Proceedings of the 7th International Conference on Geotechnical and Geophysical Site Characterization
Barcelona, 18 - 21 June 2024

Site characterization of large hydropower projects

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ABSTRACT

Hydropower plays an important role in the context of the energy transition contributing to the reduction of the CO2 emission through a permanent power production as run-of-river scheme as well as for energy storage as pump-storage-scheme. Nowadays large hydropower plant designs comprise tunnel, cavern and shaft excavation work known as head race and pressure tunnel or pressure shaft. The powerhouse is often placed within a large underground cavern. The results of a ground investigation phase including the determination of in-situ parameters derived from tests in boreholes drilled from the surface are crucial for a preliminary design of the hydropower plant. Additional in-situ measurements are frequently carried out within an exploratory tunnel to confirm the first predictions and to characterize in detail the mechanical and hydraulic properties of the rock mass. Solexperts portfolio of in-situ well tests comprise the assessment of hydraulic properties vs. depth through hydraulic testing of isolated borehole sections along the borehole axes, the determination of geomechanical parameters like deformation- and Young's modules through borehole dilatometer tests and rock stress measurements conducting hydraulic mini-frac tests. Plate load tests which use surficial loading are performed in small tunnels or test adits to measure the deformation characteristics of a rock mass on a larger scale.

Keywords: site characterization, measurements of in-situ parameters, hydraulic properties, geomechanical parameters

1. Introduction

The design of underground excavations for large hydropower projects in the 21st century rely on 3D FEM models. The results are essential for the designer as well as for the engineer on site. With such highly processed information, short-term decisions can be made about the design even during the construction progress reducing geological risks while optimizing the budget.

The computer models e.g. "building information models" (BIM) have developed rapidly over the last decades. Furthermore, 3-dimensional coupled hydraulic and hydromechanical models are widely used. Despite the developments and technical advances of in-situ borehole testing techniques and equipment enhancements during the same period, the site investigation scopes still do not consider these advancements. In fact, the standard scope of work of such a site characterization phase often still reflects very limited and older methods and measurement systems.

This paper summarizes our experience of many ground investigation projects carried out during the last decades proving the added value of the state-of-the-art in-situ borehole tests.

The in-situ borehole test portfolio described below comprises hydraulic testing in packer sealed off intervals, dilatometer tests and in situ stress measurements as well as large scale plate load tests and includes examples, discussion of test procedure enhancements leading directly to test time and cost reduction, as well as new testing methods and system developments which pave the way towards a reliable and comprehensive model input data set.

2. Site characterization from the surface

The ground investigation program of large hydropower projects (HPP) including the excavation of tunnels, caverns and shafts comprise usually an in-situ borehole test phase including core recovery, geophysical borehole logging and in-situ borehole testing. The latter consists of hydraulic tests for assessment of the hydraulic properties, dilatometer testing for the determination of the E- and D-Modules and hydraulic mini-frac tests for the quantification of the rock stress magnitude and orientation. The testing equipment comprises a downhole single or double packer system, downhole sensors (pressure, temperature, orientation), data transmission and valves. The surface units consist of a data acquisition system, surface sensors (e.g. flow) and a flow control system. The system may be deployed by tubing or wireline depending on the dip of the borehole and, in case of the hydraulic test, on the flow rates.

Previously acquired core and geophysical logging data are essential to define the target test zones and the locations of the inflatable packers.

In the following chapters the main test types are described and discussed in detail partly by means of case studies presenting the state-of-the-art testing methods.

2.1. Hydraulic Tests

A proper assessment of hydraulic properties of the rock mass is not only important for the design of the later drainage system but also crucial for a risk-controlled excavation phase of any underground construction. Unpredicted, sudden inflow events during excavation may create hazardous conditions for life and material causing considerable costs and time delays. Current scope of works considers only limited hydraulic assessment in tunnel exploratory phases. Methods are often based on traditional concepts with only minor adaptions to newer developments and without considering modern approaches nor heterogeneities. Two examples for enhancement of hydraulic testing are presented in this chapter.

2.1.1. Modified water pressure tests (Lugeon tests) vs. hydraulic testing

Water pressure tests or Lugeon tests are commonly applied to assess hydraulic properties during the ground investigation stage of tunnel, shaft, or cavern excavation projects. Maurice Lugeon (Lugeon, 1933) first developed this type of water pressure test to obtain a design criterion for the injection for sealing curtains below dams. The interpretation is based on empirical models and was revised multiple times during the years. The state-of-the-art testing method is described in the norm ISO/DIS 22282-3 (2006) and includes some recommendations suggested by Steiner et. al. (2006). In addition, Vaskou (2019) describes some adaptation to allow the use of modern and efficient equipment. However, he states that Lugeon tests may be used as preliminary definition of hydrostratigraphic units, but they should never be a substitute full hydrogeological tests which have a wider scope. One of the reasons is that the results of Lugeon tests do not include any concept of heterogeneities. Furthermore, it is not a pure hydraulic test but rather a hydromechanical test during which the hydraulic conductivity may be increased due to opening of fractures caused by the injection pressure increase. Consequently, the results should only be used for the original scope: the grout injection design, but not for hydraulic modelling.

The traditional water pressure (Lugeon) test includes 3 increasing pressure injection and 2 decreasing pressure injection steps, each of 10 minutes of injection time. The total test time is about 1 h and the test interpretation is based on steady state flow conditions which in most cases are not achieved during such short injection periods. In contrast, the enhanced test method proposes a longer, initial pressure stabilization phase (pressure shut-in recovery, PSR) followed by a prolonged first injection step and the recording of the final pressure recovery phase (see Figure 1). Consequently, the testing time required for the enhanced water pressure test increases from about 1 h to 3 or 4 h. The first prolonged injection phase allows the interpretation of the transient flow phase applying e.g. the Jacob-Lohman method (Jacob et. al, 1952). The test example shown in Figure 1 also illustrates the importance of the first PSR test phase: without recording the PSR initial pressure level the initial head evaluation would be erroneous.

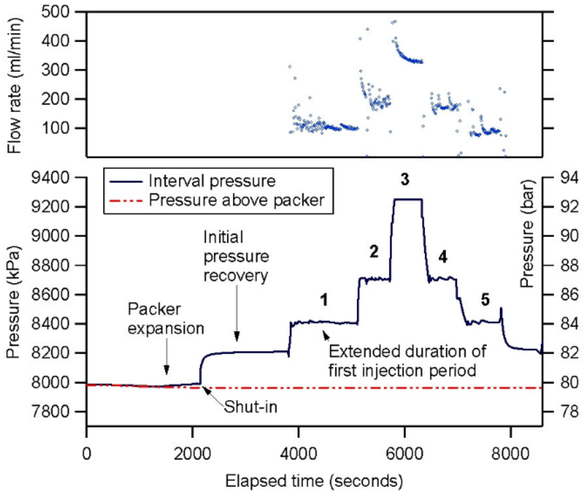

Figure 1: Example of an enhanced Lugeon test extracted from the ISO/DIS 22282-3 (2006). The initial pressure recovery is usually referred to as PSR (**p**ressure **s**hut-in **r**ecovery).

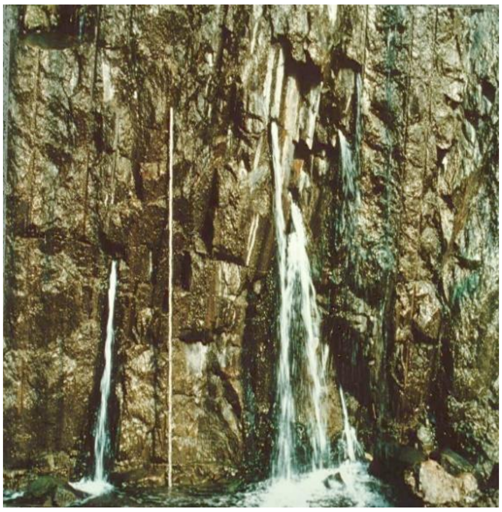

Figure 2: Heterogeneity observation in a tunnel: Groundwater outflow with different outflow rates at discrete spots at the tunnel wall show the distribution of individual and small-scale preferential flow paths and at the same time demonstrates the limitation of a continuum assumption. (courtesy of Prof. Kovari)

A fundamental limitation of the water pressure tests is that the interpretation is mainly based on continuum assumption or at least the assumption that the features are equally distributed over the test section or the section of interpretation (ISO/DIS 22282-3, 2006). This does not reflect the reality as shown in the expample of Figure 2. The neglection of heterogeneities may lead to an erroneous hydraulic flow model and/or a considerable underestimation of the hydraulic conductivity values by orders of magnitude.

Deeper hydraulic knowledge is required to establish a proper and comprehensive hydrogeological model, which can be achieved through in-situ tests that focuse only on the hydraulic characterization rather than tests that combine hydraulic and mechanical effects, meaning without stepwise increase of injection pressure. In addition, the test method should also allow the determination of the heterogeneity which is a common phenomenon in groundwater hydraulics.

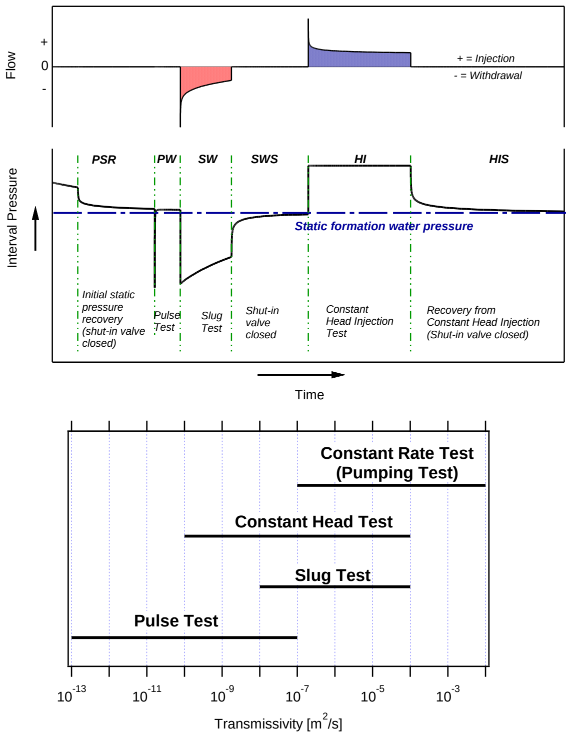

Figure 3: Top: Idealised test sequence showing a combination of various hydraulic testing methods; Bottom: Different test types used for hydraulic test campaigns vs. assumed transmissivity.

A hydraulic test sequence combines several test methods to allow flow model interpretation and proper assessment of the hydraulic properties (Figure 3, top). In lower to intermediate permeability rocks, a test series consisting of an initial pressure stabilization phase (PSR) followed by a short term pulse withdrawal (PW) and a consecutive slug withdrawal test (SW) including the later shut-in phase (SWS), a constant head injection test (HI) together with corresponding pressure recovery (HIS) is suggested. Constant head injection tests are preferred due to the minimal influence of the wellbore storage phase. However, the injection pressure needs to be defined with care to avoid fracture opening on one side but also to generate suitable signals (flow rates and pressure) within the measurement range of the sensors. Generally, withdrawal tests are required if groundwater samples need to be taken in order to avoid the injection of a fluid which differs from the formation fluid which could alter the natural pore-water geochemistry. Ideally a test sequence should include both water injection and water extraction phases to reduce the uncertainty in the formation pressure estimation.

In addition, the test types and the test sequence depend on the estimated transmissivity (see Figure 3, bottom). Often, pre-test information is limited leading to frequent adjustments during the test campaign. In such cases it is important that an experienced test engineer with a broad equipment pool is onsite to decide which test type and test sequence is most effective to obtain all the required data and adjusts constantly test methods and duration based on pre-analysed real time data.

Modern state-of-the-art data interpretation is based on the analysis of the transient data set. In a first step the different flow phases are identified in a log Delta time-, log Delta-P- (Delta-P: pressure response)/log Derivative Delta-P diagnostic plot as shown in Figure 4 (top). Based on the diagnostic plot a suitable flow model can be selected and the corresponding data set interpreted either analytically or by an inverse numerical model approach. An example for an analytical analysis is shown in Figure 4 (bottom) where the delta pressure data during the infinite active radial flow phase (IARF) follows a straight-line. This procedure assures a reliable parameter estimation because it is based mainly on an aquifer response. All other effects e.g. borehole (wellbore storage) and borehole near field effects (skin effects) as well as boundary effects are not or almost not present within this time period.

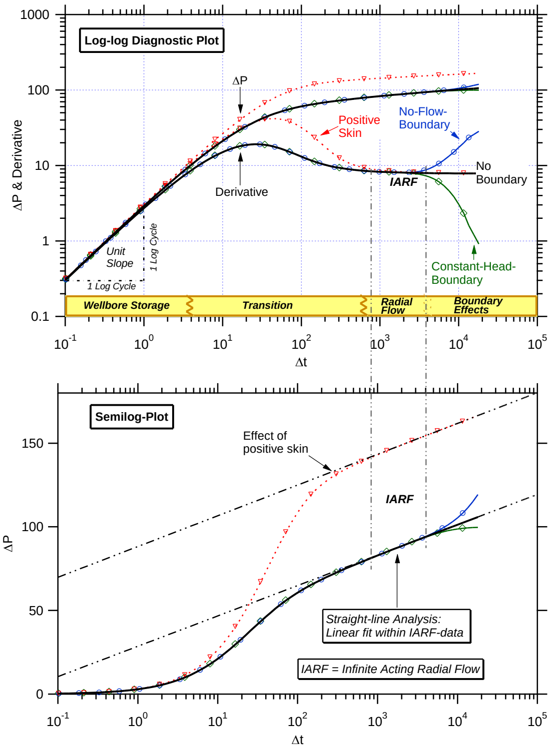

Figure 4: Top: log-log plot showing the different flow phases. Bottom: semi-log plot with straight line approach on the selected flow phase (IARF).

Furthermore, inverse numerical modelling and a post-numerical uncertainty analysis allow quantifying the confidence in the estimated parameter values using stochastic methods. This approach provides parameter ranges and their associated probabilities, enhancing the reliability of the results.

2.1.2. Outlook: Periodic pump tests

Recent development in hydraulic testing applies procedures frequently used in electro-technical applications, and which are basis for modern communication technologies. The innovative technique of Renner et. al. (2006) called periodic pump tests is derived from the harmonic transfer function determination (Crosnier et. al., 1985) and the sinusoidal oscillation method (e.g. Fischer, 1992) applied to a damped free oscillation of a borehole-aquifer system resulting from sudden changes of the flow rate (withdrawal, no flow, injection). Renner et. al. (2006) applied two evaluation methods: injectivity and interference analysis. The injectivity analysis is applied on the active flow well and the interference analysis on observation wells. The methods rely on a characterization of the relation between flow rate and pressure in a periodically pumped well and the relationship between pressure in the pumping well and monitoring wells.

Using this method offers several operational advantages over conventional hydraulic tests such as the possibility to apply it in fully transient flow phases (e.g. pressure recovery after drilling etc.), zero net flow and no need for high delta pressures. In addition, Renner et al. (2006) pointed out that the characterization of heterogeneity is crucial for a detailed description of the subsurface flow pattern. Their results indicate that the method is sensitive to subsurface heterogeneity. Furthermore, periodic pump test can be applied to estimate the vertical hydraulic conductivity from a single hole test.

This method was established and verified during the last two decades in several research projects. The test procedure as well as the analysis algorithm are proved and ready for industrial applications.

2.2. Dilatometer Tests

Dilatometer tests are used to determine the deformation and elastic moduli of rock mass under in situ conditions. In the older literature and frequently in the scope of work of current tenders worlwide, the Goodman jack probe is still requested as an in-situ instrument for the determination of the E- and D-modules.

The Goodman jack probe consists of a hydraulic cylinder combined with half shell type load plates and electric displacement sensors. The advantage of this technique is the high pressures that can be applied via the cylinders. The disadvantage of the method, especially in rock, are the half-shell-shaped load plates, which have to be adapted exactly to the borehole diameter; otherwise and this is in general the case, the hydraulic pressure is only transferred to the borehole wall as a line load.

The Goodman jack probe is built for a borehole diameter that is common for exploratory drilling, especially in Anglo-Saxon countries. Apart from the advantage of high pressures applied to the borehole wall, this probe has the disadvantage that it only has a deformation accuracy of only 0.01 mm where 1 µm would be adequate for hard rocks.

Conversely, if this probe is used in rocks of low strength, the measuring range of 5 mm is completely inadequate to apply slightly higher probe pressures to the borehole wall. If one also adds to this disadvantage the above-mentioned effect of an incomplete load plate-borehole wall contact and, in addition, also considers the small borehole diameter as a deficiency, Fecker (1997) concludes that the Goodman Jack is obsolete today from both technical and rock mechanical points of view.

State-of-the-art dilatometer probes measure the deformation behaviour of the rock by an inflatable packer to exert a high pressure on the walls of a drillhole measuring the radial displacement of the borehole wall. Typically, nitrogen is used to pressurize the packer sleeves against the borehole wall. The crucial ability of the packer is its adaptation to the effective borehole diameter and unevenness of the borehole wall. Furthermore, the norm ISO/DIS 22476-5 (2023) which is the only approved method, mandates the use of displacement transducers in three directions with direct contact to the rock of the borehole wall and provide high resolution in the µm range (see Figure 5). The pressure and the displacement data are gathered downhole and from there transmitted to the surface data acquisition system, where it is displayed in real time to achieve a proper test control. In addition, it is recommended to measure the orientation of the probe by means of a compass to capture the anisotropic geomechanical behaviour.

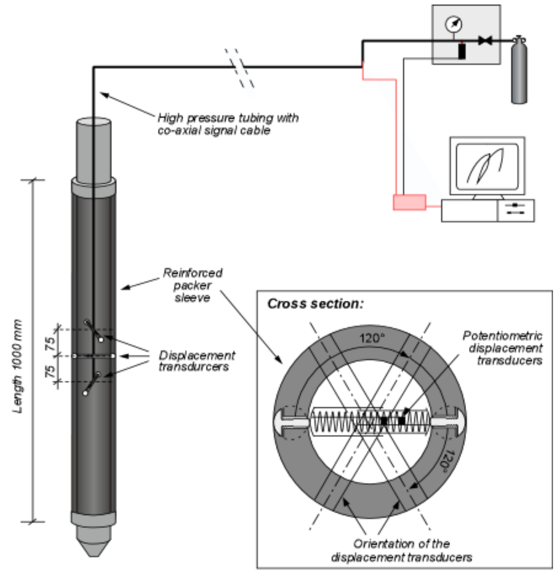

Figure 5: Schematic setup of the Solexperts dilatometer which is according to the norm EN ISO 22476-5.

2.3. Hydraulic Mini-fracTests

Hydraulic fracturing (Haimson and Cornet, 2003) is the most efficient in-situ method to characterize rock stress, in particular at great depth. However, testing procedures and test analysis require great experience. Stress estimation must be performed with great care under consideration of the specific site conditions.

Generally, hydraulic mini-frac (HF) tests are carried out during one trip in the hole starting with the deepest test section. According to our experience at least 8 HF tests each borehole should be performed. Subsequently to the HF tests, the double straddle packer probe is replaced by the impression packer probe (Figure 6). Individual impression packer test requires one **r**un-**i**n-**h**ole (RIH)/**p**ulling-**o**ut-**o**f-**h**ole (POOH). Despite the higher quantity of roundtrips, the impression packer technique has several advantages compared to imaging tools, like acoustic borehole imagers (ABI) or optical borehole imagers (OBI).

- After closure the induced fractures have a width of only some micrometres, which is close to the detection limit of the imaging tool. Pressurizing the impression packer beyond the fracture reopening pressure yields a reliable image of the thin fracture traces,
- Impression packer tests can be conducted in boreholes of any inclination,
- Impression packer tests have only little limitations with respect to the borehole fluid.

A current research and development project aims on the improvement of the fracture orientation measurements by integration of an acustic borehole televiewer in the injection interval which will allow (starting 2026) online fracture orientation determination during the fluid injection.

Figure 6: Impression packer for the determination of the fracture orientation.

Hydrofracturing for stress determination is generally carried out by using a double straddle packer system with a small interval length of about one meter between the inflatable rubber packers in order to capture a fracture free borehole section. Typical injection rates are several liters per minute by using water as frac fluid and a total injection fluid volume in the order of tens of liters. In most cases, the hydrofrac tool is inserted to depth via high pressure drillpipes which requires an onsite drill rig. The drillpipes also serve as hydraulic pressure line to set the packers and to inject the frac-fluid into the frac-interval. However, this method is quite slow and expensive because it requires the drill rig with the rig crew onsite during the entire test procedure and thus Solexperts applies the wireline concept which allows a fast and almost continuous "stress logging" similarly to conventional geophysical data logging in the absence of a drill rig (Figure 7). It enables Solexperts to perform HF tests in deep boreholes for a low budget since there are no cost for the rig and the rig crew.

Figure 7: Lean and cost-efficient set-up for mini-HF measurements in a 2000 m deep borehole in Australia showing the double packer probe. No drill-rig and crew required.

A typical downhole pressure and injection flow rate record of a hydrofrac stress measuring operation in crystalline rock is shown in Figure 8. It demonstrates a pressure pulse test (P - Test) for rock mass permeability determination, fracture initiation (frac-cycle), various fracture reopening phases with different injection flow rates (refrac-cycles) and the shut-in pressure, marked by a sharp break in the record after the injection is stopped.

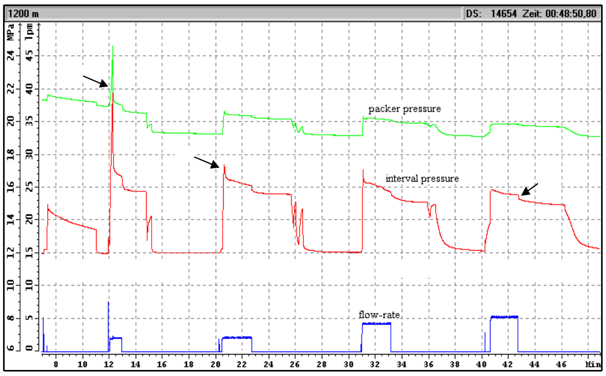

Figure 8: Typical pressure and injection flow rate record of a hydraulic mini-frac test.

3. Site characterization from exploratory tunnel and tunnel adits

This chapter discusses the particular situation for in-situ borehole testing where the boreholes are drilled from underground. This chapter also deals with the possibility of determining the load-deformation behaviour of the tunnel wall by carrying out load plate tests.

3.1. Hydraulic Tests

In general, the test methods do not differ between the two test settings (surface and underground). However, there is large potential for improvements as the hydraulic conditions within a tunnel are artesian which allows alternative equipment setup for hydraulic testing described below. The artesian pressure conditions for dilatometer require an equipment modification. In addition, plate load tests may be performed in tunnel niches. Mini-HF test results may be very beneficial by optimizing the tunnel liner design.

3.1.1. Case study: Enhanced hydraulic testing procedure, Glendoe Tunnel Collapse in Scotland

A 71 meter long section within the Conagleann Fault Zone which penetrates the headrace tunnel of the Glendoe HPP collapsed in 2009 after watering the tunnel. The original concept for the Glendoe headrace tunnel was for a drill and blasted, shotcrete-lined tunnel apart from areas where a full insitu concrete or steel liner was required. An alternative design was proposed using a TBM for construction in the design–build contract. It was calculated that using this method, the tunnel could remain 60% unlined (Hencher, 2019). Different causes were discussed which may explain the collapse like “the deterioration of thin single shears” when submerged, “by slaking”, “between good rock in between” followed by progressive collapse, dominated by erosion or a large-scale wedge failure and rock collapse on incipient discontinuities (Hencher, 2019).

The collapsed tunnel section needed to be by-passed by a diversion tunnel. Therefore, in 2010 exploratory boreholes from underground and from surface were drilled to assess the hydraulic properties and geomechanics parameters around the planned diversion tunnel. Hydraulic tests and stress measurements were performed within these boreholes. The objective was to obtain a depth profile of in-situ stress and hydraulic properties (head; transmissivities and hydraulic conductivities). Solexperts proposed an alternative approach for the hydraulic profiling within the boreholes drilled from the headrace tunnel applying a multi-packer system instead of a simple straddle packer configuration. The advantages are:

- The entire borehole can be saturated in upwards inclined boreholes using the built-in saturation and degassing lines.
- Once installed, the system directly measures the pressure distribution within the borehole.
- Allows simultaneous testing within several intervals optimising the tests by providing longer pressure monitoring and testing times.
- When two near-by boreholes are equipped with multi-packer systems, the interference pressure responses from the systems allows to derive robust estimations of the full set of hydraulic properties including heterogeneities.

In addition, the test types and test procedure were optimized to obtain representative data within the minimum time. Therefore, constant head injection tests and pulse injection/withdrawal tests were performed during the daytime shift while the pressure recovery was recorded during the night-, unattended periods.

3.2. Dilatometer Tests

Dilatometer systems deployed in boreholes drilled from underground need to cope with artesian conditions. The dilatometer is sealing off the borehole section below the packer down to the bottom of the borehole leading to an increasing water pressure in this section which may superpose secondary effects affecting the E- and D-Module measurements and cause a hazardous situation when deflating the dilatometer packer. The Solexperts dilatometer can therefore optionally be equipped with a water by-pass to allow the drainage of water around the dilatometer packer element.

3.3. Plate Load Tests

Plate load tests are used for in situ determination of deformation characteristics and elastic properties of rock masses. The results of the tests are used to determine the deformations of the tunnel wall if it acts as a rock abutment and is to be loaded by the completed structure. This method is often used to plan the type of tunnel lining for pressure shafts in hydroelectric power stations. Ideally, the maximum load on the rock surface during the test should be around 1.5 to 2 times the planned structural load.

The test equipment consists of two bearing plates, a ball joint, and several extension elements. The load is applied by one or more hydraulic jacks. Deformation measurements of the rock mass below the loading plates is made with two multiple-point, several meter long borehole extensometers installed in centred drillholes below both load-bearing plates. Furthermore, the load pressure data is acquired, and a load control system guaranties a constant load during an extended period. Figure 9 presents a general horizontal setup. A second plate load test is usually performed in vertical direction to capture the anisotropic geomechanical behaviour.

Experience has shown that the upper limit for a standard and manageable test setup for installation in rock niches or access tunnels is a maximum rock load of around 10 MPa with a load surface diameter of 700 mm. The required press force is then approximately 4000 kN.

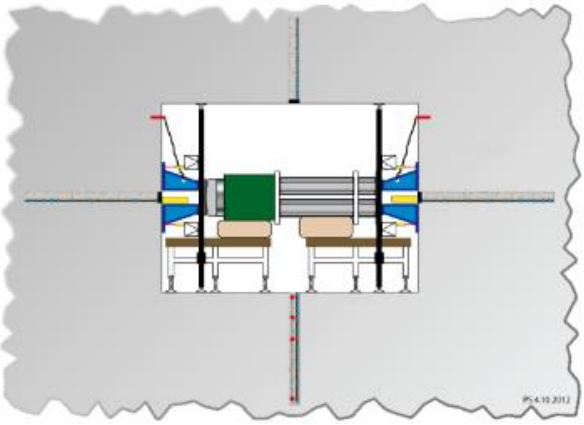

Figure 9: General horizontal plate load test setup with bearing plates, hydraulic jack and the mutli-extensomter installed in axial direction.

Figure 10: Example for horizontal plate load test setup showing the bearing plates, hydraulic jack (green), extention and the load support arrangement.

The labour-intensive installation of the test setup in general takes about one working week and requires heavy load machines for moving the different equipment elements to designated locations, as well as the drilling of the extensometer borehole and the preparation of a flat rock wall surface to attach the bearing plates. A typical plate load test setup is shown in Figure 10

Currently exist two suggested methods of the ISRM (1981) and of the German "Working Group 19 - Experimental Rock Technology" (Mueller et.al., 1985). Furthermore, ASTM international published a standard (ASTM D4394-17, 2017). A typical procedure is covering five loading/unloading cycles, each of it with a stepwise increasing load until the peak load is reached. Each incremental load step should be kept constant for at least 10 minutes. If the rock exhibits pronounced creep behaviour, creep tests with a load duration of the incremental steps of 24 h or more are also recommended. The test duration for a typical test with 5 load cycles is approximately 24 hours. If creep tests are necessary, the test duration can be several days. A typical multi-extensometer response of the applied load cycle is shown in Figure 11.

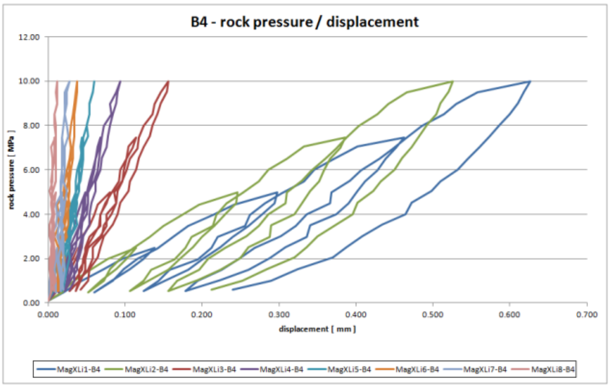

Figure11: Example of a typical plate load test. Multi-extensometer response of the applied load cycles and prolonged peak loads. Shallow extensometer show a large deformation which decreases with increasing extensometer depth.

3.4. Hydraulic Mini-FracTests

This chapter presents a typical example how in-situ rock stress data can improve the of tunnel liner design and leading to significant cost savings and risk reduction.

3.4.1. Case study: Interpretation of in-situ stress profiles leading to steel liner optimization and risk reduction for shaft excavation

Within the Xe Pian – Xe Namnoy hydropower project in Laos in-situ stress measurements applying the hydraulic fracturing method were performed in a 750 m and 440 m deep borehole. The boreholes were located at the pressure shaft (PSDH-1) and intercepting the high-pressure headrace tunnel 695 m downstream of the bottom elbow of the pressure shaft (PSDH-2).

The wireline straddle packer system with downhole push-pull valves and with a high hydraulically stiffness allowed a cost-efficient test procedure and at the same time obtaining a high quality and reliable stress data set. We used various graphical procedures discussed by Baumgärtner et al. (1989) for the interpretation of the characteristic hydraulic mini-frac tests pressure values (breakdown-, re-opening and shut-in pressure) to obtain highly accurate stress measurements (Longden, 2016).

Figure 12 (left side) shows the minimum principal stresses in relation to the anticipated internal water pressure in the pressure shaft vs. elevation. It can be observed that the internal water pressure cannot induce hydraulic fractures at the location of the vertical pressure shaft (PSDH-1). However, at the intercept position of PSDH-2 with the high-pressure headrace tunnel 695 m downstream of the bottom elbow of the pressure shaft the minimum principal stresses is remarkably similar to the internal water pressure of the power waterways (Longden, 2016). Based on these results no steel liner was required at the vertical pressure shaft at the position of PSDH-1. However, due to low deformation modulus and slaking potential of some mudstone horizons a steel enforced concrete was proposed in the basic design. In addition, the designer proposed a liner optimization within the high-pressure tunnel by interpolating the minimum stress data between both boreholes (Longden, 2016).

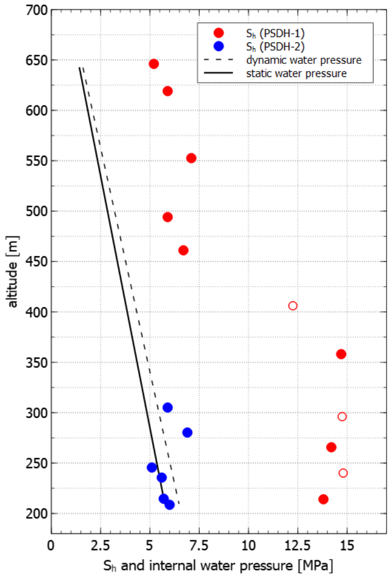

Figure 12: Minimum principal stresses and internal water pressure water pressure vs. elevation.

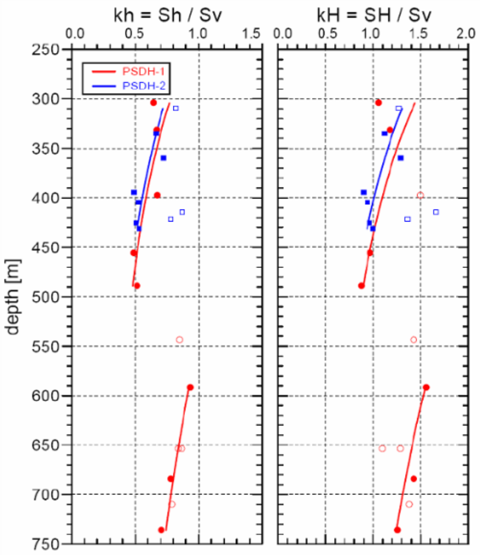

Figure 13: Normalized stress plots for boreholes PSDH-1 and PSDH-2.

Regarding the excavation of the vertical pressure shaft a raise boring procedure could cope with the consequences of the stress anomalies shown in Figure 13 (right side). The S_h/S_v ratio increases below 500 m which can be explained with an unconformity between two major rock formations - which most likely would have caused engineering problems during excavation. In such a case, raise boring may be the best excavation method with the lowest risk involved.

4. Conclusions

Hydraulic- and geomechanical in situ borehole tests are crucial for the design of underground constructions as they provide valuable information in addition to geophysical and core data. Proper in-situ test equipment/-performance, adaptions during testing and a careful and appropriate data interpretation are key factors to obtain highly reliable and representative estimates of the hydraulic and geomechanical properties during a ground investigation project for tunnel-, shaft- or cavern design.

We have found in numerous projects that the in-situ measured rock stress data was an important input parameter for the design of underground structures. In some cases, the pre-existing tunnel liner design required a full revision after obtaining rock stress data.

The well-known water pressure tests or Lugeon tests are hydro-mechanical tests developed about 90 years ago for the design of grout injection below dams. Since then the test setup, sequence and interpretation were updated and improved. Despite the limited scope and significance of the results, these tests are frequently used for the prediction of the hydraulic behaviour of underground excavation projects, due to their simplicity, low costs and familiarity among the civil engineers. Drawbacks of this approach are a large uncertainty in flow prediction and poor pressure head estimations as well as the negligence of heterogeneities and flow boundaries which may lead to “unpleasant surprises” during excavation. We suggest to apply only enhanced Lugeon tests within the scope of their design and we recommend that groundwater flow should only be predicted based on a full transient hydraulic test sequence.

Today such a prediction should be based on a robust numerical model which requires a proper flow model and reliable hydraulic parameters based on results of a properly conducted hydraulic test campaign performed by experienced test engineers, using project-specific selected equipment including calibrated, highly accurate sensors. Furthermore, the test campaign design should be a mutual process between the civil engineer, the drilling crew and a specialized hydraulic test engineer/- company to achieve the best results within the minimum time and budget.

Combining the latter with the observations of Misstear (2001) and Renard (2006) that standard interpretation methods are often misused, it becomes clear that only a close involvement test experts of an innovative and specialized company leads to reliable predictions and generate an added value for the overall project.

Acknowledgements

This paper relies on the work of many Solexperts colleagues which provided data and was inspired by many fruitful discussions within our team. In addition, we thank Prof Kovari for making his extensive collection of images available to us.

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