Interpretation of rock mass deformability measurements using large flat jack tests

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ABSTRACT: Large flat jack tests are used to assess rock mass deformability in the design stages of large projects. This test consists in cutting a thin slot in the rock mass in which a flat jack with large dimensions is inserted; oil pressure inside the jack loads the slot walls while the rock mass deformation is measured by displacement gauges located inside the jack and at the surface. The main difficulty regarding interpretation of large flat jack tests has to do with the effect of the tension crack that may develop in the rock mass during the tests. A three-dimensional numerical model was developed for the interpretation of large flat jack test results. The model was used to establish the relations between the *in situ* stress perpendicular to the slots, the rock mass tensile strength, the applied pressures and the crack depth.

SUBJECT: Modeling and numerical methods

KEYWORDS: Field measurements, numerical modeling, rock properties, site characterization

1 INTRODUCTION

Rock mass deformability plays a significant role in the design of large structures such as concrete dams, large bridges, underground caverns and tunnels, since their behaviour depends on the displacements undergone by the rock mass. For the design of these types of structures, it is not adequate to characterize rock mass deformability just using laboratory tests on intact rock specimens, and extrapolating their results to the rock mass based on subjective indices such as the RMR, Q or GSI values. In situ tests involving relatively large and representative rock mass volumes can provide reliable estimates of rock mass deformability, and allow reducing uncertainties during design stages.

Large flat jack (LFJ) tests are one of the field techniques used to assess the rock mass deformability that allow testing relatively large volumes of rock mass (Rocha 1974). LFJ tests begin with cutting a thin slot in the rock mass using a disk saw, and inserting a flat jack. Then, hydraulic pressure in the flat jacks applies loads to the slot walls, while rock mass deformation is measured at several locations by displacement transducers.

The equipment for opening 1.50 m deep 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 disk saw supporting column to cut the slot down to the desired depth. Once the slot is cut, a flat jack is introduced and the central hole is filled with mortar (Figueiredo *et al*. 2010).

Each flat jack consists of two steel sheets, less than 1 mm thick, welded around the edges (Fig. 1a). Inside the flat jack there are four transducers for measuring the opening of the slots (Fig. 1b). Each transducer consists of two small steel cantilevers with four electric strain gauges. They are calibrated before being placed inside the jack in contact with both sides of the jack. Displacements are also measured at the surface of the rock mass. Previously to slot cutting, two pairs of measuring pins are placed 100 mm to each side of the slot and 175 mm from the jack axis of symmetry (Fig. 1c).

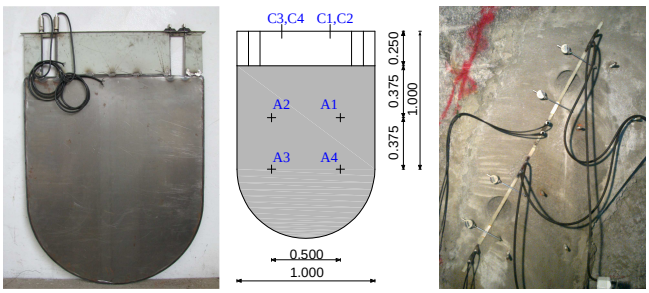

Figure 1. a) Large flat jack; b) location of the displacement transducers; c) ready for testing jacks in two contiguous slots.

The flat jacks are initially filled with oil and a low initial pressure, usually of about 0.05 MPa, is applied, in order to guarantee that the jacks are in contact with the slot wall. A LFJ test consists of, at least, three loading and unloading cycles with increasing maximum pressures. The raw test results are the pressure *versus* displacement curves obtained in the test.

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, two co-planar contiguous slots are usually opened for each test.

Interpretation of flat jack test results is not straightforward, due to the development of a tensile crack along the plane of the slots as applied pressures increase. Crack initiation and propagation depends not only on applied pressure but also on the *in situ* stresses and rock mass tensile strength, which are generally unknown parameters (Pinto 1981, ISRM 1986).

To deal with this difficulty, a three-dimensional numerical model was recently developed for the interpretation of the large flat jack test results, enabling to simulate several cases of test geometries with two co-planar contiguous slots. The model allows simulating an actual large flat jack test protocol with several loading and unloading cycles (Figueiredo *et al*. 2011), and can also be used for estimating the initial *in situ* stresses perpendicular to the slots (Figueiredo *et al.* 2010).

Applications of the model to several cases are presented in this paper. They consider different cases regarding the relation between the initial stress normal to the slots and the rock mass tensile strength, the applied pressures, the loading and unloading cycles, or the loaded area (one or two loaded flat jacks). The influence of the tension crack on the test results is assessed and discussed.

2 NUMERICAL MODEL

For the interpretation of LFJ tests, a three dimensional finite differences model using the software FLAC3D (Itasca 2009) was developed. It can simulate a LFJ test, with two co-planar contiguous slots, performed at an angle between the plane of the slot and the rock mass surface (Figueiredo *et al*. 2010). The mesh is a 30m×30m×15m solid and has 149,440 zones.

In order to simulate with detail the crack initiation and propagation into the rock mass, a very refined mesh around the slots was required, since they are just a few millimetres thick. Figure 2 (top left) shows a view of the mesh, and Figure 2 (top right) displays a middle vertical cross-section. The dark zones are the refined mesh, which is presented magnified at the bottom.

To simulate the tension crack, in the plane of the slots, interface elements with a finite tensile strength were used. Interface elements remain elastic for stresses below a given tensile strength; otherwise, a crack develops and the displacements versus pressure curves reveal a nonlinear behaviour.

The numerical model performs calculations that simulate both the cutting of the slots and the loading-unloading cycles. The initial stages comprise the following steps:

- installation of the in situ state of stress;
- completion of the central hole for the right side column;
- opening of the right side slot and filling of the central hole with mortar;
- completion of the central hole for the left side column;
- opening of the left side slot and filling of the central hole with mortar.

Afterwards, loading and unloading cycles can be modelled, considering all possible loading cases (Fig. 3):

- two loaded jacks in two contiguous slots;
- one loaded jack in two contiguous slots;
- a single flat jack in one slot.

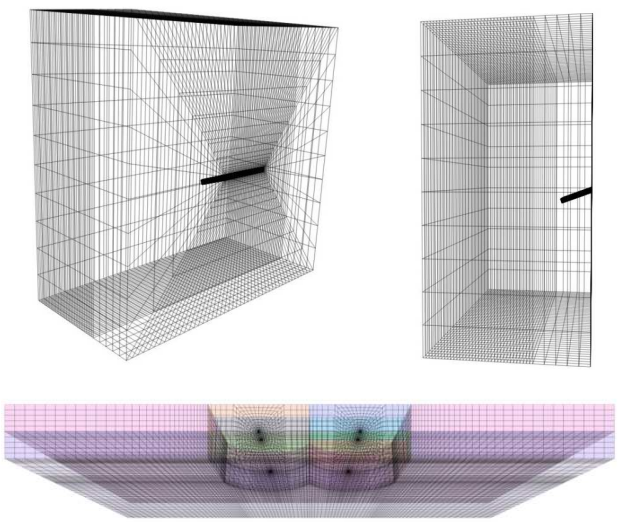

Figure 2. Three dimensional finite difference model.

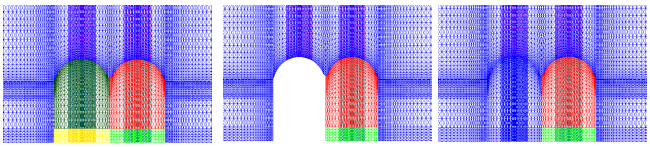

Figure 3. Interface for typical cases in LFJ tests: A – two slots and two loaded flat jacks; B – two slots and one loaded flat jack; C – one slot and one loaded flat jack.

The model allows assessing the depth of the crack *h* for each loading step, and the evolution of the displacements in the rock mass, namely at the location of the transducers and along the alignments presented in Figure 4.

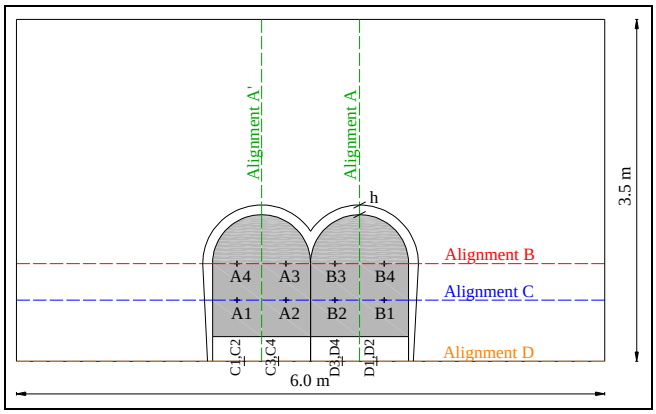

Figure 4. Location of the measuring points and alignments.

3 CALCULATION OF THE TENSILE CRACK DEPTH

3.1 *General*

Pressures applied by the jacks to the slot walls often induce tensile stresses along the edges of the slots that exceed the tensile strength of the rock mass, and therefore a crack starts to develop on the plane of the slots. 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 if the crack is visible at the rock mass surface.

Besides the applied pressure, two other parameters influence the development of the crack during a LFJ test: the tensile strength of the rock mass σ_t, and the initial *in situ* stress component perpendicular to the plane of the slots σ_{zz}. 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, it can be nearly equal to the tensile strength of the rock, whereas in weak and fractured rock masses its value is so low that it can be neglected.

3.2 *Influence of the in situ stresses and tensile strength on the tensile crack depth*

In this section, following an approach by Pinto (1983), the relations between crack depth h, applied pressure p, *in situ* stress σ_{zz}, and tensile strength σ_t are presented. Considering a rock mass with an isotropic, elastic and linear behaviour, the tensile stress σ_1 at the tip of the crack resulting from the application of a pressure p by the flat jacks may be written as a function $f(h)$ of the tensile crack depth h:

$$\sigma_1 = f(h)\, p \tag{1}$$

Likewise, the compressive stresses σ_2 at the edge of the crack for a null applied pressure by the flat jacks may be written as a function $g(h)$ of the tensile crack depth:

$$\sigma_2 = g(h)\, \sigma_{zz} \tag{2}$$

The crack reaches a given depth h when the tensile stress σ_1 due to the application of the pressure p is equal to the sum of the compressive stress σ_2 and the tensile strength of the rock mass σ_t:

$$\sigma_1 = \sigma_2 + \sigma_t \tag{3}$$

Substituting equations (1) and (2) in equation (3), and dividing both sides by $f(h)$, the following equation is reached:

$$p = \frac{g(h)}{f(h)}\sigma_{zz} + \frac{1}{f(h)}\sigma_t = \psi(h)\,\sigma_{zz} + \varphi(h)\,\sigma_t \tag{4}$$

Finally, a simple relation between p, σ_{zz} and σ_t is reached:

$$\frac{p}{\sigma_{zz}} = \psi(h) + \varphi(h)\frac{\sigma_t}{\sigma_{zz}} \tag{5}$$

Equation (5) shows that, for each value of the tensile crack depth, the ratio p/σ_{zz} varies linearly with the ratio σ_t/σ_{zz}. It was here assumed that the functions $\psi(h)$ and $\varphi(h)$ are well represented by quadratic functions of h, given by:

$$\begin{aligned} \psi(h) &= a + b\,h + c\,h^2 \\ \varphi(h) &= d + e\,h + f\,h^2 \end{aligned} \tag{6}$$

Thus, equation (5) can be written as:

$$\frac{p}{\sigma_{zz}} = a + b\,h + c\,h^2 + d\frac{\sigma_t}{\sigma_{zz}}h + e\frac{\sigma_t}{\sigma_{zz}}h + f\frac{\sigma_t}{\sigma_{zz}}h^2 \tag{7}$$

Equation (5) can also be used to determine the ratio p/σ_t. In this case, the equation of the three dimensional surface can be written as follows:

$$\frac{p}{\sigma_t} = a\frac{\sigma_{zz}}{\sigma_t} + b\frac{\sigma_{zz}}{\sigma_t}h + c\frac{\sigma_{zz}}{\sigma_t}h^2 + d + e\,h + f\,h^2 \tag{8}$$

Equation (8) is used for the particular and unlikely case when the *in situ* stress σ_{zz} is null and equation (7) cannot be used.

3.3 *Calculation of the tensile crack depth*

In order to establish relations between the tensile crack depth and the ratios σ_t/σ_{zz} and p/σ_{zz}, a parametric analysis involving a very large number of numerical calculations considering plausible values for the parameters was performed. The result of each calculation is a set of values (h; σ_t/σ_{zz}; p/σ_{zz}) approximately complying with equation (7).

Five values of the tensile strength σ_t were considered (0, 1, 2, 4 and 8 MPa), the in situ stress was set as 1 MPa, and pressures p between 0.5 and 32 MPa were numerically applied to the slot walls. All calculations were performed using the numerical model presented above, and considering a Young's modulus of 1 GPa and a Poisson's ratio of 0.2.

Considering the most common case of LFJ tests (two loaded slots), each calculation rendered as final result a set of values (h; σ_t/σ_{zz}; p/σ_{zz}). Linear multiple regression enabled to determine parameters a to f and to define the most probable three-dimensional surface relating crack depth and the ratios σ_t/σ_{zz} and p/σ_{zz}. This surface is presented in Figure 5, which, given estimates of the tensile strength and of the in situ stress, allows to determine the tension crack depth.

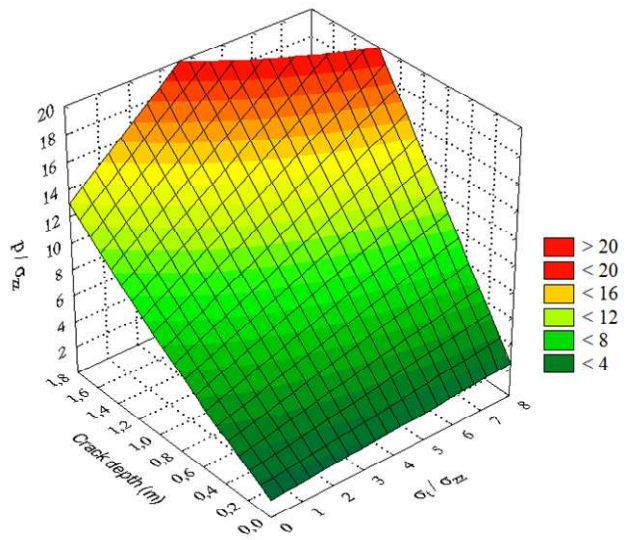

Figure 5. Three-dimensional surface relating crack depth with the ratios p/σ_{zz} and σ_t/σ_{zz} (two loaded slots case).

Considering that one of the variables does not change, equation (7) can also be used to obtain the graphs relating the two remaining variables. So, the following graphs were created:

- relation between tensile crack depth and p/σ_{zz} for several values of the ratio σ_t/σ_{zz} (Fig. 6);
- variation of p/σ_{zz} with σ_t/σ_{zz} for several values of the tensile crack depth (Fig. 7);
- variation of p/σ_{zz} with the crack depth for several values of the ratio σ_{zz}/σ_t (Fig. 8).

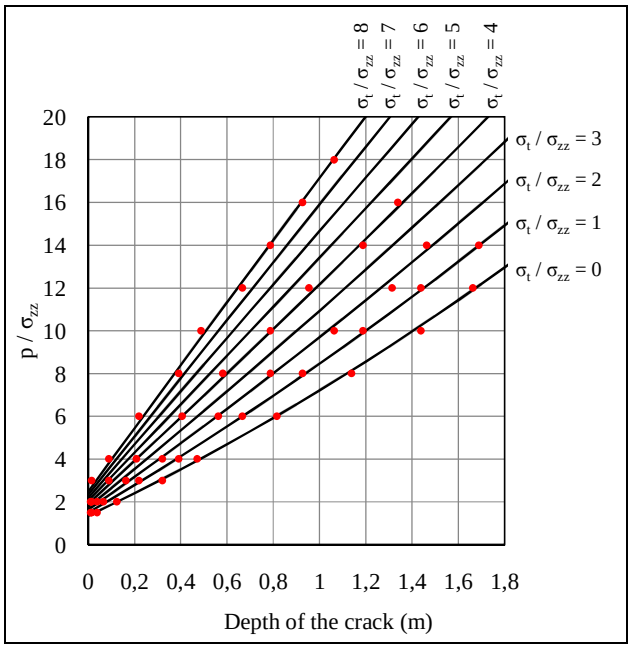

Figure 6. Variation of the ratio p/σ_{zz} with the tensile crack depth for several values of the ratio σ_t/σ_{zz}.

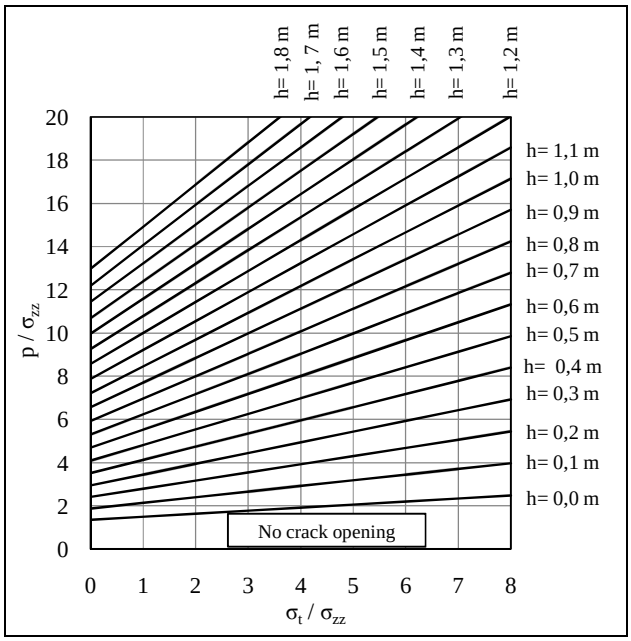

Figure 7. Variation of the ratio p/σ_{zz} with the ratio σ_t/σ_{zz} for several values of the tensile crack depth.

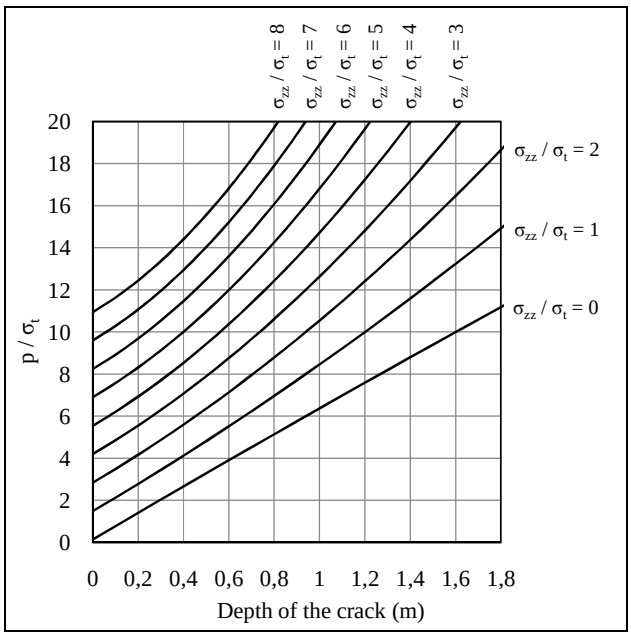

Figure 8. Variation of the ratio p/σ_t with the tensile crack depth for several values of the ratio σ_{zz}/σ_t.

Dots displayed in Figure 6 correspond to some of the calculations performed with the numerical model. They show that a good approximation was reached.

As LFJ tests can be used to assess *in situ* stresses σ_{zz} (Figueiredo *et al*. 2010) and tensile strength does not vary over a wide range of values, using Figure 7 it is possible to estimate crack depth propagation as pressure is applied during loading and unloading cycles of a LFJ test.

The same approach was followed to define similar relations for the remaining types of LFJ tests described in Figure 3: one loaded flat jack in two contiguous slots, and one loaded jack in a single slot.

Figure 9 presents graphs relating the ratio p/σ_{zz} with the tensile crack depth for all the three analyzed cases. Figure 10 shows the normal stresses on the interface for $p/\sigma_{zz} = 4$ MPa and for a null value of the rock mass tensile strength, allowing to appraise the extent of the tensile crack (in red) around the slots.

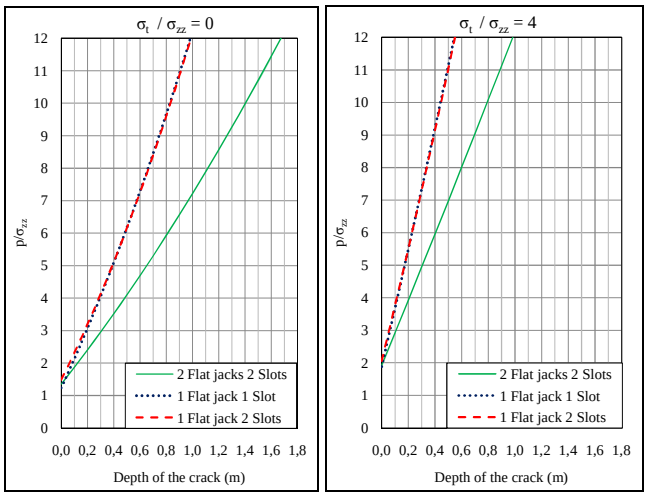

Figure 9. Variation of the tensile crack depth with the ratio p/σ_{zz} for $\sigma_t/\sigma_{zz} = 0$ and $\sigma_t/\sigma_{zz} = 4$.

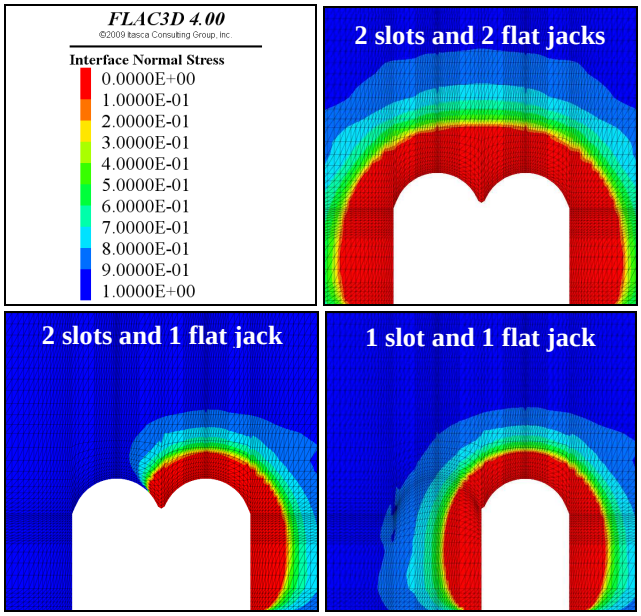

Figure 10. Normal stresses on the interface for p/σ_{zz} = 4 MPa and σ_t/σ_{zz} = 0.

4 CALCULATION OF THE YOUNG'S MODULUS

Several methodologies have been implemented in order to estimate the Young's modulus from the results of large flat jack tests. The model that has been used so far is based on the theory of elasticity for homogeneous, isotropic and elastic bodies and allows simulating a particular case, in which the slots are normal to the rock surface, and they are inserted in an infinite space from a rectangular testing chamber with a typical size: 3.5 m long and 2.5 m wide (Pinto 1983). 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:

$$\delta_i = k_i\,(1 - \nu^2)\,\frac{\Delta p}{E} \qquad (9)$$

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

Coefficients k_i may be used for interpretation of tests results independently of the rock mass mechanical parameters (modulus of deformability, Poisson's ratio, tensile strength, *in situ* stress). Pinto (1981, 1983) presents the values of k_i for several combinations of loaded jacks and slots, given the tensile crack depth. Once having defined the values of k_i at the location of each 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 (9):

$$E = (1 - \nu^2)\,\Delta p\,\frac{\sum k_i^2}{\sum k_i \delta_i} \qquad (10)$$

The numerical model presented in this paper was used to calculate values of k_i for a large number of situations, including several that couldn't be considered with the previous methodology. For each situation, considering a modulus of deformability of 1 GPa and a Poisson's ratio equal to 0.2, the numerical model was used for calculating, for each pressure increment, the tensile crack depth and the displacements at the locations where all displacement gauges are placed. Equation (9) is then used to obtain the values of the coefficients k_i for each crack depth.

Figures 11, 12 and 13 show the diagrams with the variation of the coefficients k_i with the tensile crack depth for the three loading cases presented in Figure 3. Table 1 presents the values of the coefficients k_i obtained with the numerical model. These diagrams show that the coefficients increase as the tensile crack depth increases till a maximum value. For instance, in the case of two slots and two flat jacks, the diagram shows that the coefficients k_i at the location of the transducers A2 and B2 are higher than the coefficients at the location of the others transducers. This may be explained since the transducers A2 and B2 are located closer to the rock mass surface in a lesser confined region and consequently the displacements are higher in these locations.

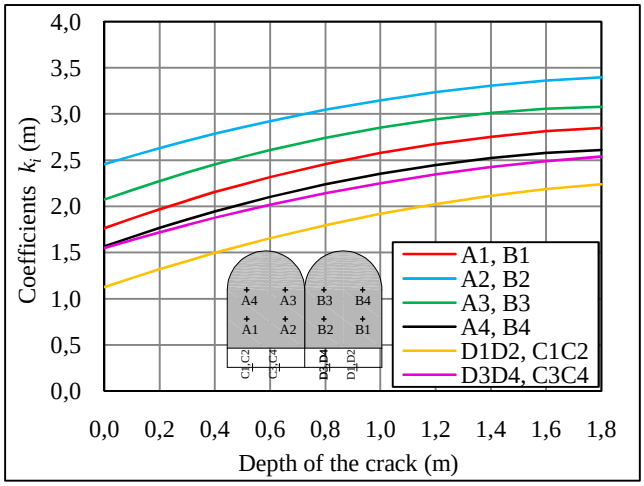

Figure 11. Variation of the coefficients k_i with the tensile crack depth. Case A: two slots and two flat jacks.

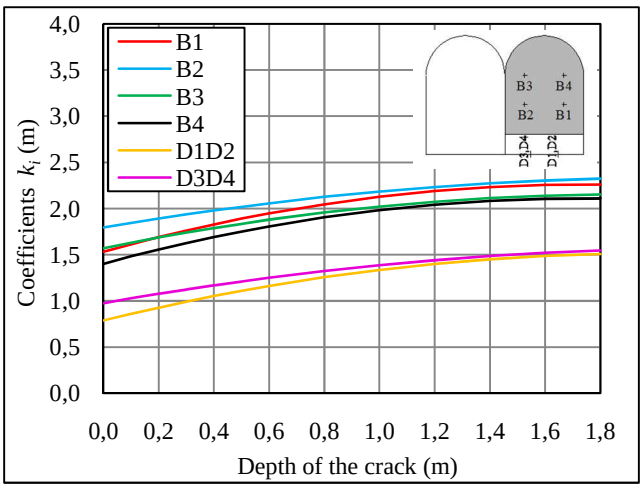

Figure 12. Variation of the coefficients k_i with the tensile crack depth. Case B: two slots and one flat jack.

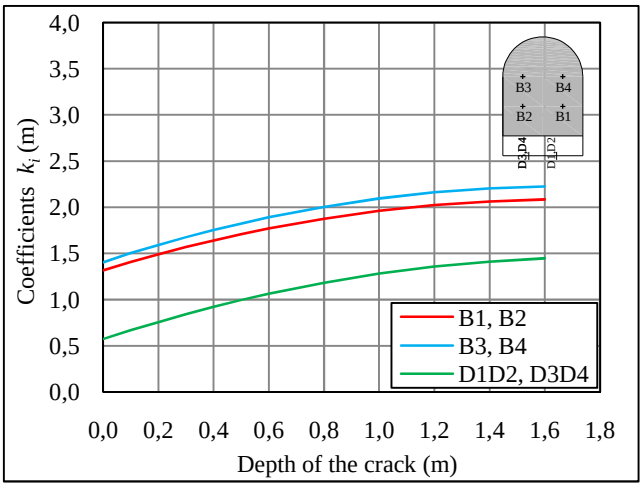

Figure 13. Variation of the coefficients k_i with the tensile crack depth. Case C: one slot and one flat jack.

Table 1. Coefficients k_i computed by the numerical model.

Case	Gauge location	Depth of the crack (m) 0.0	0.2	0.5	1.0	1.6
A	A1, B1	1.764	1.969	2.237	2.577	2.811
	A2, B2	2.458	2.630	2.856	3.149	3.362
	A3, B3	2.083	2.279	2.533	2.851	3.056
	A4, B4	1.569	1.767	2.025	2.352	2.577
	C1C2, D1D2	1.115	1.313	1.576	1.920	2.182
	C3C4, D3D4	1.542	1.716	1.947	2.252	2.487
B	B1, B2	1.317	1.490	1.708	1.961	2.082
	B3, B4	1.406	1.590	1.824	2.094	2.225
	D1D2, D3D4	0.572	0.757	0.994	1.281	1.446
C	A1, B1	1.532	1.689	1.888	2.126	2.255
	A2, B2	1.795	1.891	2.018	2.183	2.303
	A3, B3	1.570	1.686	1.835	2.020	2.138
	A4, B4	1.401	1.555	1.750	1.982	2.105
	D1D2	0.787	0.926	1.107	1.335	1.486
	D3D4	0.975	1.076	1.210	1.386	1.519

5 DISCUSSION AND CONCLUSIONS

Large flat jack tests were developed mainly for the study of concrete dams foundations. Its use decreased in the last decades due to the high costs of field tests, and also to the sometimes excessive 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 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. LFJ tests using two adjacent jacks are well suited to cost-effectively characterize rock mass deformability, since they are able to mobilize a relatively large volume of rock.

A difficulty in the interpretation of flat jack test results has to do with the tensile crack that may develop in the plane of the slots as the applied pressures increase. Crack initiation and propagation depend on the in situ stresses, rock mass tensile strength and applied pressure. Recently, a numerical model was developed for the interpretation of LFJ tests reproducing the exact geometry of the test and all test stages, as well as the development of the tension crack. This numerical model allows to estimate *in situ* stresses perpendicular to the slots and to model rock mass deformation during the loading and unloading cycles of the LFJ tests (Figueiredo *et al*., 2010 and 2011).

This paper presented a methodology for determining the tensile crack depth for several geometries and loading conditions, from the values of the applied pressure, the tensile strength and the initial stress normal to the jacks. It was demonstrated that, for each value of the tensile crack depth, the ratio p/σ_{zz} varies linearly with the ratio σ_t/σ_{zz} and, therefore, all calculations could be done as a function of these adimensional parameters. Values of the coeficients k_i for calculation of the modulus of deformability were presented as a function of the tensile crack depth for several common geometries and loading conditions.

Studies are now being carried out that consider different situations as regards the inclination of the slots with respect to the rock face and different bounday conditions that simulate different test chamber geometries.

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