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Application of a global interpretation model for assessment of the stress field for engineering purposes

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ABSTRACT: Release of the in situ stresses is often the most relevant action in underground projects. Several different field methods are available to measure the in situ state of stress. Some allow the evaluation of the complete state of stress at a given point, while others only supply a single stress component. The paper presents a global methodology for evaluation of the most likely natural stress field from in situ test results. Some case histories are presented as examples of application. One example deals with the case of an underground powerhouse where high horizontal stresses were determined by overcoring tests, which were later confirmed by flat jack tests performed during the construction of access adits. A second one considers the analysis of a testing programme where overcoring and flat jack tests were both performed during the initial testing programme in different locations. The last one refers to the results of overcoring tests in the vicinity of existing underground caverns, which have to be adequately considered in order to estimate the natural state of stress.

1 INTRODUCTION

Release of the state of stress is often the most relevant action during the excavation of an underground work, and it can affect the location and orientation of the cavern or tunnel, the design of the support, as well as the construction method used.

The large number of factors that influence the in situ stresses in rock masses make of its characterization a difficult task. These factors include lithological and deformability heterogeneities, topography and the existence of nearby excavations, the action of water, the mechanical properties of rocks or even the actions of man. Owing to these factors, the state of stress presents a significant spatial variability and its characterization requires execution of in situ tests using the most appropriate test techniques and a global interpretation model for analysis of the obtained results.

Several authors present descriptions, limitations and fields of application of existing test techniques (*e.g.* Cornet 1993, Amadei & Stephansson 1997 Fairhurst 2003, Hudson *et al.* 2003, Ljunggren *et al.* 2003), which are usually grouped as follows:

- methods based on hydraulic fracturing;
- methods based on the complete stress release;
- methods based on the partial stress release;
- methods based on the observation of the rock mass behaviour.

LNEC uses small flat jacks (SFJ), when there is direct access to the rock mass inside adits or wells, and a 3D cell (Strain Tensor Tube – STT) to perform overcoring tests, when the zones of interest can only be reached using boreholes.

SFJ is a method of partial stress release. It consists in cutting a 10 mm slot in a rock mass surface with a circular disk saw, introducing a flat jack in the slot and applying a pressure until the deformation caused by opening of the slot is compensated. A single stress component is obtained.

STT is a complete stress release method that allows determining all stress components at a given location using a borehole overcoring technique. STT cells are 2 mm thick epoxy resin hollow cylinders with 10 embedded strain gauges at its mid thickness, sampling homogeneously the 3D space (Pinto 1983). The cell is cemented in a 37 mm diameter borehole and the in situ stresses are released by overcoring with a larger diameter, thus obtaining a 120 mm diameter core. Strains are measured before and after overcoring and the stresses are calculated using the elastic constants obtained in a biaxial test of the recovered core with the STT cell.

2 GLOBAL MODELS FOR THE IN SITU STRESSES IN ROCK MASSES

Tests for determination of the in situ stresses in rock masses are usually scarce in numbers and their results, due to the point wise nature of stress, only allow to characterize the state of stress, or in some cases just some of its components, in the precise locations where they are executed. After the interpretation of the results of each test (as in STT tests), or of sets of tests (as in SFJ tests), it is useful to apply global models that integrate the results from various tests performed in different locations. These models are used to assess the influence of the main factors that affect the stress distribution in rock masses, namely the ground surface topography generated by tectonic or eroding processes, the existence of underground or surface excavations, as well as the heterogeneity and the variability of the mechanical properties of the rock mass. The influence of these factors can be considered jointly or separately.

Global interpretation models start by establishing a set of assumptions regarding the stresses in the rock mass. In some cases, based on the particular geometric conditions of a given problem, it may be reasonable to set forward some assumptions regarding the directions of the principal stresses. Assumptions regarding the variation of the stress components may also be justified. It is common to consider that the vertical and horizontal stresses increase linearly with depth, since the stresses are, in a large proportion, due to the weight of the overlaying ground.

The global interpretation model used in the analyses presented in this paper is based on the following assumptions:

- The natural in situ stress is calculated for an initial situation, prior to the disturbance in the stress field caused by significant topographic changes, such as the excavation of a deep canyon by a river, or caused by any underground excavations in the area of interest.
- The principal initial in situ stresses σ_j^0 are zero at the ground surface and vary linearly with depth: $\sigma_j^0 = k_j \gamma h$, where γ is the unit weight of the rock mass, h is the depth and j is an index that takes the values 1, 2 and 3.
- One principal initial in situ stress is vertical, and therefore the other 2 are horizontal.

The existing natural stress field results from the initial stress field, characterised by the parameters k_j, and from the effect of the superficial and underground excavations that disturbed the initial conditions. It is calculated through the application of analytical solutions in simple problems or, in the more complex cases, using 3D numerical models.

The parameters k_i are determined from the measured stress components obtained in all in situ stress measurements, which may have been carried out in different locations and using different methods, and from the geometry of the excavations, using the following methodology, which is derived from a procedure proposed by Sousa *et al.* (1986):

- A vector M_i is constructed with all the measured stress components, where i is an index that takes values from 1 to N.
- Each of the 3 principal initial in situ stresses, with unit k_j values, is considered separately, and this corresponds to 3 loading cases E_i.
- Each loading case E_i is applied to the rock mass model, and the stress components at the measuring points are calculated (6 for each overcoring test plus 1 for each flat jack test).
- A matrix A_{ij} is constructed, which represents the N stress components at the different measuring points, for each loading case E_j.
- Using the principle of superposition of effects, the following expression can, then, be written:

$$A_{ij}\, k_j = M_i\, (i = 1, 2, \ldots, N) \quad (j = 1, 2, 3) \tag{1}$$

This system of linear equations is usually highly redundant. Its resolution by the least squares method enables to determine the parameters k_j, with which it is possible to calculate the most probable in situ state of stress at any point in the rock mass.

3 APPLICATION EXAMPLES

LNEC was asked to perform in situ stress measurements in rock masses for the design of the re-powering projects of the Picote II, Bemposta II and Salamonde II hydroelectric projects, in the North of Portugal. These re-powering projects consist in the construction of new hydraulic circuits and larger underground powerhouses close to the dam valleys.

The state of stress in the vicinity of the powerhouses is influenced by the topography of the ground, in particular by the shape of the river valleys, which result from the erosive action of the river over geologic time. In addition, in some cases, the results of tests do not reproduce directly the natural stresses, since they were determined near underground openings that change the stress field around them. To interpret the results of various tests in order to obtain an estimate of the natural stress fields, it was necessary to perform global analyses, making use of numerical models.

3.1 *Picote II re-powering scheme*

The existing Picote hydroelectric scheme, on the Douro River, consists of a concrete arch dam and an underground powerhouse with a hydraulic circuit in the right bank of the river. The re-powering scheme is also to be built in the right bank, close to and surrounding the existing power plant, and includes a new hydraulic circuit (a 300 m long headrace tunnel and a 150 m long tailrace tunnel), a larger powerhouse cavern and several adits (Figure 1). The new powerhouse cavern is 68 m long, 23 m wide and 58 m high at the turbine hall. The cavern is located 150 m below surface and only 80 m away from the existing one.

To characterize the in situ stresses, three STT overcoring tests were performed in each one of two parallel boreholes (STT1 and STT2), drilled from an existing adit (LNEC 2006). The boreholes are 50 m apart and dip 70°. The tests were carried out at the following depths: STT1 – 39.80 m, 66.10 m and 78.35 m; STT2 – 41.00 m, 60.60 m and 77.45 m.

In all tests, one of the principal stresses was approximately in the direction of the borehole and the other two were approximately parallel and normal to the river axis. In some tests, stress levels were considerably higher than initially expected, especially taking into account the rock coverage. This is the case of the test in STT1 at 78.35 m with an almost hydrostatic stress of around 20 MPa.

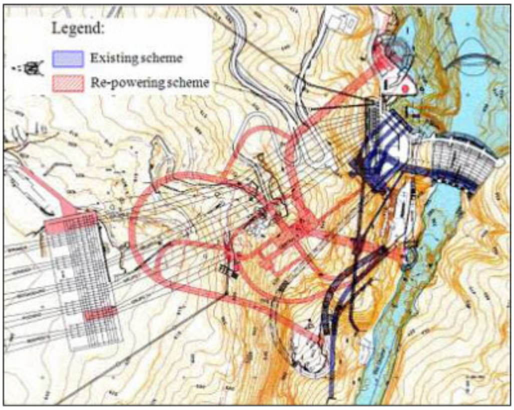

Figure 1. Layout of the Picote II re-powering scheme (in red).

In this example, the main factor that affects the in situ stresses distribution within the granitic rock mass is the topography of the steep river valley. For the interpretation of the test results a 2D numerical model was developed, using the finite difference software FLAC (Itasca 2005). The model considers a vertical cross-section of the rock mass in the zone of the new powerhouse, approximately perpendicular to the river and parallel to the boreholes. The mesh has 1,000 m in the horizontal direction, 700 m in the vertical direction from elevations 0 to 700 m, and an axis of symmetry on the left boundary, which represents the river bed. The mesh has 200 × 300 zones, and is more refined close to the test locations with 2.5 m × 1.75 m zones (Figure 2). The associated system of coordinates has axis 1 horizontal, in the plane of the model, axis 2 vertical, and axis 3 normal to the plane.

The global interpretation method presented in section 2 was used for calculation of the in situ stresses, with the following additional assumptions:

- the rock mass is continuous, linear elastic, homogeneous and isotropic, with $\gamma = 27\,\mathrm{kN/m^3}$;
- the initial in situ stress corresponds to the situation before excavation of the river valley;
- the initial vertical stress σ_2^0 is equal to the weight of the overlying rock ($k_2 = 1$);
- the depth h is measured from elevation 700 m;
- plane strain conditions.

Applying this procedure to the overcoring tests carried out for the Picote II project, the following values were determined: $k_1 = 1.70$ and $k_3 = 1.75$.

Figure 3 shows the principal stresses calculated in the overcoring test locations. The stresses are clearly influenced by the proximity of the canyon. The ratio of σ_I (sub-horizontal) over σ_{III} (sub-vertical) is very high (between 4.5 and 5.1).

Based on this analysis, recommendations to the designer regarding the state of stress to consider in the powerhouse cavern calculations were issued:

- The initial in situ state of stress should be obtained from an initial situation prior to the excavation of the valley, with a vertical stress equal to the weight of the overlying rock mass and with isotropic horizontal stresses equal to 1.75 times the vertical stress.
- This initial in situ state of stress shall be considered for simulation of the excavation of the valley due to the erosive effect of the river, and the resulting state of stress shall be the starting point for the design computations of the powerhouse.

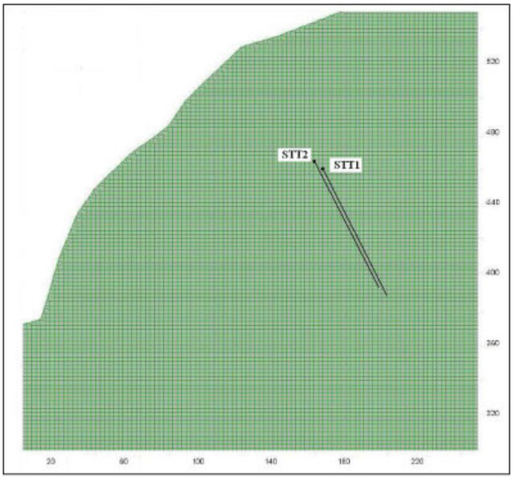

Figure 2. Mesh detail and location of the boreholes.

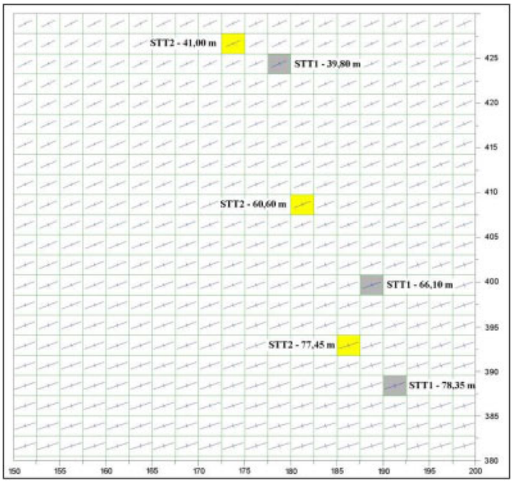

Figure 3. Stresses calculated in the overcoring test locations.

Owing to the high horizontal stresses calculated and to the relatively scarce information obtained at the design phase, it was decided to perform additional stress measurements, using the small flat jack method, once excavation of the adits reached the proximity of the underground powerhouse. These tests confirmed the existence of high horizontal stresses (about four times the vertical stresses), thus confirming the results obtained in the earlier stages.

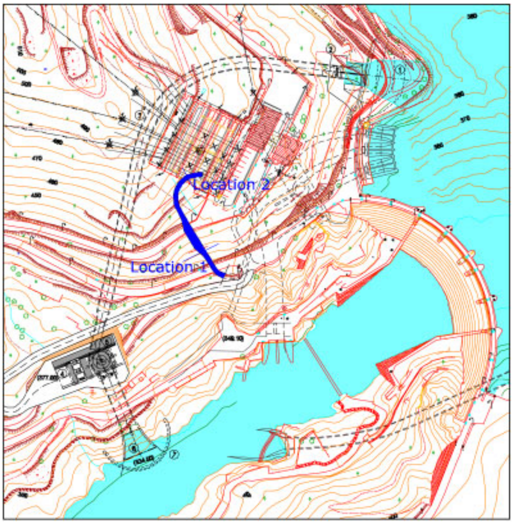

Figure 4. Layout of the Bemposta II re-powering scheme.

3.2 *Bemposta II re-powering scheme*

The Bemposta II hydroelectric scheme lies downstream from Picote II on the Douro River. The re-powering project includes a new hydraulic circuit and a new powerhouse, which is an 80 m high and 30 m diameter shaft.

Test measurements for design of the excavations took advantage of the existence of adits used during construction of the existing powerhouse. In one of these adits, two locations were selected (Figure 4):

- location 1, at the river bed level, at a depth of 95 m, 120 m from the river axis;
- location 2, at a level 20 m higher than location 1, at a depth of 130 m, 225 m from the river axis.

The adit cross section at location 1 is normal to the river and at location 2 is parallel to the river.

At location 1, three small flat jack tests were performed on the adit wall and three overcoring tests were performed in a borehole STT1, perpendicular to the adit wall and dipping 45°. At location 2, three flat jack and two overcoring tests were performed. Borehole STT2 for the overcoring tests was also perpendicular to the wall and dipped 45°.

The main factor that affects the in situ stress distribution within the rock mass is the topography of the river valley. Besides, the tests were done close to the adit, which affects the local stress field. Furthermore, two different types of tests were used and they were performed at two distinct locations. Estimation of the stress field for design of the underground openings requires, therefore, a global interpretation model that integrates all the information.

The global interpretation method presented in section 2 was used for calculation of the in situ stresses, with the following additional assumptions:

- the rock mass is continuous, linear elastic, homogeneous and isotropic, with $\gamma = 27\,\mathrm{kN/m^3}$;
- the initial in situ stress corresponds to the situation before excavation of the river valley.

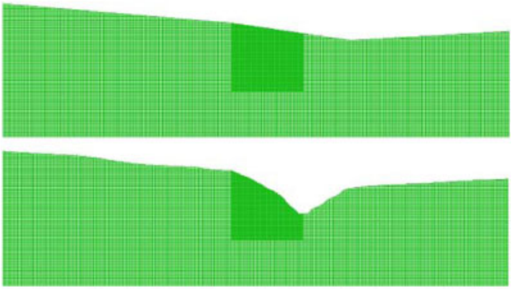

Figure 5. Numerical model (2D) with the terrain topography before and after the river eroding effect.

For modelling this situation a 3D numerical model is necessary. However a global 3D model would be very large and difficult to handle. To overcome this problem, a methodology similar to the one used by Wittke (1990) was implemented.

In a first stage, a 2D numerical model with plane strain conditions was built with FLAC. Figure 5 shows the grid with the ground topography before and after the excavations of the valley by the river. Opening of the adit in location 2 was also simulated. The grid was more refined close to the river bank in the zone where the tests were performed.

This 2D model allowed calculating the stress components at the measurement points in location 2, but not in location 1, due to the adit orientation at that location. A second numerical model had to be built for this purpose. It is a $100 \times 100\,\mathrm{m}^2$ 3D model using FLAC3D (Itasca 2006), with a unit width, centred at the adit in location 1. Grid blocks are $0.5 \times 0.5 \times 1\,\mathrm{m}^3$ and the approximate shape of the adit is also modelled (Figure 6). The stresses applied on the boundary of this model were the stresses resulting from the application of each of the loading cases E_i in the 2D model. With this 3D model the stress components at the measurement points in location 1 were calculated.

Application of this procedure to the tests carried out for the Bemposta II project, gave the following results: $k_1 = 0.60$ $k_2 = 0.91$ and $k_3 = 0.75$. This corresponds to an initial vertical stress nearly equal to the weight of the overburden, and smaller horizontal stresses, 1.5 times lower than the vertical stresses. With these values, it is then possible, to estimate the state of stress at any location in the rock mass, namely around the shaft of the new powerhouse. This is presented in Figure 7, which displays the end result of the global interpretation model.

3.3 *Salamonde II re-powering scheme*

The Salamonde II hydroelectric scheme is located on the Rabagão River in the north of Portugal. The re-powering project includes a new hydraulic circuit and a new underground powerhouse.

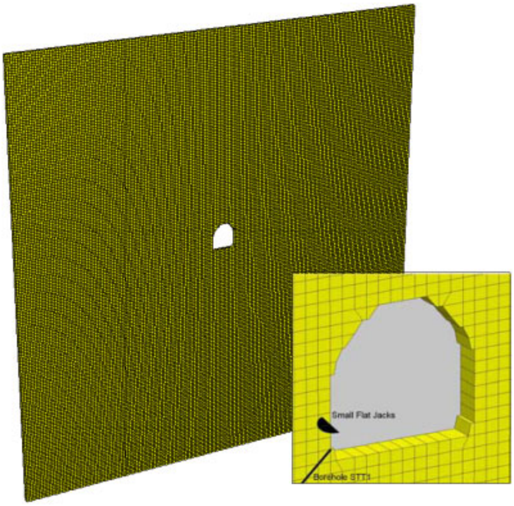

Figure 6. Numerical model (3D) with the adit near location 1.

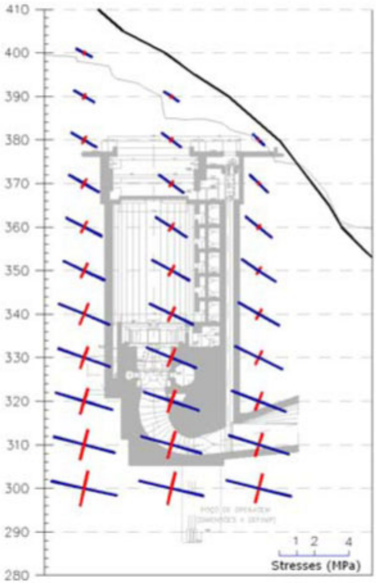

Figure 7. State of stress along the direction perpendicular to the river around the new powerhouse.

Test measurements for design of the excavations took advantage of the caverns of the existing powerhouse. Six STT overcoring tests were performed from 2 boreholes: S8 at the ground surface, and S13 at the existing valve chamber (Figure 8). In each borehole 3 tests were performed.

The main factor that affects the in situ stress distribution within the rock mass is, in this case, the existence of the old powerhouse cavern. In this example the topography of the river valley was not considered of particular relevance.

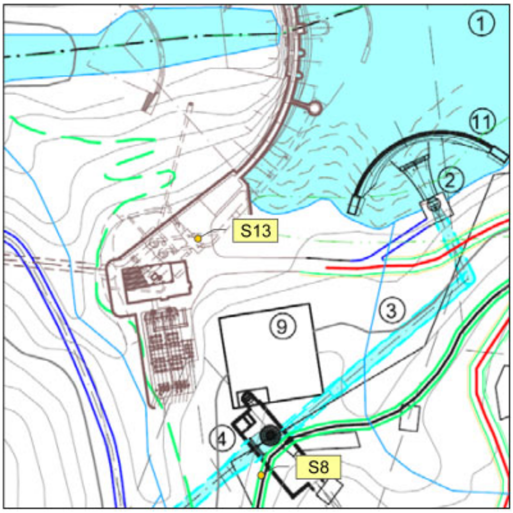

Figure 8. Layout of the Salamonde II re-powering scheme.

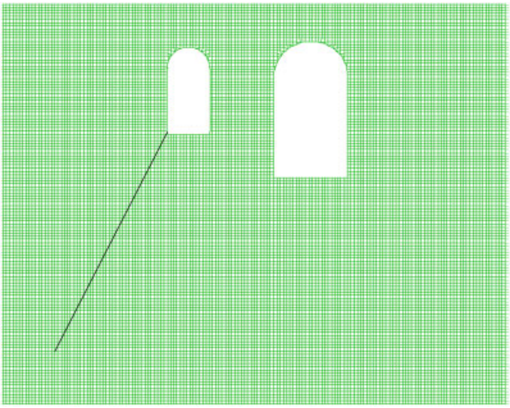

Figure 9. Mesh detail and location of borehole S13.

The global interpretation method presented in section 2 was used for calculation of the in situ stresses, with the following additional assumptions:

- the rock mass is continuous, linear elastic, homogeneous and isotropic, with $\gamma = 27\,\mathrm{kN/m^3}$;
- the initial in situ stress corresponds to the situation before excavation of the existing powerhouse caverns;
- plane strain conditions.

For interpretation of the three tests of borehole S13 a 2D mathematical model was used, that represents a cross section of the existing powerhouse caverns. Figure 9 shows the FLAC mesh, where these caverns and borehole S13 are represented.

Application of this procedure to the tests carried out in borehole S13 of the Salamonde II project, gave the following results: $k_1 = 0.90$ $k_2 = 1.43$ and $k_3 = 1.05$. The high vertical stresses that were calculated (1.43 times the overburden weight) may be due to the vicinity of the river valley, which was not considered in the model. The horizontal stresses are around 1.5 times lower than the vertical stress.

4 CONCLUDING REMARKS

The in situ stress is a parameter of great importance for the design of underground openings, but it is at the same time very difficult to estimate. This difficulty has to do with several sources of uncertainty that affect its estimation.

On one hand, the available measuring devices and methods have their own inherent measuring uncertainties. On the other hand, the measured quantities are often not stresses, but strains, displacements or other quantities. Transformation models that yield stresses based on the measured quantities and on a set of assumptions regarding stress-strain relationships, test geometry and others, also add uncertainty into the stress measurement results. Finally, spatial variability is an unavoidable characteristic of the state of stress in rock masses and corresponds to another major source of uncertainty in the in situ stress estimation.

A methodology using a global model that integrates the results of stress measurements obtained by several methods, in different locations, in zones with stress fields that are disturbed by nearby excavations, was presented. This methodology incorporates assumptions regarding the stress field, which may be found reasonable approximations of reality, as well as prior knowledge. Heterogeneity of the rock mass can also be considered.

The application examples demonstrate the importance of using a global interpretation model in the averaging of the results of a set of in situ stress measurements. The variability of the stress field and the uncertainties that affect its estimation makes it very hard to interpret individual measurements and, when this is done, the possibility of obtaining erroneous estimates of the stress field is very high. On the contrary, use of a global interpretation model in the application examples that were presented, resulted in the estimation of stress fields that can be directly used for design purposes.

The in situ stress testing programme should be prepared having in mind the global interpretation model deemed adequate for each project. The tests should be located in such places that allow to capture important features of the stress field variation and should also have in mind the numerical model that will be used for the analysis of the results.

Sometimes, only long and expensive boreholes are able to reach the rock mass around an underground excavation, but in other cases depth may make them unfeasible. These difficulties may be overcome by performing additional tests as soon as exploratory or access adits reach the zone of interest, namely using direct measurements such as flat jack tests, and in this way update the values of the stress field.

The number of in situ tests performed during the site characterization stage to support the design is often very scarce. This was also the case of the examples presented. As a consequence, it is usually impossible to make any statistical inference about stress variability. Thus, the values of the in situ stresses to be used in design should be carefully defined and it is advisable to use available mean results and to perform judicious sensitivity analysis.

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REFERENCES

Amadei, B. & Stephansson, O. (1997) *Rock stress and its measurements*, Chapman and Hall Publication, London.

Cornet, F.H. (1993). Stress in rock and rock masses. *Comprehensive Rock Engineering*, Vol. 3, (Hudson, J., ed.). Pergamon Press, Oxford, pp. 297–327.

Fairhurst, C. (2003). Stress estimation in rock: a brief history and review. *International Journal of Rock Mechanics and Mining Sciences*, Vol. 40, pp. 957–973.

Itasca (2005). *FLAC, Version 5.0, User's Manual*. Itasca Consulting Group, Minneapolis, USA,

Itasca (2006). *FLAC3D, Version 3.1, User's Manual*. Itasca Consulting Group, Minneapolis, USA.

Hudson, J.A., Cornet, F.H. & Christiansson, R. (2003). ISRM Suggested methods for rock stress estimation – Part 1: Strategy for rock stress estimation. *Int. Journal of Rock Mechanics and Mining Sciences*, Vol. 40, pp. 991–998.

Ljunggren, C., Chang, Y., Janson, T. & Christianson, R. (2003). An overview of rock stress measurement methods. *Int. Journal of Rock Mechanics and Mining Sciences*, Vol. 40, pp. 975–989.

LNEC (2006). *Tests for the geomechanical characterisation of the rock mass of the new Picote powerhouse* (in Portuguese). Report 71/06-NFOS, LNEC, Lisbon.

LNEC (2008). *Tests for the geomechanical characterisation of the rock mass of the new Bemposta powerhouse* (in Portuguese). Report 296/08-NFOS, LNEC, Lisbon.

LNEC (2009). *Repowering of Salamonde. Overcoring tests for determination of the state of stress* (in Portuguese). Report 406/09-NFOS, Lisbon.

Pinto, J.L. (1983). *Deformability of rock masses* (in Portuguese). Research Programme, LNEC, Lisbon.

Sousa, L.R., Martins, C.S., & Lamas, L.N. (1986). Development of the techniques of measurement and interpretation of the state of stress in rock masses. *Proceedings of the IAEG Int. Congress*, Buenos Aires.

Wittke, W. (1990). *Rock Mechanics: Theory and applications with case histories*. Springer-Verlag, Berlin, Heidelberg, New York, Tokyo.