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ORIGINAL PAPER

Construction of Structural Geological Model Using Monte Carlo Simulation

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Abstract To optimize the prediction of structural geological conditions in the underground as of data collected at the surface, due to the usual great uncertainties involved, we discuss new perspectives for the construction of structural geological models, bearing in mind the common doubts involved and their implications in the safety of infrastructure works, mining, etc. This paper presents a statistical simulation applied to structural geological measures (*dip-dip direction*) obtained from schists during the design and construction of civil works through a correlation between surface data with different depth levels. Angular structural geological measures of joints and foliations converted in direction cosines were subjected to the PERMANOVA test to verify the amplitude of differences at different depth levels. The asymptotic results allowed to determine regions of confidence built around centroids through statistical simulation, allowable consistency was considered in regions where the differences in the simulated values were small enough from a practical point of view, considering that the difference between joint structures and foliation structures is smaller in the former. The foliation is a characteristic structure of rock deformation just like the joints.

Keywords Structural Geology · Applied Geology · Monte Carlo Simulation Method · Geotechnics

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1 Introduction

Seeking to understand the interaction between human activity and geological environment, aiming at positive or negative previsions in a project, and it is need of eventual prevention is the main focus of most of Geology Applied to Engineering, be it civil construction, mining, oil or environment (Hasui and Mioto 1992; Pastore et al. 1998; Sadowski 2014, among others). The correct prediction of structural geology involving the spatial dispositions of contacts between different lithologies and their respective discontinuities are one of the main geological determinants of the stability of large foundations and excavations, open-cast or underground. There are important practical engineering problems in rock mechanics and, all stability analyzes carried out in rock engineering are subject to uncertainties thus generating geological risks, these risks may cause the execution of the work not to meet the pre-established requirements, causing financial losses and risks to human life, as well as serious problems of environmental issues.

Geological risk assessment in places of difficult viewing and access, such as underground conditions, aims to minimize the inherent faults in the data collection or exploration of the conditions of the rock masses in-depth, reducing errors is important to the safety of employees during the work, the control of the planned expenses, as well as the durability of the civil works, promoting social, financial and environmental safety. The mistake in the predictability is related to the number of uncertainties that are contained in several stages of the works, which are inseparable in geotechnics (Costa 2005), because of this, Ang and Tang (2007) highlight the importance of identifying them and, perform careful analyses to provide helpful guidance toward the solution of complex problems in civil engineering and rock mechanics.

In general, geological risk analyses are performed through deterministic analysis of the geotechnical parameters. These methods frequently do not quantitatively consider the randomness and variability of the parameters involved in the project, making it difficult to identity uncertainties (Hoek et al. 1997). In this case, the analysis does not demonstrate exactly the degree of predictability of the underground conditions of the works, in other words, the identification of the error percentage in the geological model. In the last years, there has been a great interest in incorporating methodologies that allow estimating the uncertainty associated with geotechnical studies, as is the case with probabilistic methods or statistical simulation (Ge et al. 2011; Montoya and Assis 2011; Hudson and Feng 2015).

This work is interdisciplinary involving Mathematics, Structural Geology, Numerical Analysis, Civil Engineering and the use of computer programs. The main proposal of the present study is to use applied statistical analyses, to structural geological data, aiming to optimize the predictions of the geological conditions in depth. The specific goals involve the following topics: (i) compilation of geological and structural data of the study area, (ii) transformation of directional data into linear data for descriptive statistical analysis, (iii) correlation between surface data and depth data, (iv) construction of the structural geological models using statistical simulation with the use of the Monte Carlo technique.

This study is applied in a practical example, and the most important target is to try to answer the question: *"Is it possible to know the data in depth using simulation?"* In the search for an appropriate answer to this question, we use the Monte Carlo simulation, to better understand the correlation between the data collected in the field, on the surface, with those existing in-depth, which is difficult to predict and/or access. It is a fact that joints do not persist indefinitely downward, and an attempt to analyze the probable depth of joints has been made by Price (1959), that took into account factors such as strain, stress, and physical properties of the materials, without, however considering the probabilities of occurrence of certain systems in depth. To try to solve this problem, we began showing the spatial orientation of the foliation and joints in stereographic projection, on the surface and in different intervals of depths. After this, we were dedicated to apply the Monte Carlo simulation, and, it is in this part, the theory and applicability become relevant.

2 Geological Setting

The structural geological data were obtained during the construction of a hydroelectric dam, in the Southeast of Brazil, in the Minas Gerais state (Fig. 1a). This area is composed of complex geology, the main tectonic unit is simplified in Fig. 1b with identification of the collection site. The dam site has a suitable topography, and an adequate upstream reservoir with several streams along the Araguari river valley. The bedrocks belong to the Brasilia belt (Fig. 1b), which is composed predominantly of metasediments rocks of the Araxá Group, local granitoid rocks and gneiss, from the Maratá Complex, also constitute the basement in the local of design.

The dam is situated in the hydrographic basin of Araguari river (Fig. 2b) in the realm of schists belonging to the Araxá Group, strongly foliated, with tectonic contacts (shear zones) with the local gneisses, causing parallelism in both gneissic banding and granitic foliation (Pacheco et al. 2017). The Maratá Complex represents a narrow strip of granitoid rocks interlayered with the Araxá metasediments and is composed of augen-gneiss and porphyritic metagranite with quartz, potassium feldspar, biotite and muscovite, frequently carrying a mylonitic texture

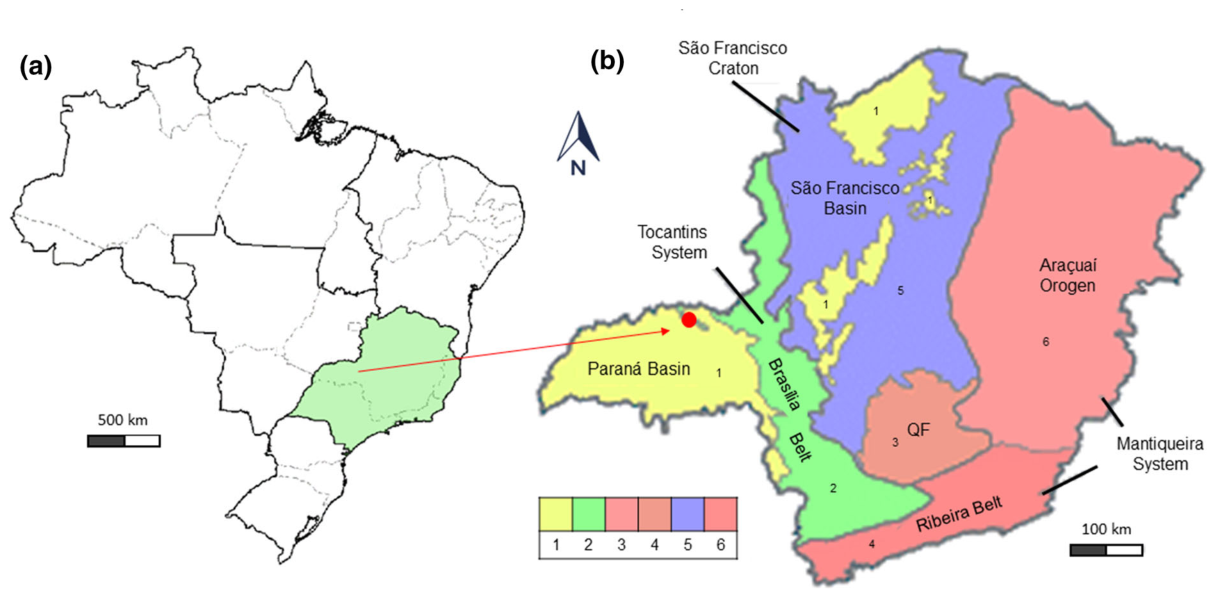


Fig. 1 **a** Boundary map of Brazilian Regions with a green highlight on the Southeast Region. **b** Minas Gerais State map shows the compartmentalization of geotectonic units identified by the number (1) Paraná Basin; (2) Brasilia belt; (3) Quadrilátero Ferrífero unit (4) Ribeira belt (5) São Francisco Craton and São Francisco Basin and (6) Araçuaí belt, and the red dot identifying the data collection location

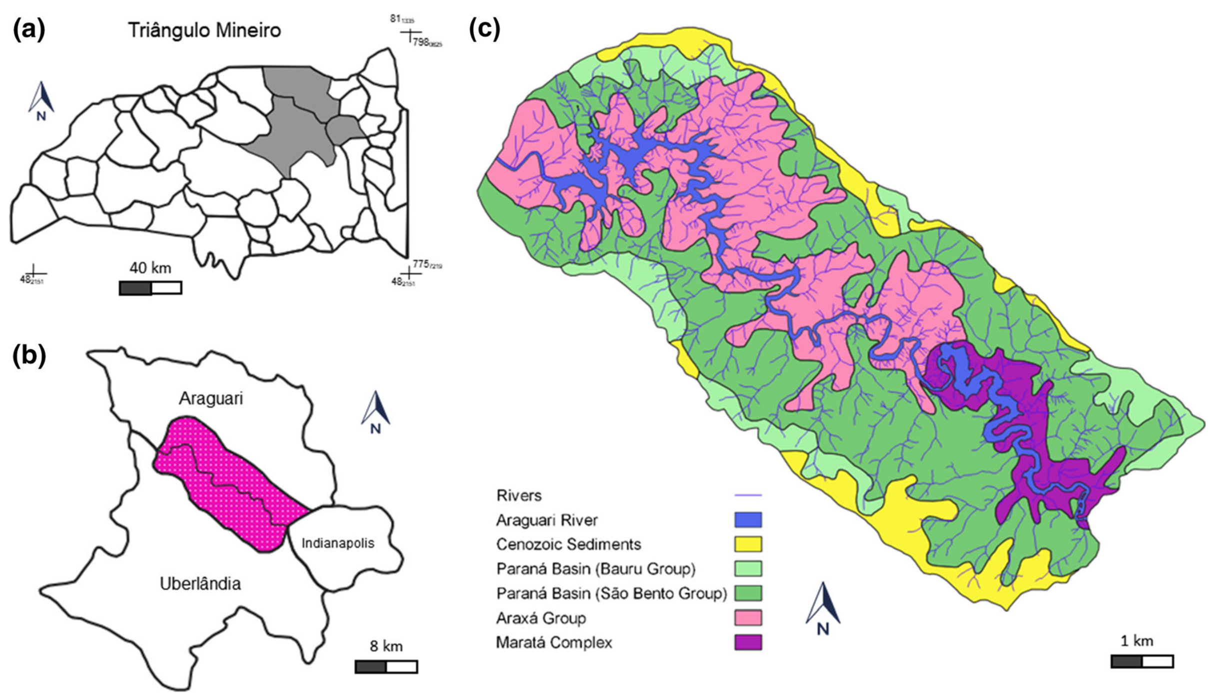


Fig. 2 **a** Map of the municipalities of the southwest of the Minas Gerais State. In gray the municipalities of Araguari, Uberlandia and Indianapolis. **b** Localization of the hydrographic basin of the Araguari river. **c** Geological map restricted to the region of the Araguari river basin with the main units in this area. Schist of the Araxá Group (pink color) and gneiss of Maratá Complex outcrop along the riversides

(Pimentel 2016; Pacheco et al. 2017) (Fig. 2c). Amphibolites interspersed in the metasediments of the Araxá Schists were interpreted as remnants of a mafic–ultramafic magmatism (Strieder and Nilson 1992; Pimentel et al. 1999); additionally, there are quartzite and micaceous mica schists, included calc-schists, chlorite-moscovite schist, garnet biotite schist, staurolite schist and feldspar schists, with few paragneiss and marble intercalations. (Pimentel 2016). The presence of anastomosed foliation, intra-folial folds, three generations of metamorphic foliations, stretching, mineral lineations, and all these structures denote the complex tectonic evolution of these metasediments (Valeriano 1993).

Araxá schists was formed by the metamorphism of sedimentary rocks that occurred during the compressive phase of the Neoproterozoic orogeny (PanAfrican/Brasilian), of which, two phases of progressive deformation can be individualized in a simple shear regime. The first deformation phase is responsible for the development of the regional foliation with NS direction dipping approximately 50° to west that characterizes the axial plane of isoclinal folds. The second deformation phase corresponds to crenulation formed by small folds whose axial planes are oriented preferably NW–SE/subvertical. This structure deforms the regional foliation of the N-S direction with plunge to east, and this change in the dip direction could be responsible for the dispersion of the foliation diagram (Pacheco et al. 2017).

3 Descriptive Analyses of Structural Geological Data

A sampling of the structural geological data was performed in two different ways: (i) first a set of the measurement were obtained during the surface mapping, resulting in 396 measures, and (ii) during the construction, 953 new additional data were gathered in the built slope, the headrace tunnel and appurtenant dam structures (Fig. 3).

All measured data are in a dip and dip-direction notation, divided between two different structures, foliation and joints/fractures. The foliation refers to repetitive and different compositional layering in the metamorphic rocks and, the joints are discontinuities formed as a result of regional stress after the rock consolidation, which are of fundamental importance in the general engineering geology.

In order to organize the statistical analyses, the structural data were separated into their different types, place of measurement, surface and depth intervals (Table 1). All data are present in supplementary materials 1, which contains the level where the measure was taken, type of structure (foliation and joints), and the transformation between dip dip-direction to direction cosines.

To perform the statistical analysis, both at the surface and depth, all data were converted into direction cosines. The transformation of dip and dip-direction measures into direction cosines X, Y, Z were made using the usual spherical coordinate systems (Mardia 1972; Fisher et al. 1993) with lower hemisphere (Fig. 4). This type of transformation is important to enable the simulation of the statistical model. The y position corresponds north direction, the dip value is transformed into θ by Eq. (1) and dip-direction value into ϕ by means of the Eq. (2)

$$\theta = 90^\circ - \mathrm{dip} \quad (1)$$

$$\phi = 360^\circ - (\mathrm{dipdirection} - 90^\circ) \quad (2)$$

3.1 Foliation and Joints

After the transformation of the measurements, it is possible to observe the spatial distribution of all the data *dip-dip-direction* that were transformed in direction cosines (Fig. 5a), where the red dots represent the direction cosines data that were obtained in-depth, the blue dots show the direction cosines data collected in the surface, each point represent one measure. The representation using stereographic projection of all these data that were transformed in direction cosines, including foliation and joints planes, shows the spatial distribution of all the planes (Fig. 5b), however, it is not possible to distinguish between foliation and joints. The density distribution and the geometrical analysis show the poles distributed uniformly around a center whose maximum point, determines the mean vector 49/277 (dip/dip-direction notation). To identify the statistical significance of each planar structure, it is necessary to proceed with an analysis separately. We begin analyzing the direction cosines of the foliation and joints differently, and it allows to visualize the direction cosines obtained for the foliation measures, it is noted that there is a greater homogeneity in the

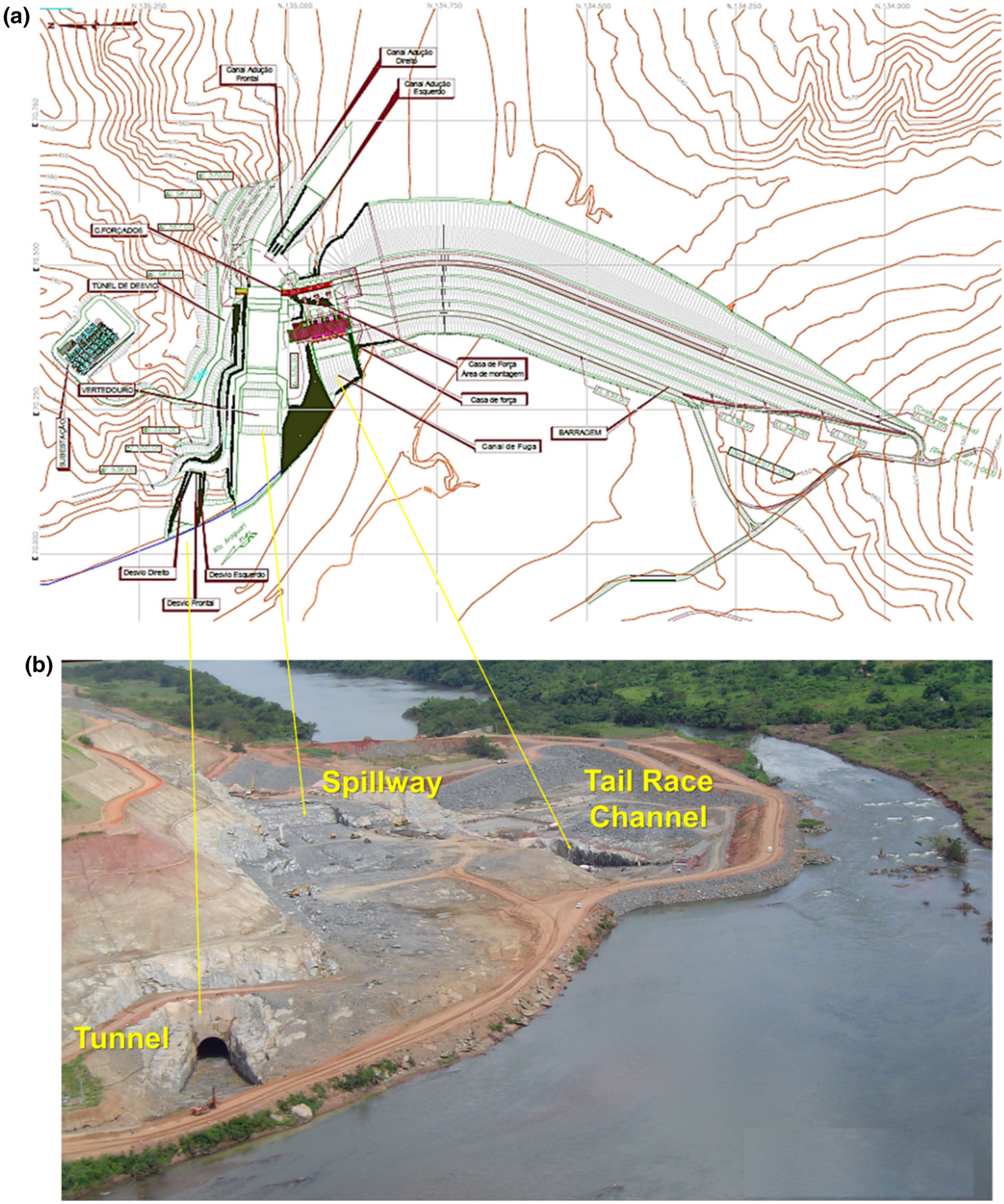


Fig. 3 **a** Illustration of the dam structure in the topographic map. **b** Photo with the identification of data sampling sites

Table 1 Distribution of data collected

Elevation	Depth (m)	Number of measures	Joints	Foliations
Surface	0	396	233	163
558–540	0–18	61	39	22
540–530	18–30	115	79	36
530–520	30–40	177	145	32
Tunnel	50	314	197	117
520–500	50–60	286	211	75

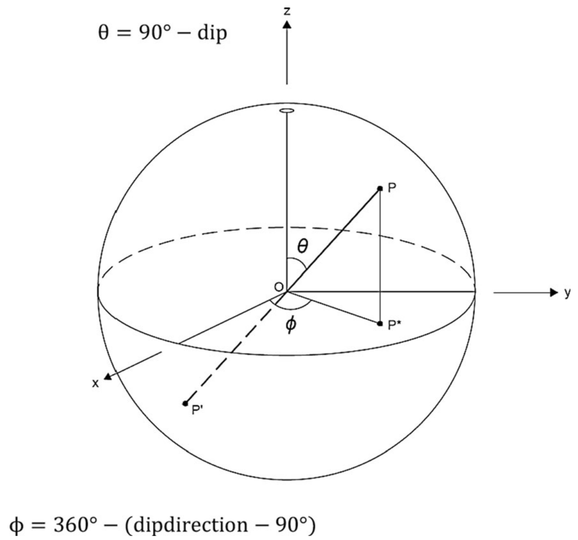


Fig. 4 Ilustration of the position coordinates used to calculate the direction cosines, the θ = latitude and ϕ = longitude, P represent polar projetion of data (Fisher et al. 1993)

spatial distribution, both in surface and in-depth (Fig. 5c), which can be seen by the representation through stereographic projection that shows a single main concentration, with *dip-dip-direction* 49/277 (Fig. 5d).

The representation of direction cosines for joint/fracture measures exhibits two principal concentrations, the red dots, representing depth joints, which have a higher frequency than blue dots, expressing surface joints (Fig. 5e). The projection of the 904 joint data, highlights four distinct joint systems, the most significant concentration named **J1**, presents the *dip-dip-direction* 87/251. The **J2** set (52/281) has characteristic the parallelism (sub parallelism) with the foliation planes. Two other sets, statistically less important, **J3** (85/344) and **J4** (30/120) complete the four joint systems identified in the area (Fig. 5f).

For the correlation between surface—depth data and to achieve a 3D structural model, it is necessary to evaluate the statistical distribution of the foliation and joints, for different depth levels. The analysis, for joint and foliation planes, was performed in three different depth intervals, as follows: we highlight the projections of direction cosines from the surface to 15 m of depth (Fig. 6a), then between 15 and 45 m deep (Fig. 6b), and finally the stretch between 45 and 60 m (Fig. 6c). The respective representations of stereographic projections, in each level, are illustrated in Fig. 6d, 6e and 6f, which were evaluated separately, show a good similarity between the three distinct depths, with a principal direction average N-S dipping to West. The larger quantity of measurements in the last stretch was due to the greater number of fractures present in the tunnel. To improve the analysis of the spatial orientations of these structures, we examined, separately, the foliation and joints measures at different depths.

3.1.1 Foliation Data

The foliation represents the main structure in this area it is direction is almost N-S with plunge 50° to West or approximately 50/270 in the dip/dip-direction notation (Fig. 7). The stereographic projection of foliation measurements reveals the similarity in the two depth ranges, from 0 to 30 m, was collected 90 measures, and between 31 and 60 m, was collected 192 measures (Fig. 7b and d). A large number of measurements below 30 m is due to the presence of the adduction tunnel at 50 m of depth, complementing the data obtained on slopes, as previously mentioned. In the range of 0 to 30 m deep, the director cosines show a dispersion (Fig. 7a) due to a low quantity of data, however, the mean value corresponds to the main direction of the foliation. Similar conditions, but with a smaller dispersion, occur in the deepest levels (Fig. 7c), although, the mean values still correspond to the orientation of the foliation (50/276) (Fig. 7b and d).

3.1.2 Joint Data

The distribution and orientation of the fracture sets is relatively consistent. Analyzing the joints measurements, obtained for the stretch of 0–40 m deep, it is possible to identify the **J1** joint system as being the most statistically significant, with dip dip-direction 88/037 and, the **J2** joint system, whose spatial distribution, using direction cosines (Fig. 8a) and stereographic projection (Fig. 8b), show a sub-parallelism with the regional foliation **J2//fol** (53/283). Two other systems (**J3** and **J4**) observed in the diagram, are quantitatively less expressive, oriented, respectively to 86/175 and 56/077 (dip-dip direction notation) (Fig. 8b), at this level there are 263 measures.

When it is observed the 41–60 m level (Fig. 8c and d), is evident a new concentration named J4 that is opposite J2, and there are 211 measures at this level. If isolating the measurement obtained in the tunnel, there is a different configuration, it is possible to identify the only J1 in the direction cosine graphic (Fig. 8e), in the stereographic projection (Fig. 8f) there are all the joint direction systems with low concertation.

To visualize the two main structures (J1 and J2//foliation) a simple model (block diagram) was constructed with these data (Fig. 9).

4 Monte Carlo Simulation

After the descriptive analyses of structural geological data, it is important to understand the statistical distribution of data, since the Monte Carlo simulation consists of generating random numbers from of the real data with a known distribution. To analyze the data distribution, some techniques were used, initially, it was applied multivariate analysis of variance (MANOVA) model (Johnson and Wicher 2007) for the direction cosines, considering the type of structure (foliation and joint) and level of depth as explanatory variables. However, the assumption of normality was not met, in other words, the data do not have a normal (Gaussian) distribution, even though homoscedasticity was verified, that in terms of statistics, homoscedasticity occurs when the variance in scores on one variable is somewhat similar at all the values of the other variable, therefore the variance of the error is constant.

Then was applied a permutational multivariate analysis of variance (PERMANOVA), which is a non-parametric model to test the hypothesis that the centroids of the groups are equal (Anderson and Walsh 2013), this analysis is used to compare groups of objects and test the null hypothesis that the centroids (confidence region—CR detailed below) and dispersion of the groups as defined by measure space are equivalent for all groups.

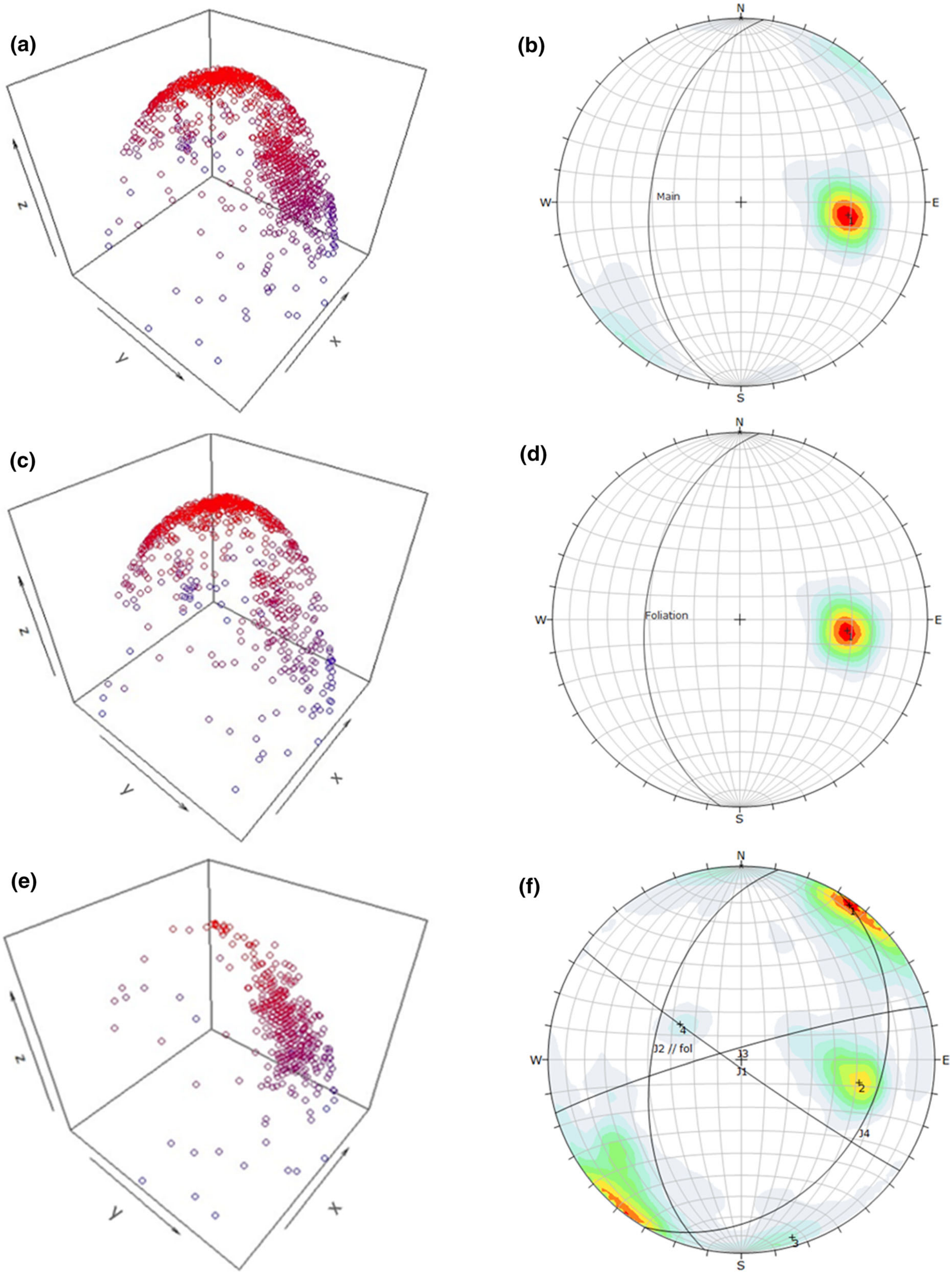
It was verified, statistically, the existence of an interaction effect between different depth levels and type of structure, tests of the depth effects were also performed for each structure, being, in both cases, significant with p-value > 0.01, this verification was done using the statistical significance analysis (Eq. 3)

$$p = 1 - \alpha \tag{3}$$

The p-value is a result of interaction or significance, α is the level of significance, that is, the probability of the study rejecting the null hypothesis, given that the null hypothesis was assumed to be true, when the p-value is below 0.05, it means that the analysis confidence region has a low error.

Although the results of PERMANOVA indicate that there is a significant difference between the direction cosines of the surface and depth, from a statistical point of view, it does not give us the magnitude of this difference from a real situation, which it was understood as an incomplete result for what one wanted to investigate, this happens because the number of measures between surface and depth is different. Since it is known that p-value naturally decreases as the sample size increases (Krueger and Heck 2019), it was decided to complement the problem from another perspective. In Mardia et al. (1995), a version is presented for the central multivariate limit theorem, in which the average vector of a sequence of independent random vectors have a asymptotic multivariate normal distribution, once the sample is large, we then assume that this asymptotic approach is reasonable (Supplementary Material 2).

Using this result, it is possible to estimate a tridimensional parameter $\theta \in \mathbb{R}$ from the direction cosine sample (X, Y, Z) with the observed data we end up with a point estimate, which is the corresponding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◀**Fig. 5** Correlation between direction cosines and stereographic projections in different situations. **a** The projection of direction cosines of all the 1349 measurements (foliation and joint at surface and depth), where the red and blue dots represent, respectively, the depth and surface data. **b** Stereographic projection, lower hemisphere, of the totality of data showing the average value of 49/277 (dip dip-direction). **c** Spatial representation of direction cosines related to foliation (445 measurements). **d** Using stereographic projection the mean value of the foliation is 48/276 (dip and dip-direction). **e** Direction cosines diagram using 904 data of joints. **f** Stereographic projection of the joints highlights four distinct sets: J1 (88/215), J2 (54/282), J3 (85/344) and J4 (30/120) using dip dip-direction notation

observed value of $\widehat{\theta}$ (simulated data). We know that estimator $\widehat{\theta}$ is a random variable (simulated data) and we often prefer to determine a *confidence region* (CR) for θ. A confidence region is a random subset of $\mathbb{R}$ (determinate by appropriate statistics) such that it is "confident", at a certain given level, that this region contain θ:

$$p(\theta \in \mathbb{R}) = 1 - \alpha \tag{4}$$

Confidence regions are particularly useful when a hypothesis H_0 on θ is rejected, due they eventually help in identifying which components of θ is responsible for rejection (Härdle and Simar 2012) (Supplementary Material 3).

The Eq. (5) describe a confidence region for μ:

$$CR = \left\{ \mu \in \mathbb{R} | (\mu - \overline{x})^{\top} S^{-1} (\mu - \overline{x}) \leq \frac{p}{n-p} F_{1-\alpha;p,n-p} \right\} \tag{5}$$

The μ value represent the ellipse of the simulation data. The CR is the interior of an iso distance ellipsoid in $\mathbb{R}$ centered at $\bar{x}$, with a scaling matrix S^{-1} and a distance constant $\frac{p}{n-p} F_{1-\alpha;p,n-p}$.

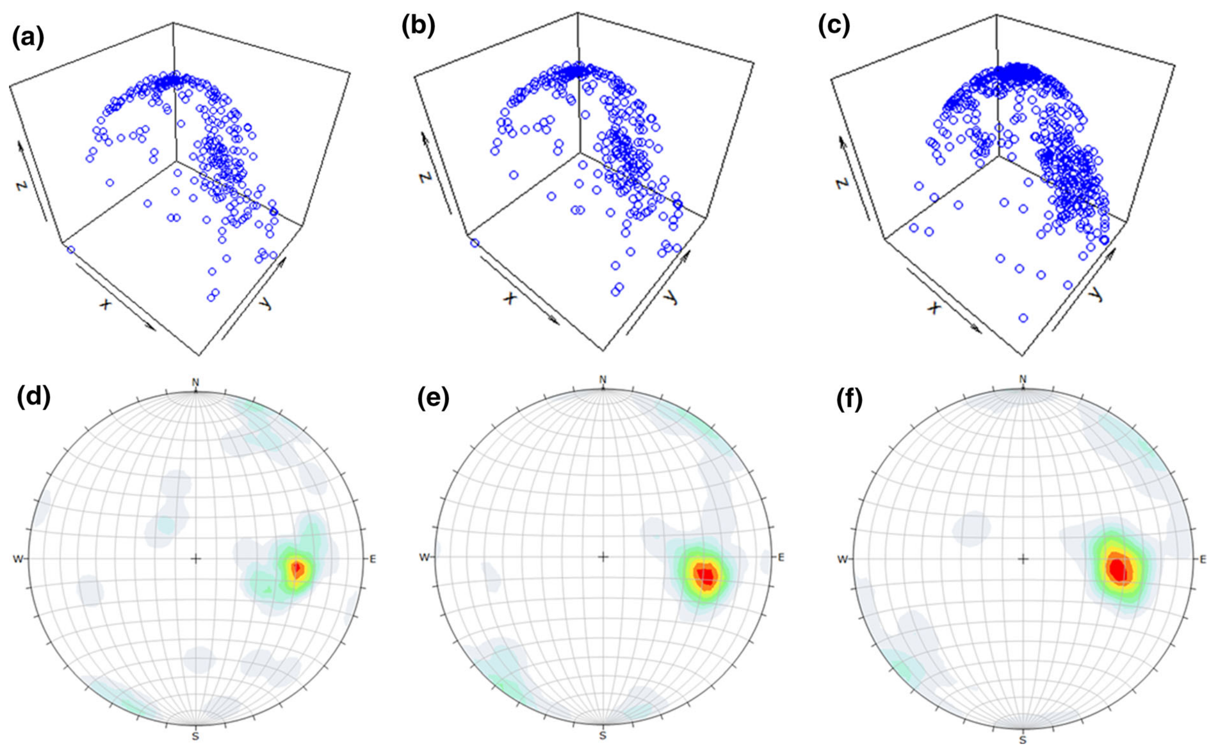


Fig. 6 Spatial representation of direction cosines and stereographic projection of the foliation and joints orientations at the three different levels of depth **a** The direction cosines graphic for the measure of the first level of 0–15 m of depth, with 431 measures **b** The direction cosines for measures of the second level of 15–45 m of depth, with 319 measures **c** The direction cosines for measures of the third level of 45–60 m of depth, with 599 measures. The stereographic projections of the three different levels are very similar (**d**, **e** and **f**). The red point in each diagram represents the main concentration of the measurements (~ NS/50 W) with some scattered spots in gray

When p is large, ellipsoids are not easy to handle for practical purposes. Thus, we are interested in finding confidence intervals for μ1, μ2, ..., μ for that simultaneous confidence on all the intervals reaches the desired level (1 − α) (Härdle and Simar 2012). With the described and calculated CR, it is possible to analyze the ellipses behavior obtained in the simulated data (Supplementary Material 4) the result.

The graphic representation of confident ellipse for foliation and joints data shows that the black ellipse is representing the simulated surface data and red ellipse represents the simulated depth data, when the ellipse is larger it means that there is a variability of the data and them is greater in relation to centroid, this happens due quantity of measure. In the case of this example, there are more measures in depth than surface, then the ellipse that represents depth is smaller than surface ellipse in both analyzes graphs (Figs. 10 and 11).

To perform the correlation between surface and depth using the simulated data, the distance between the two ellipses is measured, when the ellipses are

Fig. 8 Projections of the direction cosines regarding the ▶ measurements of joints obtained at the following depths: **a** 0 to 40 m, showing the J1 and J2 system concentration; **c** 41–60 m, highlighting the J4 concentration; **e** and 50 m-depth in adduction tunnel, with a highlighting of J1 system. The respective stereographic projection diagrams for theses depths show the following joint systems: **b** J1 (88/037), J2//fol (53/283), J3 (85/355) and J4 (56/077); **d** J1 (87/047), J2//fol (43/273), J3 (85/175) and J4 (28/122) and **f** J1 (82/049), J2//fol (33/268), J3 (84/167) and J4 (32/144) (**f**), all the data are dip-dip direction notation

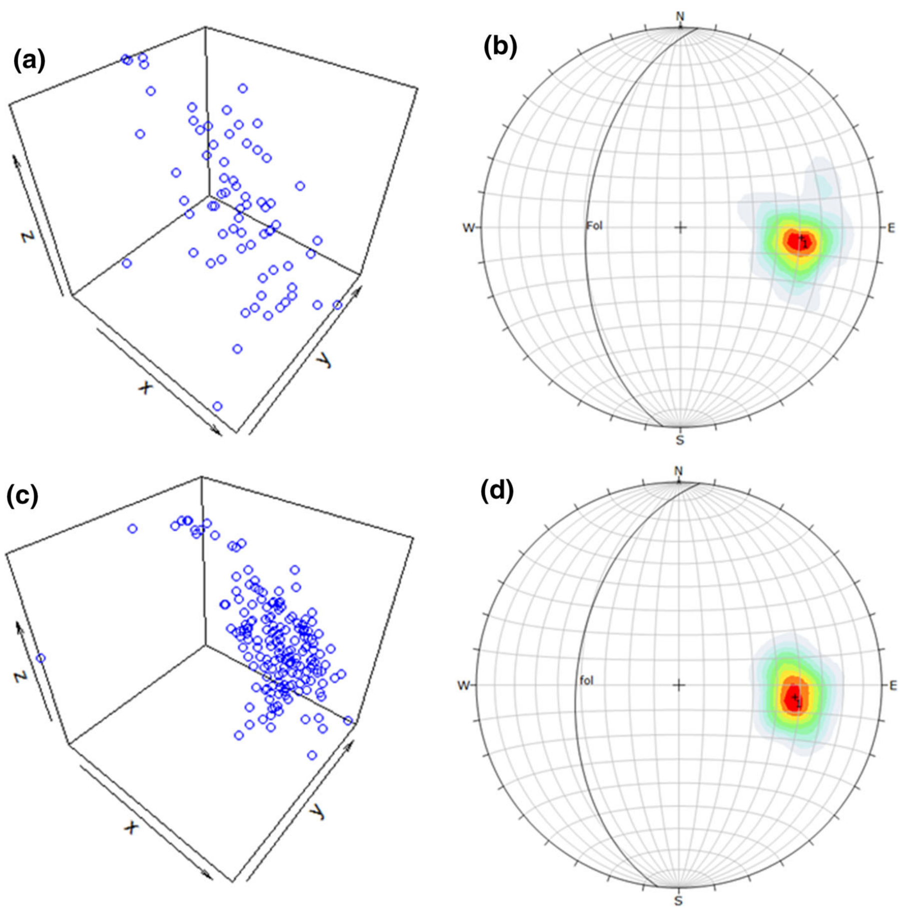
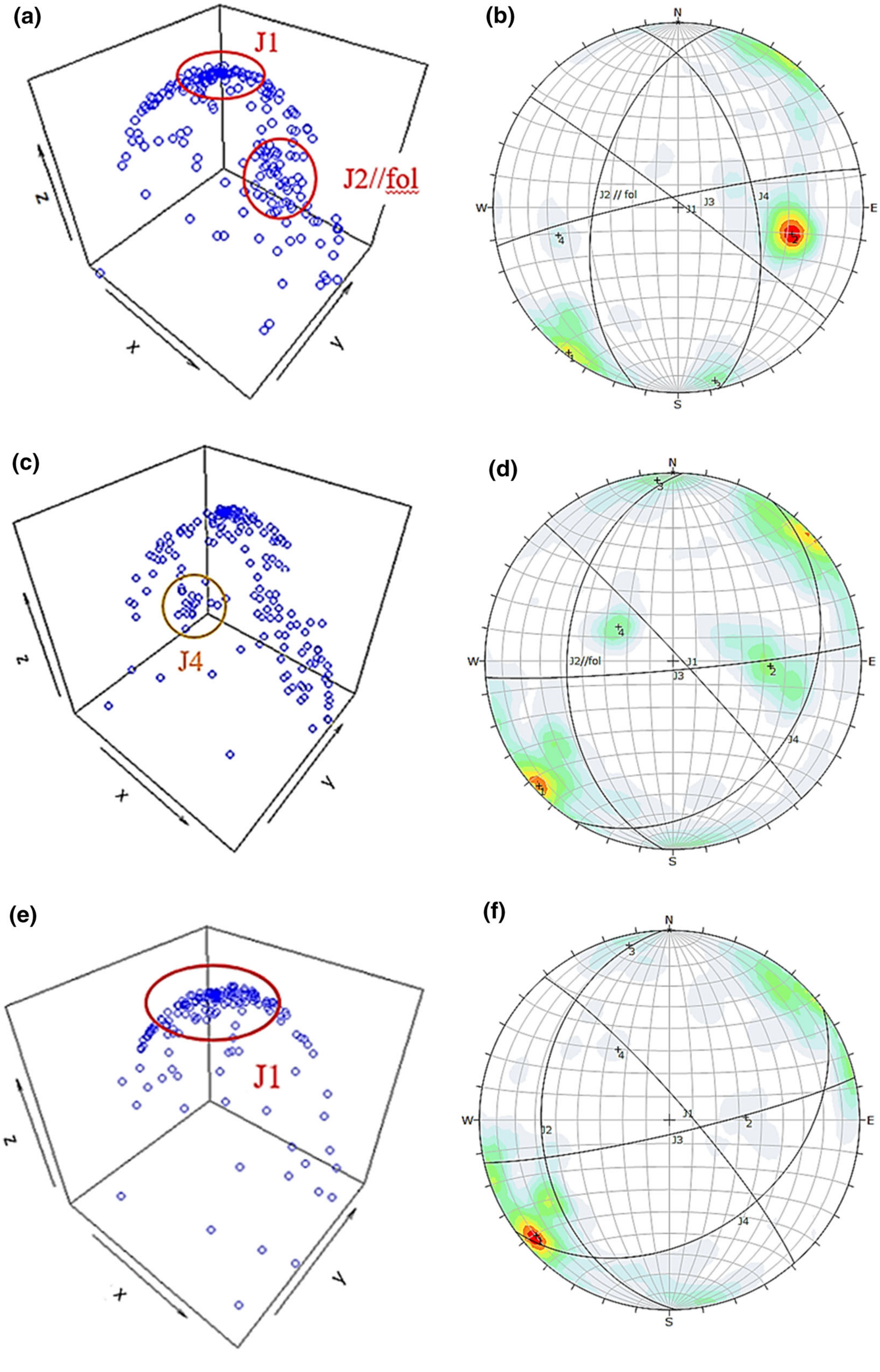


Fig. 7 The direction cosines and the stereographic projections for foliation measurements obtained from 0 to 40 m of depth, respectively diagrams (**a**) and (**b**), with 90 measures. Statistically, the average value is 50/276. Diagrams c and d correspond to the same representations for the 41–60 m of depth, with 192 measures. At both depth intervals, the mean value corresponds to the spatial orientation 49/276 (dip dip-direction notation)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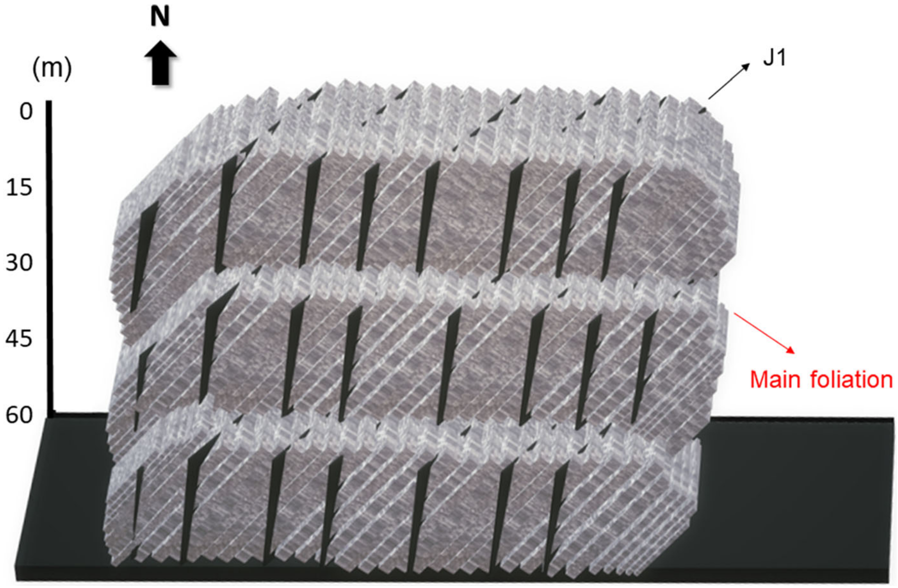

Fig. 9 Simplified block diagram showing the foliation, in the gray color, and the *J1* joint system in black color

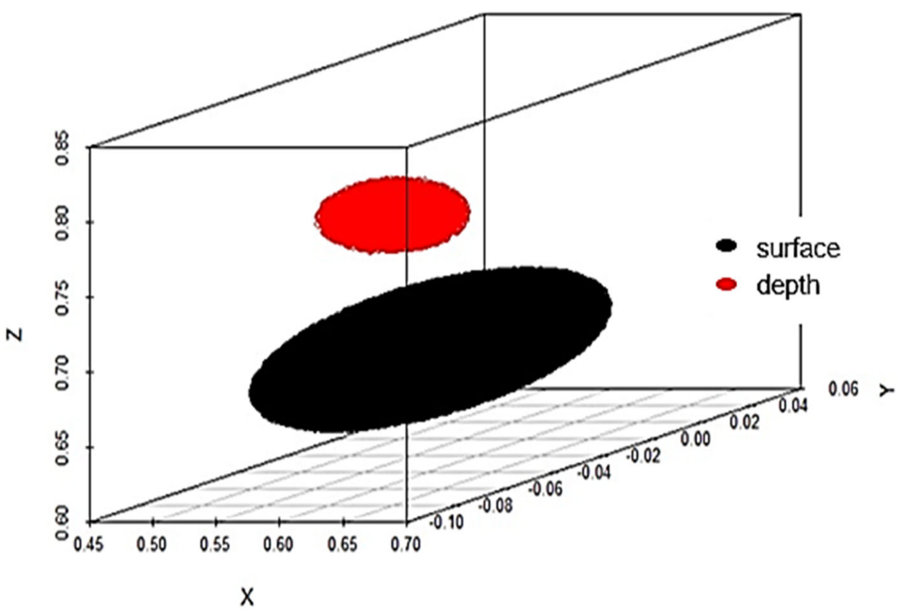

Fig. 10 Graphic representation of confidence ellipse of foliation data, the three axes correspond to direction cosines and red ellipse is a simulate data of depth and the black ellipse is a simulate data of surface

overlapping, it means that the simulation data is equal, if there is a distance between them, it means that there is a difference, in general we can obtain the magnitude of this difference with measure of Z axis. The Z direction cosine can range from 0 to 1, where 0 means that the both simulation data is equal, if the distance is 1, it means that the simulation data for surface is totally different to depth, in others words, if the distance is 0 we will have 0% difference between surface and depth, in the other hand, if we have the

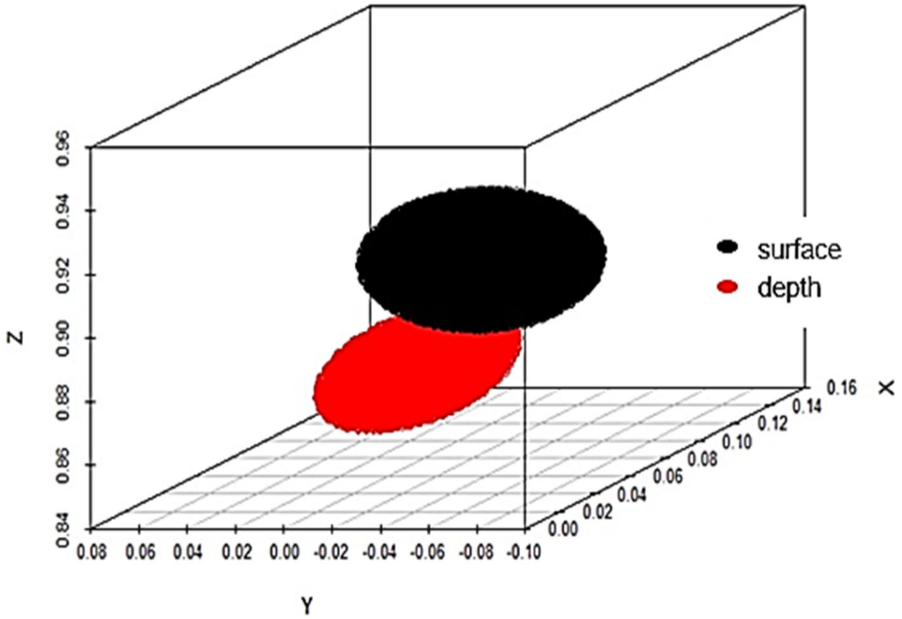

Fig. 11 Graphic representation of confidence ellipse of joints data, the three axes correspond to direction cosines and red ellipse is a simulate data of depth and the black ellipse is a simulate data of surface

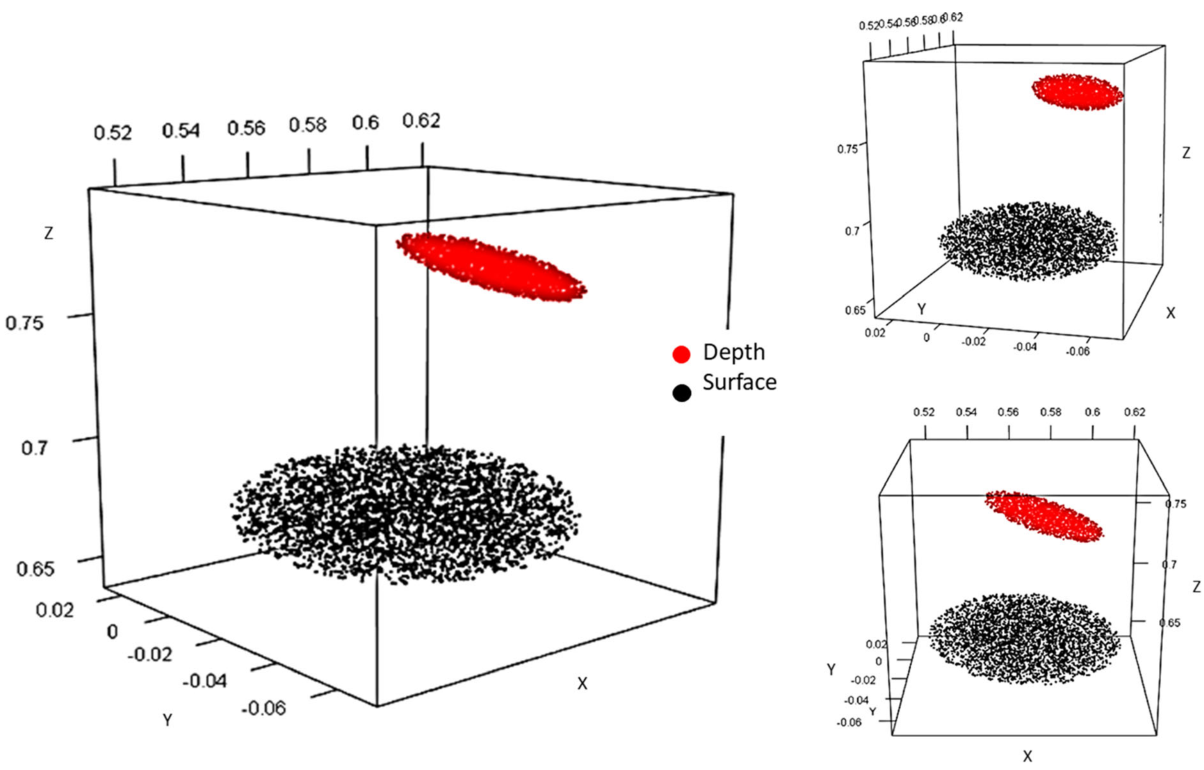

Fig. 12 Graphic representation of confidence ellipse of foliation data showing the different views and the three axes of the direction cosines, the red points concentration is the simulated data based on real depth data and the black points concentration is the simulation data based on real surface data

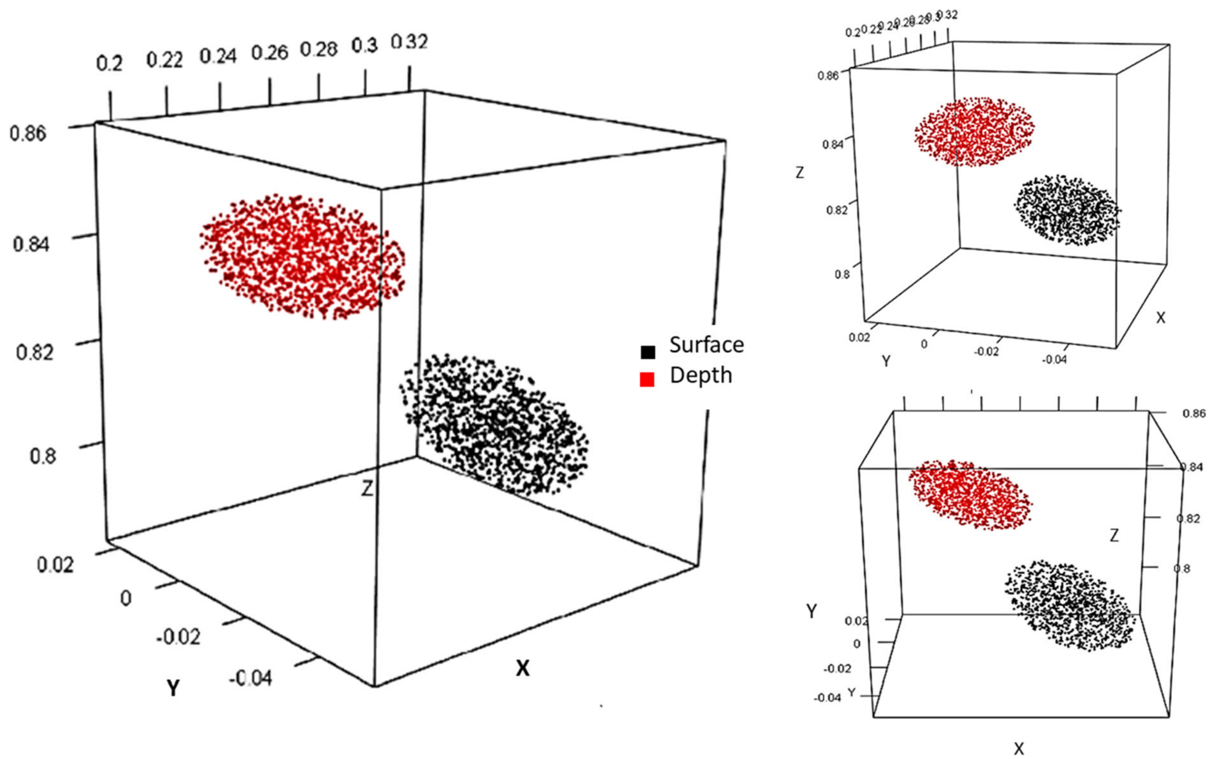

Fig. 13 Graphic representation of confidence ellipse of joints data showing the different views and the three axes of the direction cosines, the red points concentration is the simulated data based on real depth data and the black points concentration is the simulation data based on real surface data

distance 1, we will have 100% difference between surface and depth simulation data, therefore, if the distance is 0.05 it is means that the difference between surface and depth simulation data is only 5%.

The simulation for foliation data presents a difference between surface and depth data. This difference can be observed using the distance between the ellipses, in this case, distance is around 0.05 (direction cosines unit), but in terms of magnitude scale, this difference does not change the feature of foliation measure (Fig. 12). Therefore, there is a resemblance between surface and depth, if it considers that 0.04–0.05 for direction cosines Z means that the difference is around 4% then the simulation is representing the real data for the foliation data. For joint simulation (Fig. 13), there is the similarity of the size of ellipse due to less variability in average values, the distance between ellipses, that means a difference with respect of surface and depth data, in magnitude scale, has 0.02–0.04 for direction cosines Z means that the difference is around 4%, thus it has the same situation for foliation.

These analyzes show that the simulation is following real measurements in the place the surface measurements are obtained. It is possible to simulate a model using the Monte Carlo methods and estimate the depth conditions. It is important to accentuate that simulation is possible for the one geological unit, all these analyzes were done for the schist of Araxá Group, rocks that compose the works area.

5 Discussion

Initially, as already mentioned, the mean values were obtained for all structures set without distinction between foliation and joint. The result of this analysis gives us a general idea of the spatial arrangement of the structures present in the studied massif. Despite the described analyses to show a certain similarity between the surface and depth data, mainly concerning the direction, these structures should be discussed separately to highlight the differences between them. To understand this contrast and undertake the Monte

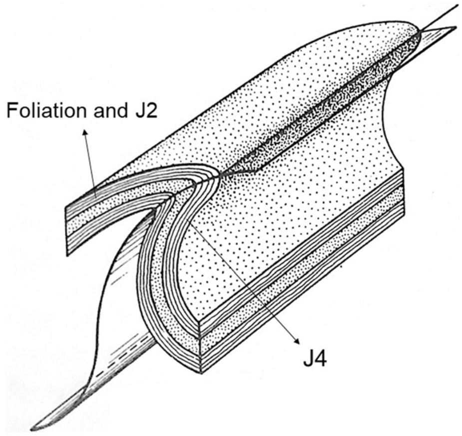

Fig. 14 Fold model shows the position of foliation and J4

Carlo simulation, the foliation and joints were examined separately, distinguishing the position of the measures on the surface and in-depth.

The directions of joints are not evident when all the measurements are plotted together in the same diagram (Fig. 5a and b), but we can distinguish only two main systems (J1 and J2), which J2 is parallel to the foliation planes. When were separated foliation and joints, it is possible to identify J1 and J2 sets plus two sets with less concentration named J3 and J4 sets (Fig. 5c and d) evidencing the real situation of arrangement of geological structures.

At different depth intervals, the mean values of the foliation orientations were calculated, the former shows no significant variation in direction and plunge along with the depth (Fig. 7b and d). When we analyze the joint orientation, we remark the appearance of the system (*J4*) with higher concentration occur in the interval of 41–60 m of depth (Fig. 8d), which has not been identified easily on the surface and the 0–40 m of depth due to a less concentration (Fig. 8b). Compared to other systems, *J4* set has a longitudinal direction to *J2//fol* with an opposite plunge, suggesting the presence of folds (Fig. 14).

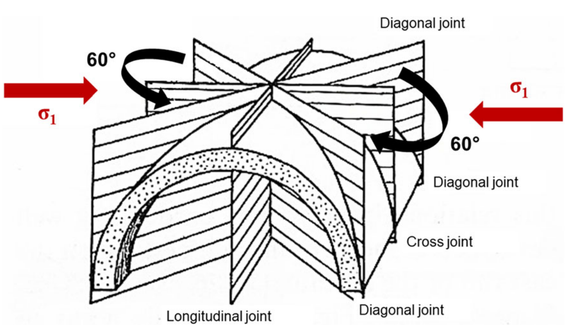

Fig. 15 Arrangement of joints and the conjugate system model

The angle between *J1* and *J3* systems is ~ 60 degrees and could be related to a conjugate system. The spatial arrangement of the conjugate system enables the identification of the $\sigma 1$ direction, that correspondent to the E–W direction, coherent with the N-S direction of the foliation planes (Fig. 15).

After the statistical treatment of the geological structures arrangement and obtaining the average of the real values, new data were created using the Monte Carlo simulation from the direction cosines. The principal idea is simulated model from real data, using the simulation based on reliability theory. Since it is possible to obtain the average real value and simulate new models using these values, it is possible to predict the conditions in inaccessible or difficult reach places. From the combination of these approaches, the Fig. 16 compares the real structural geological data, in plant and section, with those obtained from the Monte Carlo simulation. We may now compare the real and simulated data and check the correspondence between the surface and depth data, calculating the percentage of this correspondence. It is important to emphasize that the simulation was performed in only a single geological unit (Schist Araxá), as mentioned above.

With the possibility to compare the real and simulated data, we can check the correspondence between the surface and depth data, calculating the percentage of this correspondence. It is important to emphasize that the simulation was carried out in only a single geological unit (Schist Araxá), as described above. Comparing the behavior of the foliation data with those created by simulation allowed us to know how close or different these data are. For example, in the foliation simulation data (Fig. 12) the similarity is around 96%, and for joint data, the difference is also low, showing similarity of round 95% (Fig. 13). These results are suggesting, favorably to use the simulation for optimization of prediction of geological conditions. These percentage values were obtained based on correlation between real data and the simulated.

The low difference between the spatial orientations of the structures in surface and depth attest that the simulation results presented highlight the feasibility of using the Monte Carlo simulation, to understand the geological structures behavior from the surface to the depth.

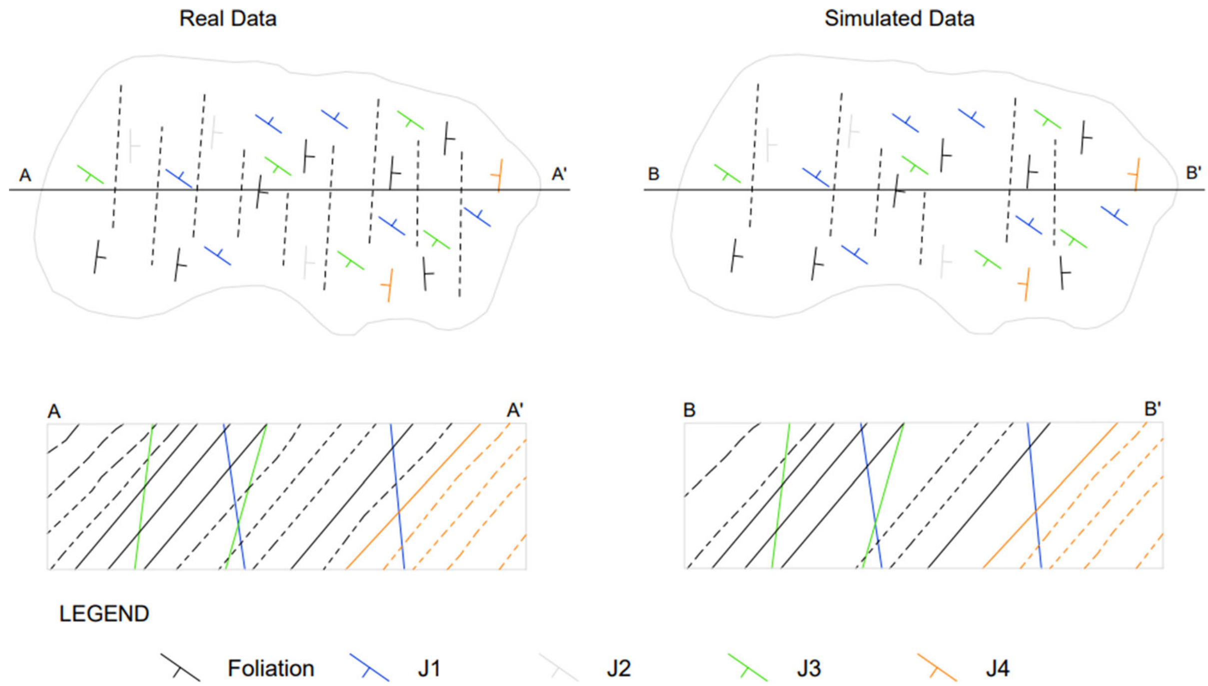

Fig. 16 The figure shows an example of the plan view using the real data with the direction of measures indicated symbols and different colors, where there are the dashed lines mean the inference of foliation position for better visualization. Below the plan view we have the respective cross section (A–A') and the right side we have a plan view with simulated data and the respective cross section simulated

The Monte Carlo simulation was construction considering the reliability theory, with the means values inside the 95% reliable, the values was simulated considering the reliability theory, due to this it is possible do the connection with real and simulated data.

6 Conclusion

Descriptive analysis shows the importance of understanding the configuration of the geological structures of rock massif and employing description of data it is possible to identify some differences and/or similarities that allowed to make a correlation between surface and depth data through Monte Carlo simulation.

The foliation measures of different depth intervals are quite similar to surface measures, indicating that the direction and plunge of foliation remain remarkably similar from the surface to a depth of 60 m, only a 4% difference can be determined through simulation. The joints measure also show a small difference among the distinct levels, however, the short difference between joints surface and depth data, as shown by the simulation, probably can be attributed to the appearance of fractures due to detonations for tunnel opening.

The regional stress pattern that creates joints of tectonic origin can be locally perturbed by human intervention in the engineering works. Rock mass strength is influenced by stress, and thus depends on the strength of the intact rock, joints formation, and its persistence, as well as orientation and strength, essential to calculating safety factors. All engineering projects must be carefully designed and constructed with an adequate factor of safety. Fall of block rocks defined by intersecting joints is the primary threat to safety and stability, consequently, prior knowledge of the probability of the presence of deep fracture or joint sets, similar to, or different from those found in surface, will allow to execute the project more safely, reducing the probability of errors due to unforeseen events during the excavation of the work, this is of paramount importance. The technique describe in this paper show us one possibility to understand and predict the condition of structures arrangement.

The results obtained in the work through the simulated data on surface and in depth, show the possibility to obtain information and create correlations between surface and depth data, and estimate the percentage of correspondence between them. We conclude that the use of Monte Carlo simulation demonstrates to be a powerful and promising tool in geological investigations for large engineering enterprises (projects). In the near future, with the aim of testing the effectiveness of the method, we will apply this simulation in different lithologies and structures of distinct geological units.

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Declaration

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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