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STRESS FIELD ASSESSMENT FOR UNDERGROUND POWERHOUSES DESIGN USING GLOBAL INTERPRETATION MODELS

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Abstract. *The most relevant action in the design of underground projects is often the release of the in situ stresses that occurs during the construction stage. 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. Interpretation of test results is seldom straightforward. The paper presents a global methodology for the evaluation of the most likely natural stress field given a set of in situ test results. Some case histories are presented as application examples. The first 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 at different locations during the initial testing programme. 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. Global interpretation models are required to transform a set of point wise test results into a comprehensive stress field to be used in design analysis.*

1 INTRODUCTION

In situ stresses, or more precisely the release of the in situ stresses, are often the most relevant action to be considered in the design of an underground work. It can affect the location and orientation of the cavern or tunnel, the whole layout of the project, the design of the support, as well as the construction method used.

Several factors influence decisively the in situ stresses in rock masses and render 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[1-5], 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[6]. 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. However, it also possible to consider other types of relations that take into account different factors, such as tectonic induced stresses.

The global interpretation models used in the analyses presented in this paper are 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 with depth. Generally a linear variation is considered – $\sigma_j^0 = k_j \gamma h$, 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 remaining two are horizontal.

The existing natural stress field results from the initial stress field, characterized 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.*[7]:

– 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 three principal initial in situ stresses, with unit k_j values, is considered separately, and this corresponds to three 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 (six for each overcoring test plus one 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:

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

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 repowering projects of the Picote II, Bemposta II and Salamonde II hydroelectric projects, in the North of Portugal. These repowering 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 repowering scheme

The international stretch of the Douro River exploited has three power plants in cascade: Miranda, Picote, and Bemposta, all built in the 50 and 60 decades of the 20th century[8]. At this location the Douro valley is narrow and deep. The reservoirs have small capacities and are unable to regulate the incoming flows. These hydropower plants were originally designed for levels of turbining flows that nowadays are considered low and their repowering is now nearly completed.

The original scheme of the Picote hydropower plant consists mainly of a concrete arch dam and an underground powerhouse with a hydraulic circuit in the right bank of the river. The re-powering scheme will also be constructed in the right bank, close to and surrounding the existing power plant. Main elements are the hydraulic circuit (a 300 m long headrace tunnel and a 150 m long tailrace tunnel), an underground powerhouse cavern and several adits. Access tunnels, connections and ventilation adits total 1,700 m of linear excavation. The cables and ventilation shaft is 180 m high. The total excavation volume is 280,000 m^3.

The new powerhouse cavern is 68 m long, 23 m wide between sidewalls and 58 m high at the turbine hall and 26 m at the assembly area. The large 600 ton turbine with a 400 m^3/s capacity, conditioned the cavern width. A reinforced concrete arch roof had to be built in order to support the crane beam that handles the turbine. The cavern is located about 150 m below surface and will be built only 80 m away from the existing one (Figures 1 and 2).

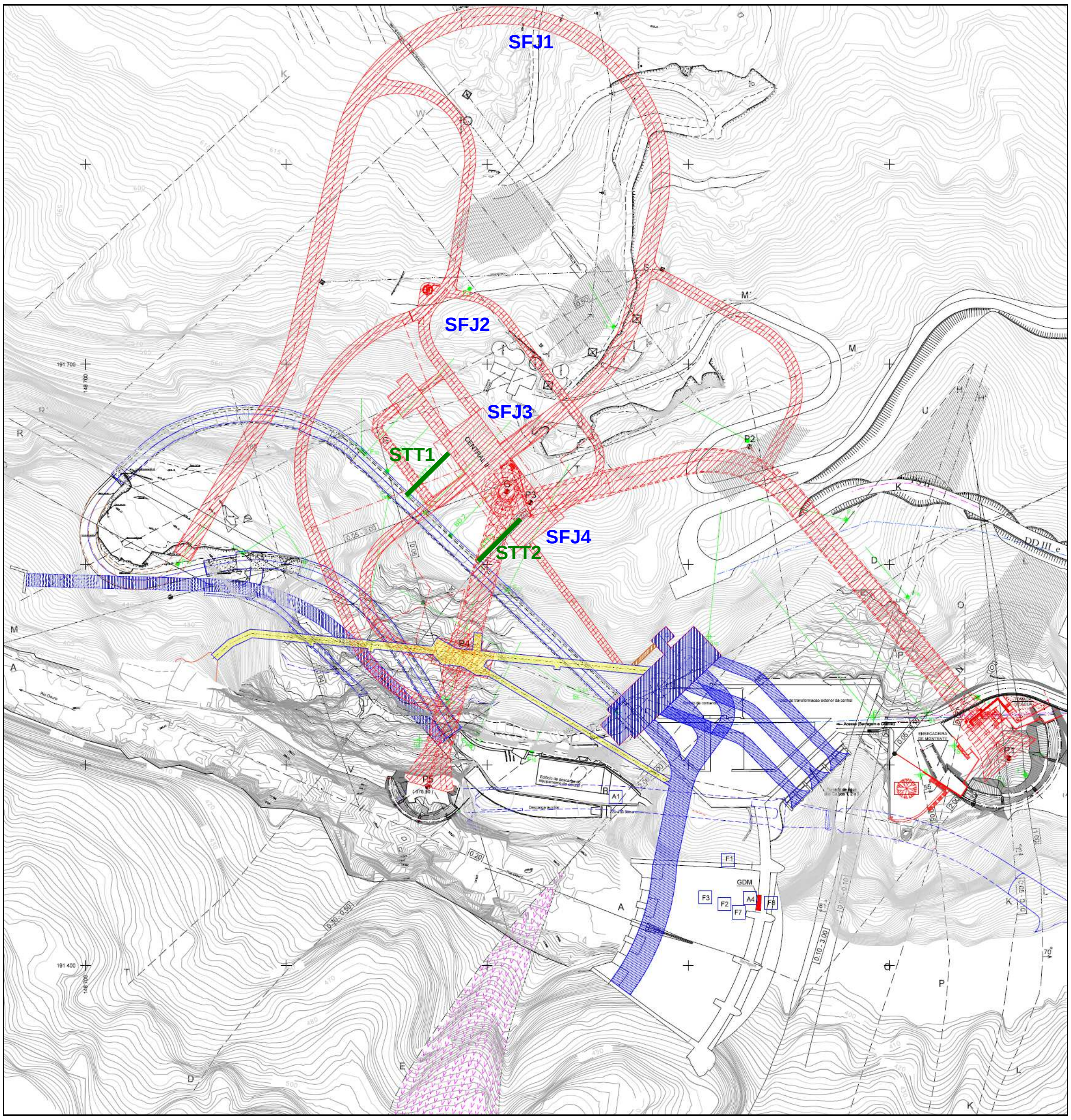

Figure 1: Layout of Picote hydroelectric scheme in blue,
and the new the Picote II repowering scheme in red

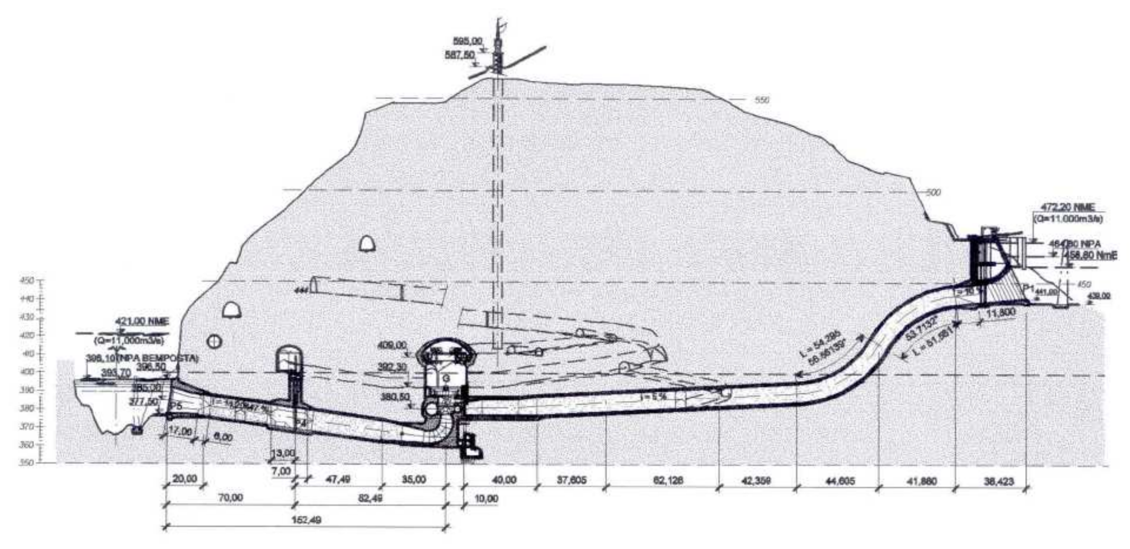

Figure 2: Underground works of Picote II repowering

The Picote hydropower plant is located in the Miranda plateau, in a zone where the Douro River flows through a valley with a canyon configuration, with almost vertical banks. The river is aligned with a WNW-ESE fault and porphyritic granite is the principal local lithology. Interpretation of geological structures was based on aerial photography, and on local observation of existing unlined adits. Most of the existing power plant excavations were carried out in a good quality rock mass.

The site characterization included analysis of geological and geotechnical information related with the design and construction of the existing hydropower plant and also with the studies conducted since the early project stages of the re-powering scheme. To study the rock mass at the new cavern location, several boreholes were drilled and an investigation programme consisting of in situ and laboratory tests was conducted by LNEC[9]. It included stress measurements by overcoring (STT) and dilatometer tests in the field, and UCS, ultra--sound velocities, brazilian, triaxial and joint shear tests in the laboratory.

Since the concrete arch structure of the roof of the powerhouse cavern is constructed before an important part of the cavern lower part benching, an important portion of the convergences is expected to load this structure. The effects of this “convergence-load” are, actually, of much more significance than the effects resulting from handling the turbine[10].

This fact justifies the importance and the need to adequately estimate the in situ state of stress. 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[8]. The boreholes are 50 m apart and dip 70º (Figure 1). 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.

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[11]. 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 3). 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.

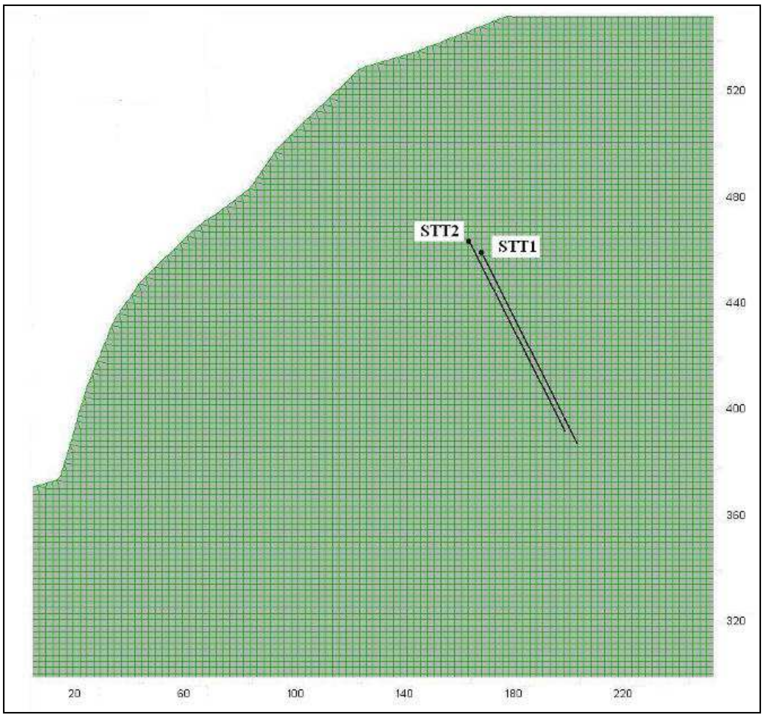

Figure 3: Mesh detail and location of the boreholes

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 γ = 27 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 4 shows the principal stresses calculated at 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[12]:

– 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.

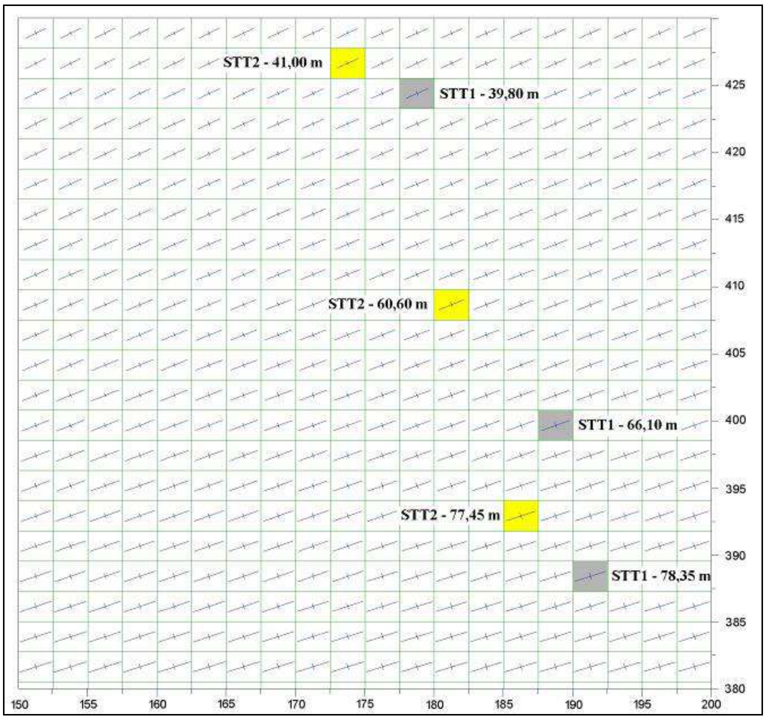

Figure 4: Stresses calculated in the overcoring test locations

– This initial in situ state of stress should be used to model the excavation of the valley due to the erosive effect of the river, and the resulting state of stress should be the starting point for the design computations of the powerhouse.

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 (SFJ) method, once excavation of the adits reached the proximity of the underground powerhouse. The locations of the SFJ tests are displayed in Figure 1 and Figure 5 presents a photo of one of the locations with the adit wall where the slots are to be cut. These tests confirmed the existence of high horizontal stresses (about four times the vertical stresses), thus confirming the results obtained in the earlier stages.

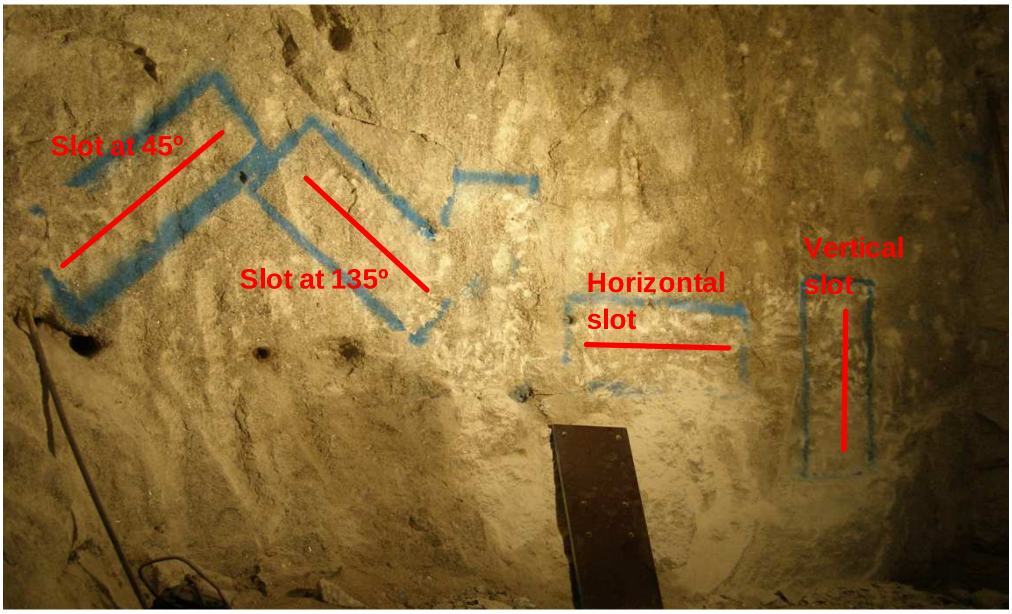

Figure 5: Location of small flat jacks tests in an adit

3.2 Bemposta II repowering scheme

The Bemposta hydroelectric scheme lays downstream from Picote on the Douro River. The repowering project aims to increase the power of the three existing Francis turbines (238 MW) with a new 193.5 MW Francis turbine. It includes a new 500 m long hydraulic circuit in the right bank of the river and a new powerhouse installed in a 80 m high and $30 \times 22\ m^2$ diameter oval shaft (Figures 6 and 7).

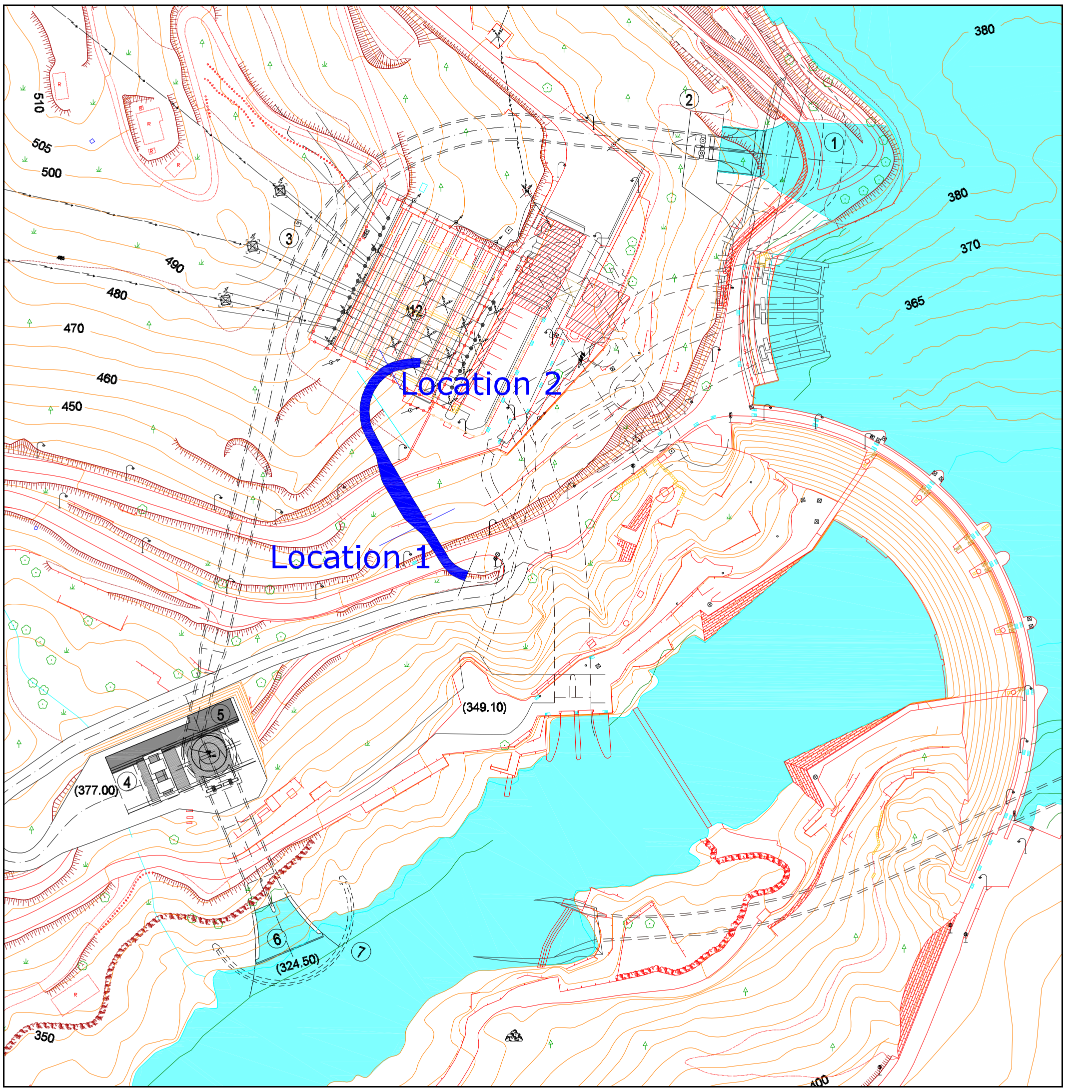

Figure 6: Layout of the Bemposta II repowering scheme

Test measurements for design of the excavations took advantage of the existence of adits used during construction of the existing powerhouse[13]. In one of these adits, two locations were selected (Figure 6):

- 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.

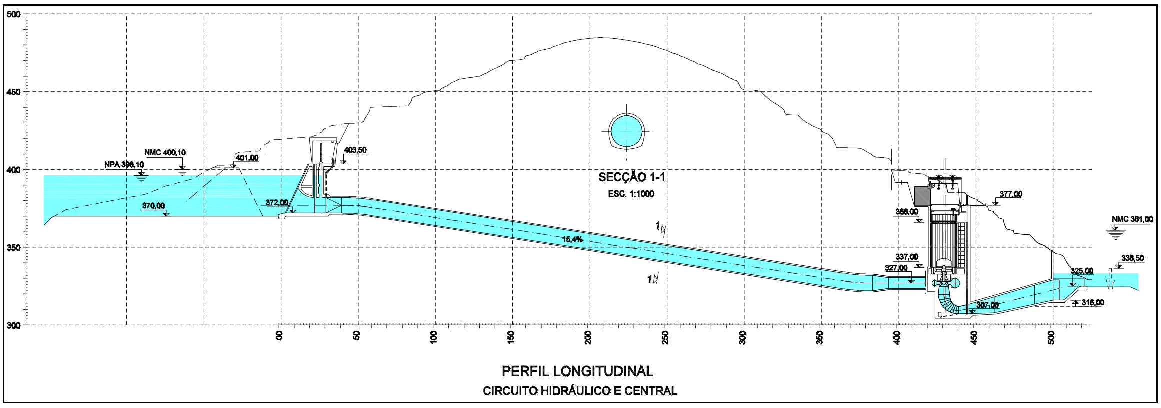

Figure 7: Layout of the Bemposta II repowering scheme

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°. Figure 8 presents both locations and the boreholes of the STT overcoring tests.

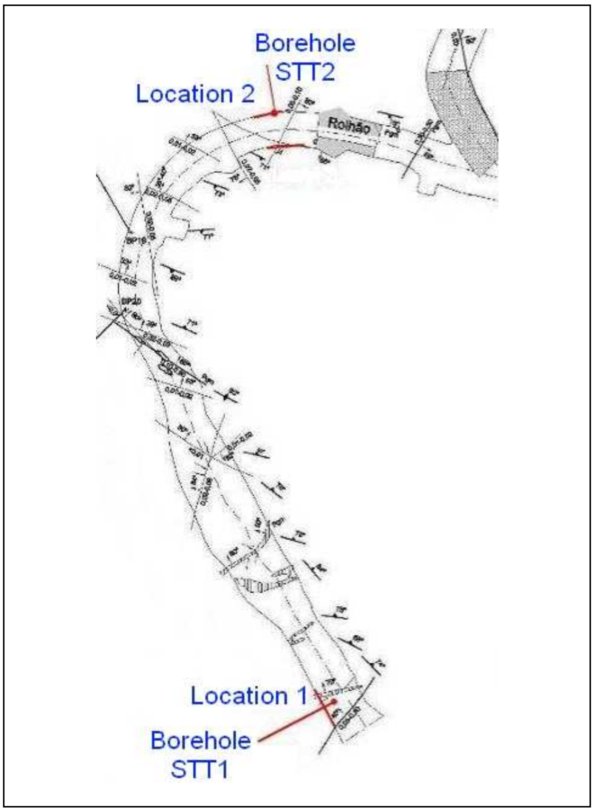

Figure 8: Locations of the smal flat jacks and overcoring tests

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 γ= 27 kN/m^3;
– the initial in situ stress corresponds to the situation before excavation of the river valley.

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[14] was implemented.

In a first stage, a 2D numerical model with plane strain conditions was built with FLAC. Figure 9 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.

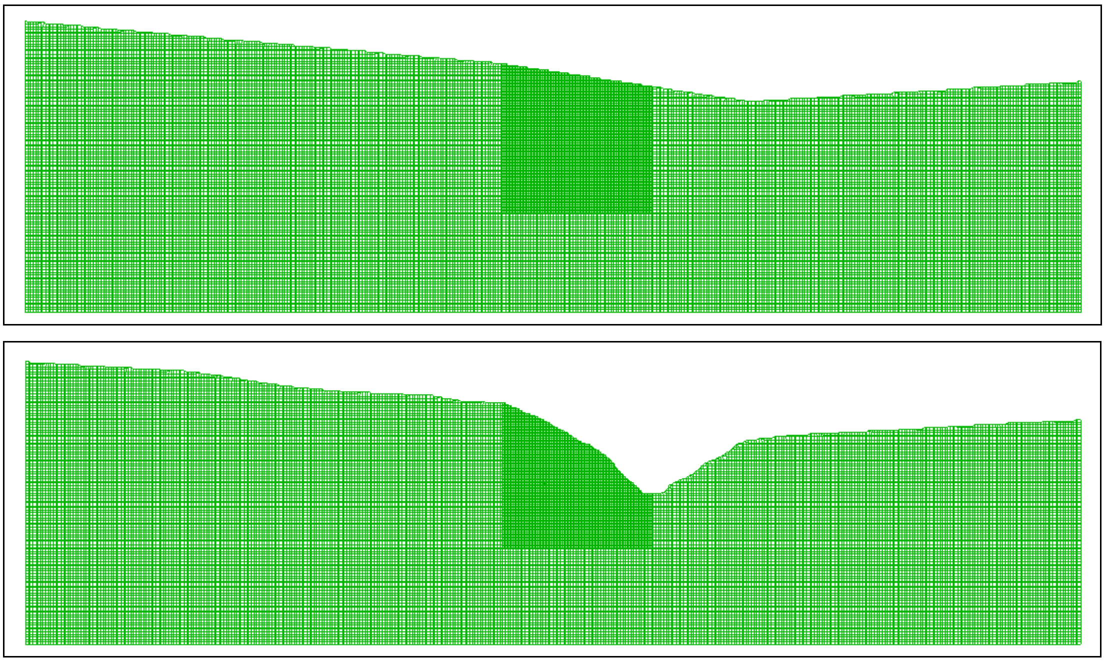

Figure 9: Numerical model (2D) with the terrain topography before and after the river eroding effect

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 100×100 m^2 3D model using FLAC3D[15], with a unit width, centered at the adit in location 1. Grid blocks are 0.5×0.5×1 m^3 and the approximate shape of the adit is also modeled (Figure 10). 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. These results are presented in Figure 11, which displays the end result of the global interpretation model that can be used in the design of the underground shaft, namely for the definition of the construction methodologies and of the primary linings and definite support.

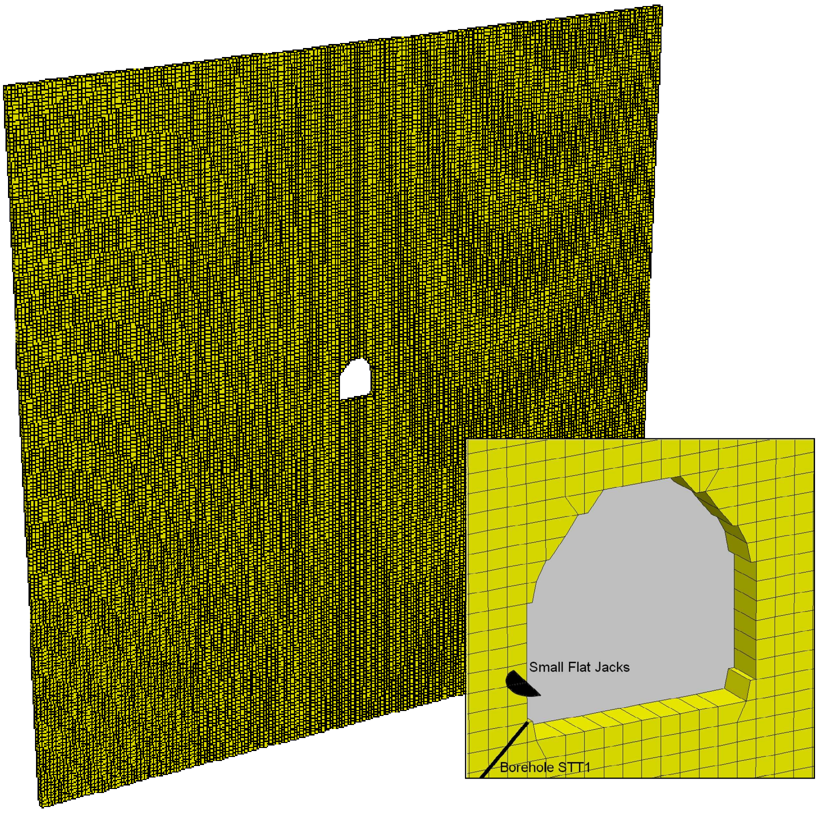

Figure 10: Numerical model (3D) with the adit at location 1

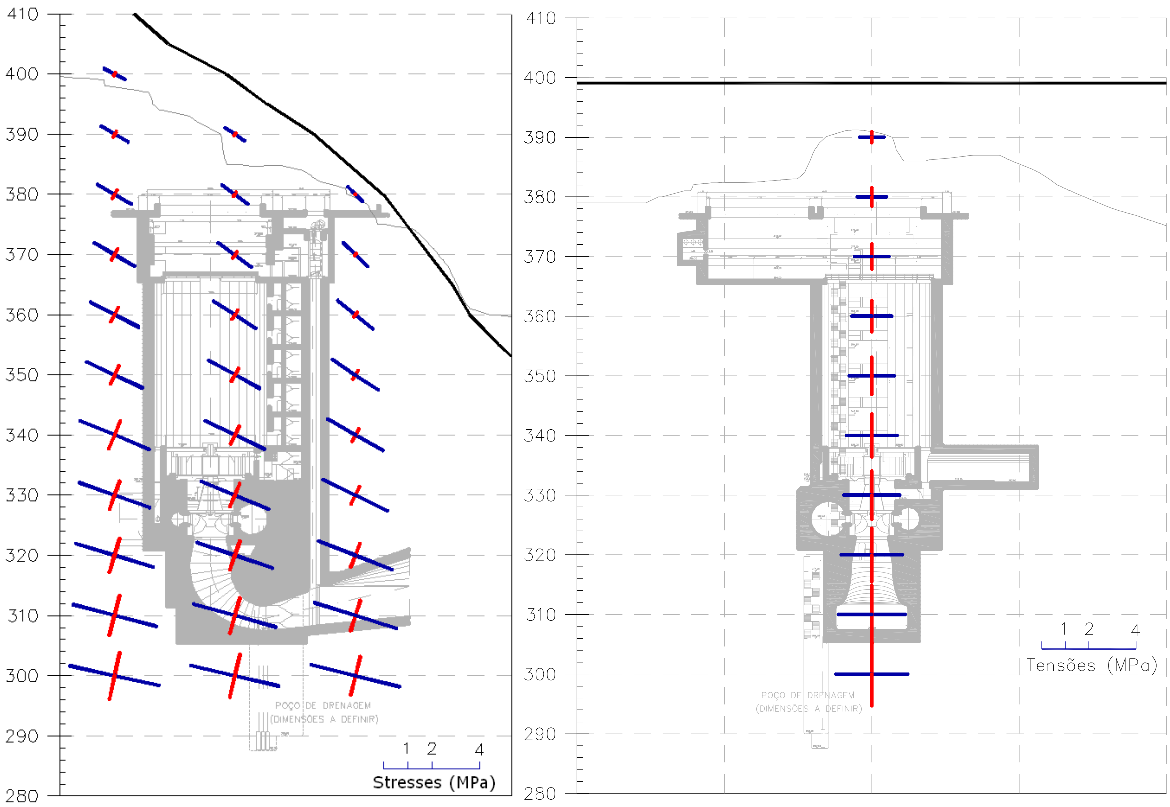

Figure 11: State of stress around the powerhouse shaft along the direction perpendicular to the river (left) and along direction parallel to the river (right)

3.3 Salamonde II repowering scheme

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

Test measurements for design of the excavations took advantage of the caverns of the existing powerhouse[16]. Six STT overcoring tests were performed from two boreholes: S8 at the ground surface, and S13 at the existing valve chamber (Figure 8). In each borehole three tests were performed.

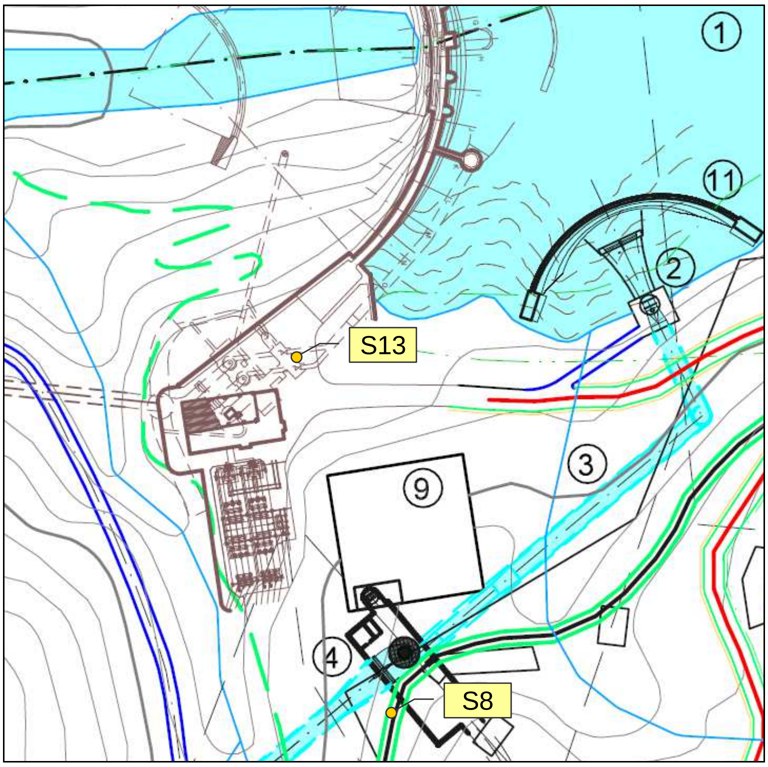

Figure 12: Layout of the Salamonde II repowering scheme

In this case, the main factor that affects the in situ stress distribution within the rock mass is the proximity of the old powerhouse cavern. In this example, location of the tests was relatively far from the surface and so topography of the river valley was not considered of particular relevance and the model just considers a horizontal topographic surface.

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 $\gamma = 27$ 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.

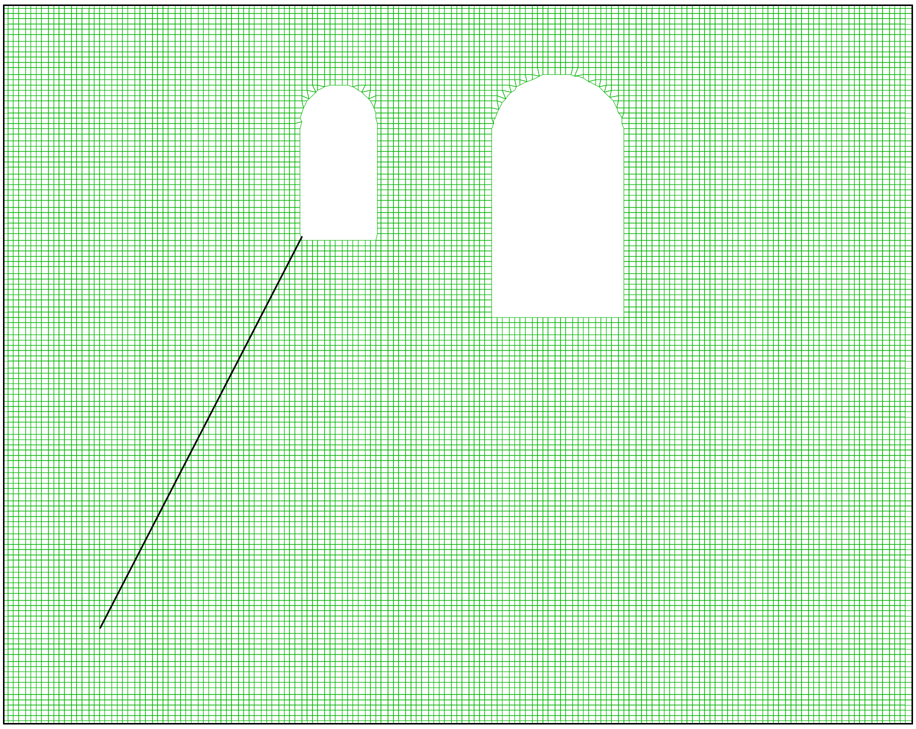

Figure 13: Mesh detail and location of borehole S13

Two analyses were performed. The first one assumes that the vertical and both horizontal initial stresses vary linearly with depth. Application of the proposed procedure with these assumptions to the tests carried out in borehole S13 of the Salamonde II project, rendered the following results: k_1 = 0.90 for the horizontal stresses in the plane of the model, k_2 = 1.43 for the vertical stresses and k_3 = 1.05 for the out of plane horizontal stresses. 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.

To try to reach a better approximation to the tests results, an additional assumption was introduced: the shear stress in the plane of the model would also increases linearly with depth. In this case, the results were only slightly different: k_1 = 0.85, k_2 = 1.46, k_3 = 1.05 and k_4 = -0.27 for the shear stresses.

A simple analysis of the deviates between the test results and the values predicted by the model shows that, in this particular case, there is no particular advantage in considering a model with more variables.

4 CONCLUDING REMARKS

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

On one hand, the available measuring equipments and techniques have their own inherent measuring uncertainties. On the other hand, the measured quantities are generally 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

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

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

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

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

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

[6] J. Loureiro Pinto, *Deformability of rock masses* (in Portuguese). Research Programme, LNEC, Lisbon (1983).

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

[8] EDP, Hydroelectric exploitation of the international strech of the river Douro – Picote – Repowering (in Portuguese). Unpublished report (2005).

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

[10] C. Esteves, N. Plasencia and C. Lima, *The application of FLAC3D on Picote II underground powerhouse*. Proc. 1st International FLAC/DEM Symposium, R.D. Hart, C.L. Detournay and P.A. Cundall (eds). Itasca Consulting Group , Minneapolis, (2008).

[11] J. Muralha, L.N. Lamas e C. Esteves, *State of stress assessment for the Picote II underground powerhouse design*. ISRM Int. Symp. Rock Characterisation, Modelling and Engineering Design Methods, SINOROCK 2009, The University of Hong Kong, China (2009).

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

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

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

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

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