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TECHNICAL ARTICLE

Evaluation of Hydraulic Conductivity of Itabirites of the Alegria Centro and Alegria Sul Open Pits, Samarco Mineração S.A., Minas Gerais State, Brazil

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Abstract Itabirites in Samarco Mineração S.A.'s open mine pits in the Quadrilátero Ferrífero region, Minas Gerais State, Brazil, were hydrogeologically characterized. Itabirites, which represent the main aquifer in the region, were divided into four lithotypes based on their mineralogical composition. Statistical analysis of fracture frequency and rock quality designation were evaluated and correlated to hydraulic conductivity results. Preliminary analysis showed a highly fractured rock mass with relatively constant fracturing with depth, regardless of lithology. Field experiments were performed to determine the hydraulic conductivity and provide input data for an analysis of fracture frequency. Infiltration tests showed a median hydraulic conductivity of 1.2×10^{-7} m/s, while packer tests indicated a median hydraulic conductivity of 9.6×10^{-7} m/s. Fracture frequency was related to hydraulic conductivity through the cubic law. Median hydraulic conductivity values for the rock types at the mine were found to range from 1.2×10^{-7} to 1.0×10^{-6} m/s.

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Keywords Cubic law · Fracture frequency · Groundwater flow · Hydrogeological characterization · Surface mine

Introduction

Statement of the Problem

The Samarco Mineração S.A. (Samarco) currently mines itabirite with an iron content between 30 and 64 % at its operating Alegria Norte open pit and has proposed two new open mines pits nearby: Alegria Centro and Alegria Sul. This itabirite rock mass belongs to the Cauê Formation, an intermediate portion of the Itabira Group (Minas Supergroup), dated between 2.42 and 2.52 Ga (Babinski et al. 1993, 1995). Part of the mineral reserve in the two new pits is located at depths that will require drawdown of the water table, but this is complicated by the fact that the Piracicaba River lies between the two proposed pits. Drawdown at Alegria Norte is currently being achieved by pumping a set of deep wells. Evaluating the impacts of water-level drawdown on the flow of the Piracicaba River will be crucial to evaluate long-term inflow from the river to the proposed pits and for stability analyses of the proposed final slopes of both pits.

Problems related to groundwater tend to be site-specific, especially in weak rock deposits where the hydrology and geology are often complex. It was therefore extremely important to have a comprehensive understanding of the area with regard to its hydrogeomechanical conditions before the design phase to characterize the properties of the rock mass in the area and facilitate pit designs appropriate to the site-specific conditions. The rock mass was hydrogeotechnically characterized, including its hydraulic anisotropy and the possible influence of this on both groundwater flow and slope stability (Carneiro 2013).

A limiting factor in the eventual deepening of the proposed open mine pits is the increased geological/geotechnical risks associated with higher water pressures and their effect on slope stability. These risks are the result of interactions between the site's geological, hydrogeological, geotechnical factors, and operational constraints (Sjöberg 1996). The main objective of this paper is to report how the hydrogeological and geotechnical properties of the rock mass were characterized and how fracture frequency data from geotechnical logging were correlated with hydraulic properties (especially hydraulic conductivity), for use in predicting inflow of water into the mine pits.

Location

Samarco's Alegria Complex comprises a set of mines located in the city of Mariana, Minas Gerais State, Brazil, approximately 120 km from Belo Horizonte, the state capital (Fig. 1). The mines are located in southern Serra do Caraça, an extremely mountainous terrain with an elevation ranging from 2,072 m at the Serra do Caraça summit to 900 m at the Piracicaba River valley. The Piracicaba River, which is a very important regional river, generally flows north to south, but its course changes abruptly at the border of the Alegria Sul area, most likely due to fracturing of itabirites from the Cauê Formation. The Palmital River also flows into the Piracicaba River at this location. Figure 2 shows the limits of the proposed pits and the waterways.

Climate at the study area is high-altitude tropical, with dry winters and rainy summers. The average annual temperature is 19 °C. The average annual precipitation between 1976 and 2012 was approximately 1,860 mm, according to the Germano Station, with 85 % of the annual precipitation occurring between October and March.

The deposits of the Alegria Complex are located in the Alegria syncline in a highly deformed zone on the eastern edge of the Quadrilátero Ferrífero (the Iron Quadrangle). The iron ore found in the area of interest is characterized by the presence of ore bodies strongly aligned with the orientation of the folds axes (Rosière and Chemale Jr 1991). Figure 3 shows (a) a simplified map of the

Fig. 1 Location of Alegria Mine

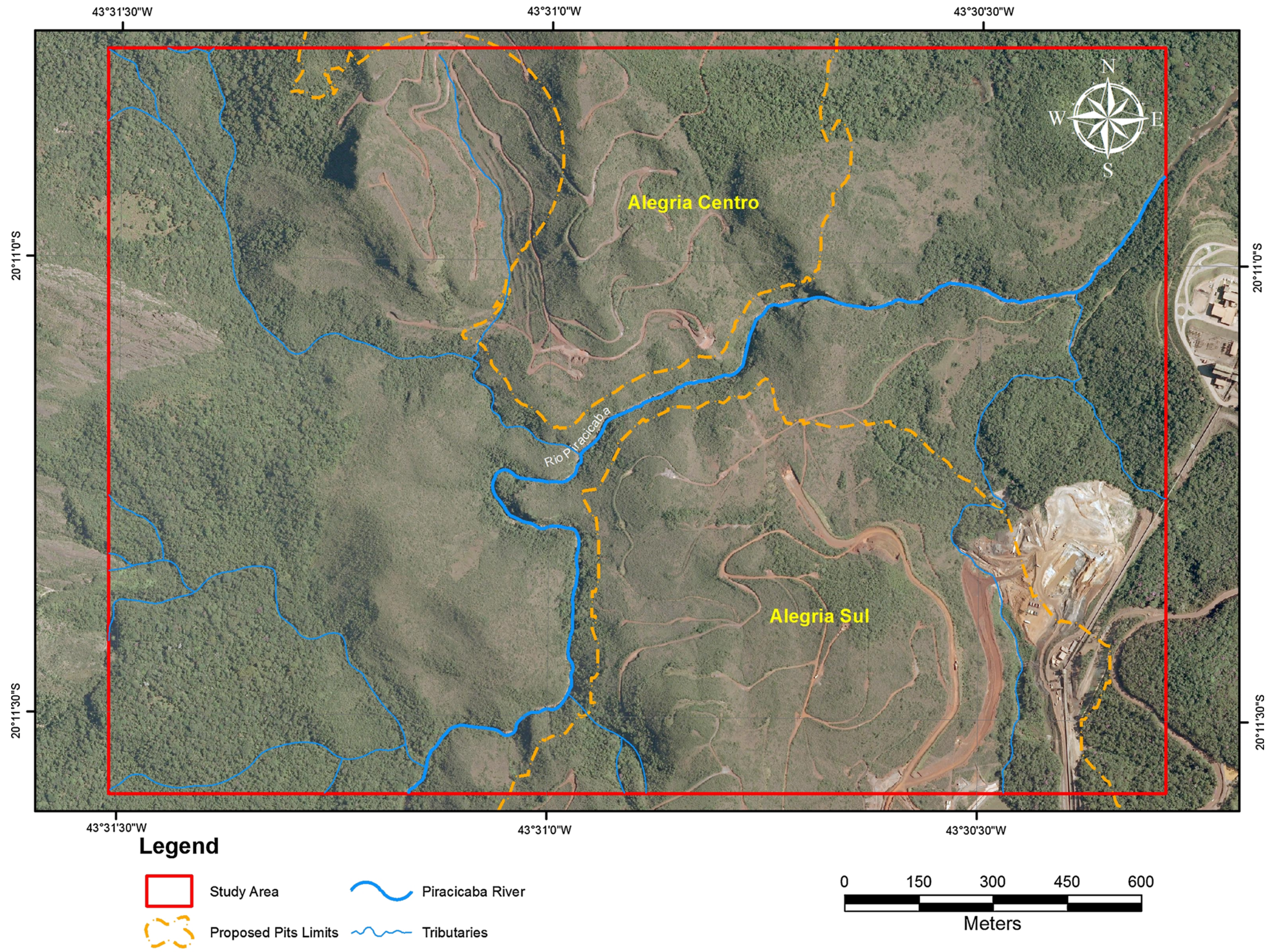

Fig. 2 Location of Alegria Sul and Alegria Centro open pits mine limits and its relation to Piracicaba River in the study area

Quadrilátero Ferrífero and (b) a geological-typological map of the Alegria Complex.

Mineralogical assembly of the banded iron formations (Klein 2005) defines different types of itabirite. Samarco uses the following four assemblies of one, two, or three minerals to distinguish the ore types: specularitic itabirites (IE), martitic itabirites (IM), goethitic itabirites (IG), and amphibolitic itabirites (IA). Geological-geomechanical superficial mapping and borehole geotechnical description of hundreds of samples has provided very good knowledge of the rock masses, and borehole logging has allowed identification of fracture sets as well as the recognition that these structures control groundwater flow in the area.

Methodology

Hydraulic testing was performed in order to acquire hydraulic conductivity values as well as information regarding hydrogeological behaviour of the main discontinuities (fractures and foliation). The main tests were infiltration tests (in observation wells) and packer tests (in the boreholes). Fracture frequency analyses were also performed in geotechnical boreholes. The aim of these analyses was to determine an average hydraulic conductivity value and correlate it with fracture frequency for each rock type occurring in the study area.

Infiltration Tests

An infiltration test is a hydraulic conductivity test performed in the saturated zone. A volume of water is introduced into the borehole and water levels are measured (Supplemental Figure 1; note, supplemental files accompany the on-line versions of journal papers, and can be accessed for free by all IMWA members). When a rock mass has a high hydraulic conductivity, water level stabilization occurs quickly and pressure transducers (slug test) can be used to automatically register water levels over time. The initial level corresponds to the static water level

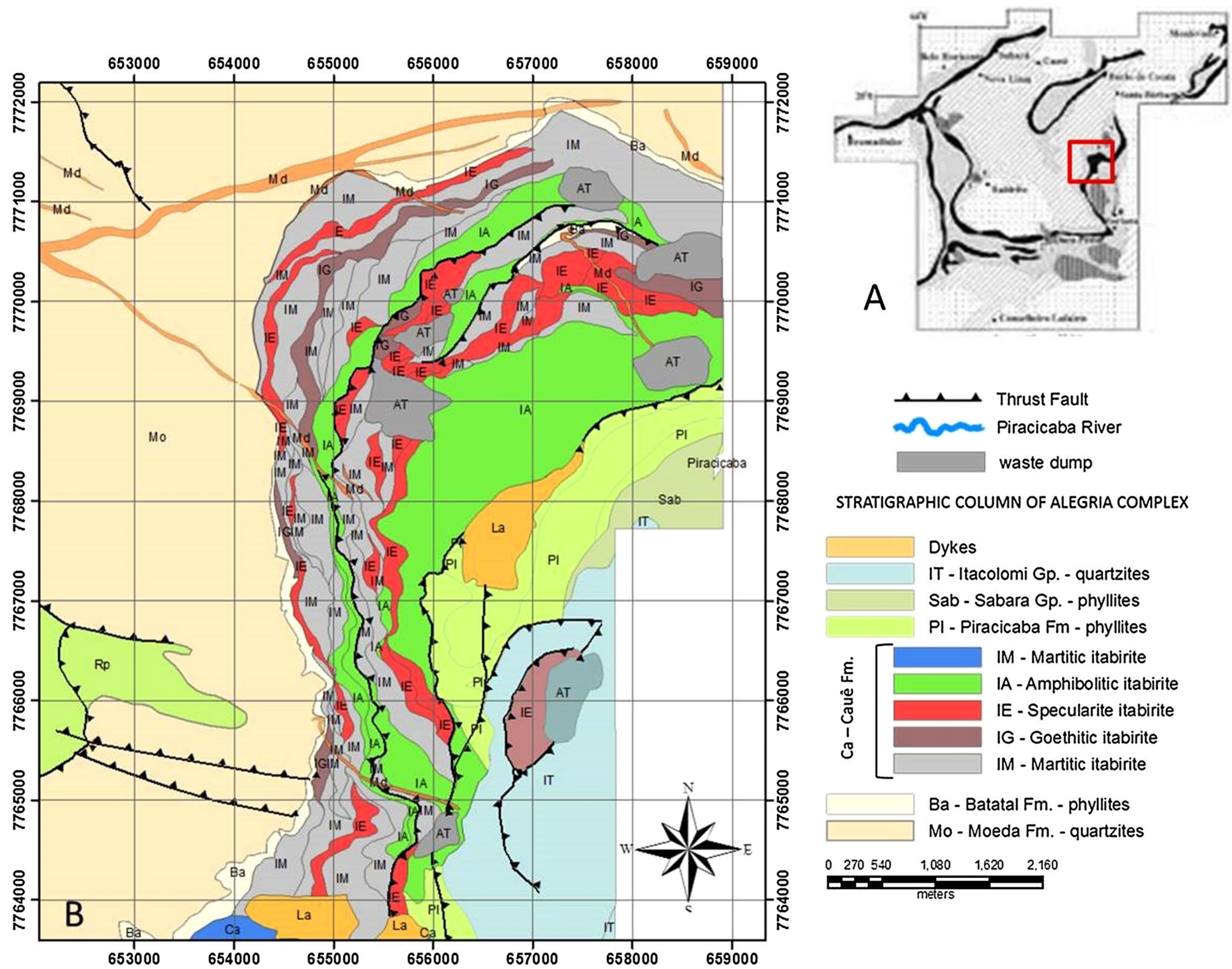

Fig. 3 Geological-typological map of Alegria Complex area

in the borehole. After a few seconds, a known volume of water was injected, causing a water level rise. The drawdown of the water level over time until it reaches the initial level defines the recovery curve. Analysis was based on Hvorslev (1951) methodology.

Packer Tests

Packer tests were used to determine both the hydraulic conductivity and transmissivity in different zones of a borehole by isolating selected borehole sections with packers inflated by nitrogen gas or water. This study was performed using an IPI (Inflatable Packers International) system with pneumatic obturators inflated by nitrogen. The equipment consists of a set of steel rods and a rubber obturator. The portion to be tested is isolated by inflation of the obturators and a rod with small holes that passes through the obturators. These small holes allow water to be injected into the test section. The advantage of this type of test over infiltration tests is that it allows hydraulic conductivity of structures and/or specific rock types to be quickly determined during drilling.

Hydraulic Conductivity and Fracture Frequency Analysis

Samarco currently has a significant geotechnical database obtained mainly from geotechnical drilling. The data indicate that the rock mass is generally poor to very poor, with average rock mass rating values between 31 and 32 in the study area (Supplemental Table 1). All lithotypes within the study area were found to be highly fractured, and the higher the degree of fracturing, the greater the groundwater seepage observed. Therefore, hydraulic conductivity was estimated by correlating the fracture frequency analysis and hydraulic conductivity values obtained from the hydraulic tests.

Fracture frequency in the main rock types was obtained from available geotechnical logs. Data used in the present study were almost entirely (97 %) collected in itabirites, as inflow into the mine pits occurs predominantly through these rocks.

The water that flows through fractured rock is proportional to both fracture frequency and fracture connectivity. To characterize the hydraulic properties, it is first necessary to determine the hydraulic conductivity of a set of discontinuities. Fracture frequency was converted to permeability using Eq. (1), developed for a set of parallel planar joints by Snow (1968, in Freeze and Cherry 1979), and called the 'cubic law,' in which the permeability is proportional to the cube of the average aperture of fractures in the rock mass:

$$K = \left(\frac{\rho g}{12\mu}\right) N b^3 \quad (1)$$

where g is acceleration due to gravity, b is the fracture aperture, N is the number of fractures per meter, ρ the is water density, and μ is the kinematic viscosity coefficient. The cubic law shows that the fracture aperture (b) is more important than fracture density (N) for determining the hydraulic conductivity; b is proportional to the cube of the aperture and N is linearly proportional to the fracture density (Hoek and Bray 1981).

Equation 1 does not consider fracture roughness and can only be applied when there is laminar flow through parallel and planar discontinuities, such that Darcy's law is valid. However, if the rock is highly fractured, then rock mass will behave hydraulically similarly to an equivalent porous material. In that situation, hydraulic properties of the rock mass can also be estimated using Eq. 1 (Louis 1976, in Giani 1992).

Location of Drill Holes Tested

Based on representative rock types and the structural setting of the studied area, tests were performed throughout the Samarco area (Supplemental Fig. 2). Due to the homogeneity of the ore body throughout the deposit, it was possible to correlate data collected throughout the area.

Results and Discussion

Packer Tests

In total, 11 tests were performed in four different boreholes in the area. However, three of these tests showed anomalous results due to high conductivity and were not considered in the present study; therefore, results from eight tests are given below. Usually, anomalous results in packer tests are due to one of two main reasons. The first is when the hydraulic conductivity of the rock mass is nearly zero. This condition prevents the test because the injected water in the borehole may return to the equipment, resulting in negative injection values. The second reason for anomalous results is the opposite condition: when the rock mass is highly conductive, the injection capacity of the available equipment may be insufficient, and it may not be possible to reach the necessary test pressure in the borehole. Then, it becomes impractical to carry out all stages of the test.

Table 1 Summary of results of packer tests

Hole ID	No. of tests	Test interval (m)	Lithotypes	K (m/s)
FCD-2223_1	2	251.5–54	IE	3.1×10^{-07}
		317.5–320	IE	2.8×10^{-07}
F24_P-4_1	2	162.5–165	IME	9.2×10^{-07}
		198.5–01	IM	1.8×10^{-07}
	3	105–108	IEM	1.0×10^{-06}
WLI 84		145–148	IME	1.3×10^{-06}
		164–167	IME	1.5×10^{-06}
WLI 86	1	207–210	IMG	1.2×10^{-06}

The packer tests were performed in the five lithotypes that were present in the four tested boreholes: IE, martitic specularitic itabirite (IME), IM, specularitic martitic itabirite (IEM), and martitic goethitic itabirite (IMG). Test results are shown in Table 1.

The IMs had a higher average hydraulic conductivity than the IEs. However, the average degree of fracturing in IM is slightly lower than in IE (Fig. 4), which does not explain its higher conductivity. Variation of hydraulic conductivity values is presumably due to fracture aperture and the higher porosity of the IM matrix.

Infiltration Tests

Infiltration tests, unlike packer tests, do not provide hydraulic conductivity information for a specific interval. The main information obtained from the infiltration tests is the hydraulic conductivity of the rock mass as a whole. Fifteen infiltration tests were performed in the same five different lithological units (see Table 2).

The infiltration tests results were grouped according to predominant mineralogy to simplify flow analysis interpretation; the two amphibolitic itabirites (IAG and IAM) were classified as IA and the two specularitic itabirites (IE and IEM) were classified as IE. The packer tests and infiltration tests results were inconsistent (Fig. 5). Packer tests are performed by injection of water under high pressure in isolated intervals of a borehole, while water is injected under gravity into the entire saturated column of the observation wells in infiltration tests. Differences between IM and IE rock types in Fig. 5 are attributed to the physical

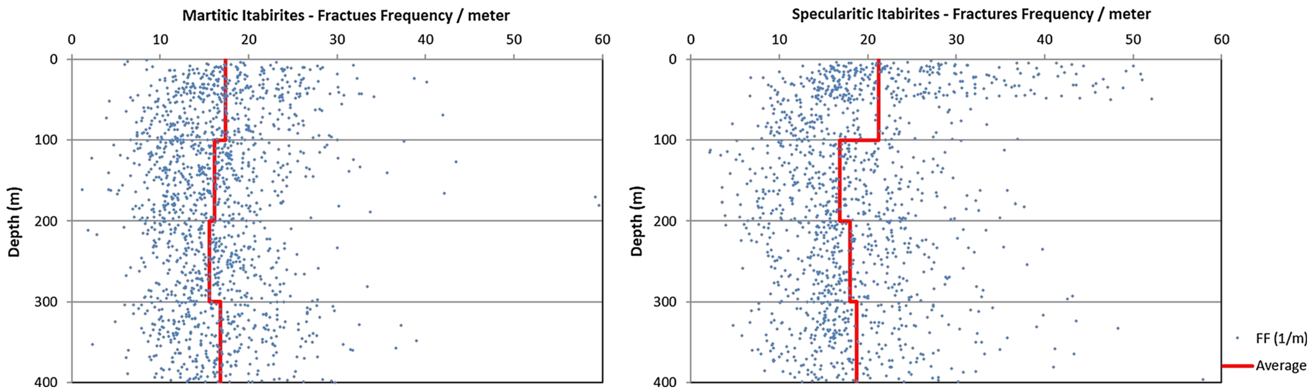

Fig. 4 Fracture frequency for Martitic and Specularite itabirites and its variation with depth

Table 2 Summary of the infiltration tests results

Mine	Hole ID	Lithotype	Elevation	Filter Depth	WT Depth	K (m/s)
Alegria Norte	OW 18	IEM	889.94	95	27.59	2.5×10^{-07}
Alegria Norte	OW 20	IEM	886.61	111	39.24	1.5×10^{-07}
Alegria Norte	OW 21	IEM	895	101	35.4	7.9×10^{-06}
Alegria Sul	OW 24	IEM	899.41	79.6	19.39	1.2×10^{-08}
Germano	OW 30	IE	795.2	230	61.49	1.8×10^{-09}
Alegria Norte	OW 34	IAG	943.18	159	140.78	8.7×10^{-08}
Alegria Sul	OW 36	IAG	863.07	79.45	10.82	3.9×10^{-07}
Alegria Norte	OW 51	IAG	892.76	141.5	77.07	2.9×10^{-07}
Alegria Norte	OW 54	IAG	792.92	185	17.9	5.2×10^{-07}
Germano	OW 58	IE	800.16	170	20.46	6.5×10^{-08}
Alegria Norte	OW 64	IEM	999.82	54.5	51.23	1.2×10^{-07}
Alegria Norte	OW 77	IEM	869	177	88.75	2.6×10^{-08}
Alegria Sul	OW 78	IEM	828.25	177	54.41	1.2×10^{-08}
Alegria Sul	OW 84	IAM	823	229	99.6	6.5×10^{-08}
Alegria Centro	OW 86	IMEG	847.87	199	87.65	2.4×10^{-07}

The high value of hydraulic conductivity obtained in the test of OW 21 is associated with a zone that has a higher degree of fracturing than is usual and, therefore, is not representative of this lithotype

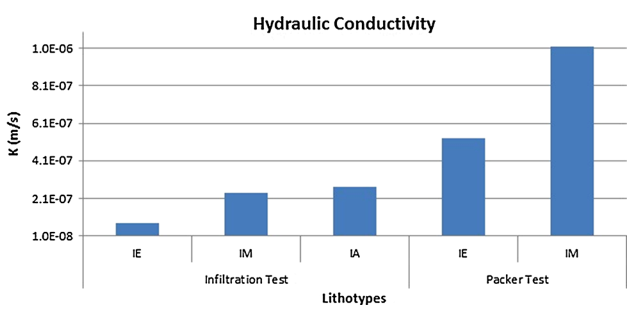

Fig. 5 Results of hydraulic conductivity obtained from Infiltration and Packer tests for the itabirites of Alegria mine

characteristics of rocks as well as differences in the two test procedures.

Hydraulic Conductivity

Figure 6 presents the distribution of hydraulic conductivity at Alegria Centro and Alegria Sul. No major difference is observed; median values are of the same order of magnitude for the main lithotypes in both areas. Furthermore, all itabirite types show similar hydraulic conductivity values, indicating lithotype homogeneity.

Fracture Frequency Analysis

Rock quality designation and fracture frequency statistical analysis was performed in the different lithotypes in order to understand spatial distribution of hydraulic conductivity in the area. The geotechnical data, discussed above, was then converted into hydraulic conductivity values using the cubic law. However, one of the cubic law variables is fracture aperture, which cannot be easily obtained and therefore is usually estimated. The hydraulic tests results were used to calibrate the apertures of fractures identified in the study area (Schlumberger Water Services 2012). Based on that, fracture aperture was adjusted so that the calculated hydraulic conductivity was equal to the

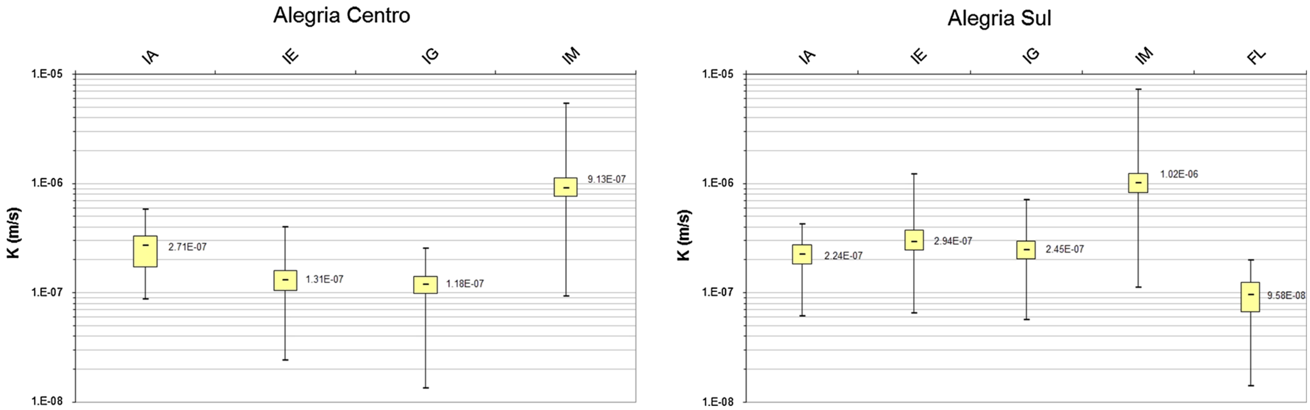

Fig. 6 Hydraulic conductivity values of itabirites found in Alegria mine

Table 3 Apertures calculated for each rock type occurring at the Alegria mine

Site	Lithology	Aperture (cm)
Alegria Centro	IE	0.00240
	IM	0.00455
	IA	0.00340
	IG	0.00240
Alegria Sul	IE	0.00270
	IM	0.00420
	IA	0.00250
	IG	0.00270

hydraulic conductivity value obtained by the hydraulic tests. The average fracture aperture values for each lithotype estimated by this method is presented in Table 3. In the future, hydraulic conductivity distribution for these lithotypes in different areas of Alegria Complex can be estimated by using this aperture and comparison with the hydraulic conductivity results.

The fracture frequency distribution for Alegria Sul and Alegria Norte (Fig. 7) shows no change with depth, as well as similar average values for both areas, though the standard deviation for the 100–200 m range was higher than at other depths. As hydraulic conductivity is correlated with this property, it must also be homogeneously distributed.

Figure 8 illustrates the average hydraulic conductivities of the rock mass. This parameter is moderately higher in Alegria Sul, which is consistent with Fig. 7. Similar to the degree of fracturing, hydraulic conductivity remains relatively constant with depth in both areas (Fig. 8). This indicates that degree of fracturing is homogeneous from the surface to approximately 400 m deep (Fig. 7).

Analysis indicates that the hydraulic conductivity for the rock mass ranges between 1.2×10^{-7} m/s and 1.0×10^{-6} m/s, with a median of 2.6×10^{-7} m/s (Table 4). These are compatible with the values obtained from both packer and infiltration tests.

Summary of Hydraulic Parameters Estimates

Table 4 summarizes the hydraulic conductivity estimates of the lithotypes in Alegria Centro and Alegria Sul. The results for the two areas are similar. Hydraulic conductivity was assumed to be the same for different geomechanical

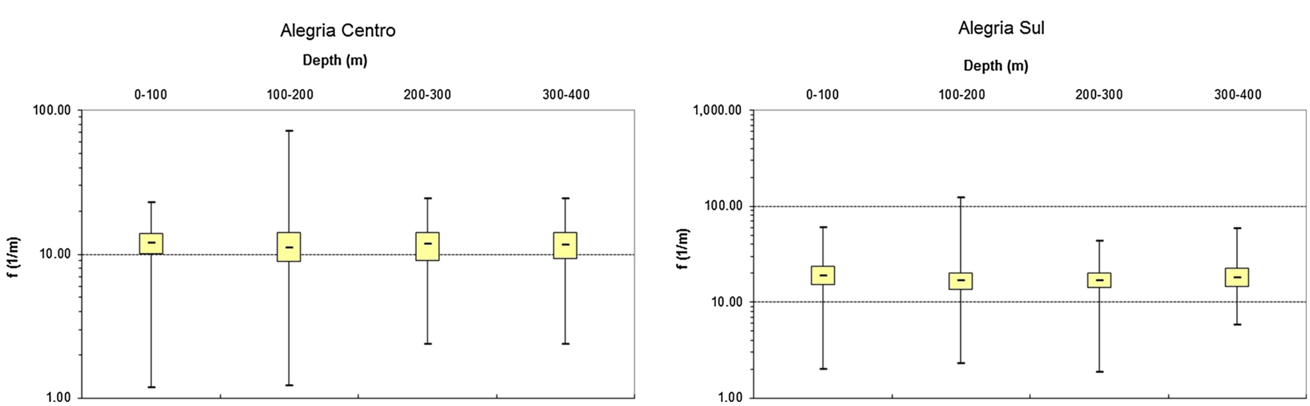

Fig. 7 Fractures frequency distribution and its variation with depth

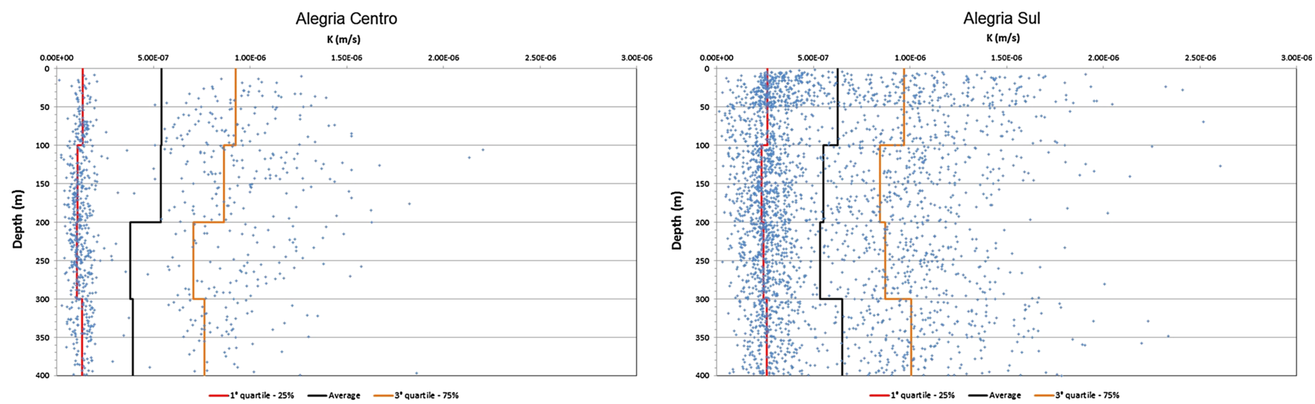

Fig. 8 Hydraulic conductivity distribution and its variation with depth

Table 4 Summary of estimated hydraulic conductivity values

Mine	Tested lithology	Hydraulic conductivity (m/s)		
		Min.	Max.	Median
Alegria Centro	IA	8.7×10^{-08}	5.8×10^{-07}	2.7×10^{-07}
	IE	2.4×10^{-08}	4.0×10^{-07}	1.3×10^{-07}
	IG	1.3×10^{-08}	2.6×10^{-07}	1.2×10^{-07}
	IM	9.4×10^{-08}	5.4×10^{-06}	9.1×10^{-07}
Alegria Sul	IA	6.1×10^{-08}	4.3×10^{-07}	2.2×10^{-07}
	IE	6.5×10^{-08}	1.2×10^{-06}	2.9×10^{-07}
	IG	5.6×10^{-08}	7.1×10^{-07}	2.5×10^{-07}
	IM	1.1×10^{-07}	7.3×10^{-06}	1.0×10^{-06}

Table 5 Average values of hydraulic conductivity for rock types of the Alegria mine

Lithology	K (m/s)
IE	7.5×10^{-07}
IM	9.1×10^{-07}
IA	2.6×10^{-07}
IG	1.8×10^{-07}

classes in each lithotype based on fracture frequency analysis, indicating that the degree of fracturing is homogeneously distributed with depth, regardless of rock mass type (Fig. 4). Table 5 presents average hydraulic conductivity (K) values based on the test results and analyses performed for each lithotype.

Conclusions

In mining, hydrogeological and geotechnical characterization has become increasingly important in decision-making and financial issues due to the need to maximise reserve utilization. Large pits reach increasing depths, and thus environmental impacts and issues related to slope safety are intensified. In this context, one can say that the most important and most complex step for this work is data collection. Detailed characterization of the rock mass is essential for prediction of future mining conditions, identifying risks, and foreseeing the possibility of large geotechnical accidents.

Although the amount of testing was insufficient to allow definitive conclusions of the overall hydraulic conductivity of the rock masses in the study area, analysis of our results suggest that the degree of fracturing observed in the geotechnical logs significantly influences hydraulic behaviour of the rock mass. The distribution of hydraulic conductivity in Alegria Centro and Alegria Sul has average values of the same magnitude, regardless of depth, indicating homogeneity of local lithotypes. Additional studies will be needed to improve the suggested correlation among infiltration tests, packer tests, and fracture frequency analysis. However, the range of infiltration values found in the present study can be used at several open pit mines in Brazil's Quadrilátero Ferrífero, as the geology and hydrogeology are quite similar to other mines in this area.

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