6TH INTERNATIONAL CONFERENCE ON DAM ENGINEERING
C.Pina, E.Portela, J.Gomes (ed.)
Lisbon, Portugal, February 15-17, 2011

NUMERICAL SIMULATION OF A LARGE FLAT JACK TEST WITH CYCLIC LOADING

Bruno Figueiredo*, Luís Lamas*, José Muralha*

* Laboratório Nacional de Engenharia Civil (LNEC)
Av. do Brasil, 101, 1700-066 Lisboa, Portugal
e-mail: brunof@lnec.pt, webpage: http://www.lnec.pt

Keywords: Rock Mechanics, Deformability, Field tests, Numerical modelling

Abstract. Large flat jack tests are one of the field techniques used to assess rock mass deformability. The paper introduces a methodology for interpretation of these tests. A three-dimensional numerical model was developed, which simulates the test with the actually applied loading and allows assessing the evolution of the displacements in the location of the transducers. The depth of the tension crack that may develop in the rock mass during the test is assessed at each test stage. The paper presents the calculations that were performed for simulation of an actual large flat jack test protocol with four loading and unloading cycles.

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 cancelation 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. The initial simulations performed with the model resulted in a methodology for determination of the initial normal and shear stresses, presented by the authors in a previous paper [8] .

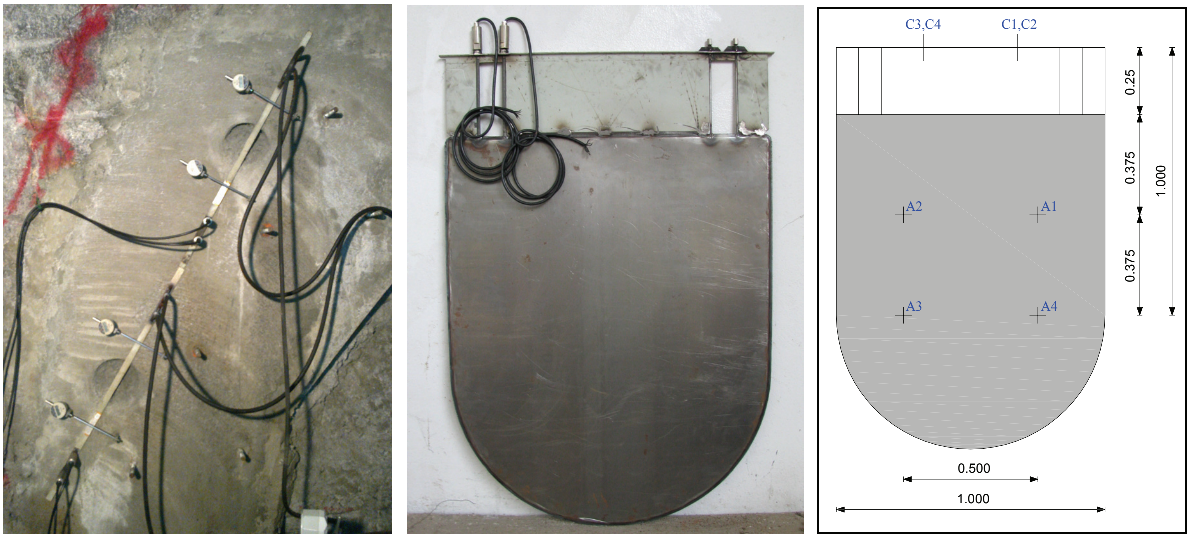
3. LARGE FLAT JACK TEST METHOD

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.

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.

(a) (b)

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



(a) (b) (c)

Figure 2: (a) flat jacks 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

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.

4. INTERPRETATION OF LARGE FLAT JACK TEST RESULTS

Interpretation of LFJ test results have been based on the theory of elasticity for homogeneous, isotropic and linear elastic bodies. A particular case is simulated, 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 [9]. 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:

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

where E is the rock mass modulus of deformability, ν is the Poisson's ratio 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):

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

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 [10] 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 (Figures 3 and 4). 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.

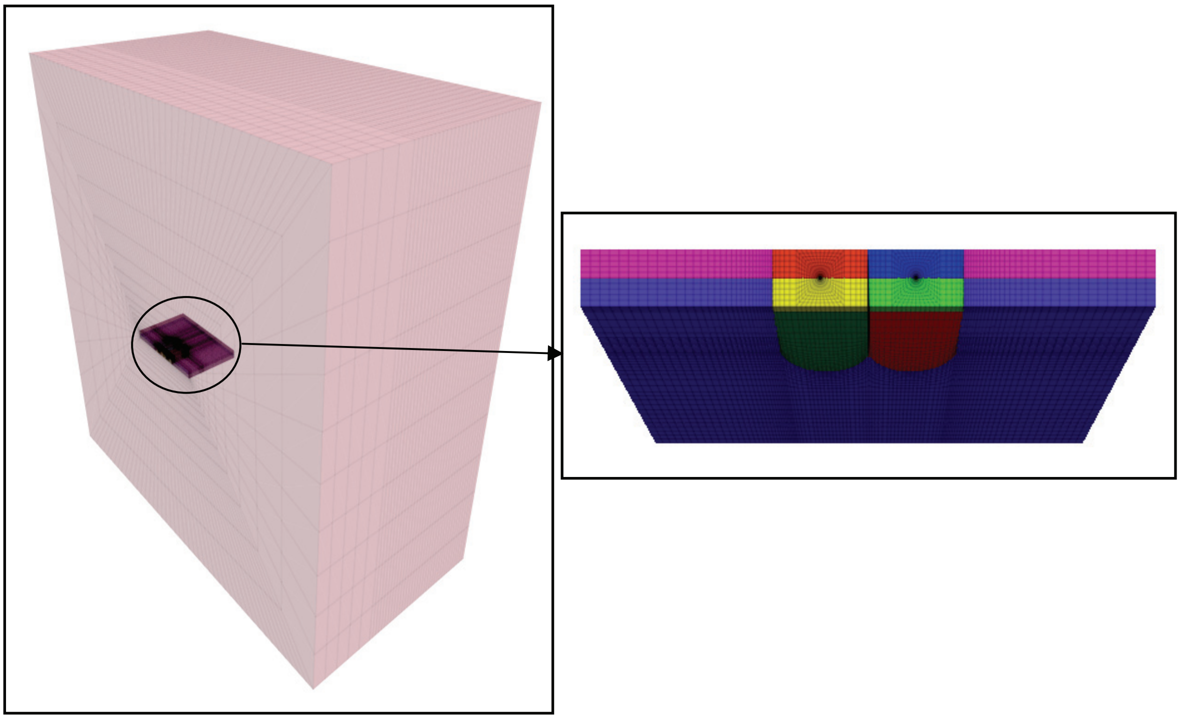


Figure 3: Perspectives of the three dimensional finite difference model

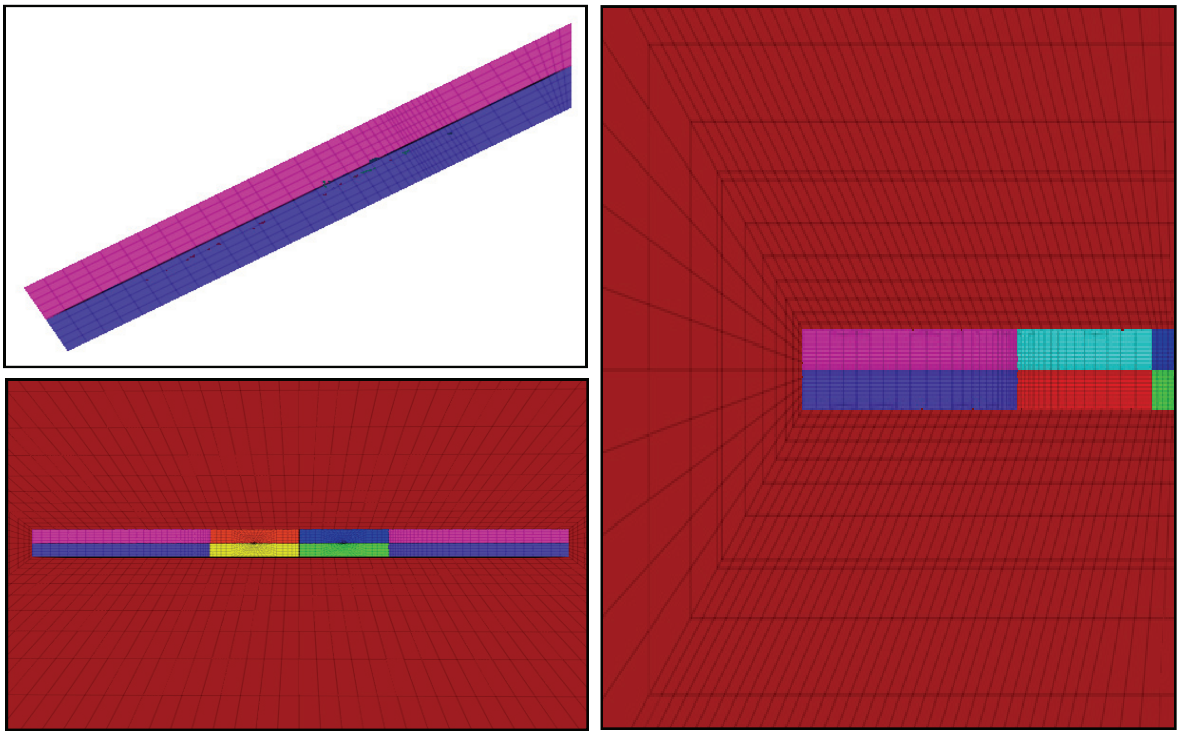


Figure 4: Sections of the three dimensional finite difference model normal to the coordinated axes

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 (Figure 5). 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.

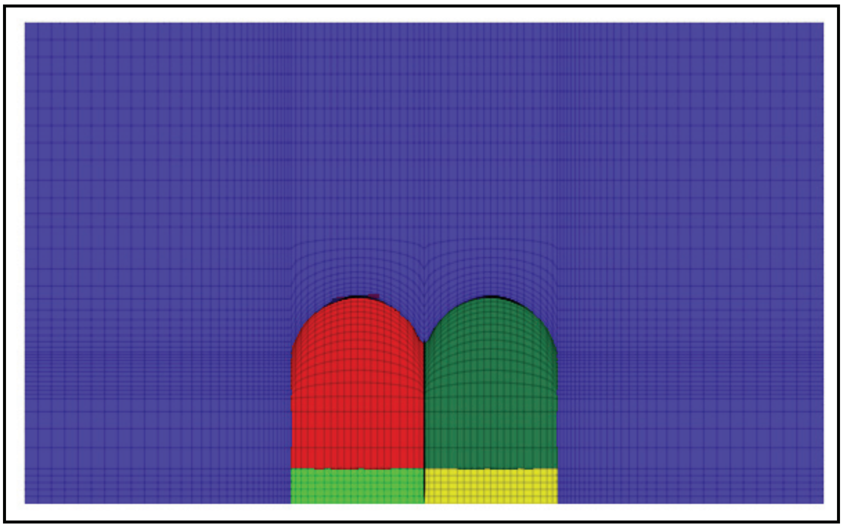


Figure 5: Top view of the interface

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 6. In this figure all the measuring points are represented.

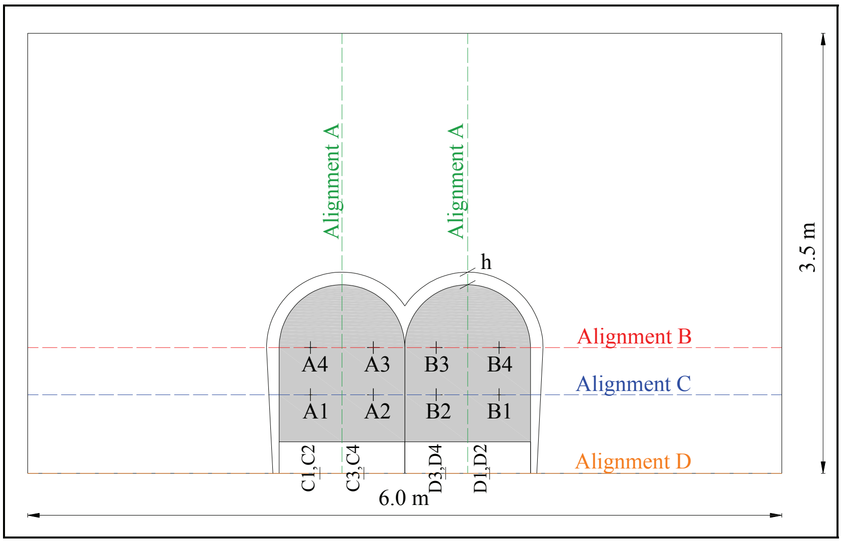


Figure 6: Top view showing the measuring points and alignments for analysis of the results

The propagation and depth of the tension crack depend on the fracture energy of the interface elements and hence on their normal stiffness. The influence of the interface normal stiffness on the crack depth was analysed and the results were presented in a previous paper [8] . Five cases were studied with $k_{n1}=k_n/10$, $k_{n2}=k_n$, $k_{n3}=k_n\times10$, $k_{n4}=k_n\times100$, $k_{n5}=k_n\times1000$, where k_n is the equivalent stiffness of one layer of elements of the continuum with 10 mm thickness. 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.

6 NUMERICAL SIMULATION OF A LARGE FLAT JACK TEST

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 7 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.

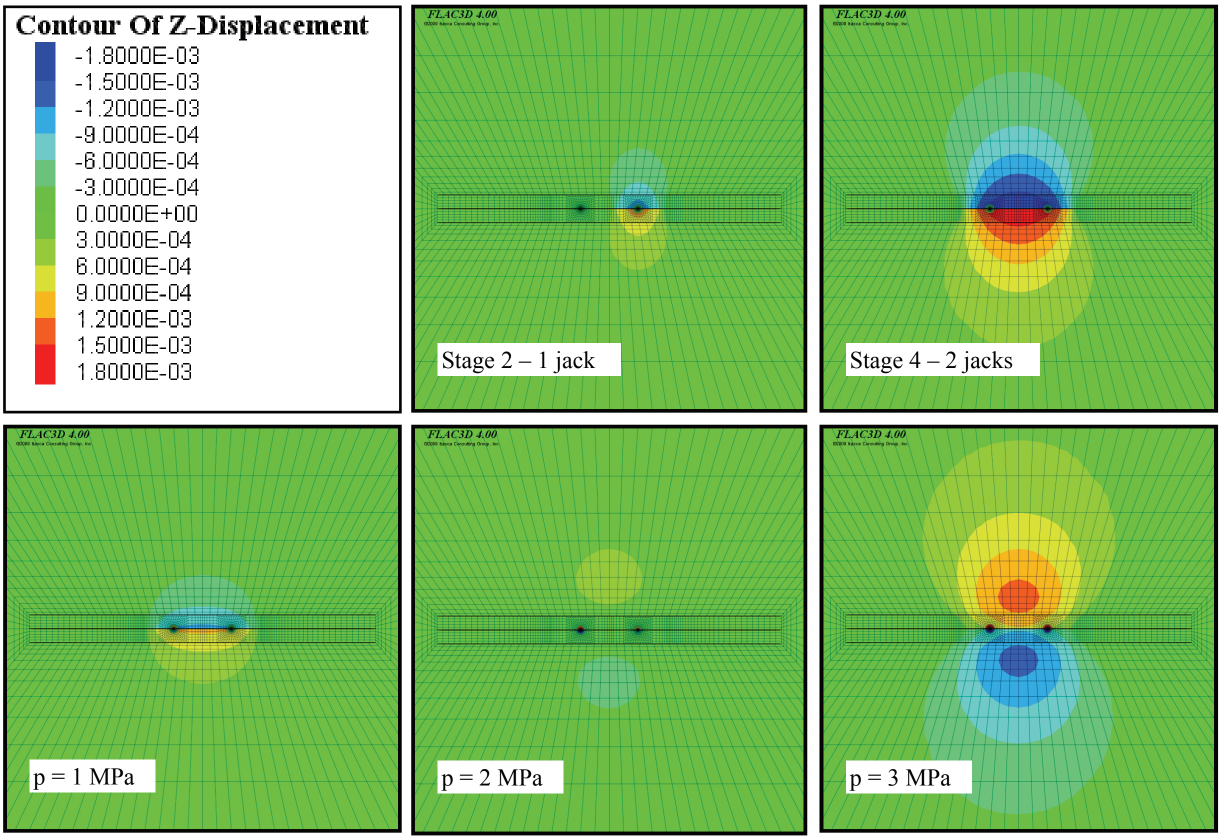


Figure 7: Vertical displacements contours at the end of the stages 2 and 4, and for pressures of 1, 2 and 3 MPa

The numerical model was then used to simulate an LFJ test with four loading and unloading cycles with maximum pressures of 2, 4, 8 and 16 MPa. A tensile strength of 4 MPa was assumed. The displacements at the location of the transducers were recorded. The loading and unloading were performed by increments, whereby the maximum and minimum of one cycle were to be reached in four increments. Figure 8 shows the displacements at the transducers A1, A2, A3 and A4, obtained at the end of each step.

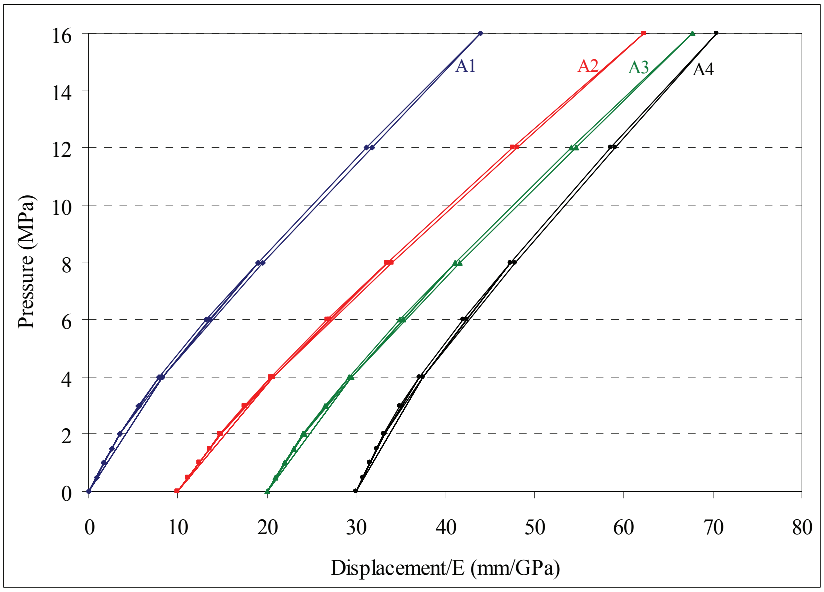


Figure 8: Calculated pressure versus displacement curves

The calculated pressure versus displacement curves present a curvature, with a decrease in stiffness as the loading progresses, and the loading and unloading branches present a hysteresis. This departure from linear elastic behaviour occurs when the stresses caused by the applied pressures exceed the tensile strength of the rock mass and consequently the tension crack in the rock mass initiates. The extent of the crack depends on the applied pressures, on the tensile strength of the rock mass and on the initial stress normal to the jacks.

For easier visualisation, the pressure versus loading path during the test is schematically represented in Figure 9. This figure represents a test with 3 loading and unloading cycles with increasing maximum pressures. The first loading follows the blue line and at a certain pressure level the tension crack is initiated, with the consequent onset of the non-linear and hysteretic behaviour. Once the maximum pressure of the first cycle is reached, unloading occurs along the red line. The loading curve of the second cycle is coincident with the unloading of the first cycle (red line) until the maximum pressure of the first cycle is reached. Afterwards, it follows the blue line up to the maximum pressure of the second cycle. The second unloading occurs along the orange line, and so does the third loading until the maximum pressure of the second cycle. Between this pressure and the maximum pressure of the third cycle the loading follows the blue line, and the final unloading occurs along the green line.

Figure 10 presents the normal stresses along alignment A (see Figure 7), on the plane of the flat jack. Stresses are represented in solid line for the first loading, in dashed line for the first unloading, and with markers for the second loading. The first, second and third cycles are represented in red, orange and green, respectively. This diagram makes it easier to understand the behaviour during successive cycles. Despite the non-linear and hysteretic behaviour, the stresses at the first and second loadings to a certain pressure are coincident. The stresses, at a certain pressure, are different in the loading and the unloading branches. The same was observed with the displacements.

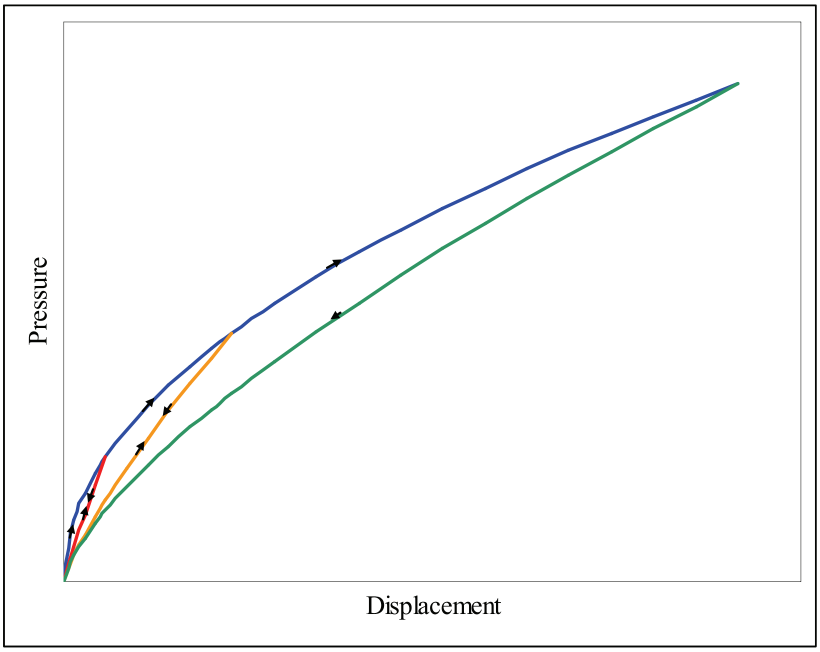


Figure 9: Typical pressure versus displacement curves

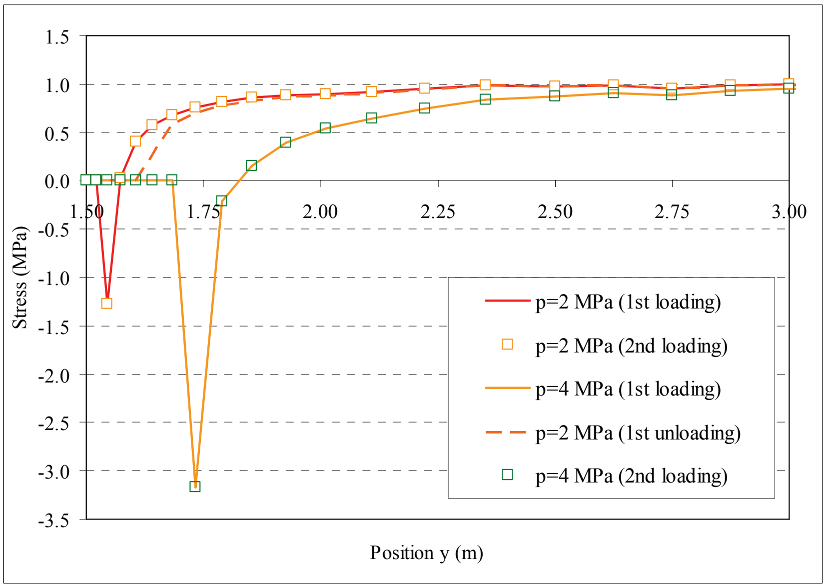


Figure 10 : Normal stresses in alignment A

7. CONCLUSIONS

Large flat jack tests were developed mainly for the study of the foundations of large concrete dams. Its use decreased in the last decades due to the high costs of 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 jacks have recently been intensively used for the investigation of large concrete dam sites in Portugal, They were found to be a reliable and robust test, when compared with plate loading tests and borehole jacking tests. By using two adjacent jacks, a relatively large volume of rock is involved, as is illustrated in Figure 7. 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 numerical calculations presented in this paper simulate a test with cycling loading up to increasing pressures. A non-linear and hysteretic behaviour was obtained after the onset of the tension crack in the rock mass. This helps explaining the results obtained in actual large flat jack tests, which are also non-linear and hysteretic. However, the test results present non-negligible permanent deformations and the curvature of the unloading cycle in positive. This behaviour is not obtained in the numerical simulations and can be attributed to other factors that are not considered in the model, such as the opening and closure of the rock mass discontinuities in the loaded volume, or creep effects. The possibility of representing these factors in the model is currently being investigated.

ACKNOWLEDGEMENTS

This work was carried out as part of LNEC Programmed Research Plan, under the project "Determination of the Geomechanical Parameters of Rock Masses".

REFERENCES

[1] Rocha, M. 1974. Present Possibilities of Studying Foundations of Concrete Dams. *Proceedings of the 3rd ISRM International Congress on Rock Mechanics*, Denver, USA, pp. 879-897.

[2] Cunha, A.P. & Muralha, J. 1990. About LNEC Experience on Scale Effects in the Deformability of Rock Masses. *International Workshop on Scale Effects in Rock Masses*, Loen. Ed. Balkema, pp. 219-229.

[3] Vrkljan, I. & Kavur, B. 2001. Experience Gained in Rock Mass Deformability Testing by Large Flat Jacks. *Proceedings of the ISRM Regional Symposium, Eurock 2001*, Espo/Finland, pp. 191-196.

[4] Hoek, E. & Diederichs, M.S. 2006. Empirical Estimation of Rock Mass Modulus. *International Journal of Rock Mechanics and Mining Sciences*, 43: pp. 203-215.

[5] Pinto, L.J. 1981. Determination of the Deformability Modulus of Weak Rock Masses by Means of Large Flat Jacks. *Proceedings of an International Symposium on Weak Rock*, Tokyo, pp. 447-452.

[6] ISRM. 1986. Suggested Method for Deformability Determination Using a Large Flat Jack Technique. *International Journal of Rock Mechanics Mining Sciences and Geomechanics Abstracts*, 23: pp. 131-140.

[7] Grossmann, N.F. & Câmara, R.J.C. 1986. About the Rock Stress Measurement Using the LFJ (Large Flat Jack) Technique. *Proceedings of the International Symposium on Rock Stress and Rock Stress Measurements*, Stockholm, pp. 375-383.

[8] Figueiredo, B., Lamas, L. & Muralha, J. 2010. Determination of In Situ Stresses Using Large Flat Jack Tests. *Proceedings of the ISRM International Symposium and 6th Asian Rock Mechanics Symposium on Advances in Rock Engineering*, New Delhi, Abstracts volume p. 27.

[9] Pinto, J.L. & Appleton, J. 1976. *Determination of the Deformability of Rock Masses Using Large Flat Jacks* (in Portuguese). LNEC report, Lisboa.

[10] Itasca. 2009. FLAC3D, *Version 4.0, User's Manual*. Itasca Consulting Group, Minneapolis, USA.