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Rock Stress Estimation for Unlined Pressure Tunnel Design

PhD Thesis summary

AUTHOR	Henki Ødegaard
INSTITUTION	NTNU
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SUPERVISORS	Bjørn Nilsen
	Roger Olsson

NTNU SINTEF NINA

Abstract

In underground hydropower projects rock tunnels are used extensively to convey water for the purpose of generating power. As these tunnels represent a major cost element in typical hydropower developments, efforts are made to ensure that the tunnel design is cost-efficient. Under Norwegian tradition the principal cost reducing measure is to keep most of the tunnel length unlined and steel line only a relatively short section of the tunnel.

This approach requires that the rock stress in the unlined tunnel sections exceeds the internal water pressure, to avoid hydraulic failure of the tunnel. Information on the underground state of stress thus is crucial. The current approach to gain information about the underground state of stress is to perform in-situ rock stress estimates. To save costs, such measurements are typically performed at relatively few test locations, leading designers to use interpolative techniques to assess stresses between and beyond test locations. As the distance between test locations increases, so does the risk of leaving tunnel sections with insufficient stress undetected (Ødegaard and Nilsen 2018).

In this thesis, a new methodology for rock stress estimation is suggested to mitigate this undesirable situation, involving a reduction of the distance between test locations by performing measurements more regularly along the entire length of unlined pressure tunnel. For this approach to be financially and practically feasible, measurements must be made more rapid and more efficiently than they are done with the currently available test methods. A new hydraulic jacking test protocol, the rapid step-rate test (RSRT), is proposed as an alternative to the available methods (Ødegaard and Nilsen 2021).

The RSRT test protocol has been developed through a series of experiments using a custom-built true-triaxial test rig, where laboratory controlled hydraulic jacking tests were conducted. The experimental results suggested that the RSRT enabled reliable estimates on fracture normal stresses, and the RSRT protocol was therefore tested in full-scale field conditions at the Løkjelsvatn HPP. The field experiments confirmed the laboratory findings that fracture closure could be detected through analysis of the fracture closure stages of the RSRT, and further that the normal stress estimates were representative for the in-situ state of stress (Ødegaard and Nilsen 2022).

Through field- as well as laboratory testing the RSRT protocol has demonstrated a promising ability in estimating fracture normal stress, and it is therefore believed that the new test protocol may serve as a rapid alternative to current rock stress estimation methods that is well suited for adoption in the proposed new rock stress testing methodology.

1. Scope and objectives

The objective of this PhD-project was to contribute to an improved basis for the final design of unlined pressure tunnels, with emphasis on rock stress estimation. To obtain this objective the research was aimed at the following subtasks:

1. Contributing to an increased awareness of the uncertainties associated with the use of traditional overburden criteria for rock stress estimation
2. Proposing an improved methodology for the estimation of rock stress in connection with final design of unlined pressure tunnels
3. Developing a hydraulic jacking test protocol that can enable rapid rock stress estimates based on simplified test procedures that are adapted to the typical underground field conditions
4. Investigating the field correlation between the new hydraulic jacking test protocol and the hydraulic fracturing (HF) tests
5. Investigating a potential correlation between acoustic emission (AE) activity and fracture normal stress by linking AE-events with fracture closure

2. Methods and findings

With the aim of developing a faster and more efficient method for estimating the underground state of stress, the research started off through an initial literature review, focusing on rock stress estimation techniques used for traditional underground hydropower projects.

Soon, these initial investigations led to a broader investigation of similar techniques used in neighbouring industries such as the deep geothermal and petroleum industry – which turned out very useful. The inspiration from these other industries was essential to the idea of developing a laboratory experiment where scaled-down rock stress estimation techniques could be tested out in laboratory-controlled environment.

The development of a custom-built true-triaxial test rig, designed and built solely for this research project, enabled efficient testing of a wide range of test protocols—eventually ending up with a novel rock stress estimation test protocol, the Rapid Step-Rate Test (RSRT).

Following the encouraging laboratory results, a field campaign was conducted, where the RSRT was performed in a full-scale field setting. The results were highly promising and served as a field verification of the laboratory results.

3. Discussion and conclusion

The outcome of my research can, in essence, be listed as follows:

- The traditional approach to rock stress estimation, using the empirical overburden criteria, is highly uncertain and should not be used for final design purposes. Stresses must be measured *in-situ*, not estimated through the traditional rules of thumb (Ødegaard et al. 2019)
- The current approach to rock stress estimation, typically only performing a bare minimum of tests, can lead to unsafe design of unlined pressure tunnels. A larger number of measurements should be performed, in a distributed manner—ideally along the entire length of pressure tunnel, not only at the "key locations"
- A new rock stress estimation technique, the RSRT, has been developed, showing highly promising results. The RSRT is fast, simple and cost-effective, and might enable more measurements for the same budget compared to the traditional rock stress estimation techniques

After the completion of the research work has the RSRT been adopted by the industry, and the test has already been conducted successfully at the hydropower projects under the planning and supervision of Ødegaard. Currently, there are also plans for additional tests at other hydropower plants. The feedback from the industry this far is that they prefer the RSRT compared to the alternatives as it is providing good test results, and it is faster and cheaper.

Multiconsult, where Ødegaard is employed, has an ongoing cooperation with the specialist company Injeksjonsteknikk AS, and the two companies together deliver the planning, execution, and reporting of RSRT tests. The RSRT is thus already commercialised.

4. References

Ødegaard H, Barkved H, Nilsen B (2019) Om tommelfingerregler og konusplassering i norske kraftverk. In: FJELLSPRENGNINGSTEKNIKK-BERGMEKANIKK-GEOTEKNIKK. Norsk forening for fjellsprengningsteknikk, Norsk Bergmekanikkgruppe og Norsk Geoteknisk Forening, pp 25.01-25.11

Ødegaard H, Nilsen B (2018) Engineering Geological Investigation and Design of Transition Zones in Unlined Pressure Tunnels. Paper presented at the ISRM International Symposium - 10th Asian Rock Mechanics Symposium, Singapore, 29.10-2.11 2018

Ødegaard H, Nilsen B (2021) Rock Stress Measurements for Unlined Pressure Tunnels: A True Triaxial Laboratory Experiment to Investigate the Ability of a Simplified Hydraulic Jacking Test to Assess Fracture Normal Stress Rock Mechanics and Rock Engineering 54:21 doi:https://doi.org/10.1007/s00603-021-02452-9

Ødegaard H, Nilsen B (2022) Simplified Hydraulic Jacking Test to Assess Fracture Normal Stress for Unlined Pressure Tunnels: A Field Experiment Using the Rapid Step-Rate Test (In press) Rock Mech Rock Eng doi:https://doi.org/10.1007/s00603-022-03063-8