

Rock Mass' Joints and Stress Variations

Geological Engineer. P. Eng. M.Sc.A.
Consulting Engineer. Brossard, QC, Canada
carlosbaisre@gmail.com



ABSTRACT

Overcoring and hydrojacking tests data from 15 hydroelectric and mining projects were analyzed considering, as a factor for stress variation, the vertical depth and the joint characteristics. A particular analysis was conducted to verify the response to stress of joints belonging to the same joint set. The data was obtained from projects that are representative of different geological environments and to a variety of depths until 1200m. The importance of the tectonic affecting the sites is brought into consideration. Understanding the variation of stresses is important for the in-situ stress testing planning. During site investigation, certain facts are a sign of the state of stress. The importance of testing for stresses from inside an underground excavation is suggested to assess and conclude about the associated stress level. The overcoring and in particular the hydrojacking test give the possibility of highlight the importance of the rock mass' discontinuities on the distribution and orientation of stresses.

RÉSUMÉ

Les données des essais de overcoring et de soulèvement hydraulique réalisés dans 15 projets hydroélectriques et miniers sont analysées sous différent point de vue, tel que la profondeur, les orientations des joints et la réponse de différentes familles de joints aux contraintes. Les projets où données ont été obtenues font partie de différents environnements géologiques et à une variété de profondeurs allant jusqu'à 1200m de profondeur. L'importance de la tectonique qui affecte les sites est mise en considération. Comprendre la variation et la distribution des contraintes est important pour la planification des essais in situ. Lors de l'investigation de site, certain faits donnent signes sur l'état des contraintes. L'importance de la réalisation des essais depuis l'intérieur des excavations souterraines est recommandée comme étant une bonne pratique pour évaluer et conclure sur l'état des contraintes. Les essais d'overcoring et particulièrement le soulèvement hydraulique donnent la possibilité de rehausser l'importance des discontinuités dans le massif rocheux dans la distribution et orientation des contraintes.

1 ROCK MASS STRESS

The relationship between σ_h and σ_v stresses changes with depth, where k varies from 1 to 4 at shallow depths and from about 0.5 to 1.5 at 1200m of depth, which is the maximum depth of the data analyzed, indicated by the dashed line in Figure 1. As depth alone does not define the level of stress, and because the approach presented in the figure does not take into consideration the regional and local particularities that induces the different level of stress measured at sites, the figure is a theoretical approximation of the stress variations with depth as a reference.

Therefore, magnitudes and orientations of stresses into the rock mass vary accordingly to the rock type (properties), tectonic, topography, depth (confinement) as well as the discontinuities orientations, aperture, fillings and alterations (joints, shears), different sizes of intrusives (dikes, bodies, etc.) and proximity to faults among other considerations. Additionally, the actual level of in situ stress, which was encrusted by past geological and tectonic evolution, at times, does not correspond to the present-day site conditions. The resulting state of stress, in a rock mass, is a mix of the enumerated factors, where certain can be more influencing than others, depending on the sets of conditions. As a matter of fact, close to the surface the remodelling by erosion has a big impact on the redistribution of stress than at great depths.

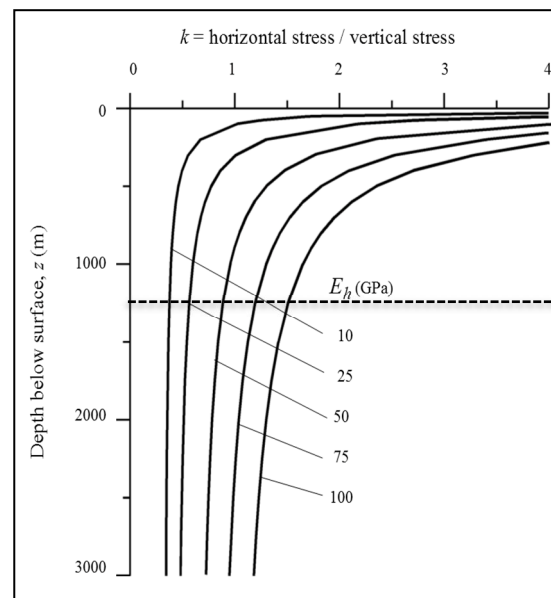


Figure 1: Ratio of horizontal to vertical stress.

For deeper excavations, the confinement impacts on

masking, eliminating and/or enhancing another factor's influences. Stress testing, by overcoring and hydrojacking, highlights the differences of sites conditions and the importance of the rock mass discontinuities.

2 OVERCORING TESTS

Figures 2 to 5 present data of 24 stress test measurements in underground overcoring testing programs at a hydroelectric and a mining project. In Figure 2 the rock cover line (RCL) is shown as a reference and to compare with the principal stress tendency with depth. The highest recorded principal stress values are: $\sigma_1=98$ MPa, $\sigma_2=56$ MPa and $\sigma_3=41$ MPa. At a depth of 687m the stresses from a mining project was included for the purpose of comparing data from different geological contexts. For that case the stress values are: $\sigma_1=15$ MPa, $\sigma_2=6$ MPa and $\sigma_3=3$ MPa, with all three values below the RCL.

Besides the stress relationship with depth, the geological and tectonic context makes the difference on the level of stress at the two sites. The mining site is located in a shield rock mass type of rocks whilst the hydro project site is set in a very active tectonic plate border influence. In a broad way, it's possible to say that the stresses in the shield are more of a relict than the stresses at the plate border influence zone, where tectonic is more active.

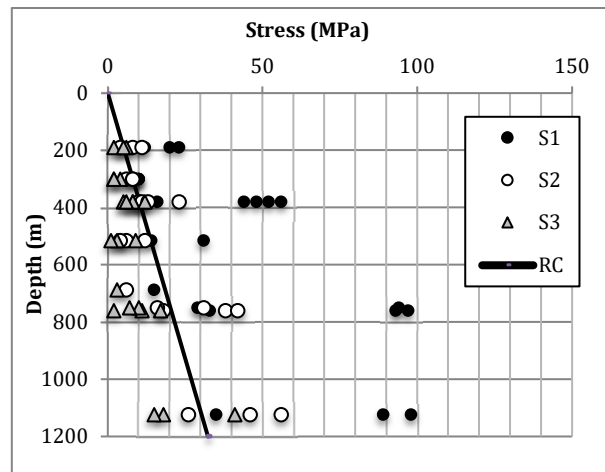


Figure 2: Stresses σ_1 , σ_2 and σ_3 vs Depth.

Figure 3 shows the stress orientations, where, with the exception of 3 points, the dips angles of σ_1 varies from horizontal to subhorizontal, and 50% of the σ_2 dips angles are subvertical. All of the principal stresses present also important variations of their azimuths. Both figures show that, for a same site, values of the principal stresses vary as much as in depth as does in its orientations. For given depths there are important variations on magnitude and orientation, but not entirely related to depth, as shown by Figures 4 and 5, where stresses' azimuth and dip variations are shown in function of its depths. The overcoring testing methodology is not directly related to joints, but the

discontinuities included in the rock mass exert its influence on the values and orientation of stress. Everything depends on the rock mass local geological composition and tectonic condition.

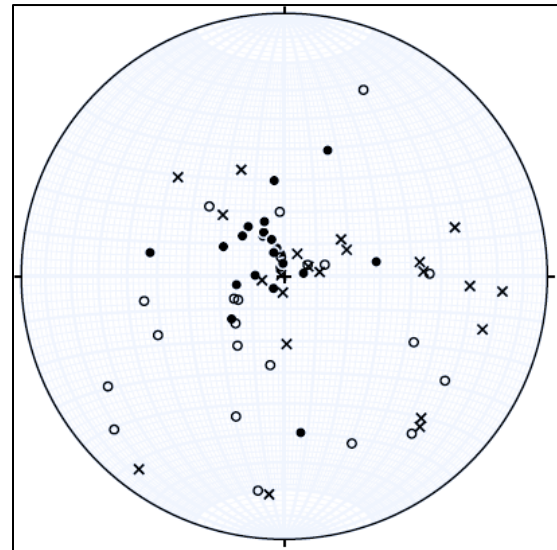


Figure 3: Stress orientation, σ_1 (●), σ_2 (○) and σ_3 (x).

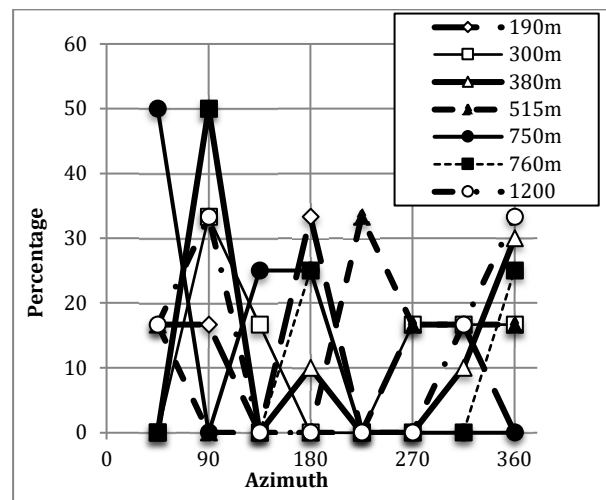


Figure 4: Azimuth variation of σ_1 and σ_2 vs. depth.

3 HYDROJACKING TESTS

The hydrojacking stress discussion is based on 383 data points obtained by testing carried out over the years in 12 hydroelectric projects up to a depth of about 300m. The data belong to different geological and topographical contexts. The testing was carried out during the investigation, engineering and construction phases.

The characteristics of each site are not discussed in this article, but sites are located in a shield rock mass and in an active tectonic border plate area. The joint that respond to the water pressure exerted during the test is often

unknown. The use of televiewer equipment (optical and acoustic survey) helps on knowing almost all the details about the joint intercepted by the borehole. One of the most important capabilities of the equipment is the possibility to know which joint reacted to pressure into the studied interval in the walls of the borehole. Generally speaking, the volume of water injected since the beginning of the testing could give a vague idea of the extent of the joints network.

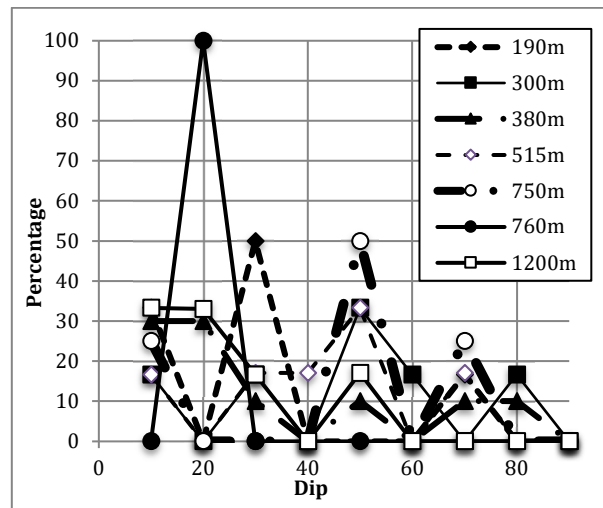


Figure 5: Dip variation of σ_1 , σ_2 vs. depth.

Figure 6 presents the data from hydrojacking tests. Joints in certain testing intervals did not jack even at high pressure; in those cases, the testing was discontinued and not considered here.

The RCL (Rock Cover Line) represents the σ_v that respond to the weight of the rock column. For the low value recorded of 0.8 MPa at a depth of 93m, the RCL at the same depth infers that σ_v should be 2.5 MPa, if the theoretical horizontal stress is 1.5 to 4.0 times higher, then the σ_h could be situated between 3.75 and 10.0 MPa. This is the range of suggested values, in Figure 1, for the σ_v and σ_h up to a depth of 100m.

The example suggests that at least all the points below the RCL should have a higher stress value in an ideal rock mass without any distortions. About 50% of the data in Fig. 6 have lower stress than the RCL. The low values respond to rock mass structures that, for one of the reasons reported before, do not have enough stress acting on it or because it cannot bear high stress. The values above the RCL represent the joints with a higher level of stress but still affected, in most of the cases, by the local conditions.

In the cases of higher stress (5.0-10.0MPa) there is not concordance neither with the increase of stress with depth. It means that it exist a conjugation of specific geological structures and a particular orientation of the principal stresses that reflects on the level of stress obtained by the testing on discontinuities. There are three different groups of stress in the figure. The first group is composed of the majority of the points, the second group is composed by

stress higher than 5.0 MPa at depths up to 150m, and the third group is at a depth of about 300m. In the latest group case, the increase in depth does not act as an important factor for the low stress values on joints; the stress level is very similar to the stress at depths between 25 and 160m.

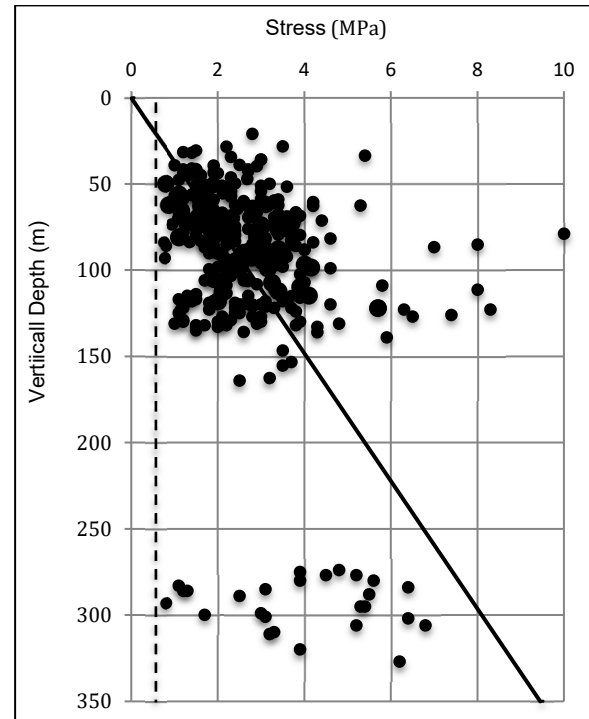


Figure 6: The collected 383 stress data points.

Again, those differences are due to the impact of geological features and/or topography, which influences the state of stress at any depth resulting in similarly low level of stress. In that sense, independently of the depth, most of the stress points are included between 0.8 and 5.0 MPa. The vertical dotted line shows that there is an apparent minimum bound at about 0.8 MPa. Every project considered here has, at least, one data point at or close to the lower bound.

Low stresses are present in rock masses and are not always noticeable as such, like water circulation following joint paths at depths. Other cases of very low or no stress are present when testing for permeability at low pressure or during drilling, when water losses occur.

Actually, there is an apparent zero stress when the permeability is too high for the pump to produce a flow capable to build-up pressure high enough to pressurize the open joint during hydrojacking testing. A naturally open joint with low level of stress occurs because the disturbance of the stress field induces the stress to circumvent sectors of the rock mass. There are also concentrations of stress due to the influence of almost the same factors. All of the data shown in the following four figures and one table are related to the same borehole with a length of 110m. This will help exemplify the difference between the joints before and after testing, which joints set reacted, and the variation of stress.

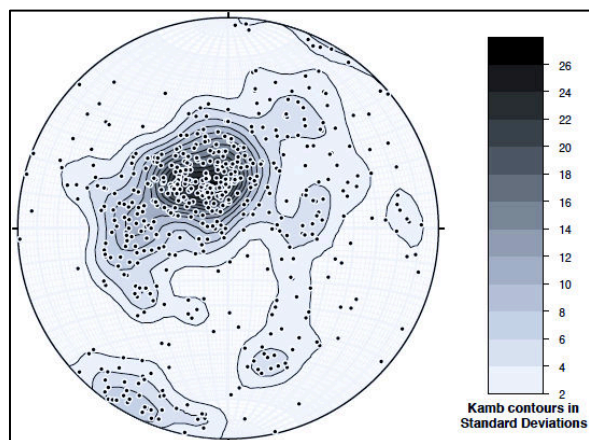


Figure 7: One borehole's entire data (537 joints).

Figure 7 displays the complete data of naturally open and closed joints for the entire borehole. The representation is clear about the distribution and importance of each joint sets.

Figure 8 presents only the joints data from all the selected 3.0m intervals of the hydrojacking tests along the borehole. In the figure were plotted 155 joints included in the intervals prior to testing. Only 2 of the joints tested were naturally opened. The joints plotted are 29% of those joint appearing in Fig 7; still the joint sets on the selected intervals are representatives of the sets present on Fig 7.

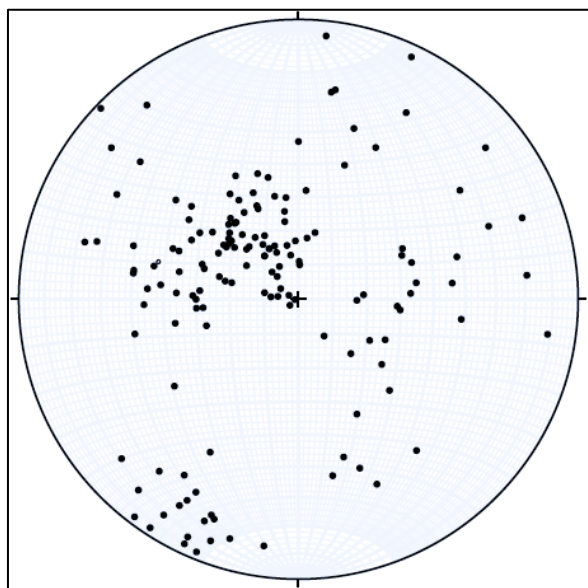


Figure 8: Existent joints in the intervals before testing.

The fact that the joint sets in Figures 7 and 8 are identical means that there are no variations, in this case, of the jointing with depth, which is indicative that the borehole was drilled in a very homogeneous sector of the rock mass. However particular joint sets are predominant at certain depths and less present in another.

Figure 9 shows the 18 joints, of the total joints tested of those presented in Fig 8, which are the only ones that reacted during the hydrojacking tests yielding the lower stress value in each testing interval. The data revealed that all of the reacting joints were present prior to the tests, of which two of those joints were naturally opened, three were partially opened and thirteen were closed.

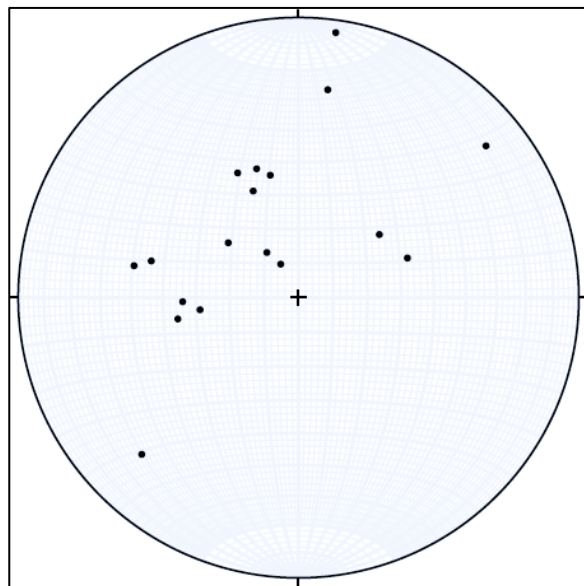


Figure 9: Joints that were opened during testing.

Most of the joints shown in Figure 9 have a dip angle that varies from 10 to 50° and just four joints have a higher dip angle. This indicates that the orientation of the low stress makes a small and variable angle with the vertical to all of the subhorizontal joints, meanwhile for the other 4 joints indicates that the lowest stress acting on those joints is closer to the horizontal.

The subhorizontal joints bring out more clearly the variations in the orientation of the low stress than the subvertical joints, in which case, the low stress changes its orientation in a lesser magnitude.

Figure 10 shows data of some of the reacting joints of Fig 9 that are useful to discuss. The variation of the measured stress is not representative of the variation of stress with depth, but rather to discontinuities. The black dots correspond to some of the subhorizontal joints and the white dots correspond to the four joints with the highest dip angles on Fig. 9.

In the figure the higher testing stresses belong to the joints with dip angles bigger than 70° and different azimuths than the subhorizontal joints. The figure confirms that the joint orientations, regarding the stress orientation, give way to variations of the jacking stress and the low influence of the rock cover or depth.

Table 1 exemplifies another aspect, complementary of the previous concepts, which is the variation of the stress acting on a same joint set. Always from the same borehole, the table presents cases that belong to the same joint set but located in different testing intervals. In interval 4 only

one of the four joints of the same set reacted to testing with a stress of 1.7 MPa.

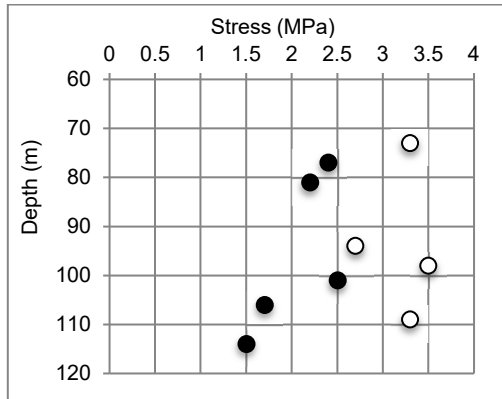


Figure 10: Stress against depth from the data of Fig. 9.

On intervals 1, 2 and 3 there are joints of the same set that did not react during the testing, nevertheless the indicated jacking pressures was attained by other reacting joints sets included in the same intervals with 3.3, 2.4 and 2.7 MPa respectively.

Table 1: Same joint sets in different testing intervals.

Interval	Depth (m)	Jacked	MPa	Dip	Dip Direction
4	104.67	No	1.7	30	048
	104.70	Yes		27	036
	104.83	No		33	038
	104.91	No		27	042
1	72.22	No	3.3	28	041
2	74.13	No	2.4	24	039
3	85.98	No	2.7	26	039

One interesting remark is that the subhorizontal joint that reacted in interval 4 was located deeper in the rock mass than the joints that did not react in intervals 1, 2 and 3 that are higher intervals. The minor influence of depth is evidenced with this example.

From the examples presented in the last 3 figures and in the table, it can be said that not all the joints belonging to the same joint set will be opened during testing along the borehole. Small variations on Dip, Dip Direction and even the type and condition of the joints could mean that a stress differential is required to jack a joint.

Because of the variations of joints conditions and the orientation of stresses, a more "favourable" joint belonging to the same or another set can be opened. This implies that the stress distribution in the rock mass is, in general, random due to the rock mass structures which disturbs the distribution of stresses. The reasons for the low stress can be attributed to its variations and distributions that are not always known, however some of the possible explanations for this phenomenon were already pointed out.

All of the above reasons suggest that hydrojacking testing should be required once the excavation is accessible; to confirm the stress level in cases where new suspicious discontinuities are found. As soon as the excavation faces are available for inspection, clues for interpreting the stress variation could be at hand. Sometimes, if present and meaningful, microtectonics could shed some light.

4 UNCLEAR JOINT STRESS CASES

It was mentioned that a minimum of 0.8 MPa or so is present in all of the 12 considered projects in Figure 6. This low value is independent of the test depth ranging from 50m to 300m, as shown in Fig. 2. There is no reasonable explanation for this constant low stress value, a minimum of stress seems to exist, no zero stress should be found.

During site investigations, while performing Lugeon tests, sometimes the naturally joint's opening is significantly big enough to prevent build-up in pressure, therefore the injected water volume goes into the rock mass with a low backpressure or none. If the open joints network extension is very large, and the pump capability is at its limit, there will be no pressure build-up. A similar situation occurs sometimes during hydrojacking tests where, it is required to test a highly permeable joint, the pressure required for jacking a joint depends on the availability of important quantities of water for long periods of time and on a huge pump capability.

But, satisfying those conditions does not necessary mean that it will be possible to jack the joint, which is naturally open to its maximum with a little room for displacement, and the backpressure generated will not be enough to jack the joint from there on.

Often, two cases of unjacked joints with high permeability occur. The backpressure could be high enough to satisfy the safety factor but because of the high permeability, which is unacceptable for its consequences (if it can be evaluated entirely) the joint should be classed as jacked. But if the joint does not intercept the tunnel, it can be considered as not relevant even with a high permeability. In other cases, the backpressure is lower or close to the safety factor, although there is no jack, the joint should obviously be considered as jacked.

The examples exhibit that at the scale of hydrojacking testing equipment, there exists joints in the rock mass for which it could be difficult to evaluate their level of stress. In those cases, a judgement must be applied regarding the consequences.

These mentioned cases of low stress are undoubtedly the results of rock mass disturbances. Sometimes the influence is evidenced by the divide of the rock mass into sectors with different mechanical behaviours.

5 CONCLUSIONS

Several partial conclusions throughout the document about the influences of disturbances on stress were already discussed.

Hydrojacking and overcoring testing were useful to expose the obvious relationship between joints and stress and its spatial variability. The variability of stress from point to point into the rock mass depends essentially on the discontinuities of the rock mass, their characteristics and distribution, that alter the stress regime from an ideal homogeneous to a heterogeneous and sometimes very complex rock masses.

Geological structures such as shears and intrusives can be the source of stress problems in its surroundings. These geological structures have an influence in the rock mass that often goes beyond hundreds of meters from its limits. Often permeability and water flows are associated with disturbed areas of the rock mass.

Many routinely but valuable information obtained during site investigation, such as the behaviour of the joints and water returns during Lugeon tests, water losses during drilling, intrusives, high joint frequency, shears, etc., are useful for suspecting the general conditions of stress and on planning for hydrojacking tests.

When testing is required to define particular underground geological structures, tests should be completed from inside out. Because If the stress surrounding the excavation, acts as a shell, there is no reason to test far away from the tunnel. Hydrojacking tests are not meant to test the stress field, just to assess the possibility of having damages due to joints jacking by water.

6 REFERENCES

Amadei, B. (1996). Importance of Anisotropy when Estimating and Measuring in situ Stresses in Rock. *Int. J. Rock Mech. Sci. and Geomech. Abstr.* Vol.33. No3. Pp293-325.

Lo, K.Y. (1978). Regional Distribution of in situ Horizontal Stresses in Southern Ontario. *Canadian Geotechnical Journal*. Vol.15.

Sheorey, PR. (1994). A theory for in situ stresses in isotropic and transversely isotropic rock. *Int. J. Rock Mech. Min. Sci. and Geomech. Abstr.* 32(1). 23-34.

Stacey, T.R, Wesseloo, J. (2002). Application of indirect stress measurement techniques to quantify stress environments in mines. *Safety in Mines Research Advisory Committee*.

Suorineni, FT. (2017). Myths of deep and high stress mining-Reality checks with case histories. *Deep Mining 2017. Eight International Conference on Deep and High Stress Mining*.