In Situ stress determination by hydro jacking tests on fractured rock mass

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ABSTRACT: Hydraulic jacking tests on fractured rock masses are performed regularly in the case of pressure tunnels, to determine the minimum stress acting on the rock, for the decision taking weather the tunnel requires or not steel or concrete lining to avoid hydrofracturing the rock.

In a series of tests performed for pressure tunnels of hydroelectric projects in the Andean region the applied pressures in these tests were extended beyond the usual ranges, reaching pressures up to 20 MPa with a flow capacity of up to 100 l/min. It was seen that with increasing or decreasing the pressure after the first opening and re-opening of the fracture several different behavior occur, being either the oscillation of the pressure or of the flow or even both, up to a point when the flow is steady.

It is interpreted that, since the whole fractured rock mass is subjected to the flow of water, the several occurrences are due to the opening of fractures at different spatial positions subjected to increased in situ stress normal to the fractures, and that the cessation of occurrences means that the maximum stress was surpassed. In this way, the first re-opening or closure of the fractures represents the measure of the minimum principal stress (σ_3) and the level when the occurrences ceased represents the measure of the maximum principal stress (σ_1).

Therefore, this test of cheap and simple performance is able to measure the magnitude of the minimum and maximum principal stresses, allowing the calculation of Ko. However, it does not provide the direction of the main stress. The test would be useful mainly in the preliminary phases of the design of pressure tunnels or rock caverns.

SUBJECT: Rock material and rock mass property testing (laboratory and in situ)

KEYWORDS: hydraulic fractures, rock stress, tunneling, rock caverns

1 INTRODUCTION

This paper aims at the presentation of a new in situ test to determine directly the minimum principal stress (σ_3) and the maximum principal stress (σ_1) by means of cheap and simple hydraulic jacking tests performed in boreholes in fractured rock masses.

Hydro jacking tests are usually performed when studying pressure tunnel sites under possible insufficient rock cover to decide whether or not that particular stretch requires steel or concrete lining to avoid hydrofracturing the rock. In the event of hydrofracturing, severe damage can occur to the rock mass, loss of water destined to hydroelectric generation or affecting hill slopes promoting landslides. An actual drastic example of rock damaged by hydrofracturing is shown in Figure 1.

The tests are run in boreholes on stretches of fractured rock separated by double packers (usually separated by 1 to 1.5m), until opening and closure of fractures are observed by sudden drop in the pressure and increase of the water inflow, indicating the value of the minimum stress acting in the rock mass.

Conventional hydrofracturing tests (Haimson, 1978 and ASTM, 2008) require a section of intact rock for the test, and the HTPF (Cornett, 1986) needs the determination of the spatial orientation of at least six known pre-existing fractures to be testes individually. On the contrary, the test herein concerned does not require a borehole section of intact rock but a jointed rock mass.

In carrying on hydro jacking tests in several hydro power projects in the Andean region, the tests were conducted well

Figure 1. Rock fracture opened by hydrofracturing in a pressure tunnel with support only of shotcrete.

beyond the usual pressure ranges for hydraulic jacking tests, since a higher capacity pump was available, attaining up to three to five times the minimum stress computed by the product of the density to the depth. Several behaviors during the tests were noticed, allowing the interpretation that the maximum principal stress was also measured additionally to the minimum principal stress. The paper describes the testing equipment, procedures and its interpretation.

2 EQUIPMENT REQUIRED AND TEST SECTION

The required equipment consists of a hydraulic pump with a minimum flow capacity of 100 l/min under a pressure of 20 to 25 MPa, double packers separated by about 1 to 1.5m, pressure and flow gages with automatic recording. A drill rig or a winch is also required do lower and raise the packers.

The mentioned pressure is required to attain the rock stresses with some additional pressure to account for the rock mass permeability. If the rock is too permeable the pump may not be able to reach the required pressure. In this case, it is recommended to select a new borehole stretch.

The test section must be selected by examining the rock cores and choosing stretches containing at least one joint, but preferably two or three joints.

3 TESTING PROCEDURE

After setting the packers in position within the borehole, the pressure is raised by steps of 2atm up to 5atm at the most, waiting between 1 and 2 min in each pressure stage, as the joints opening pressure is to be determined as close as possible. This is called the “slow” cycle.

In the conventional Lugeon testing the objective is to measure the permeability and its eventual changes under a constant pressure, to see the behavior of the joint seepage under a dam, for instance, reason why the pressure is maintained for longer periods. On the contrary, in these hydro jacking tests it is not necessary to spend more time in each stage as the response of the ground to the pressure is very quick.

When equaling the minimum confining pressure of the ground, plus eventual joint strength that might exist, the joints will open. This is noticed by the change in relationship between pressure and flow, as exemplified by the graph of Figure 2. In this Figure 2 the points of opening and closure of fractures are marked respectively as “O” and “C”.

The pressure is continued in similar steps to the maximum capacity of the pump, and then decreased under the same pressure steps. When the pressure is somewhat less than that of the minimum confining strength, the open joint will close, making the pressure to flow relationship to return to the original value. This closure pressure is a direct measure of the minimum principal stress, or σ_3. It should be also the measure of the pressure acting normally to the joint that first opened.

In the phase of increasing pressure, it is possible to notice more than one changes of pressure to flow ratios, as shown in Figure 3, indicating that other joints, with different orientation opened up on their turn.

After finishing the load and unload “slow” cycle, a “fast” loading and unloading cycle, was carried on, increasing and decreasing continuously the pressure, with the whole cycle occurring is about 5 min. or even somewhat less. The results were surprisingly very close to the “slow” cycle, indicating that the ground response to the pressure is very quick. This “fast” cycle works as a confirmation of the important points of the previous curve where changes were noticed. Figure 3 show the curves of both “slow” and “fast” cycles, with very good reproducibility.

It is recommended to run several tests at different depths in the same borehole.

4 PARTICULAR OCCURRENCES IN THE TEST.

Several other particular behaviors may occur during the test, consisting either as an oscillation (or jerking) of the flow or of the pressure alone, or even both of them together. This means that the pressure in some of the fractures of the jointed system has equaled the ground pressure on it, causing slight decrease of the pressure when some water is admitted in it, following closure that promotes increase of pressure with another opening of the joint and so on.

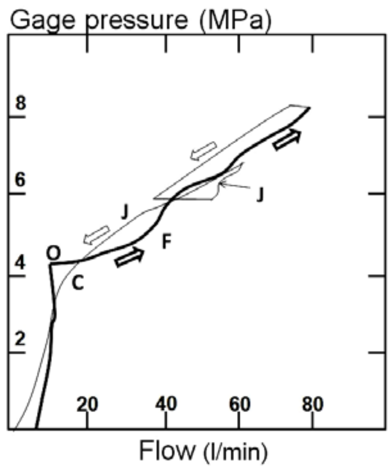

Figure 2. Graph of flow x pressure for a test in one cycle of loading and unloading.

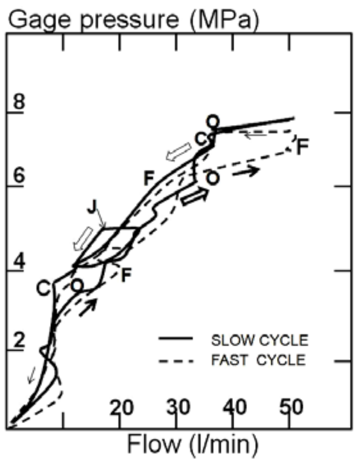

Figure 3. Graph of flow x pressure for a slow and fast cycles of the same borehole section tested.

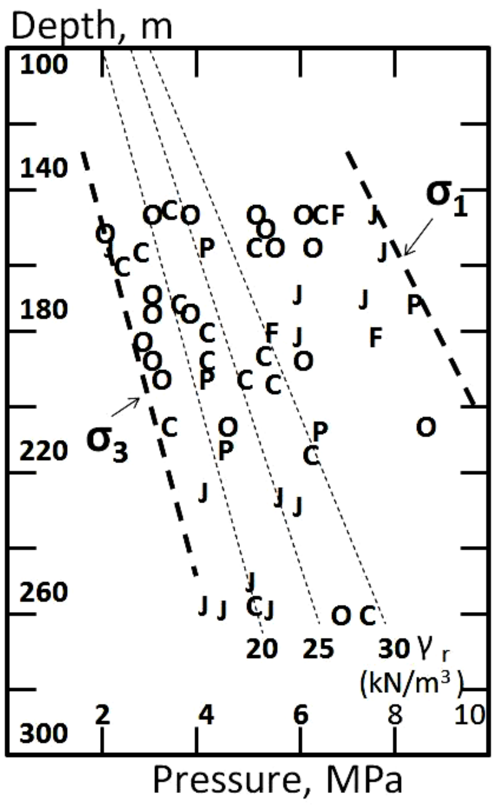

Figure 4. Graph pressure x depth of the several tests made in the same power project site. The lower and upper limit lines indicate the minimum and maximum principal stresses.

These occurrences may repeat under different pressures in the same test as the several hydraulically connected fractures are subjected to different ground pressures normal to each one and react when the water pressure reaches the correspondent value. The points where these oscillations occur in the curves are indicated in Figures 2 and 3 as "F" for the flow and as "P" for the pressure.

Another important event sometimes observed is the "spontaneous jacking", indicated as "J" in the same Figures 2 and 3, when the equipment changes the pressure spontaneously either in the load or unload phase, reaching another stabilized pressure that may be higher or lower than that of the test. The difference in pressure is usually limited to about 1 MPa. This event means that the equipment is working as a piezometer, controlled by the ground pressure acting on some of the joints.

5 INTERPRETATION

Each of the test curves must be interpreted marking the points of joints opening and closure. All the values may be then plotted on a graph relating the pressure to the depth of the tests, as shown in Figure 4, presented as an example from tests performed at a hydro power project site with pressure tunnel and underground cavern. It can be seen that the graph has a lower limiting curve (at left) corresponding to the first joint re-opening (or closure) for each of the tests, which corresponds to the minimum principal stress, or σ_3. These values are the same as the calculated by the product of the rock density by the minimum distance to the surface, which may be the neighbor hillside in case of inclined surface.

In some cases the opening pressures correspond to a value lower than the product of the depth to the rock density. However, the difference to the line corresponding to the actual rock density is exactly the pressure due to the height of the water column above the test depth. This means that the effective pressure principle applies also to the rock mass.

At increased pressures of each test the several mentioned behaviors may occur, indicating that greater ground pressures are equaled at joints at different orientations until a point above which no more events are noticed and the flow rate is continuous. This point is marked by an upper limiting line (right dashed line of Figure 4) and represents the maximum principal stress, or σ_1 (as proposed by Kanji, 1993 and 1998).

From these two values the Ko coefficient may be derived as the relationship between σ_1 and σ_3, considering that σ_3 is the vertical stress.

6 CONCLUSIONS

Provided a pump with adequate high capacity is available and the jointed rock mass permeability is limited, this type of test is capable of determining both the minimum and the maximum principal stress acting in a rock mass (σ_1 and σ_3), from which the Ko coefficient may be calculated.

However, the horizontal direction of the maximum principal stress is not known. This direction sometimes can be deduced by structural geologic methods or determined by other types of tests at surface, as small flat jacks at surface, for instance.

The test herein described is of low cost and of easy procedure, and do not require determining the fracture orientation (usually done by impression packers, borehole TV of acoustic emission imaging, necessarily with orientation devices). Therefore, it is very useful in preliminary studies for the design of underground workings.

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