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Three-dimensional geological and geotechnical models constructed by geostatistical interpolation

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Article

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Abstract

This paper proposes to construct three-dimensional geological-geotechnical models using the geostatistical interpolation from geomechanics parameters of rocks as lithology and fracturing, plus Rock Designation Quality and Rock Mass Rating classification systems. Generally, the geostatistical interpolation is used to analyze the mining, but this project aims to optimize the prediction of the geological conditions during the initial assessment for infrastructure projects. In this way, the correct predictions of the geological conditions allow us to minimize the inherent risks of failures in the predictability of the structural and geometric patterns of the rocky mass in depth. The proposed procedure aims to ensure the safety of the workers during a complex enterprise. The control of the expenses, as well as the enterprise's durability after construction, promotes social, financial, and environmental security. This methodology has been applied using data from the construction of two different sites, located in Minas Gerais state (Brazil). It was used 44 drill data, 28 from site I and 15 from site II. The results of models showed that it is possible to predict the geological conditions using this geostatistical interpolation; it is possible to affirm that geostatistical interpolation has been effective in the evaluation of geomechanical parameters.

1. Introduction

The correct geological prediction, involving geotechnical parameters of the rock mass, is directly associated to lithological setting and their respective arrangement of discontinuities and weathering evolution are the main determinants of future stability of large excavations, both open pit and underground. Most analysis about the prediction of deep geological conditions carried out in engineering works are subject to uncertainties thus generating geological risks that can cause financial losses and risks to human life, as well as environmental problems, these uncertainties occur due to difficulty of determining deep geological conditions.

The boreholes are fundamental to obtain geotechnical subsurface data; however, the data is punctual and actually is necessary to infer the data for obtaining all the geotechnical settings. To make these inferences two-dimensional sections are created using geotechnical parameters relationships from the boreholes. Aiming to improve the prevision geotechnical conditions in depth, this paper proposes the application of geostatistical interpolation using borehole parameters to construct three-dimensional models.

Research discussing the application of statistical methodology in geotechnical projects is increasing, the authors as Luzi et al. (2000), Refice & Capolongo (2002), Costa (2005), Flores (2008), Assis et al. (2012), Restrepo (2011) and Montoya (2013) shows the importance of statistical methos applied geotechnical analyses, for this reason, the application of geostatistical interpolation through geotechnical parameters to obtain the highest possible reliability of the 3D geotechnical model.

2. Materials and methods

For this construction, it was necessary to compile available geological data, which were made through data collection, such as geological maps, papers, and manuscripts available on the online tools, as Scholar Google, Elsevier, Science Direct. The result of geological compilation is described in the Geological Setting item. The first 3D model was based on lithological characteristics.

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In addition to geological setting, parameters obtained from the descriptions of boreholes were used, and the classification of these parameters is described below with each item that was used for the construction of de 3D geotechnical model.

2.1 Geotechnical parameters

The first parameters is fracturing degree, these data were classified based on Table 1, where the borehole was classified for each meter, considering the fracturing degree and the fracture set with the larger spacing, and the lower the degree of fracturing (Table 1). The colors indicate the categories on created models.

The second model was based on the RQD (Rock Quality Designation) classification, developed for Deere (1988). This parameter shows the quality of the rock that is defined by the percentage of the recovered intact core greater than 10 cm. The equation for RDQ percentage is:

$$RQD\,(\%) = \frac{\sum length\ of\ \ core\ pieces \geq 10\ cm}{total\ core\ run\ length} \tag{1}$$

The RQD classification is shown on Table 2, with the color indication correspondent between the classification and geotechnical model.

Finally, all the boreholes were classified using Rock Mass Rating (RMR) classification (Bieniawski, 1989). The ranking summary is in the Table 3, and similarly for the RQD classification system, the colors indication accords to RMR classification system.

2.2 Interpolation geostatistics

All the parameters were treated as categorical variables for the application of geostatistical interpolation. The information correlated with each other because there is a spatial correlation between them, with which one can define a regionalized variable with spatial distribution and variation.

The regionalized variable is the set of real values that consists of a random function Z (x) with a set of random variables, with their mean values m, variance S^2, and an accumulated distribution function. The regionalized variables can be subdivided into continuous and discrete, in the case of geotechnical parameters, such as degree of fracturing, and rock quality index. Therefore, discrete variables are treated according to their category within the ranges, so they are categorical variables (Yamamoto & Landim, 2013).

The relationship between values of the same variable, obtained at points separated by distance h, is called covariance where h represents a vector between two points, x_1 and x_2 in three-dimensional space. The covariance, for 3D spatial analysis, is calculated for vertical, horizontal and inclined directions according to the geological structure of the rock mass at depth (Yamamoto et al., 2013).

For the application of interpolation, the geotechnical parameter has been treated as categorical variables and transformed into a binary codification by means of the equation (Journel, 1983):

$$I(x,k) = \begin{cases} 0, \text{ if } Z(x) \neq \text{ kind k} \\ 1, \text{ if } Z(x) = \text{kind k} \end{cases} \tag{2}$$

After this transformation, a categorical variable is composed of k kinds with k indications functions. These functions have an average, calculated from Equation 3, after this, it is possible to generate a multi-quadric equation, from that function is possible to execute the estimate unsampled points based on existing points.

$$E[I(x,k)] = \frac{f_k}{N} = P_k \tag{3}$$

where P_k is the mean and $N = \sum_k f_k$ is total numbers of points.

3. Geological setting

The data used in geotechnical models construction had been obtained by compilation of literature data as geological map (Figure 1) and forty-three boreholes, with localization

Table 1. Fracturing Classification.

Fracturing Scale	Description	Fractures for meter
5	Extremely Fractured	< 60 mm
4	Very Fractured	60 - 200 mm
3	Moderately Fractured	200 - 600 mm
2	Slightly Fractured	0.6 - 2 m
1	Fractured	> 2 m

Table 2. RQD classification (Deere, 1988).

RQD (Rock Quality Designation)	Description of Rock Quality
0 – 25 (%)	Very poor
25 – 50 (%)	Poor
50 – 75 (%)	Fair
75 – 90 (%)	Good
90 – 100 (%)	Excellent

Table 3. RMR Classification (Bieniawski, 1989).

Rock Mass Rating (RMR) value	Rock Class	Rock Conditions
≤ 20	V	Very poor
21 - 40	IV	Poor
41 - 60	III	Fair
61 - 80	II	Good
81 - 100	I	Excellent

indicated in Figure 2. These boreholes were carried out during the construction of project located at Araguari River, which is between the cities of Uberlândia and Araguari in the state of Minas Gerais.

The project was developed on the geological basement composed of gneiss and granite (Maratá Complex) and schist (Araxá Group). Two areas were analyzed through the boreholes, where they were chosen to install the constructions in the I and II locations.

Along the Araguari River, there is a predominance of metasedimentary rocks from the Araxá Group, in some places, it is possible to observe outcrops of granitic rocks from the Maratá Group. The contact between these groups is tectonic. In general, it is not possible to observe cut-off relations. The Araxá Group is composed of a variety of quartz-mica schists, predominantly muscovite-biotite-quartz schist, it is gray in color and has medium to coarse granulometry. The Maratá Group is formed for Augen-gneiss and porphyritic meta-granite.

The basement is characterized by a thrust tectonic regime produced during the regional compression phase of the Brasiliana Orogenesis, where two deformation phases were identified, both by simple shear. The first event developed the main penetrative foliation, which the principal directions are predominantly NS to NW-SE. The foliation of the posterior phase developed parallel to the axial plane of the second generation of folds, with eastward bending (Pedrosa-Soares et al., 2017).

These configurations are important to understand the arrangement of the lithology model created and described in the results item.

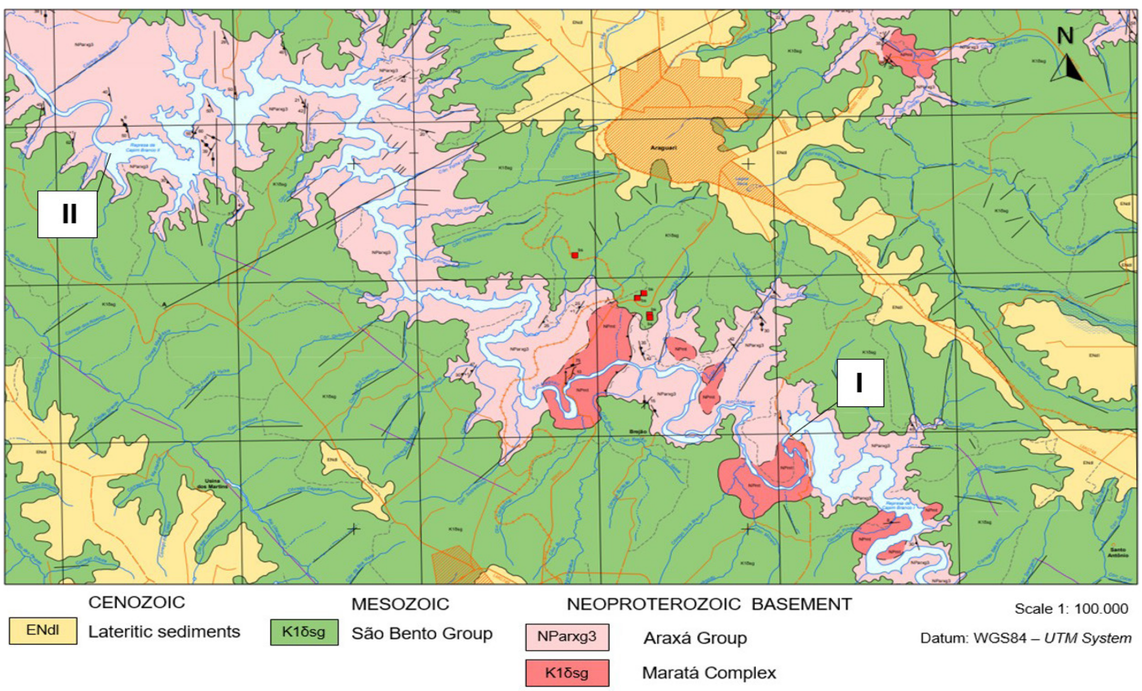

Figure 1. Geological map of the areas with the position of the dams. Adapted from Pedrosa-Soares et al. (2017).

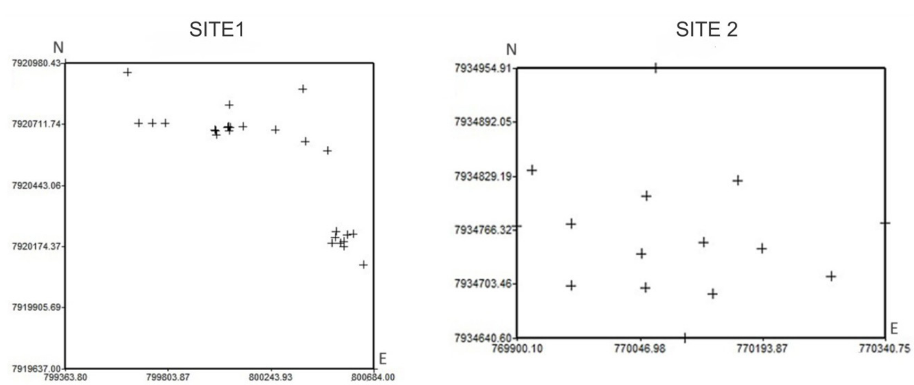

Figure 2. The borehole site simplified

4. Geotechnical data

Complementary of the geological setting, it was available forty-four boreholes, with the site simplified in the Figure 2, there are two sites when the borehole was executed, the site 1 with the information of borehole described in the Table 4.

The coordinate system used is SAD 69, due to the data used.

Table 5 provides information about the boreholes in area II.

The geotechnical classification was done for each borehole and all the layers described received the respective geotechnical parameter. The example of classification and parameters used is represented in Table 6.

5. Three-dimensional model results

In the software for interpolation, it is possible to perform interpolations for the construction of 3D geotechnical models, using geological and geotechnical parameters that have been achieved by means of borehole classification. It was possible to create four geological-geotechnical models for each local. It is important to mention that the directions of the regional foliation were considered for the construction of 3D models and the interpolation of parameters.

5.1 Lithological models

The lithological models were obtained from the identification of contacts between lithological units. Site 1 shows different positions between granites, gneiss, quartz-schist, and mica-schist. Certainly, there is a contact between Maratá Complex, represented by green and gray colors in the model, and Araxá Group, blue and red in the model. The Figure 3 illustrates the general visualization of the model, the Figure 4 and Figure 5 show different positions of visualizations contributing to the understanding of the relationship between the positions of geological units and, the influence they have on geotechnical parameters. In most of the model there is a soil cover, which is represented by the yellow color on all surfaces.

The 3D lithological model obtained for site II highlights the position of the Araxá units, where we can observe two different units belonging to the Araxá Group. The former is the Quartz-Schist, represented by the red color, and the latter, the Mica-Schist, expressed by the blue color. Figure 6

Table 4. Information from boreholes in site I.

Sample	E (m)	N (m)	Elevation (m)	Depth (m)
SM 100	800557.24	7920197.74	611.09	28.02
SR 101	800557.93	7920173.10	591.41	28.10
SR 102	800007.10	7920683.97	623.44	63.00
SR 103	800071.40	7920698.52	673.45	73.00
SR 104	800125.67	7920702.77	w688.92	90.09
SR 105	799789.81	7920718.00	567.65	12.19
SR 106	799735.48	7920718.30	574.33	5.83
SR 107	799678.21	7920718.30	571.27	4.91
SR 108	800390.67	7920636.56	717.84	110.00
SR 109	800061.51	7920702.94	671.74	58.24
SR 110	800067.20	7920684.80	677.43	54.62
SM 111	800066.50	7920798.40	674.42	73.03
SM 112	800057.12	7920699.84	676.99	75.12
SM 113	800005.30	7920688.98	627.72	65.07
SR 114	800263.35	7920688.52	717.19	113.07
SR 115	800011.95	7920664.20	624.92	36.82
SM 1	800640.00	7920094.00	619.11	40.00
SM 2	800570.00	7920225.00	628.33	38.60
SR 3	800382.00	7920868.00	639.11	49.20
SR 4	799363.80	7920980.43	801.59	37.17
SM 5	800684.00	7919637.00	611.43	40.11
SR 6	799630.41	7920941.89	676.28	43.00
SR 7	800596.24	7920230.20	612.16	25.00
SR 8	800544.00	7920187.30	604.08	36.00
SR 9	800504.90	7920189.30	596.08	40.00
SR 10	800518.87	7920214.10	605.36	35.00
SM 13	800525.70	7920238.50	614.91	30.00
SR 14	800487.70	7920595.43	661.91	42.00

Table 5. Boreholes information of the site 2.

Sample	E (m)	N (m)	Elevation (m)	Depth (m)
SR 200	770134.50	7934691.50	546.05	53.10
SR 201	770100.23	7934640.60	525.63	30.10
SM 202	770192.60	7934744.36	578.73	34.50
SM 203	770122.85	7934751.77	565.77	31.50
SR 205	770053.10	7934699.25	556.12	55.85
SR 206	770048.33	7934738.64	558.62	57.94
SR 207	769900.10	7934770.94	537.65	20.04
SR 208	769964.66	7934700.89	524.93	20.04
SR 209	769965.10	7934773.86	542.77	21.20
SM 210	769917.18	7934836.43	545.46	63.57
SM 211	770055.00	7934806.62	571.69	70.00
SM 212	770275.41	7934712.75	549.27	47.67
SM 214	770065.44	7934954.91	541.15	23.90
SM 215	770340.75	7934775.25	569.60	20.66
SM 216	770163.73	7934823.68	588.82	58.24

Table 6. Borehole example classification.

Depth of beds		Borehole position		Parameters			
Inicial depth (m) *SR 200*	Final depth (m)	Azimute	Dip	Lithology	Fracturing	RQD	RMR
0.00	8.50	0.00	90.00	soil	-	-	-
8.50	9.30	0.00	90.00	quartz-schist	Very Fractured	49-25%	Fair
9.30	10.98	0.00	90.00	quartz-schist	Moderately Fractured	74-50%	Good
10.98	12.00	0.00	90.00	quartz-schist	Fractured	89-75%	Good
12.00	18.00	0.00	90.00	quartz-schist	Slightly Fractured	89-75%	Good
18.00	19.50	0.00	90.00	quartz-schist	Very Fractured	49-25%	Fair
19.50	38.57	0.00	90.00	quartz-schist	Fractured	100-90%	Excellent
38.57	39.40	0.00	90.00	quartz-schist	Fractured	100-90%	Good
39.40	53.10	0.00	90.00	quartz-schist	Fractured	100-90%	Excellent

shows the two different positions of the visualization of the lithological model.

The cross-section allows to identify the contact arrangement and the configuration inside the model between the units (Figure 7).

5.2 Fracturing model

The 3D model on fracturing was developed based on the classification of the boreholes. The site 1 showed the existence of areas with high degree of fracturing, highlighted by color red (Figure 8a). The comparison between the fracture models and the lithological models allows verifying a relationship between them. For example: an area of high probability of instability due to the high rate of fracturing corresponds to the quartz schist rocks. In the fracture model, however, the rocky massif has a low degree of fracturing. When the viewing position is changed (Figure 8b), an extremely fractured region is observed in depth.

For site 2, the fracturing model shows an unsteady layer on the surface, due to residual soil cover (Figure 9a) in the upwards vision of the 3D fracturing model. When the visualization changes to the base of the rock mass, a specific area, classified as very fractured, is represented by the blue color on the model, however, most of the rock mass suggests a stable area, with low rate of fracturing (Figure 9b).

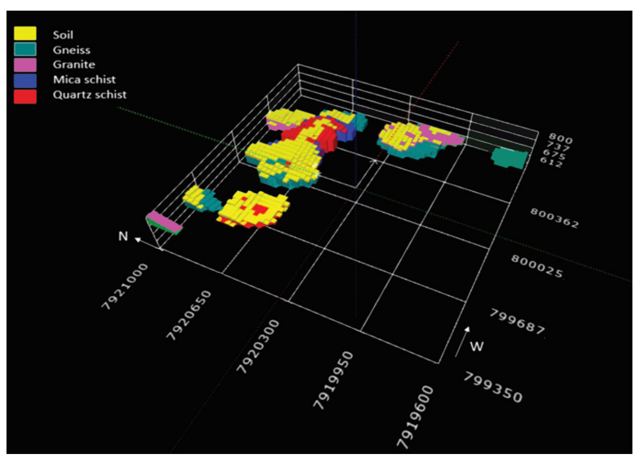

Figure 3. 3D lithological model constructed for site I.

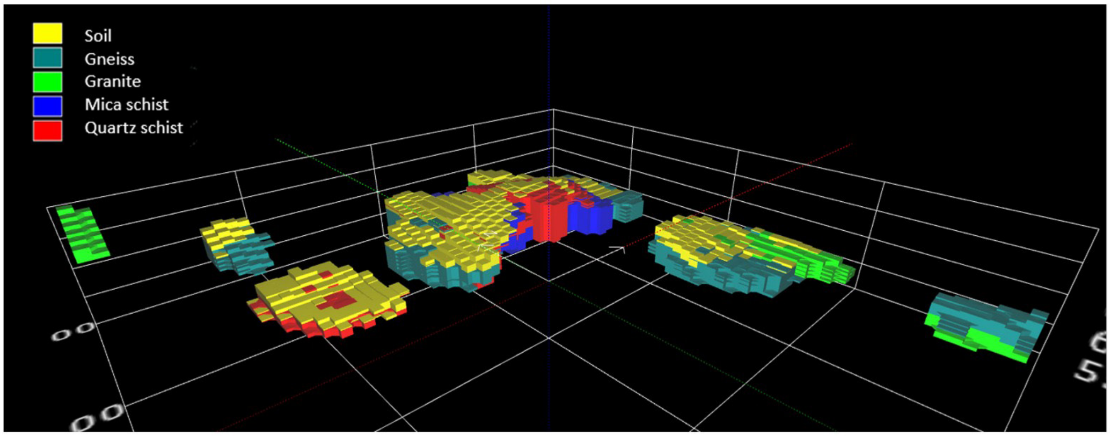

Figure 4. 3D lithological model constructed for site I, front face of the model, the green line represents north direction

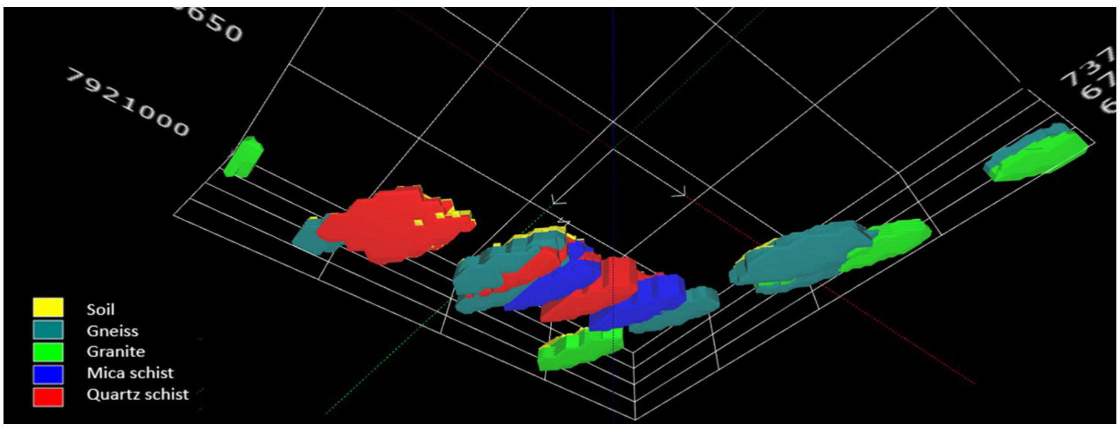

Figure 5. 3D lithological model constructed for the site I, bottom face of the model.

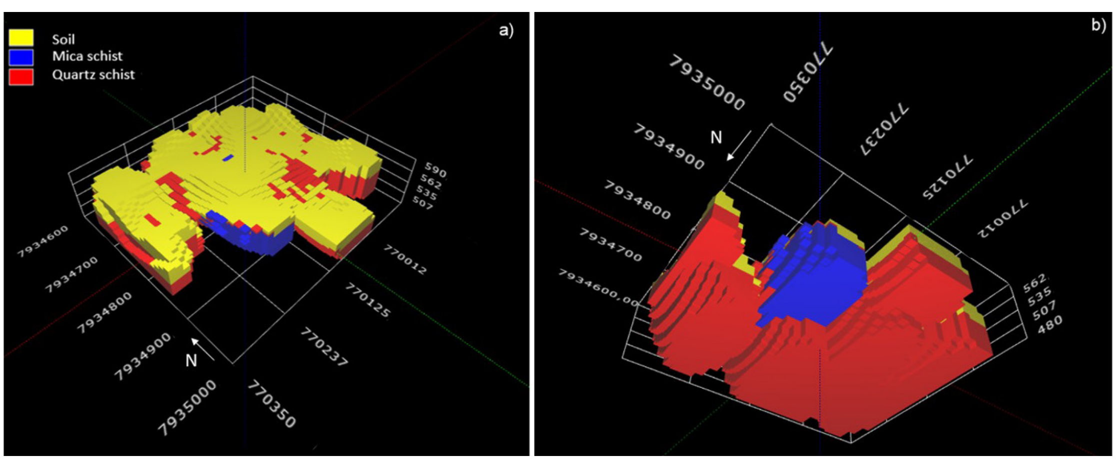

Figure 6. 3D lithological model constructed for the site II, (a and b) superior face and bottom face respectively.

5.3 RQD model

One of the most important geotechnical parameters of rocks is the RQD, this one has a relationship with the degree of fracturing, highlighting the places of occurrence of the most intense, due to this it was developed the RQD model using the general classification of each borehole, meter to meter.

Figure 10a shows the RQD model for site I with the general visualization and the Figure 10b three cross-sections to make it easy to visualize the conditions of the RQD in depth.

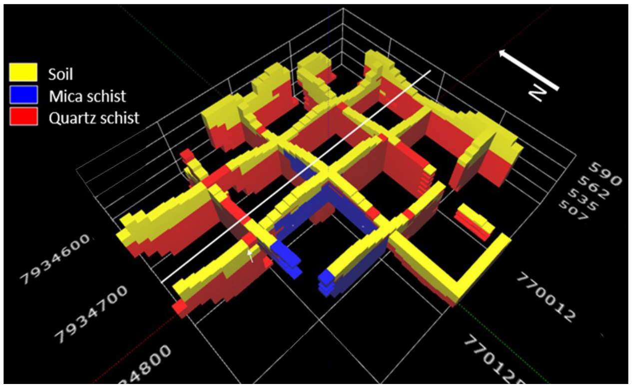

Figure 7. 3D lithological model constructed for site II.

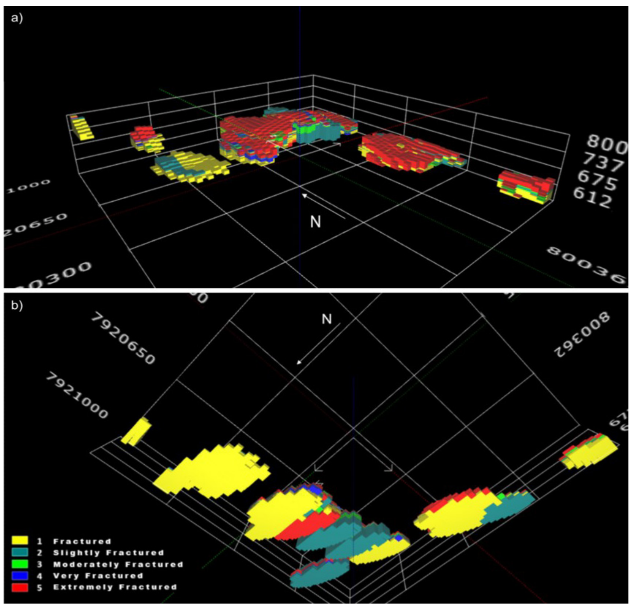

Figure 8. (a) 3D fracturing model constructed for site I, (b) bottom face of the model.

The Figure 11 illustrates the model for site II. The first shows a normal stratigraphic view, while the second is an inverted view. Both show the persistence of bad conditions in the classification of RQD in specific areas enhanced by the red color.

5.4 RMR-Model based on classification system.

This parameter shows the merge of the data, resulting in a final classification of rock mass. This kind of classification is usual for geomechanical analysis.

For site I the surfaces of the layers show the initial stage of rock decomposition, consequently they are classified as poor (Figure 12a and Table 3). As the deep increases the massive becomes good or excellent (Figure 12b).

Site 2 brings an idea similar to the RQD model due to the specific area with low quality RMR in most of the rock mass (Figure 13).

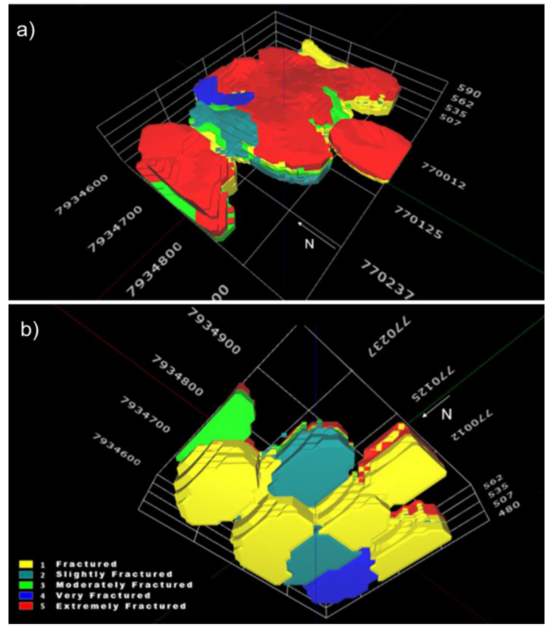

Figure 9. (a) Upwards vision of the 3D fracturing model constructed for the site II, (b) bottom face of the model.

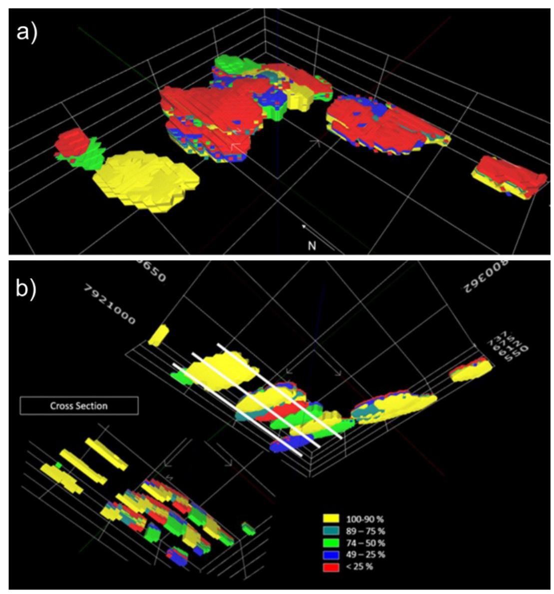

Figure 10. (a) 3D RQD model for site I with upwards visualization, (b) bottom face of the model and with cross section.

6. Discussion

The results show the possibility to establish links between the geotechnical parameters analyzed and the statistic interpolation for both sites examined.

At site I, the lithological model exhibits the arrangement of the distinct geological units with the trend N-S (Figure 3 to Figure 5), observed due to the 3D model construction, this trend of units position is difficult to establish observing only the punctual sample (as the boreholes).

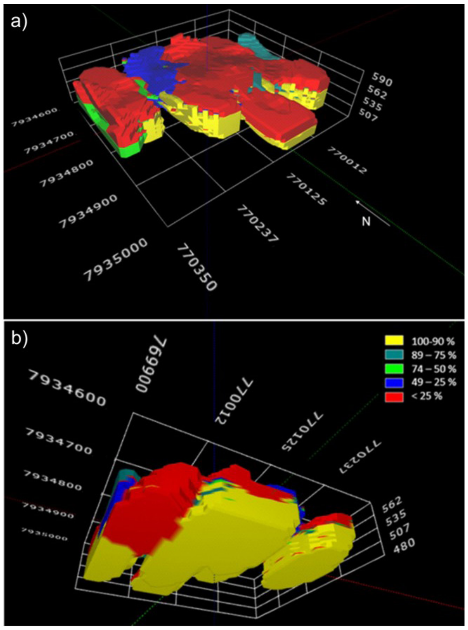

Figure 11. (a) RQD model construction for site II, (b) bottom view.

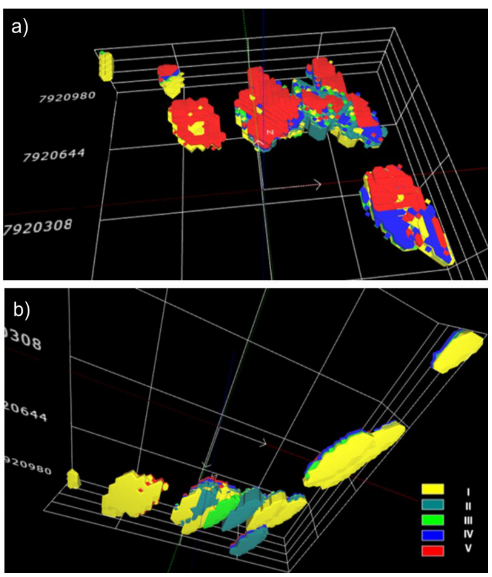

Figure 12. (a) RMR model construction for site I, (b) bottom view.

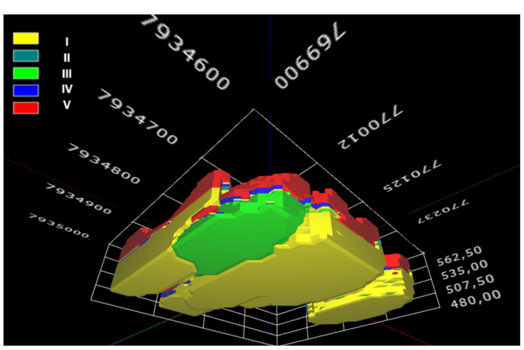

Figure 13. RMR model construction for site II, bottom view.

The fracturing model has a similar direction, which can be observed in the lithological model, for both areas. It is important to emphasize that there is one specific area with high degree of fracturing, and this area corresponds to a geological unit classified as mica-schist but we remark that there is another site, also with mica-schist, that not correspond to a high instability (Figure 8).

The positioning trend repeated in the RQD and RMR models confirmed that there is an area with high instability related to fracturing (Figure 10 and Figure 12), but analyzing the other geotechnical parameters, like used for RMR classification, we conclude that although the rock mass presents a fractured area, to classify the rock mass as class III, an unstable area, it has a low weathering action (Figure 12). However, most of the area can be categorized as good rock (class I and II).

Analyzing the site II, it presents the singular conditions, because it is not possible to observe the lithological arrangement trend, and the rock mass is almost homogeneous (Figure 6 and Figure 7). There are two different geological units with the same origin and classification, both are schists. The presence of mica can make the massif unstable, as observed in the fracturing model (Figure 9) and RQD model (Figure 11).

The RMR models (Figure 13) show that most of the massif was classified as excellent, but as class III, in the fractured area. It is essential to emphasize that the interpolation method enables visualizing the unstable area, that it is not possible with only the borehole (punctual sampling).

7. Conclusion

This project highlights the importance of the use of new techniques for the construction of 3D geotechnical models aiming to optimize the predictions of geological conditions in depth. 2D sections do not use all the boreholes simultaneously, just those close to the section. This type of analysis is usual and important although there is a considerable percentage of uncertainty, some problems have already been solved with this kind of technique but aiming to minimize the percentage of uncertainty the use of interpolation geostatistical was proposed.

The use of geostatistical interpolation from geotechnical parameters showed to be efficient in 3D geological models, allowing the visualization of the specific areas of instability, for example, site I and site II, where there are sectors with high fracturing among areas with low fracturing. We conclude that geostatistical interpolation is an adequate tool for developing geological-geotechnical models. This technique does not replace the professional's technical knowledge but improves the technique of building geological-geotechnical models making them closer to reality.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Bruna Catarino Xavier: conceptualization, data curation, visualization, writing – original draft. Marcos Egydio-Silva: conceptualization, data curation, methodology, supervision, validation, writing – original draft. Georg Robert Sadowski: formal analysis, data acquisition, investigation, methodology. Jorge Kazuo Yamamoto: formal analysis, methodology, software.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

Declaration of use of generative artificial

This work was prepared without the assistance of any generative artificial intelligence (GenAI) tools or services. All aspects of the manuscript were developed solely by the authors, who take full responsibility for the content of this publication.

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