

DETERMINATION OF IN SITU STRESSES USING LARGE FLAT JACK TESTS

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SYNOPSIS

Large flat jack tests are used to assess rock mass deformability in the design stages of large projects. The paper introduces a methodology for interpretation of the tests, with which it is also possible to obtain the in situ normal and shear stress components on the flat jack plane. The main problem regarding interpretation of large flat jack tests has to do with the effect of the tension crack that may develop in the rock mass, depending on the loading pattern, the rock mass tensile strength and the in situ stress normal to the jack. The three-dimensional numerical model that was developed simulates the test with the actually applied loading and accounts for the development of the tension crack. Model results show that the extent of the tension crack is irrelevant for the determination of the in situ stresses. Therefore, the in situ stress values can be used as an important parameter for interpretation of the test results, and furthermore constitute one more output of this reliable in situ test.

1. INTRODUCTION

The deformability of rock masses plays an important role in the design of several types of structures, because their behaviour depends on the displacements undergone by the rock mass. This is, in particular, the case of concrete dams, large bridge foundations, underground caverns and tunnel linings. For design of these types of important structures built in or on rock masses, it is not adequate to characterize the rock mass deformability by only using laboratory tests on intact rock specimens, and extrapolating their results to the rock mass based on some indices such as the RMR, the Q or the GSI values. For these cases, in situ deformability tests are essential.

Several types of borehole jacking tests are available to evaluate rock mass deformability, but they involve small volumes of rock mass and their results should be considered as index properties. They should be used for zoning the rock mass according to a deformability parameter, usually the dilatometer modulus, but they often do not supply reliable estimates of the rock mass deformability at a representative volume.

Plate loading tests are widespread in situ deformability tests, but in many cases they do not yield satisfactory results, because the rock mass in the tested zone is often disturbed by the excavation, and the tested volumes are still not representative of the rock mass [1]. To avoid both these shortcomings, large flat jacks (LFJ) are preferably used, as they allow testing relatively large volumes of rock mass and determining the deformability inside the rock mass, in less disturbed conditions [2].

In situ deformability tests are time consuming and expensive, but LFJ test results have been found to supply reliable results [3] [4]. Use of this type of tests has recently increased, mainly for the study of the foundations of several large concrete dams in Portugal, and this generated the interest in improving its interpretation models, namely by using numerical models that simulate in detail the most important features of the tests.

2. LARGE FLAT JACK TESTS AND IN SITU STRESSES

LFJ tests consist in cutting a thin slot in the rock mass, by means of a disk saw, and inserting a flat jack that is then pressurized in order to load the slot walls while measuring the rock mass deformation with several displacement transducers. In order to obtain a mean value of the modulus of deformability in large rock volumes, as well as information about the rock mass heterogeneity, a group of two co-planar contiguous slots is usually opened for each test.

The pressures applied by the jacks to the slot walls often induce tensile stresses at the tip of the slot that exceed the tensile strength of the rock mass, and therefore a crack starts to develop in the plane of the slots [5] [6]. Since

determination of the rock mass modulus of deformability depends on the extent of the crack at each test stage, interpretation of the test results can be problematic due to the lack of information regarding the crack extent, which is difficult to evaluate even when the crack is visible at the surface of the rock mass.

Two main parameters influence the development of the crack during an LFJ test: the tensile strength of the rock mass and the initial in situ stress component normal to the plane of the flat jack slot. The former is a rock mass property, which depends on the rock tensile strength and on the jointing pattern. In good quality rock masses, without important joints at the test location, it can be nearly equal to the tensile strength of the rock material obtained in the laboratory, whereas in weak and fractured rock masses its value is so low that can be neglected.

The in situ stress component normal to the flat jack slot can be determined by LFJ tests according to the same principle used in normal flat jack tests: the stress value corresponds to the pressure applied by the jack that compensates the displacements that result from the slot opening. However, since in LFJ tests the area of the slot is larger than the area loaded by the jack, the cancellation pressure does not directly match the existing stress. Grossmann and Câmara [7] have proposed a change in the test procedure in order to obtain the in situ stress, but it was not implemented. The numerical model presented in this paper allows the calculation of the in situ stresses and considers the test and loading geometry, as well as the crack formation.

3. LARGE FLAT JACK TEST METHOD

The equipment for opening the slots includes a cutting machine, with a 1.00 m diameter diamond disk saw mounted at the end of a rig that houses the system that transmits the rotating movement to the disk. A central 168 mm diameter hole with a depth of 1.10 m is previously drilled by the same machine, in order to allow the introduction of the disk's supporting column. The disk saw cuts 1.50 m deep slots (Figure 1). Once the slot is cut, a flat jack is introduced and the central hole is filled with mortar (Figure 2 (a)). Usually tests are carried out with two flat jacks side by side, and therefore this procedure is repeated for the second jack.



Figure 1 – Cutting machine: (a) opening the central hole; (b) cutting the slot

Each flat jack consists of two steel sheets less than 1 mm thick, welded around the edges, and contains four transducers for measuring the opening of the slots, located inside the flat jack (Figure 2 (b) and (c)). The transducers are formed by two flat steel springs, fixed to one of the flat jack walls and kept in contact with the other due to their own spring action, which are instrumented with four electric strain gauges forming a full bridge, thus providing automatic temperature compensation.

Previously to slot cutting, two pairs of measuring pins (C1, C2 and C3, C4) are placed at the surface of the test chamber, 100 mm to each side of the slot and 175 mm from the jack axis of symmetry (Figure 2). Relative displacements of the measuring pins during opening of the slots are measured by displacement gauges. Their values are used for determination of the in situ stresses.

The flat jacks are then inflated with oil so as to adjust to the surface of the slots and a low initial pressure is applied, usually of about 0.05 MPa. A LFJ test consists of, at least, three loading and unloading cycles with increasing maximum pressures. Displacements are measured, for each flat jack, with the four internal transducers and the two transducers mounted on the test surface. The raw test results are the pressure versus displacement curves obtained in the test.

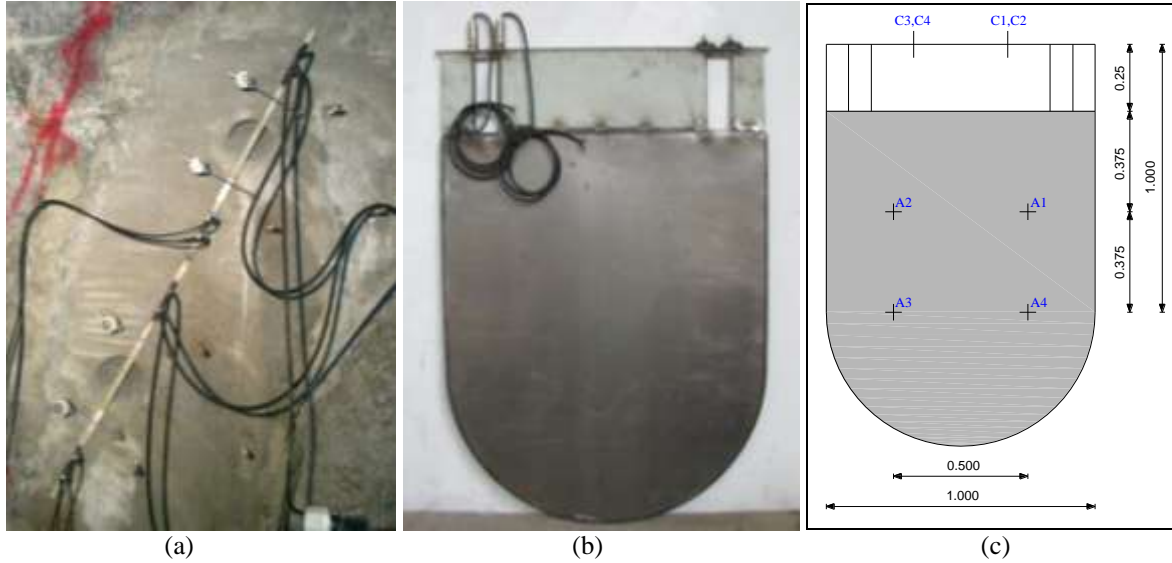


Figure 2 – Large flat jacks: (a) installed in two contiguous slots, ready for testing, showing the displacement gauges installed at the surface; (b) flat jack; (c) scheme with the location of the displacement transducers

4. INTERPRETATION OF LARGE FLAT JACK TEST RESULTS

Interpretation of LFJ test results is based on the theory of elasticity for homogeneous, isotropic and linear elastic bodies and simulates a particular case, in which the slots are normal to the rock surface and are inserted in an infinite space from a rectangular test chamber with a typical size: 3.5 m long and 2.5 m wide [8]. The slot opening δ_i at measuring point i , corresponding to the variation of the pressure applied on the slot walls Δp , is given by:

$$\delta_i = k_i (1 - \nu^2) \frac{\Delta p}{E} \quad (1)$$

where E is the rock mass modulus of deformability and k_i is a coefficient depending on the stiffness, shape, number and combination of flat jacks, the location of the measuring point i , the shape of the test chamber and the depth of the crack developed in the rock mass, at the tip of the slot.

Pinto [5] presents values of k_i for several combinations of flat jacks, provided that the depth of the tension crack is known. Once having obtained the values of k_i at the location of each displacement transducer, the most probable value of the deformability modulus E of the rock mass can be obtained by minimising the sum of the squares of the differences between both sides of equation (1):

$$E = (1 - \nu^2) \Delta p \frac{\sum k_i^2}{\sum k_i \delta_i} \quad (2)$$

The difficulty in the interpretation of the test results lies in the estimation of the depth of the tension crack. Three different methodologies have been used to estimate this key parameter:

- If the tensile strength of the rock mass and the initial in situ stress component normal to the flat jack surface are known, the depth of the tension crack can be calculated [5].
- The modulus of deformability is calculated for several values of the tension crack depth using equation (2). For each of them the least square method is used in order to minimize the sum of the squares of the deviation of the real deformation from the theoretical deformation. The most probable crack depth is the one that leads to the smaller deviation, and the most probable modulus of deformability is obtained for that crack depth [6].
- The average modulus of deformability for the first loading is calculated for each test pressure, assuming that no crack develops, and is plotted against the pressure. Usually, after an initial increase, due to the recompression of the rock mass, the modulus remains constant for increasing pressures. This indicates that the rock mass behaves linearly and that no crack has yet formed. The decrease of the modulus is a sign of the initiation of a tension crack. The modulus of deformability the rock mass is considered to be the value obtained before initiation of the crack. For each pressure, the length of the crack is the value that provides again the already determined modulus.

5. NUMERICAL MODEL

A three dimensional finite differences model using the software FLAC3D [9] was developed, which can simulate a LFJ test, with two co-planar contiguous slots, performed at any angle between the plane of the slot and the rock mass surface. The mesh is a 30m×30m×15m solid and has 149,440 zones (Figure 3). Around the slots a very refined mesh was required because of the small width of the slot, and also in order to simulate with detail the crack initiation and propagation into the rock mass. The flat jacks are located at mid-thickness of this refined mesh. Interface elements with a finite tensile strength in the plane of the slots were used to simulate the tension crack. The interface remains elastic if stresses remain below the tensile strength. Otherwise, a crack develops and a nonlinear behaviour characterizes the displacement versus pressure curves.

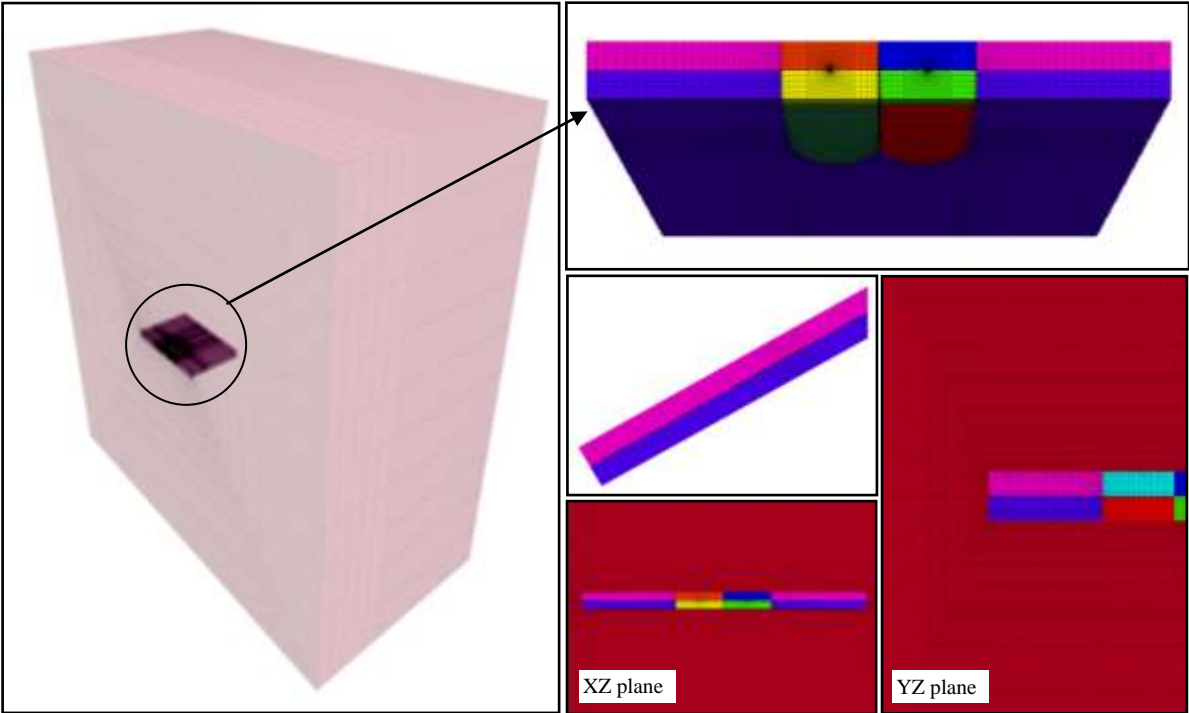


Figure 3 – Three dimensional finite difference model

The calculation process considers the following stages, which simulate the site procedure for cutting the slots: 0 - installation of the initial state of stress; 1 - completion of the central hole for the right side column; 2 - opening of the right side slot and filling of the central hole with mortar; 3 - completion of the central hole for the left side column; 4 - opening of the left side slot and filling of the central hole with mortar.

The loading and unloading cycles are then simulated, separately or simultaneously, in each jack. For each loading step, the model allows assessing the depth of the crack h and the evolution of the displacements at the location of the transducers, so that the coefficients k_i are calculated. Stress versus displacements diagrams can be obtained along the alignments shown in Figure 4. In this figure all the measuring points are represented.

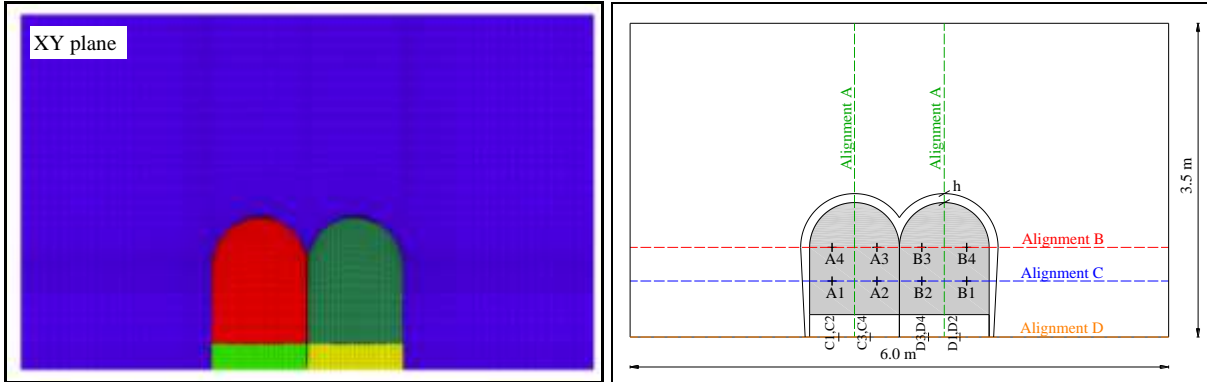


Figure 4 – Top view and geometry of the refined mesh

The propagation and depth of the tension crack depend on the fracture energy of the interface elements and hence on their normal stiffness. In order to analyse the influence of the interface normal stiffness, five cases were studied with $k_{n1}=k_n/10$, $k_{n2}=k_n$, $k_{n3}=k_n \times 10$, $k_{n4}=k_n \times 100$, $k_{n5}=k_n \times 1000$, where k_n is the equivalent stiffness of one layer of elements of the continuum with 10 mm thickness. A tensile strength of 4 MPa was considered. Stages 0 to 4 were first simulated, and a uniform pressure of 6 MPa was applied on the slot walls. Figure 5 shows how the displacements and the stresses in alignment A are influenced by the interface normal stiffness. As expected, the depth of the crack increases with the stiffness of the interface elements. However, the differences in the results for interface stiffnesses higher than k_{n2} are not significant, and this value was used in the remaining calculations.

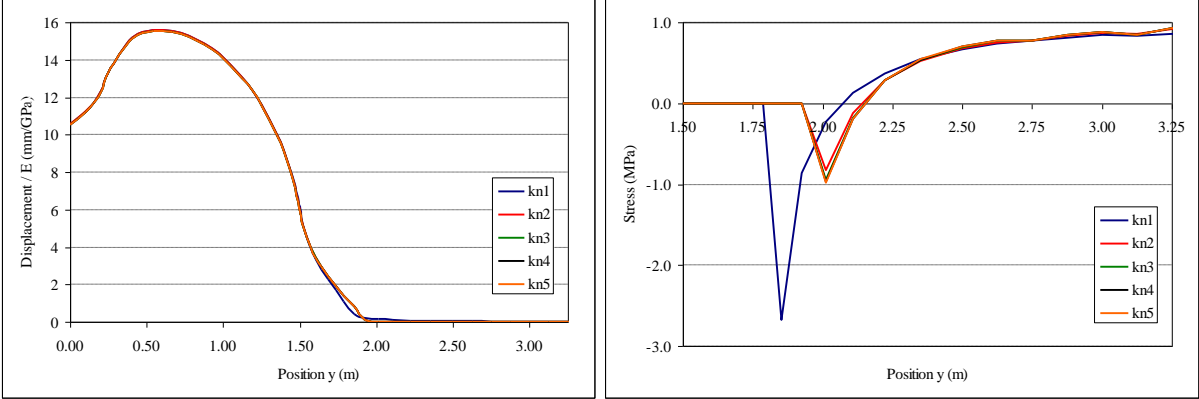


Figure 5 – Influence of the interface normal stiffness on the propagation of the tension crack

6. DETERMINATION OF THE IN SITU STRESS

The numerical model was first used to simulate stages 0 to 4 (presented in the previous section), which correspond to cutting two contiguous slots normal to a vertical rock surface, in a rock mass with a modulus of deformability $E = 1$ GPa and a Poisson’s ratio $\nu = 0.2$. In this calculation a unit initial state of stress normal to the slots $\sigma_z = 1$ MPa and zero tensile strength of the rock mass $\sigma_t = 0$ MPa were considered. Once the slots were cut, the calculation proceeded by loading the flat jacks with increasing pressures. Figure 6 shows the vertical displacements contours obtained at the end of stages 2 and 4, and for applied pressures p of 1, 2 and 3 MPa.

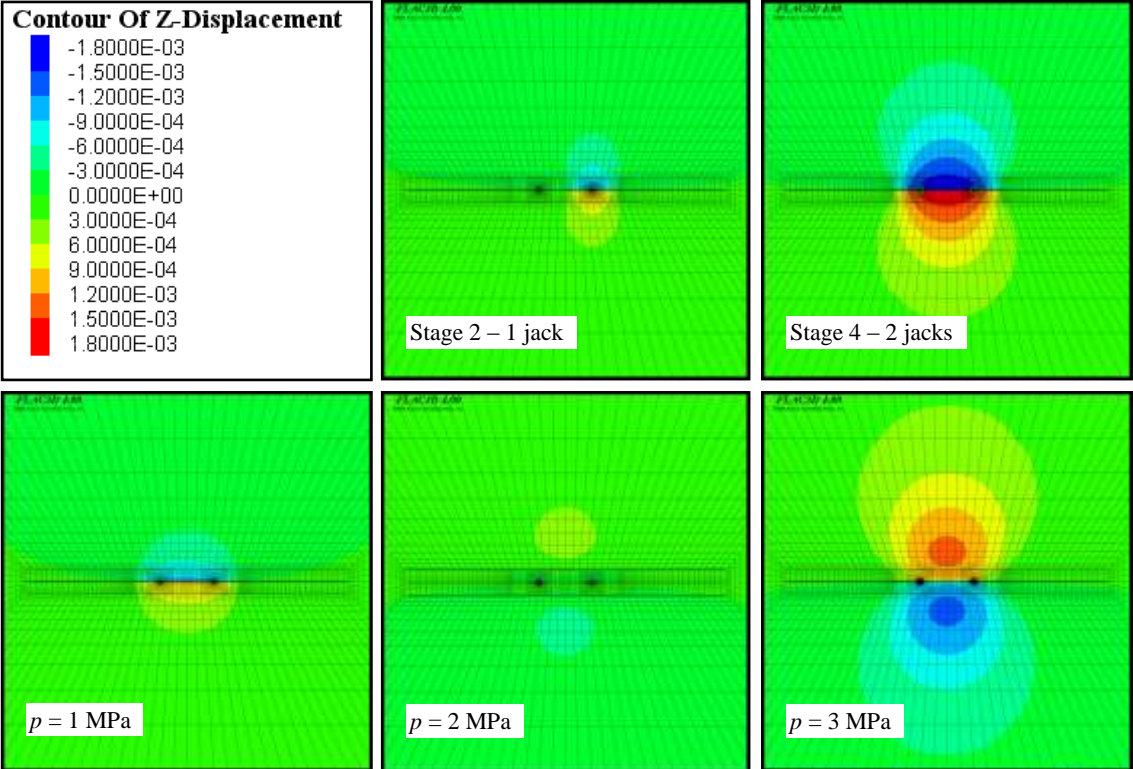


Figure 6 – Vertical displacements contours at the end of the stages 2 and 4, and for pressures of 1, 2 and 3 MPa

Figures 7 (a) and (b) are diagrams of the relative vertical displacements obtained during stages 1 to 4 (cutting of the slots) and for pressures p of 1, 2, 3 and 4 MPa at the locations where displacements are measured in LFJ tests: gauges installed at the rock surface and transducers inside the jacks. In order to normalize the displacements, they were divided by the modulus of deformability. Positive displacements mean slot opening. It can be seen that the pressures that correspond to the cancelation of the displacements due to the slot opening (cancelation pressures, p_c) are different for all transducers, because the jacks do not load the entire area of the slot. For an initial stress of 1 MPa, cancelation pressures of 2.14 and 2.07 MPa are obtained for D1-D2 and for D3-D4, respectively.

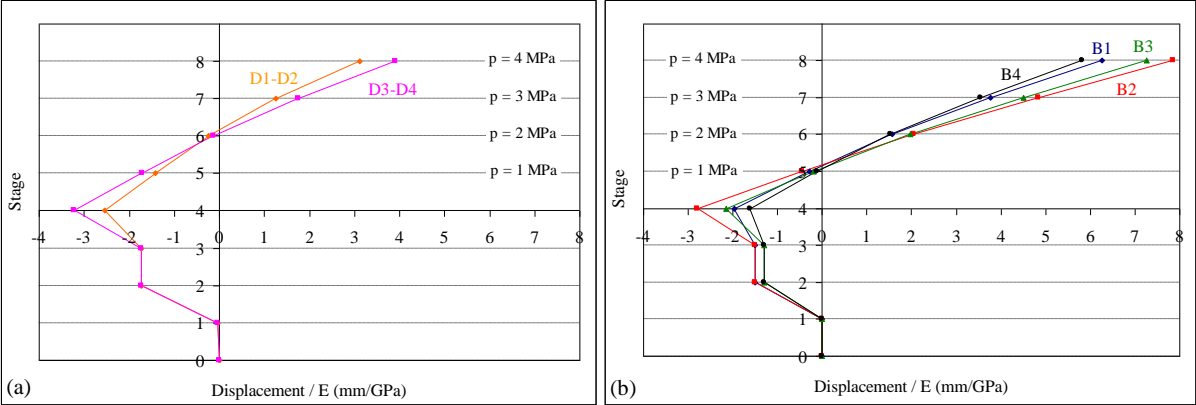


Figure 7 – Relative vertical displacements during slot opening and jack pressurization calculated for the location of the transducers (a) on the rock surface, (b) inside the flat jack

In order to check the influence of the tension crack on these results, these calculations were repeated for tensile strengths of 4 and 8 MPa. Figure 8 (a) shows the relative vertical displacements calculated along alignment A for these three values of the tensile strength, for an applied pressure of 2 MPa, which is approximately the cancelation pressure. The stresses are presented in Figure 8 (b). It can be seen that the influence of the tension crack on the slot opening is negligible. In order to illustrate the effect of the loaded area on the displacements, Figure 8 (a) also represents the vertical displacements along alignment A obtained for a uniform pressure applied on the whole slot surface, for the same value of the displacement at the surface.

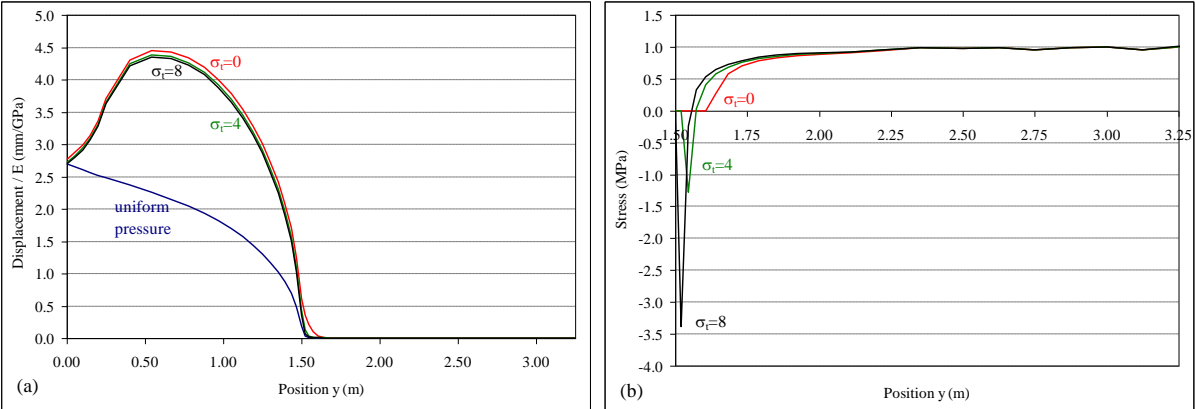


Figure 8 – Results for $p = 2$ MPa along alignment A: (a) relative vertical displacements; (b) normal stresses

The same calculations were performed for in situ stresses of 2 and 4 MPa, and they also confirmed that the tension crack effect on the cancelation pressure is negligible. Table 1 shows the values of the ratios of the cancelation pressure and the initial stress (p_c/σ_y) at D1-D2 and D3-D4. In order to check if other components of the initial state of stress influence the displacements measured in the tests up to the cancelation pressure, two additional calculations were performed with a unit horizontal stress $\sigma_x = 1$ MPa and a unit shear stress $\tau_{xz} = 1$ MPa. As expected, it was confirmed that their influence was also negligible (less than 0.5%). Initial stresses out of the plane of the surface were not considered, because they are zero at the surface.

Table 1 – Ratios of the cancellation pressure and the initial stress (p_c/σ_z)

σ_t (MPa)	0			4			8		
σ_z (MPa)	1	2	4	1	2	4	1	2	4
D1-D2	2.142	2.146	2.153	2.193	2.166	2.162	2.228	2.196	2.175
D3-D4	2.073	2.076	2.078	2.107	2.089	2.082	2.129	2.110	2.091

Values in Table 1 show that the ratio p_c/σ_z varies between 2.142 and 2.228 for displacement D1-D2 and between 2.073 and 2.129 for displacement D3-D4. Therefore, estimates of the initial stress normal to the slots can be calculated from the cancellation pressures as:

$$\text{at } D1-D2: p_c = 2.19 \sigma_z \quad \text{at } D3-D4: p_c = 2.10 \sigma_z \quad (3)$$

The calculation performed for a unit initial shear stress $\tau_{xz} = 1$ MPa led to interesting results regarding its influence on the calculated horizontal displacements, which are represented in Figure 9 (a). The relative horizontal displacements due to the opening of the slots, between D1 and D2 and between D3 and D4 are $\delta_{x12} = 1.30 \times 10^{-3}$ m and $\delta_{x34} = 1.82 \times 10^{-3}$ m, respectively. The relative vertical displacements are four orders of magnitude lower, and therefore negligible. This means that, if the relative horizontal displacements due to the opening of the slots are measured, then the initial shear stress can also be obtained. The most practical way to do this is by measuring the change of the distance between points D1 and D4 (Δl_{14}) or between points D2 and D3 (Δl_{23}), shown in Figure 9 (b), and to calculate the initial shear stress τ_{xz} from them.

$$\tau_{xz} = \delta_{x23} \frac{E}{\delta_{x23}^{ref}}, \quad \text{with} \quad \delta_{x23}^{ref} = 1.56 \times 10^{-3} \text{ m} \quad \text{and} \quad \delta_{x23} = a - \left\{ \left[\Delta l_{23} + (a^2 + b^2)^{0.5} \right]^2 - (b + \delta_{z23})^2 \right\}^{0.5} \quad (4)$$

δ_{x23}^{ref} is the reference relative horizontal displacement between points D2 and D3, due to the opening of the slots, calculated for $\tau_{xz} = 1$ MPa and $E = 1$ GPa. The expression for δ_{x23} is obtained from geometrical considerations from Δl_{23} and from δ_{z23} , which is the value of the relative vertical displacement between points D2 and D3 due to cutting of the slots, measured on site. Since $\Delta l_{23} = -\Delta l_{14}$, calculations can be made with any of them or from the average of their absolute values. In the expression for calculation of τ_{xz} the value of E obtained from the interpretation of the LFJ tests shall be used.

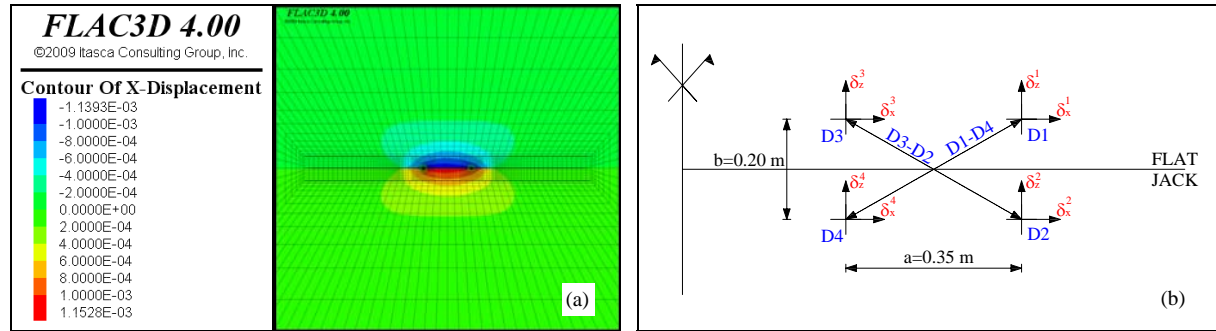


Figure 9 – Initial shear stress: (a) field of horizontal displacements; (b) measurement scheme

7. CONCLUSIONS

Large flat jack tests were developed 40 years ago, mainly for the study of the foundations of large concrete dams. Its use decreased significantly in the last decades due to the high costs of any field tests, and also to the extensive use of classification systems and of empirical correlations that provide estimates of the rock mass deformability, based on a number of rock mass characteristics. However, for the design of important structures, sensitive to rock mass deformation, after a preliminary investigation using indirect methods and empirical procedures, it is essential to obtain field values of the deformability from reliable tests.

Deformability tests using large flat jack tests have recently been intensively used for the exploration of large concrete dam sites in Portugal, and they were found to be a reliable test, when compared with plate loading tests and borehole jacking tests. Besides, they are relatively easy to perform. Using two adjacent jacks, a relatively large volume of rock is involved, as is illustrated in Figure 6. Interpretation of the test results has constituted a problem, due to the uncertainty brought by the formation of the tension crack. The numerical model that was

developed provides help in the test interpretation, by reproducing the exact geometry of the test and all test stages, as well as the development of the tension crack.

The initial simulations performed with the numerical model resulted in a methodology for determination of the initial normal and shear stresses, presented in this paper. The initial normal stress is an important parameter for interpretation of the test, because of its relation with the depth of the tension crack. The interest of this methodology is that, with the LFJ tests, which are tests performed for determination of the rock mass deformability, it is also possible to obtain reliable estimates of the in situ stresses.

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