11TH INTERNATIONAL SYMPOSIUM FIELD MONITORING IN GEOMECHANICS

How can reliable, high quality in-situ test data related to a hydro power project exploration phase help to improve the tunnel or cavern design, reduce risks and save costs?

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Abstract

Hydropower plants and pump storage schemes play a crucial role for the energy transition towards renewable energy sources. Present-day hydro power plant design comprises extensive underground excavation which minimizes the maintenance expenditure during the operational phase and the environmental impact.

Prior to construction and during the exploration phase boreholes are drilled from surface or from reconnaissance galleries. Within these boreholes geomechanical and hydraulic in-situ tests are conducted to assess the rock mechanical and hydraulic parameters. Case studies at selected sites demonstrate how the conduction of high quality in-situ tests led to reliable test data which subsequently contributed to improve the tunnel or cavern design, reduce risks and save costs.

The use of recent advances in the measurement technologies and the proper application of hydraulic tests and data interpretation are discussed showing how appropriate in-situ testing and data analysis can improve the quality of information leading to a considerable reduction of risks and at the same time saving time and funds.

Keywords: borehole in-situ testing, groundwater hydraulics, geomechanical measurements, hydropower plants

1. Introduction

The design of underground excavation projects in the 21st century rely on very large databases that nowadays can be efficiently processed using 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 and at the same time optimizing the budget.

The computer models e.g. “building information models” (BIM) have developed rapidly over the last decades. Furthermore, 3-dim. 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 time period, the site investigation scopes still do not consider these advancements. In fact, the standard scope of work often still reflects very limited and older methods and measurement systems.

This paper summarizes our experience of many projects carried out during the last decades showing the added value of the in-situ tests. The two case studies in chapter 2 show the direct contribution of rock stress measurements to improvement of tunnel liner design, cost saving and risk reduction. In chapter 3 improvement of the test procedures are discussed; on one side the enhancements lead directly to test time and cost reduction; on the other side new testing methods and system developments pave the way towards a reliable and comprehensive model input data set.

2. Stress data as input for optimization of tunnel design and shaft excavation method

2.1. 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 Solexperts (MeSy brand) 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 hydrofrac pressure values (breakdown-, re-opening and shut-in pressure) to obtain highly accurate stress measurements (Longden R.J., 2016).

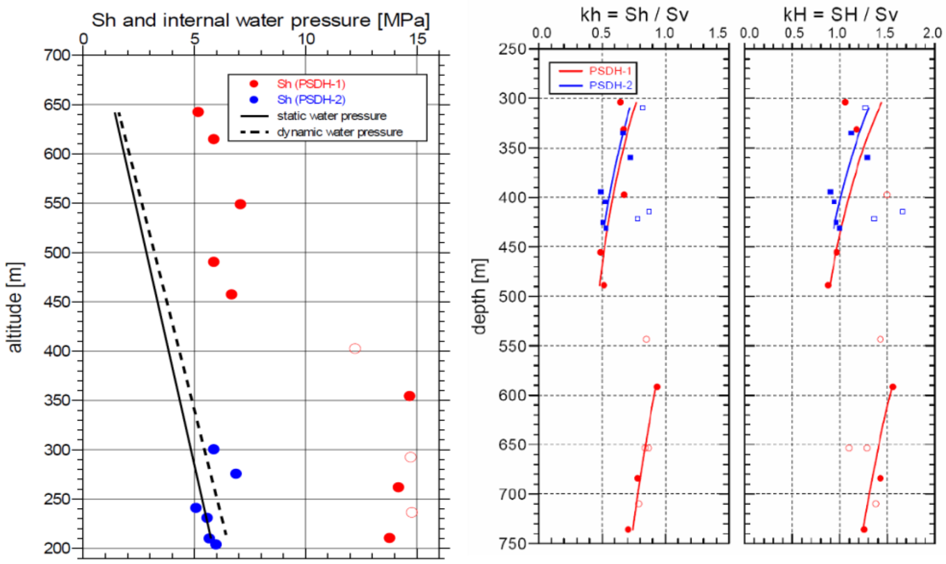


Figure 1: Left side**:** Minimum principle stresses and internal water pressure water pressure vs. elevation.

Right Side: Normalized stress plots for boreholes PSDH-1 and PSDH-2.

Figure 1 (left side) shows the minimum principle stresses with 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 principle stresses is approximately equal to the internal water pressure of the power waterways (Longden R.J., 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 R.J., 2016).

Regarding the excavation of the vertical pressure shaft a raise boring procedure could cope with the consequences of the stress anomalies shown in Figure 1 (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 probably would have caused engineering problems during excavation. In such a case, raise boring may be the best excavation method with the lowest risk involved.

2.2 Modification of a pre-existing tunnel design due to in-situ stress measurement results

Within a pressure tunnel of a HPP in Latin America, Solexperts performed hydraulic fracturing tests to verify the tunnel design which envisaged a tunnel completion without steel liner. The borehole granite rock core samples supported the design. The core recovery was very good with a very low discontinuity frequency granite indicating a high minimum in-situ stress (Figure 2, left side).

However, the measured characteristic pressure for fracture initiation P_c, re-opening P_r and shut-in P_{si} (which corresponds to the minimum principle stress) are considerably below the static water pressure in the tunnel (Figure 2, right side). Consequently, the tunnel design was adjusted including a steel tunnel liner. Only in-situ stress measurements were able to provide objective and reliable data to achieve a proper tunnel design and to avoid very high subsequent costs due to a possible tunnel collapse.

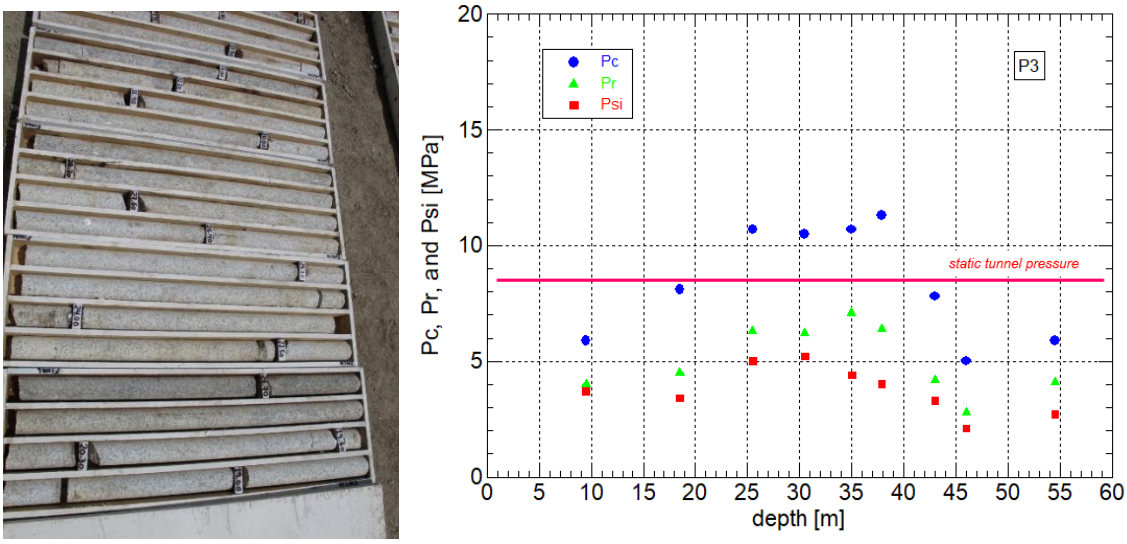


Figure 2: Left side: Core samples of the granite rock with very good core recovery and low discontinuity frequency.

Right side: Result of hydraulic fracturing tests in relation to the static water pressure in the tunnel.

3. Proposed in-situ testing improvements

3.1 Enhanced hydraulic testing procedure; case study: 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 in situ 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 the year 2010 exploratory boreholes from the tunnel and from the surface were drilled to assess the hydraulic properties and geomechanics parameters around the planned diversion tunnel. Hydraulic tests and stress measurements were performed by Solexperts 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 period. Therefore, constant head injection test and pulse injection/withdrawal tests were performed during the day time shift while the pressure recovery was recorded during the night-, unattended periods.

3.2 Using a raise boring borehole for in-situ testing

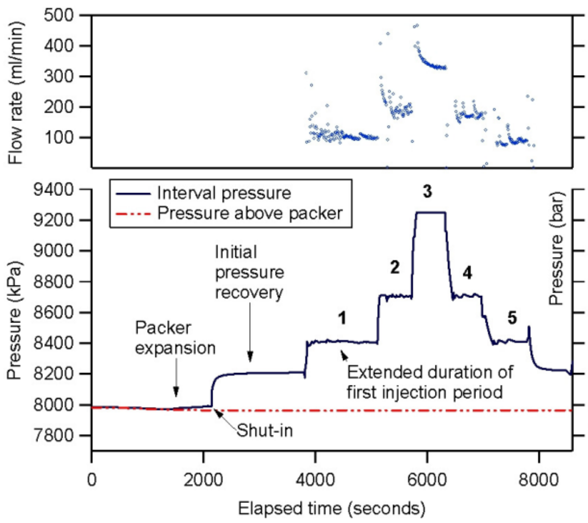
Raise boring is a drilling method in which a circular shaft is drilled along a pilot hole from bottom to top. The application of this method related to vertical pressure shaft of a hydro power projects in Luxembourg was described by Künstle et. al (2011). Raise boring is currently considered the most economical method for constructing shafts. Moreover, the pilot borehole may additionally used to conduct hydraulic and hydraulic fracturing tests to assess aquifer properties and rock stress parameters creating an additional added value to the overall project. Although the borehole diameter of the pilot borehole may be quite large the Solexperts test equipment pool can cope with diameters up to 8.5 inch. The acquired data may be used for shaft completion as well as for the general design of the different excavations and for the hydraulic model.

4. Applying modern hydraulic testing methods

A deeper knowledge of the hydraulic properties and a good hydrogeological model around a futures underground excavation are crucial for a proper design and an efficient, risk-controlled excavation. Unpredicted, sudden inflow events during excavation may create hazardous conditions for live 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 the following 2 sub-chapters.

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

Water pressure tests or Lugeon tests are commonly applied to assess hydraulic properties during a ground investigation phase in advance of tunnel, shaft or cavern excavation projects. This type of water pressure test was first developed by Maurice Lugeon (Lugeon, 1933) 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). However, the results are still limited to the original scope and does 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 or stimulation 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.



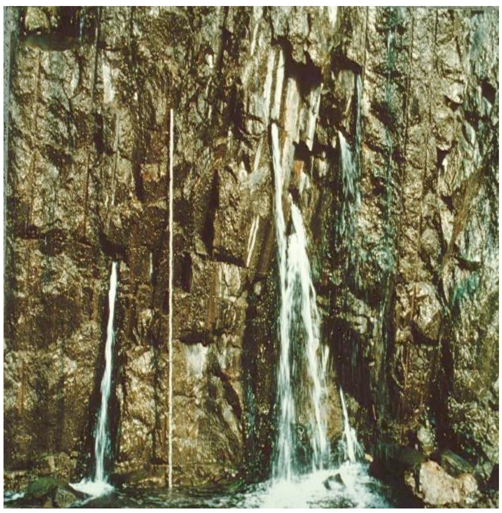


Figure 3: left side: Example of an enhanced Lugeon test extracted from the ISO/DIS norm 22282-3 (2006). The initial pressure recovery is usually referred to as PSR (pressure shut-in recovery).

Right side: 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.

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 present during such short injection periods.

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 3, left side). Consequently, the testing time period 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 4 (left side) illustrates also the importance of the first PSR test phase: without recording the PSR initial pressure level the initial head evaluation would be erroneous.

A general limit 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 norm 22282-3, 2006). 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 obtained only through in-situ tests focused on the hydraulic characterization rather than through testing a combination of 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, right side).

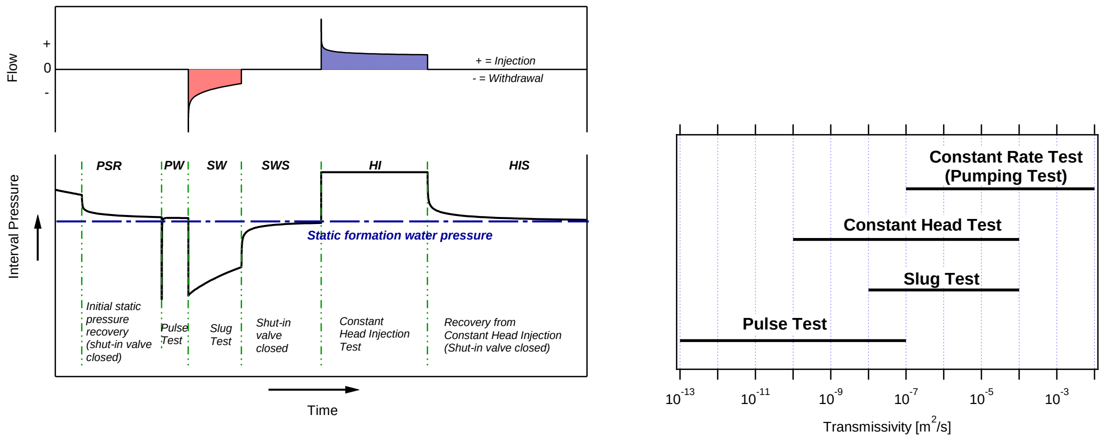


Figure 4: left side: Idealised test sequence showing a combination of various hydraulic testing methods.

Right side: 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 4, left side). 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 because of the negligible influence of the well bore 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 different from the formation fluid which could alter the natural pore-water geochemistry. However, a test sequence should comprise water injection and water extraction phases if possible.

In addition, the test types and the test sequence depend on the estimated transmissivity (see Figure 4, right side). Pre-test information often is very rare causing frequent adaptions even 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 the most expedient and efficient to obtain all the required data and that adjustments regarding testing method and duration are taken rapidly based on pre-analysed real time data.

Modern state-of-the-art data interpretation is based on the analysis of the transient data set where 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 shown in Figure 5 (upper diagram). Based on the diagnostic plot a suitable flow model can be selected and the correspondent data set interpreted either analytically or by an inverse numerical model approach. An example for an analytical analysis is shown in Figure 5 (lower diagram) where the delta pressure data during the infinite active radial flow phase (IARF) follows a straight-line. This procedure assures a quite reliable parameter estimation because it is based mainly on an aquifer response. All other effects e.g. borehole (well bore storage) and borehole near field effects (skin effects) as well as boundary effects are not or almost not present within this time period.

Furthermore, inverse numerical modelling and a post-numerical uncertainty analysis allows to quantify the confidence in the estimated parameter values by stochastic methods indicating parameter ranges and their probabilities.

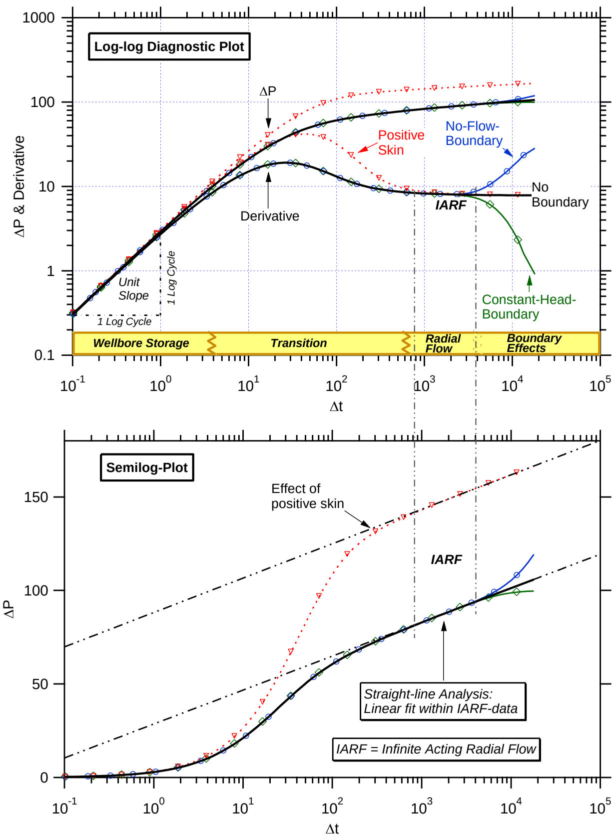


Figure 5: upper diagram: log-log plot showing the different flow phases.

Lower diagram: semi-log plot with straight line approach on the selected flow phase (IARF).

4.2. Outlook: Periodic pump tests

Recent development in hydraulic testing apply procedures frequently used in the electro-technical applications and which are basis for modern communication technologies (Renner et. al, 2006). The innovative technique of Renner et. al. (2006) is based on periodic pump tests and the approach is related to harmonic transfer function determination (Crosnier et. al., 1985) and the sinusoidal oscillation method (e.g. Fischer 1992, Kranz et. al. 1990; Stewart et al. 1961) applied to a damped free oscillation of a borehole-aquifer system due to sudden changes of the flow rate (withdrawal, no flow, injection). Renner et. al. (2996) 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 relation between pressures in a periodically pumped well and a monitoring well, respectively (Renner et. al. 2006).

There exist several operational advantages applying this method compared to conventional hydraulic well tests e.g. 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 (2006) pointed out that 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 application.

5. 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 high 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 the implementation of the rock stress data, resulting in a direct added value for the project.

The well-known water pressure tests also called as 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 in advance of underground excavation projects, because of the simplicity, low costs and familiarity among the civil engineers. Drawbacks of this approach are a great 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.

In our days such a prediction should be based on a robust numerical model which requires a proper flow model and reliable hydraulic parameters based on reliable results of properly conducted hydraulic test campaign performed by experienced test engineers and applying 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) that “standard interpretation methods are often misused” and further Rennard (2005) that “the importance of the need of good education in well hydraulics for providing a solid understanding of the flow behaviour rather than cookbook recipes” it is obvious that only a close involvement of an innovative and specialized company with experienced hydrogeologists leads to reliable predictions which certainly are able to generate an added value for the overall project.

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