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Determination of the stress field in a mountainous granite rock mass

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ABSTRACT

The design of an underground hydroelectric power scheme in northern Portugal has required the characterisation of the local stress field. Nineteen hydraulic tests have been conducted in two, 500 m deep, vertical boreholes. In addition twelve overcoring tests together with twelve flat jack tests have been performed from an existing adit located some 1.7 km away from the location of the hydraulic tests. Results have been integrated into a stress model that takes into account both topography and tectonics effects. Most of the data are consistent with a linearly elastic, gravity loaded model, provided a very soft geomaterial is considered. This implies that the stress field in this granite rock mass is controlled by gravity alone and shear stress relaxation along faults and fractures but is unaffected by present-day tectonics.

1. Introduction

The re-powering scheme of the Paradela hydroelectric infrastructure developed on the Cávado River in Northern Portugal involves a new 10 km long power conduit and a powerhouse complex located about halfway in the conduit and 500 m below ground level. It includes a new powerhouse cavern, a valves chamber and a large surge chamber with several adits. The local geological formation is mostly granite (Fig. 1).

The design of this new scheme requires a sound understanding of the regional stress field and this has prompted an *in situ* stress measurement campaign. Results have raised important questions on the relative influence of topography and regional tectonics as well as on that of the rock mass rheological characteristics. Such issues have been frequently addressed in the literature [1,2] and we describe here after results derived from a stress determination strategy somewhat similar to that proposed for the International Society of Rock Mechanics (ISRM) [3].

After identifying the objective of the stress determination campaign, we present results obtained with three different methods, namely hydraulic tests in 500 m deep boreholes as well as overcoring and flat jack tests conducted at different locations. Then we introduce the numerical model that has been developed for integrating the various measurements in order to identify an optimum solution. This model helps to discriminate the respective contributions of gravity and tectonics and provides means to determine the long-term rock mass rheological behaviour that best fits observations.

2. Stress determination campaign

2.1. Objectives and design of the campaign

The design of the underground excavations planned for hosting the new powerhouse as well as the valves and large surge system implies a complete 3D characterisation of the stress field at the location of the excavations. But the design of the 10 km long pressure tunnel requires only a sound evaluation of the minimum principal stress magnitude all along the tunnel as well as an estimate of its extreme local variations.

On site, two 500 m deep vertical boreholes (PD19 and PD23) were available in the immediate vicinity of the planned underground powerhouse. Further a horizontal adit located some 1.7 km from the vertical boreholes, with a $2.4 \times 2.0\ m^2$ rectangular cross section, was excavated some 50 years ago and provided the opportunity for further stress measurements (Figs. 1–3).

It was decided to run a combination of hydraulic fracturing (HF) tests together with hydraulic tests on pre-existing fractures (HTPF) in both vertical boreholes in order to constrain the direction and magnitude for the three principal stress components at the location of the excavation. Further the objective was also to provide data on the spatial variability of these quantities along the vertical direction.

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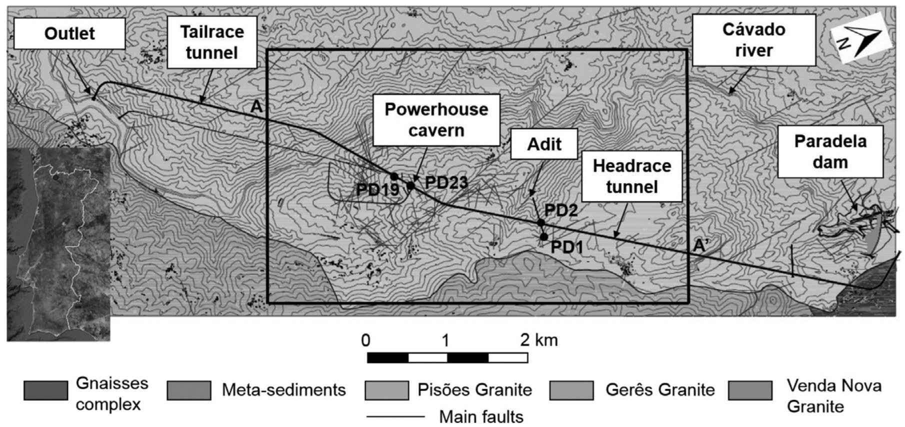

Fig. 1. Layout of the Paradela II hydroelectric repowering scheme (courtesy of Energy of Portugal-EDP).

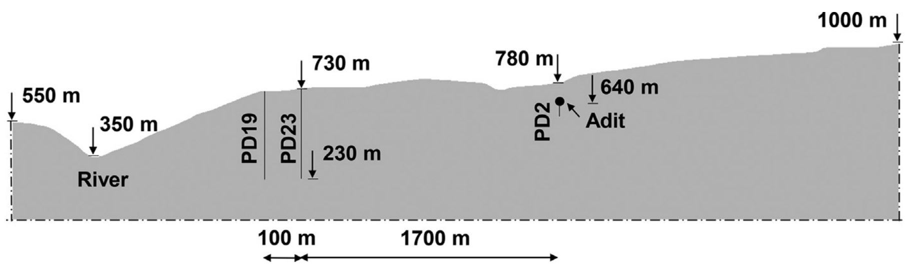

Fig. 2. Vertical cross-section *A–A'* along the pressure tunnel showing the relative location of the adit with respect to the 500 m deep vertical boreholes PD19 and PD23.

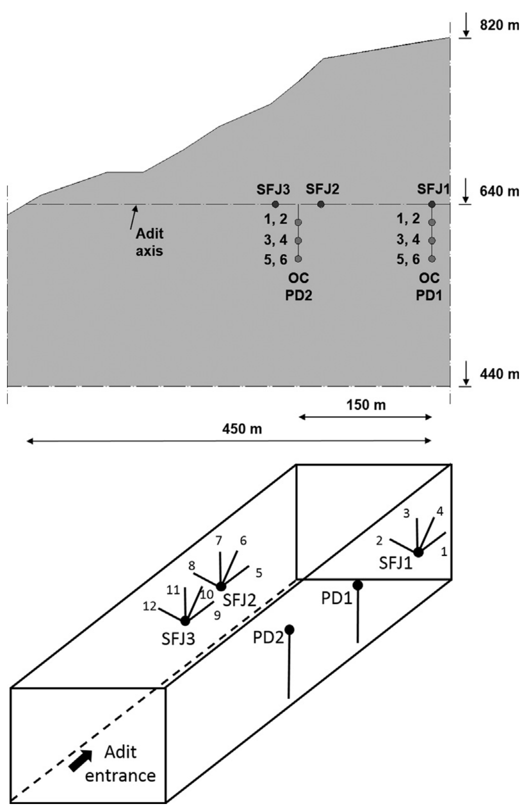

Fig. 3. Vertical cross-section along the adit axis (above) and three dimensional scheme of the adit (below) showing the location of overcoring and flat jack tests.

Validity of these results for other locations would be established next, through further testing conducted in the adit. Hence it was decided to run overcoring and flat jack tests in the adit in order to combine various measuring techniques for this stress evaluation, as recommended by the ISRM [3].

Locations of the various boreholes are shown on Figs. 2 and 3. The 60 m deep boreholes PD1 and PD2 are 150 m apart and have been drilled specifically for overcoring measurements (Fig. 3). The three locations SFJ1, SFJ2 and SFJ3 of flat jack tests are also shown on Fig. 3.

2.2. Hydraulic tests

Hydraulic tests involved two different techniques, hydraulic fracturing (HF) and hydraulic testing of pre-existing fractures (HTPF), following the procedures described by Haimson and Cornet [4].

For HF, a portion of a borehole free of pre-existing fractures is isolated with a straddle inflatable packer. The pressure is progressively raised in the isolated interval till a hydraulic fracture develops at the so called breakdown pressure P_b. Then the fracture is extended till it reaches zones outside the domain of influence of the borehole. When the fracture stops, the hydraulic injection system is kept shut so as to monitor the subsequent pressure decay for some time (a few minutes). This testing period is called the shut-in period. At the end of shut-in, the system is shortly bled off (a few seconds) and the subsequent pressure build-up is observed for a few minutes. This part of the test is called flow-back and ends the first testing cycle. This testing cycle is reproduced at least twice and sometimes more, when results show some drifting from one cycle to the next (Fig. 4).

The pressure at which the fracture closes is called the instantaneous shut-in pressure $P_{s.}$ It is equal to the normal stress component acting on the fracture plane, *i.e.* the natural minimum principal stress component when the hydraulic fracture has propagated far enough from the borehole.

The HTPF procedure is very similar to the HF procedure except that the isolated borehole portion is supposed to include one single pre-existing fracture. The pressure is raised sufficiently