Hydrofracturing in Situ Stress Measurements in Itabirite Brazilian Ferriferous Quadrilater, and their Limitations

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Hydrofracturing *in situ* stress measurements in Itabirite Brazilian Ferriferous Quadrilater, and their limitations

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ABSTRACT: This article presents a first attempt to carry out measurements (magnitudes and orientations) of the *in situ* stress in itabirite rocks in the region of the Brazilian Ferriferous Quadrilater obtained by hydraulic fracture tests at a depth of 399 m. Previous studies available in this rock mass consider estimated values of *k* index (S_h / S_v), and it is not a practice adopted to carry out *in situ* stress tests in this region and rockmass to support geotechnical analysis. The area of study is located at a depth of 500 m in a pit; therefore, the determination of the *in situ* stress distribution is very important to assess the stability of the mining open pit. The activities, from the planning to the execution of the tests, and the results are presented. The rock mass under study shows the presence of different geological structures, such as banding and foliation, which resulted in difficulties with performing the tests, and only 12.5% of the tests were successful. The results contribute to understanding the strains and stresses induced by mining activities in slopes in the Brazilian Ferriferous Quadrilater and their impacts on surrounding structures. For a better determination of the regional *in situ* stresses in the rock mass of the Brazilian Ferriferous Quadrilater, it is recommended to perform hydraulic tests on pre-existing fractures.

KEYWORDS: *In situ* stress, hydraulic fracture, mining slope, Brazilian Ferriferous Quadrilater.

List of symbols:

- P_b – Breakdown pressure
- P_r – Reopening Pressure
- P_s – Shut-in pressure
- S_H – Maximum horizontal stress
- S_h – Minimum horizontal stress
- S_v – Vertical stress
- $k_H = S_H / S_v$
- $k_h = S_h / S_v$
- γ – rock mass density
- V_p – P wave velocity
- V_s – S wave velocity

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1 Introduction

Knowledge of the stress distribution in rock mass is one of the major concerns of rock mechanics (Leeman, 1959; Amadei and Stephansson, 1997; Zhang, 2012). Until now, there has been no specific method to determine with precision the *in situ* stresses in any rock mass. It is generally accepted that in places where rock mass structures are relatively uniform and horizontal, such as in beddings and in extensive planes of sedimentary rocks, the vertical force at a certain depth (h) will develop a uniform vertical stress S_v proportional to the rock overburden. However, cracks and other heterogeneities affect the stress distribution. In addition, the magnitude and orientation of the forces change throughout geological time. Folds and faults are created as a response to past forces, and all this creates a heterogeneous system of forces that is dominated by the tectonic regime.

Because of its extensive use in the determination of *in situ* stresses in rock mass at great depths, the hydraulic fracture test (Haimson 1978; Bjarnason et al., 1989; Tunbridge et al., 1989; Ljunggren et al., 2003; Haimson and Cornet, 2003; Zhao et al., 2005; Subrahmanyam, 2019; Singh and Sahoo, 2000; Gowd et al., 1986; Ulf Lindfors, 2007; Qitao et al., 2016) was utilised to study the itabirite rocks found in the Brazilian Ferriferous Quadrilater. In addition, the study interpreted the borehole images, because it was demonstrated that this is important to determine the effects of hydrofracturing on the *in situ* stress measurement (Li et al., 2013; Wang, 2018; Han et al., 2020).

2 Hydraulic Method – Hydraulic Fracture Test

The hydraulic fracture test consists of the fluid injection into probing holes that are sealed at intervals to induce the propagation of tensile stresses on the walls of the rock borehole. This technique was first applied in the oil industry in the 1940s to increase the yield in locations of low permeability to oil flow, and its use to determine the stress status by hydraulic fracture operations was proposed at the beginning of the 1960s.

The classic concept to interpret the pressure data of hydraulic fractures was developed by Hubbert and Willis (1957). This theory requires that a rocky material that is assumed isotropic, elastic, homogeneous and impermeable. One of the main stresses is assumed to be vertical and equal to the rock overburden.

A section of the probing hole that usually has a length of less than 1 m is sealed above and below the fracture test section (Rummel et al., 2004). This sealed section is then cyclically pressurised and depressurised with a fluid, normally water.

The fracture plane is usually parallel to the axis of the hole, and two fractures are initiated simultaneously at diametrically opposed locations in the periphery of the hole. The hydro-fracture will start at a certain point and propagate in the direction that offers the least strength. Then, the fracture will develop in the direction perpendicular to that of the minor main stress.

The orientation of the fracture is obtained from the traces formed by the fracture on the hole walls and coincides with the major main stress in vertical or subvertical holes where it is assumed that the one of the main stresses is parallel to the hole. The hole orientation can be determined with a printing shutter and a compass or by geophysical methods, such as micro-scanning or hole filming (Ljunggren et al., 2003).

3 Case Study

This article presents a first attempt to carry out *in situ* stress measurements in this region, since previous studies available in this rock mass consider estimated values of k , and it is not a practice adopted to carry out *in situ* stress tests in this region and rock mass to support geotechnical analysis.

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The case study deals with the slope of a mining open pit in the Brazilian Ferriferous Quadrilater that has been monitored by prisms and visual inspection and, more recently, by land radars, satellite images, inclinometers and extensometers. The pit materials have been extensively studied in the laboratory and show a contracting behaviour under shear, especially when subjected to low confinement stresses (<1 MPa), which may explain the observed deformations (Itasca, 2019).

It is very difficult to measure the values and directions of *in situ* stresses in regions such as the Ferriferous Quadrilater, where the effect of tectonism has already occurred. The difficulty in measuring *in situ* stresses in the Brazilian Ferriferous Quadrilater, is associated with the multiple deformational events (3 phases) that occurred in the region, associated with large topographical differences with steep reliefs conditioned by extensive shear zones and faults that impose intense fracturing on the rocks; as well as layers of deep weathering that can reach more than 400 m in depth, making it difficult to find stretches of hard rock with little fracture to carry out the tests.

For this reason, previous studies of the case study slope assumed that the most representative values were $k = 1.5$ (Coffey, 2017) and $k = 1.2$ (Itasca, 2019). In principle, this assumption is conservative because the horizontal displacements and the shear stress tend to be overestimated. The value $k = 1.5$ has been utilised in other studies in the region of the Ferriferous Quadrilater by authors such as Figueiredo and Costa (2005), and good approximations of the *in situ* stresses have been obtained (Coffey, 2017). whose results were validated by back analysis, so that the values used were well calibrated.

Another study in a copper mine in northern Brazil in 2016 had problems in some tests related to the saturation of pores and microcracks of the rock mass, the occurrence of horizontal hydrofracturing, the non-occurrence of the expected trend in the pressure vs. time graph, large differences between the measured and calculated values of the vertical stress and some measurements of the horizontal stress that were incoherent. For this reason, most of the test results had to be discarded, and only the credible values were utilised.

4 Location of the Study and Field Research

The rock mass of the zone under study (Figure 3) are characterised by the presence of several geological structures, such as banding and foliation, which create difficulties for measuring the *in situ* stresses. In addition, this region is characterized by a mountainous topography with the presence of several valleys and mining open pits in the surroundings, which may influence the distribution of *in situ* stress acting on the site. Five probing holes were located to obtain samples of the compact rock with a low number of fractures and to allow the execution of the hydraulic fracture tests.

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Figure 3. Geological map of the case study area.

Two holes (Holes A and B) were located inside the pit in alignment with the slope under study to encounter the bodies of Compact Hematite and the Basic Compact Rock, and two other holes (C and D) were located in the surroundings (outside) of the pit to the north and west in Zone 1 (Figure 3) to measure the *in situ* stress without an influence or with a reduced influence of the geometry of the existing pit. All probing holes were arranged vertically.

The holes inside the pit that the segments of compact rock contained substantially fractured material, the possibility of performing hydraulic fracture tests being ruled out due to the risk of having a connection between the cracks created by the fracturing to already existing cracks, which would correspond a low chance of success of the test.

The hydraulic fracture tests were performed in the holes outside the pit. Hole C, to the west of the pit, had a depth of 443.50 m, and it entered the Compact Dolomitic Itabirite lithology at 371.55 m. The hole diameter was reduced to 75.70 mm (NQ) at 396.80 m to allow the execution of the hydraulic fracture test. Figure 4(a) shows pictures of the core samples obtained from Hole C.

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Figure 4 – Specimens pictures: (a) Hole C, (b) Hole D with *disking*, (c) Hole E.

Hole D was drilled to the north of the pit under study. Its depth was 500.10 m, and at 335.05 m, compact material was encountered. However, there were only isolated parts of compact rock, so it was defined not to perform the hydraulic fracture test in this hole. Considering the characteristics of the materials, the chances of a successful interpretation of a classic hydraulic fracture test would be extremely low.

A curious fact (due to the expectation of low stress levels) was a phenomenon similar to stacking in some parts of the probing specimens, which showed the possibility of the occurrence of diskings. Figure 4(b) shows pictures of the core samples obtained in Hole D with the possible stacking of some of them.

Hole E was located in another zone identified more to the south of the pit under study in Zone 2 (Figure 3). Despite the relatively long distance (approximately 2 km), this region is a potential location to obtain compact material. This hole had a depth of 441.40 m and the Compact Dolomitic Itabirite was found at 266.80 m, alternating with the Compact Dolomite lithology until a depth of 426.50 m, where a passage of Friable Itabirite Goethite occurred. The hole diameter was reduced to NQ at a depth of 281.65 m to allow the execution of the hydraulic fracture test.

Were performed samples from Holes C and E with the same lithology and from the same depths where the *in situ* stress tests. Samples with relevant discontinuities were disregarded. The *P* wave test in all the samples to verify the existence of any relevant discontinuity in the sample, which can be indicated by a low V_p value, but can not be identified visually. If there was no low V_p value, the sample was be subjected to the V_s wave test. Table 1 presents a summary of the depths, lithologies and characteristics at which the tests were performed. The maximum hydrofracturing pressure utilised in the tests was 41.4 MPa (6000 psi).

5 Equipment Utilised in the Tests

The equipment used in the hydraulic fracture test included the following:

- Double inflatable shutter for high pressures, with an outer diameter of 66.80 mm, and rubber elements with the same nominal diameter and a differential pressure of 34.5 MPa (345 bar) to work in NQ holes;

- High-pressure soil and rock testing machine, consisting of two triplex high-pressure pumps, two pressure accumulators, analogic and digital pressure gauges, a digital flowmeter with a 0 to 100% regulator potentiometer, pressure transducers, safety valves to avoid exceeding the 41.4 MPa (6000 psi) operating limit, a data acquisition module, a laptop outlet connection and an automated pneumatic system to maintain the necessary pressure difference between the rubber elements and the segment under test. The laptop has data acquisition software installed and configured to operate the soil and rock testing machine (Rede and Geosol, 2019).

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Table 1
Depths of the segments tested in each hole – hydraulic fracture.

Drill hole	Test interval (m)	Lithology	Fracture degree	Observation
<u>Hole C</u> Zone 1	391.35 – 390.65	Dolomitic Itabirite	Low	breached
	392.85 – 392.15	Dolomite	Low	subvertical banding
	395.35 – 394.65	Dolomitic Itabirite	Low	low banding
	399.35 – 398.65	Dolomitic Itabirite	Low	low banding
<u>Hole E</u> Zone 2	291.49 – 290.79	Itabirite	High	banding
	300.49 – 299.79	Itabirite	High	banding
	308.29 – 307.59	Itabirite	High	banding
	318.29 – 317.59	Itabirite	High	banding

6 Results

In total, eight tests involving Holes C and E were performed. Only the test at a depth of approximately 399.00 m performed in Hole C seems to have returned a reasonable result. All the other tests showed curves with features compatible with opening in the foliation planes.

The program RGLDip 6.2 identified an induced hydrofracturing in the test at 399.00 m, which had its attitude identified as N264/87 (Figures 5 and 6), that is with an approximate *N/S* direction coincident with the direction of the regional foliation, although with a subvertical dip. Table 2 presents the hydraulic fracture test data carried out in Hole C at 399.00 m depth.

Table 2
Hole C test record, with determination of P_b , P_r and P_s .

Probe	Depth (m)	P_b (MPa)	P_r-1 (MPa)	P_r-2 (MPa)	P_r-3 (MPa)	P_r average (MPa)	P_s-1 (MPa)	P_s-2 (MPa)	P_s-3 (MPa)	P_s average (MPa)
<u>Hole C</u>	399.00	6.71	6.53	5.91	5.65	6.03	3.59	3.21	3.45	3.42

Figure 5. Identification of the induced hydrofracturing.

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Figure 6. Hydrofracturing attitude.

The results of the test performed at a depth of 399.00 m in Hole C are shown below in Table 3 and Figure 7, for which it was possible to obtain the values of S_H (maximum horizontal stress) and S_h (minimum horizontal stresses), which are done by the following equation:

$$S_H = 3 * S_h - P_r \quad (1)$$

The results were obtained from Equation (1), where $S_h = P_s$ is the arithmetic average of P_s -1, P_s -2 and P_s -3, and P_r is the average of the reopening pressures P_r -1, P_r -2 and P_r -3.

Table 3

Results of the hydraulic fracture test, with determination of S_H , S_h , γ , S_v , k_H and k_h .

Probe	Depth (m)	Hydrofracturing orientation		S_H (MPa)	S_h (MPa)	γ (kN/m ³)	S_v (MPa)	S_H/S_h	k_H	k_h
		Direction (°)	Dip (°)							
<u>Hole C</u>	399.00	N264	87	4.22	3.42	24.0	9.58	1.24	0.44	0.36

Figure 7. Record of the hydraulic fracture test in Hole C.

From left to right, the 1st cycle corresponds to the hydrofracturing formation (breakdown pressure, P_b), followed by the 2nd, 3rd and 4th cycles that correspond to the reopening and development of the hydrofracturing induced at a depth of 399.00 m in Hole C. The values of P_r -1, P_r -2 and P_r -3 and those of P_s -1, P_s -2 and P_s -3 were obtained from the graph of Figure 7 utilising the HidroFrat program. The HidroFrat software was developed by FURNAS CIA in Brazil. It is a software that use Newton Raphson solution. It is not a commercial software.

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The hydrofracturing has an approximate *N/S* subvertical orientation, which can be seen in Figure 8. This hydrofracturing direction seems to be conditioned by the foliation of the region, which has an *NNW/SSE* direction. The plane representation in the stereonet is defined due the hydrofracture attitude is a planar structure. In this case study this attitude is close to the regional alignment.

The SH/Sh ratio has a value of 1.24, which meets the condition $SH \leq 3Sh$; otherwise, there would have been traction in the hole, and the test would have been disregarded (Rede and Geosol, 2019).

Figure 8. Stereonet of the hydrofracturing with attitude N264/87

7 Discussion of Results

The classic HF test has the fundamental assumption that one of the principal stresses must be approximately vertical or parallel to the borehole axis. According to Dight (2006), the assumption is generally correct at except close to fault systems, which occur in most mineralized systems. As the rock mass is quite anisotropic, this the hypothesis of HF may not be representative in this case. In addition to this limitation of hydrofracturing, there are discussions about uncertainties in determining the true shut-in pressure, problems related to fluid penetration in the porous space of rocks and issues related to the propagation of the fracture after its initiation in the hole wall, according to Amadei (1997).

Although the hydraulic fracture test is widely applied to estimate *in situ* stress, its field results could present a low accuracy. Many tests were performed in this study, and only approximately 12.5% of the results could be used. There were different problems, such as the determination and localisation of adequate material for the test (in general, ferriferous materials are extremely banded), problems due to the movement of the cladding and the hole walls that broke the tools, bursting of a rubber tip piece that was difficult to replace (specific imported equipment and pieces).

Another point to be highlighted is that the hydraulic fracture test requires detailed planning, which must consider the definition of the hole location, the determination of the segments to be tested (to be representative of the *in situ* stresses), the opening and maintenance of the probing spots and the availability of different pieces of equipment such as probes and specific fracturing and imaging equipment.

Specific funds and contracts are needed for this purpose, and the rig must be available from the drilling of the boreholes until the execution of the tests, as well as incentive from the company' top management and, consequently, regarding the various interface areas. If the execution of tests is an isolated initiative of the local team, so that resources, contracts and part of the budget from other

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Excluído: Another study in a copper mine in northern Brazil in 2016 had problems in some tests related to the saturation of pores and microcracks of the rockmass, the occurrence of horizontal hydrofracturing, the non-occurrence of the expected trend in the pressure vs. time graph, large differences between the measured and calculated values of the vertical stress and some measurements of the horizontal stress that were incoherent. For this reason, most of the test results had to be discarded, and only the credible values were utilised.¶

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areas of the company are used when available, this can hinder the success of the test execution and, consequently, of obtaining the results. If the contract for the execution of the HF test does not provide for the availability of a specific rig on account of the works, as well as the necessary support of the rig during the test, different interests may occur in the same workplace, such as prioritizing the productivity of drilling (meters to be drilled) versus the detailed and careful analysis of each section associated with the search for quality in the performance of the HF test (Penido *et al.*, 2020).

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8 Conclusions

The results presented in this study will help elucidate the strains and stresses induced by the mining activities in slopes in the Brazilian Ferriferous Quadrilater region and their impacts on the surrounding structures. Thus, the results may allow a more refined analysis from the determination of a most probable range of the variation in the k parameter that is more reliable and the definition of models to represent the rock mass behaviour.

The better understanding of the strength parameters and the deformation of the materials involved in this study may increase the quality of the assessments of the failure mechanisms and the operational practices to reduce the probability of slope rupture, increase the safety of such assessments and optimise practices related to mine dumps.

The rock mass analysed in this study (and in general, all rocks of the Brazilian Ferriferous Quadrilater) are characterised by the presence of different geological structures, such as banding and foliation, so that it is very difficult to perform tests to measure the *in situ* stress in these rock masses. It is not a practice adopted to carry out *in situ* stress tests in this region and rock mass. Due to the high anisotropy of these tested rock mass, the adoption of a mean k index is not applicable. The uncertainty of the geological settings led to the use of a simplified geological model.

From the hydrofracturing at a depth of approximately 399.00 m, values of $S_v = 9.58\text{MPa}$, $S_H = 4.22\text{ MPa}$ and $S_h = 3.42\text{ MPa}$ were obtained with a hydrofracturing attitude of $N264/87$, which indicated that the higher main horizontal stress S_H could be regionally conditioned by N/S alignments. The k values obtained based on the successful test are $k_H = 0.44$ and $k_h = 0.36$. Note that these values are much lower than the values that were used previously, which were $k = 1.5$ (Coffey, 2017) and $k = 1.2$ (Itasca, 2019). In fact, this value is close to the minimum reference limit as Brady B. and Brown E. (2007). This value can be explained by the fact that this location could be a stress relief zone, probably caused by topographic influence of two valleys lateral to the drill hole, as well as due to the proximity of the open pit under study.

The results of the HF tests are related to a range of values close to the minimum horizontal stress, although this is not representative because a positive FH test was only obtained at a depth of 399 m, precluding comparison with other controls at different depths. The single HF result at a depth of 399 m does not allow us to conclude that the results are representative to the *in situ* stresses in dolomitic itabirites.

The HF evaluate elastic responses. For an adequate analysis of the results, in addition to the evaluation of similarities among the obtained values, it is necessary to carefully evaluate the geological and lithological conditions of the site, as well as the efficiency of the *in situ* tests and the integrity of the samples.

The HF tests showed little efficiency in the analysis of the itabirite rock mass, with only 12.5% of the tests being successful.

It is needed to continue studies to determine the *in situ* stresses by other methods, compare the results and define the actual applicability of each method based on the type of rock under study.

Considering that a large part of the problems and difficulties came from the characteristics of the rock mass, which are, in general, extremely fractured, and for a better determination of the regional *in situ* stresses in the Brazilian Ferriferous Quadrilater, it is need to perform a greater

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amount of hydraulic fracture tests and hydraulic tests on pre-existing fractures, where a pre-existing fracture should be sought in each segment chosen for the test to build a matrix solution. The drawback of this alternative is that it would need at least six valid tests, each with at least three pressurisation and depressurisation cycles, in which each fracture to be pressurised must have a different attitude than the other ones to proceed with the necessary calculations.

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Excluído: From the hydrofracturing at a depth of approximately 399.00 m in hole FG-00024, values of $S_v = 9.58 \text{ MPa}$, $S_H = 4.22 \text{ MPa}$ and $S_h = 3.42 \text{ MPa}$ were obtained with a hydrofracturing attitude of N264/87, which indicated that the higher main horizontal stress S_H could be regionally conditioned by N/S alignments. The k values obtained based on the successful test are $k_H = 0.44$ and $k_h = 0.36$. Note that these values are much lower than the values that were used previously, which were $k = 1.5$ (Coffey, 2017) and $k = 1.2$ (Itasca, 2019). In fact, this value is close to the minimum reference limit as Brady B. and Brown E. (2007). This value can be explained by the fact that this location could be a stress relief zone, probably caused by topographic influence of two valleys lateral to the drill hole, as well as due to the proximity of the open pit under study.¶

Excluído: The rockmass analysed in this study (and in general, all rocks of the Brazilian Ferriferous Quadrilater) are characterised by the presence of different geological structures, such as banding and foliation. Therefore, it was very difficult to perform the tests to measure the *in situ* stress in these rockmasses. It is not a practice adopted to carry out *in situ* stress tests in this region and rockmass¶

Excluído: The “ k ” value has a strong influence on the results of the analyses. Tests to define not only the magnitude but also the orientation of the *in situ* stresses are fundamental to guarantee the reliability of the stress-strain analyses that must be done to assess the safety of the mining pits. ¶

The results presented in this study will help elucidate the strains and stresses induced by the mining activities in slopes in the Brazilian Ferriferous Quadrilater region and their impacts on the surrounding structures. Thus, the results may allow a more refined analysis from the determination of a most probable range of the variation in the k parameter that is more reliable and the definition of models to represent the rockmass behaviour.¶

The better understanding of the strength parameters and the deformation of the materials involved in this study may increase the quality of the assessments of the failure mechanisms and the operational practices to reduce the probability of slope rupture, increase the safety of such assessments and optimise practices related to mine dumps. ¶

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