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In Situ Stress Field Estimation for Underground Structures Design

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SUMMARY: The paper introduces and presents instances of application of methodologies for analysis of the stress field obtained from the results of in situ stress measurements using the overcoring, hydraulic fracturing and flat jacks methods. These methodologies integrate all stress measurements, and use numerical models of the rock mass that represent the ground topography and the underground excavations, so that the most likely stress field in the zone of interest for the design of several large underground structures is obtained.

KEYWORDS: state of stress, in situ tests, underground structures

1 INTRODUCTION

Estimation of the stress field in a rock mass from in situ tests results is not an easy task. On one hand, all testing methods have limitations, inherent to its nature, and assumptions such as verticality of one principal stress or the rock mass linear elastic behaviour. On the other hand, the stress field presents significant spatial variability, influenced by ground topography, existing excavations, rock mass heterogeneity, tectonic forces, or time dependent effects (Figueiredo et al., 2012). However, release of the in situ stresses is often the most relevant action for design of underground structures, and the magnitude and the direction of the stresses can influence the location and orientation of a cavern, the support design and the excavation method. Therefore, characterization of the state of stress calls for in situ tests using the most appropriate test techniques for each situation and a global interpretation model for analysis and integration of their results, so that reliable initial stress values are provided to the designer.

Several stress measurement programmes took place in the last decade for design of large underground powerhouse caverns in the North of Portugal, requested by the owner (EDP – Energies of Portugal). This paper summarises the testing methods that were used, relevant aspects of the testing programmes, the analysis of the results and the main conclusions.

2 TESTING METHODS

Overcoring tests are a complete stress release method that allows determining all stress components at a given location in a borehole. LNEC's STT cells that were used are 2 mm thick epoxy resin hollow cylinders with 10 embedded strain gauges. The cell is cemented in a 37 mm diameter borehole and the in situ stresses are released by overcoring with a larger diameter. Strains are measured during overcoring and the stresses are calculated using the elastic constants obtained in a biaxial test of the recovered core with the cell. Figure 1 presents an STT cell and a diagram with the typical evolution of the measured strains during the overcoring process.

The flat jack method is based on partial stress release. LNEC's SFJ test consists in cutting a 10 mm slot in a rock 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 reverted. A single stress component is obtained. Usually several tests in slots with different orientations are performed (Figure 2).

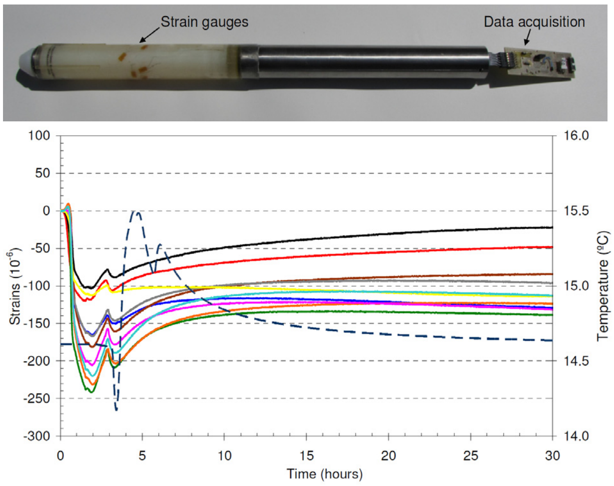


Figure 1. Overcoring cell and typical test results.

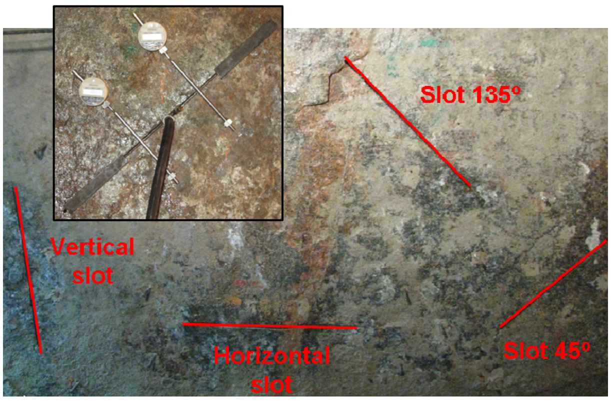


Figure 2. Flat jack array of slots and instrumentation.

Overcoring tests are used when the zones of interest can only be reached with boreholes, in most cases during the geotechnical exploration programme. Flat jack tests require direct access to rock mass surfaces and are usually performed when zones in the vicinity of the caverns are reached during construction. Often their goal is to confirm previous stress field estimates.

Two types of hydraulic tests were performed by the University of Strasbourg, together with LNEC's overcoring and flat jack tests, for design of a 500 m deep cavern (Figueiredo, 2013): hydraulic fracturing (HF), where fractures were induced in the rock by applying water pressure in a borehole section, isolated by packers (Figure 3), and hydraulic tests on pre-existing fractures (HPTF), where an isolated existing fracture, located in a borehole section, is opened by applying water pressure.

Figure 4 shows the insertion of the hydraulic fracturing equipment in a borehole and an electrical image of a tested fracture.

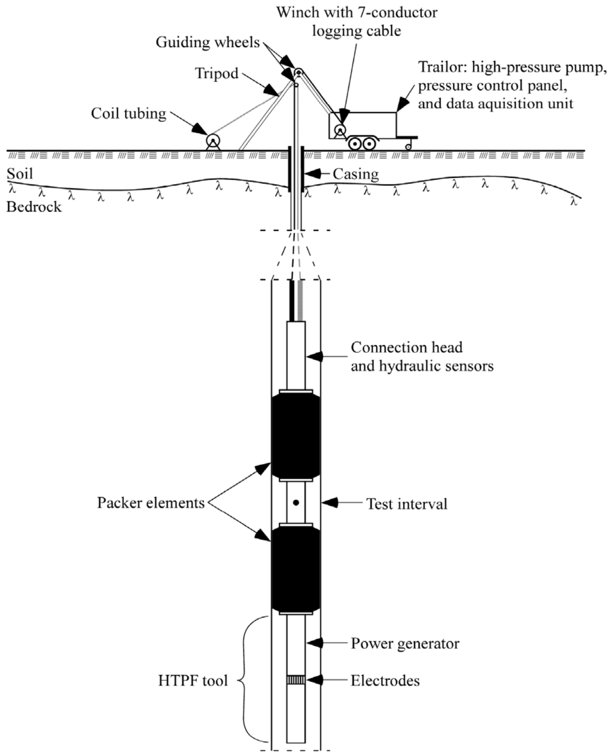


Figure 3. Hydraulic fracturing device.

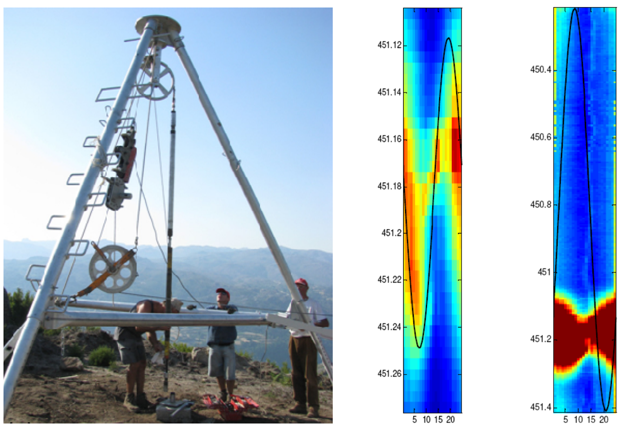


Figure 4. Hydraulic fracturing equipment and image of a tested fracture.

3 STRESS STATE GLOBAL ANALYSIS

The number of tests performed for in situ stress determination is usually scarce and they only allow characterizing the stress state in the locations where they are executed. After interpretation of the results of each individual test, it is useful to apply global interpretation models. They integrate the results from tests in different locations and consider the influence of the main factors that affect the stress field in the rock mass: significant topographic changes, such as the excavation of a deep canyon by a river, or existence of underground excavations in the area of interest, as well as the variability of the rock mass mechanical properties.

Global interpretation models use a number of assumptions, in order to obtain the natural stress field to be used in design. It is common to consider that stresses increase linearly with depth, since they are, in a large proportion, due to the weight of the overburden. Moreover, based on the geometric conditions of a given problem, it may be reasonable to predefine one or the three principal stresses directions.

The global interpretation model used in the analyses presented in this paper (Lamas *et al.*, 2010) is based on the assumption that the components of the initial stress field, σ_j^0 (where j that takes values from 1 to 6), prior to the disturbance caused by significant topographic changes or existing excavations, vary linearly with the depth: $\sigma_j^0 = k_j \gamma h$, where γ is the rock mass unit weight and h is the depth.

The natural stresses in the zone of interest are calculated from the initial stresses, using analytical solutions in simple problems or 2D and 3D numerical models in complex cases.

The parameters k_j 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:

- A vector M_i is assembled with all the N measured stress components.
- Six separate loading cases, E_j, corresponding to the six initial stress components, σ_j^0, with unit k_j values, are applied separately in the rock mass model and the stress components at the measuring points are calculated (6 for each overcoring and 1 for each flat jack test).
- A matrix A_{ij} is assembled, which represents the N stress components at the different measuring points, for each loading case E_j.
- Using the superposition principle, the following expression can, then, be written:

$$\sum A_{ij}\, k_j = M_i \quad (i = 1,\ldots,N) \quad (j = 1,\ldots,6) \qquad (1)$$

This system of linear equations is usually highly redundant and can be solved by the least squares method, thus obtaining the six k_j values. It is then possible to calculate the most probable natural in situ state of stress at any point of the rock mass, σ_m, with the following equation:

$$\sigma_m = \sum k_j \sigma_{mj} \quad (m = 1,\ldots,6) \quad (j = 1,\ldots,6) \qquad (2)$$

4 PICOTE II CAVERN

The Picote II hydroelectric repowering scheme, on the Douro River, includes a power conduit and a powerhouse cavern (68 m long, 23 m wide, 58 m high), located 150 m below the surface, in granite rock mass (Figure 5).

For characterizing the natural in situ stress field the geotechnical investigation included six overcoring tests in two parallel boreholes, inclined at 70º, drilled from an existing adit. The test results showed that one principal stress had the direction of the borehole and the other two were nearly parallel and normal to the river axis. The stress levels were considerably higher than expected for the local rock overburden.

In this case, the main factor affecting the in situ stress distribution in the rock mass is the topography of the steep river valley. For the global interpretation of the stress measurements 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 powerhouse, approximately perpendicular to the river and parallel to the boreholes. The mesh around the powerhouse cavern location has 2.50 m×1.75 m zones (Figure 6).

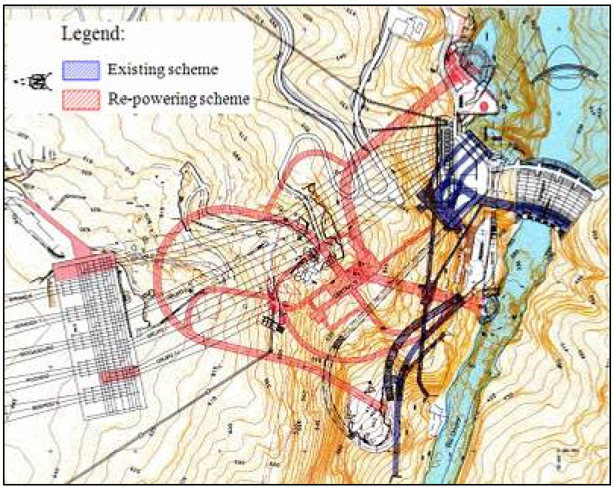


Figure 5. Layout of the Picote II scheme (in red).

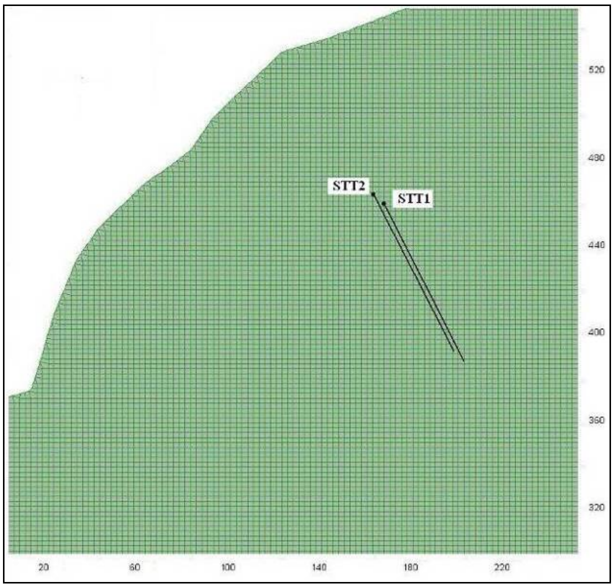
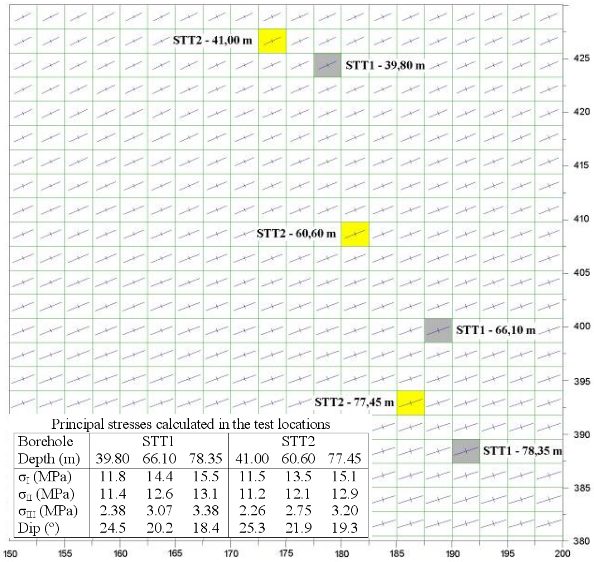


Figure 6. Mesh detail and location of the boreholes.

Based on the analysis of the model results, recommendations regarding the state of stress to be considered in the cavern design were: i) the natural 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 ground and with isotropic horizontal stresses equal to 1.75 times the vertical stress; ii) this initial stresses should be considered for simulation of the valley excavation due to the erosive action of the river, and iii) the resulting natural state of stress should be used for the powerhouse design.

Since this analysis led to high horizontal stresses, it was decided to perform additional stress measurements (Figure 7), using the flat jack method, once the adits' excavation reached the proximity of the powerhouse. These tests confirmed the high horizontal stresses (nearly four times the vertical stresses), thus confirming the results obtained in the earlier stages.



Principal stresses calculated in the test locations

Borehole	STT1			STT2		
Depth (m)	39.80	66.10	78.35	41.00	60.60	77.45
σ_I (MPa)	11.8	14.4	15.5	11.5	13.5	15.1
σ_{II} (MPa)	11.4	12.6	13.1	11.2	12.1	12.9
σ_{III} (MPa)	2.38	3.07	3.38	2.26	2.75	3.20
Dip (°)	24.5	20.2	18.4	25.3	21.9	19.3

Figure 7. Stresses calculated in the test locations.

5 BEMPOSTA II SHAFT

The Bemposta II hydroelectric scheme lies downstream from Picote II, on the Douro River. The re-powering project includes a new powerhouse installed in a 80 m high and 30 m diameter shaft. Stress measurements for design took advantage of the existence of adits used for construction of the original powerhouse. Two locations were selected (Figure 8): location 1, at the river bed level, at a depth of 95 m, 120 m from the river axis; location 2, 20 m above 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.

The following tests were done: at location 1, three flat jack tests on the wall and three overcoring tests in a borehole normal to the adit wall, dipping 45º; at location 2, three flat jack tests on the wall and two overcoring tests in a borehole normal to the wall, dipping 45º.

The main factor affecting the in situ stress distribution in the rock mass is the topography of the river valley. Besides, the tests were done close to the adit, which locally disturbs the stress field. Moreover, two different types of tests were used and they were performed at two distinct locations. Estimation of the stress field required, therefore, a 3D global interpretation model to integrate all these data.

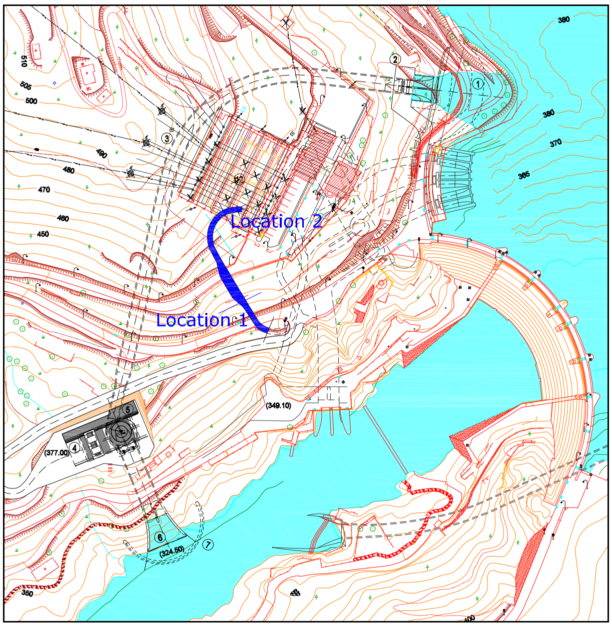


Figure 8. Layout of the Bemposta II re-powering scheme.

In a first stage, a 2D numerical model in plane strain was built with FLAC. Figure 9 shows the grid with the 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, where the tests were performed.

With this 2D model it was possible to calculate the stresses at the measurement points in location 2, but not in location 1, due to the adit orientation. A second numerical model had to be built for this purpose. It is a 100×100 m^2 3D model using FLAC3D (Itasca, 2006), with a unit width, centred at the adit in location 1. Grid blocks are 0.5×0.5×1 m^3 and the approximate shape of the adit was also modelled (Figure 10). Stresses resulting from application of each of the loading cases, E_j, in the 2D model were applied at the boundary of the 3D model, thus enabling the calculation of the stresses in the measurement points at location 1.

Application of this procedure to the stress measurements carried out for Bemposta II, allowed 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 11, which displays the end results of the application of the global model.

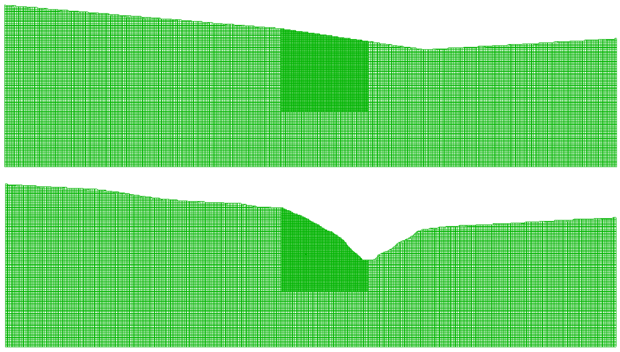


Figure 9. Numerical model (2D) with the ground topography before and after the river eroding effect

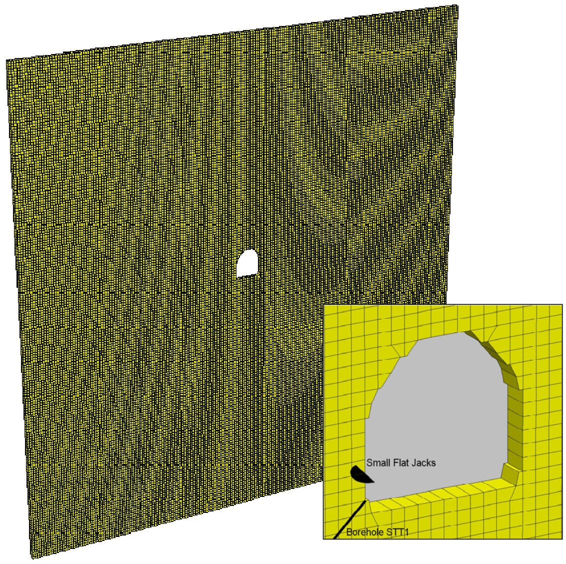


Figure 10. Numerical model with the adit near location 1.

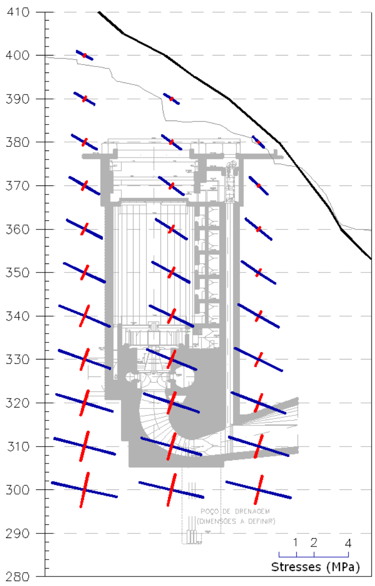


Figure 11. Natural state of stress in the zone of the new powerhouse, in a vertical plan normal to the river.

6 PARADELA II SITE

The planned Paradela II reversible hydroelectric scheme, on the Cávado River, has a 10 km long power conduit, with a powerhouse located halfway in the conduit, at the depth of 500 m, in a good quality granite rock mass (Figure 12).

Stress measurements were carried out by overcoring in two vertical boreholes, drilled from an existing adit, at test depths from 160 m to 250 m. For determination of the stress field down to the depth of interest, the University of Strasbourg, with LNEC's support, carried out HF and HPTF hydraulic tests in two 500 m deep boreholes. The location of both types of tests is indicated in Figure 12. Exploration of the results of all the tests performed at this site resulted in a doctoral thesis (Figueiredo, 2013).

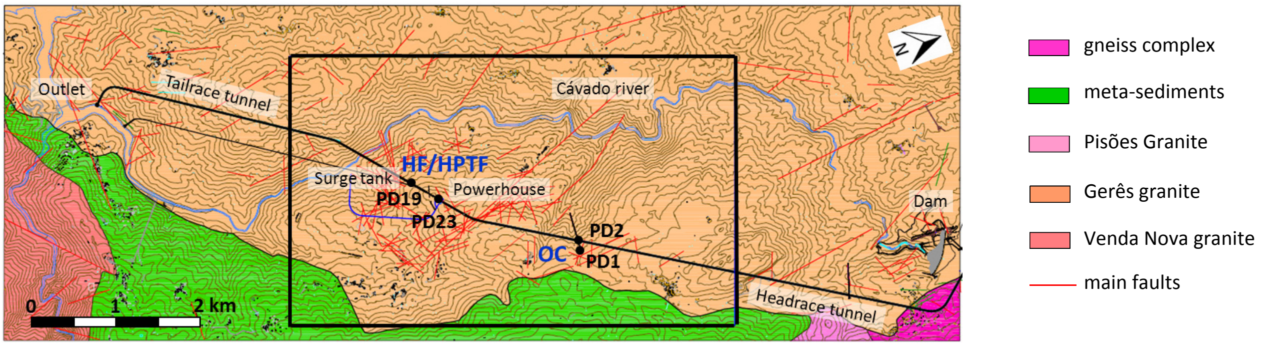


Figure 12. Layout of the Paradela II scheme with the location of the overcoring and hydraulic tests.

A very large FLAC3D model (Figure 13), was used to model the topography of this mountainous region, in order to calculate the gravitational stresses at the test locations and to compare them with the measured stress values.

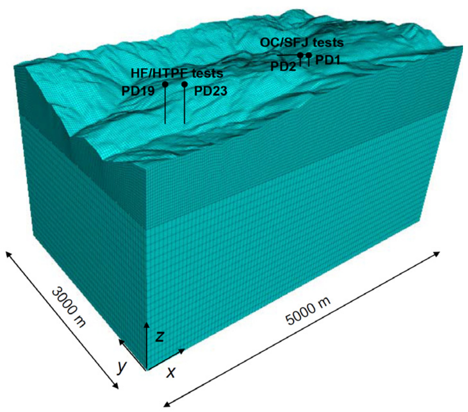


Figure 13. Global perspective of the Paradela II model.

A discrepancy was found in the horizontal stresses, which are much higher in nature than the results of the model. Several possible explanations, such as tectonic forces, rock mass heterogeneities and time dependent effects, were investigated. The latter were found to produce a good fit between the calculated and measured stresses, considering a Maxwell viscoelastic behaviour for the rock mass. Since the rock mass was modelled as a linear elastic, homogeneous medium, this viscoelastic behaviour was simulated by increasing the Poisson's ratio. In this case, the "equivalent" Poisson's ratio that gave the best fit was 0.47.

Figure 14 presents the variation with depth of the normal stresses measured in the fractures where hydraulic tests were performed and the corresponding calculated values. An inversion analysis of all hydraulic tests results produced the principal stress profiles displayed in Figure 15, where σ_I is vertical, which show a good agreement with the calculated values.

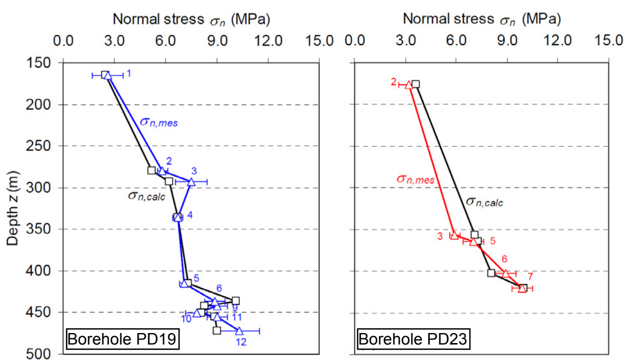


Figure 14. Normal stresses measured in hydraulic tests ($\sigma_{n,mes}$) and calculated with a viscoelastic model ($\sigma_{n,calc}$).

The calculated principal stress profiles at the location of the overcoring tests are presented in Figure 16 together with the measured values.

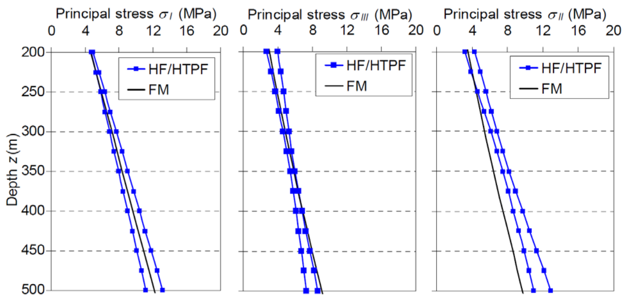


Figure 15. Stress profiles obtained from the hydraulic test results (HF/HTPF) and the viscoelastic model (FM).

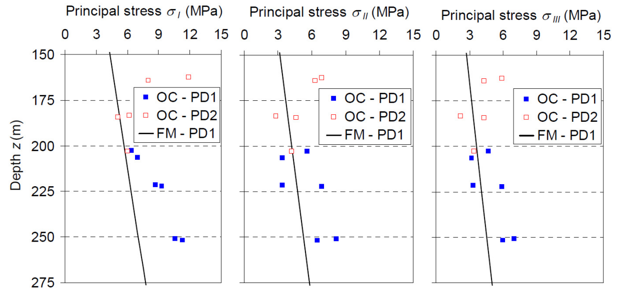


Figure 16. Stresses obtained from the overcoring test results (OC) and the viscoelastic model (FM).

With the exception of the vertical stress, σ_I, in one of the boreholes, which is often over-estimated by these tests, and of the stresses obtained close to the existing adit, the agreement between measured and calculated horizontal stresses is generally satisfactory, with differences smaller than 1.5 MPa.

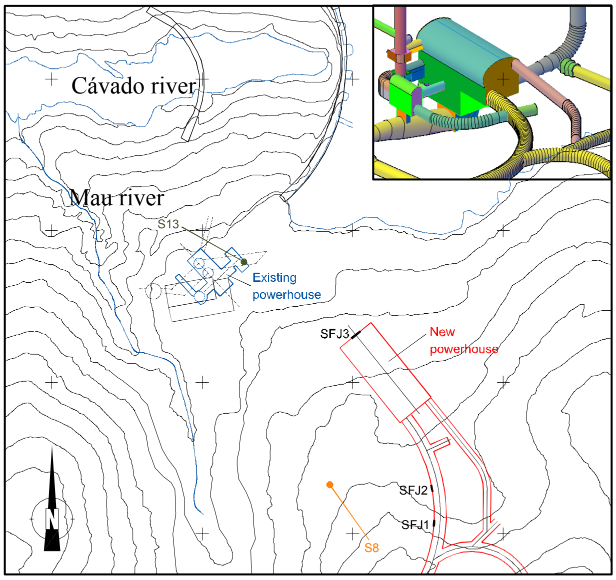


Figure 17. Layout of the Salamonde II scheme.

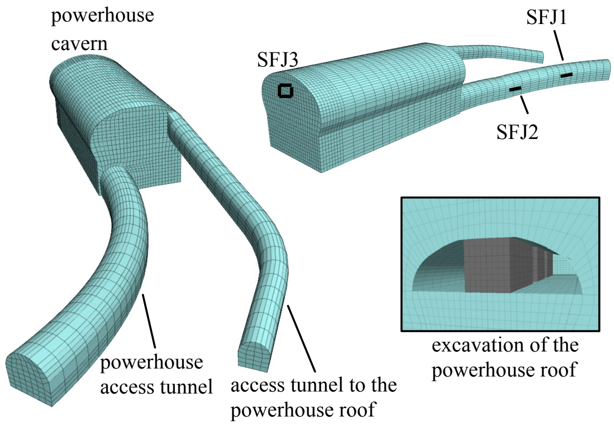


Figure 18. Perspective of the underground works.

7 SALAMONDE II CAVERN

The Salamonde II re-powering hydroelectric scheme is located on the Cávado River and includes a 2 km long power conduit and a powerhouse cavern (66 m long, 26.5 m wide, 56 m high), excavated in a good quality granite rock mass (Figure 17), at a depth of 150 m.

Before excavation started, overcoring tests were carried out in two sub-vertical boreholes (S8 and S13, shown in Figure 17) for the design of the cavern. During excavation, as soon as access to the powerhouse vicinity existed, 10 flat jack tests were performed in three locations (SFJ1, SFJ2 and SFJ3).

Figure 18 shows the two adits where flat jack tests were performed and the geometry of the early excavation stage of the powerhouse, when tests in location SFJ3 took place.

The global interpretation of all stress measurements, with consideration of the ground topography and of the existing excavations at the time when the tests were done (Espada *et al.* 2013), was carried out using a 3D numerical model built with FLAC3D (Figure 19) and the methodology presented in section 3. It was assumed that one of the initial principal stresses is vertical and corresponds to the weight of the overlying ground. The natural in situ stress field, prior to the excavations, was thus obtained superimposing four loading cases, E_j, corresponding to the three stress components in the horizontal plane and the vertical stress.

The results obtained are presented in Figure 20. The rotation of the sub-vertical principal stress is consistent with the expected influence of the Mau River (Figure 17). The larger and the smaller sub-horizontal principal stresses are normal and parallel to the direction of the Cávado river, respectively. At the level of the powerhouse they are approximately 1.3 and 0.6 times the vertical stress.

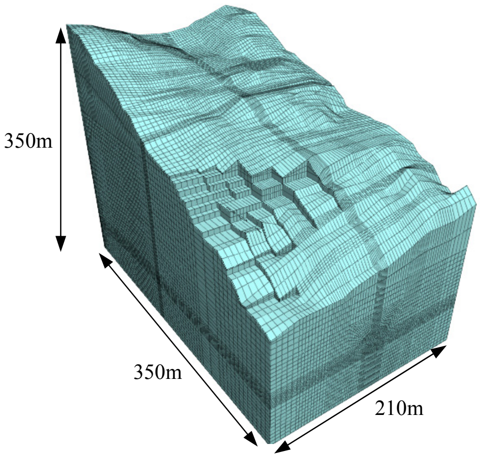


Figure 19. Global perspective of the Salamonde II model.

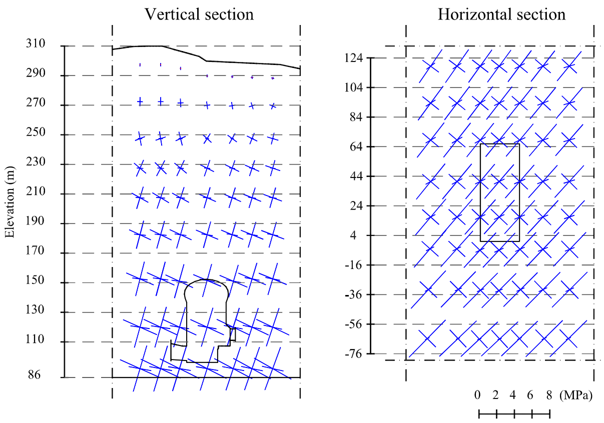


Figure 20. Natural principal stresses in the zone of the new powerhouse.

Figure 21 is a contour plot of the maximum principal stress in the upper part of the powerhouse, showing the excavation as it was during the SFJ tests. The vertical stress concentration in the rock pillars is notorious.

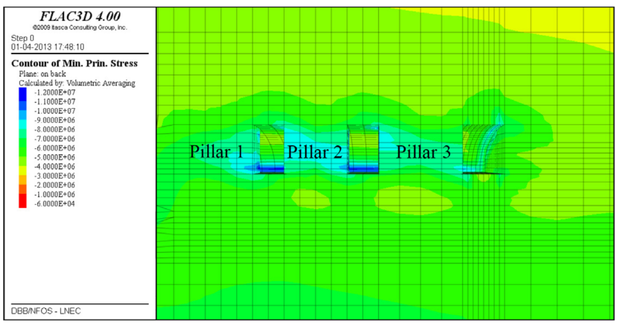


Figure 21. Contour of maximum compressive principal stress in a vertical longitudinal section in the powerhouse.

8 CONCLUSIONS

The application examples show the evolution of LNEC's experience in measuring and assessing in situ stresses and demonstrate that the use of global models for interpretation of the test results, considering the ground topography, nearby excavations and other relevant features, is essential in order to provide meaningful values for the design. On the contrary, individual test results are of little interest.

Considering the features of each project, the global interpretation model must be planned in combination with testing programme, already bearing in mind the location of the tests.

ACKNOWLEDGEMENTS

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REFERENCES

Espada, M.; Lamas, L.; Leitão, N. and Figueiredo, B. (2013) Global methodology for evaluation of the stress field in a rock mass from in situ tests. Application to the Salamonde II powerhouse cavern. In Kwasniewski and Lydzba (eds), *Rock Mechanics for Resources, Energy and Environment; Proc. EUROCK 2013,* Wroclaw: 425-430. London: Taylor & Francis.

Figueiredo, B. (2013) *Integration of in situ stress measurements in a non-elastic rock mass*, PhD thesis, University of Strasbourg, 208 p.

Figueiredo, B.; Cornet, F.H.; Lamas, L. and Muralha J. (2012). Effect of topography on distribution of in situ stresses due to gravity and tectonic loadings at Paradela site. In *Rock Engineering and Technology for Sustainable Underground Construction, Proc. EUROCK 2012, Stockholm*. Befo and ISRM.

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.

Lamas, L.; Muralha, J. and Figueiredo, B. (2010) Application of a global interpretation model for assessment of the stress field for engineering purposes. In Xie (ed.), *Rock Stress and Earthquakes*; *Proc. 5th Int. Symp. on In-Situ Rock Stress, Beijing*: 631-636. London: Taylor & Francis.