Ingenieria geologica***. Madrid: Pearson Educacion, 2002.

WICKHAM, G. E.; TIEDEMANN, H. R.; SKINENR, E. H. Support determination based on geologic predictions. *In*: NORTH AMERICAN RAPID EXCAVATION AND TUNNELING CONFERENCE (RETC), 1st, 1972, Chicago, Illinois. ***Proceedings*** […]. New York: AIME, 1972. p. 43-64.

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