Multiconsult

Rapid Step-Rate Test — a new hydraulic jacking test for rock stress estimation

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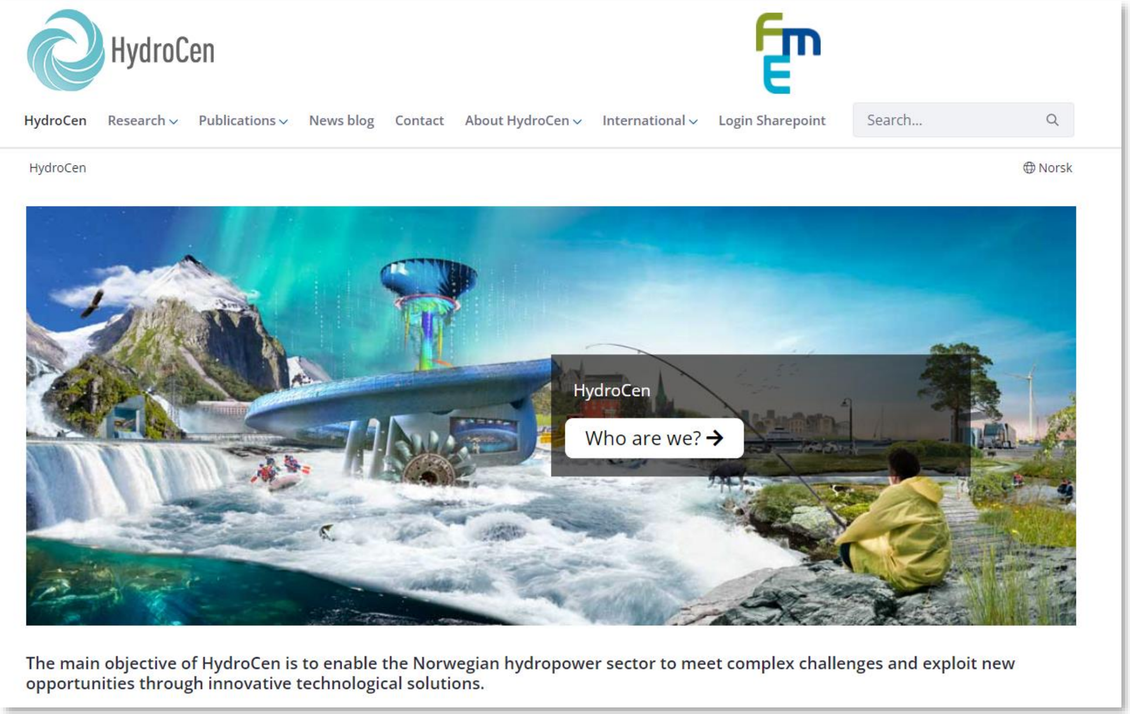
Background

- PhD project within Norwegian Research Centre for Hydropower Technology (HydroCen), NTNU
- Title: “Rock Stress Estimation for Unlined Pressure Tunnel Design”
- Research topic requested by HydroCen industry partners



https://www.ntnu.edu/hydrocen

Agenda

1. Introduction and background
2. Development of new test protocol
3. Results from laboratory and field
4. Conclusions

Unlined pressure tunnels

- Tunnels used to convey water for energy production – no impermeable liner

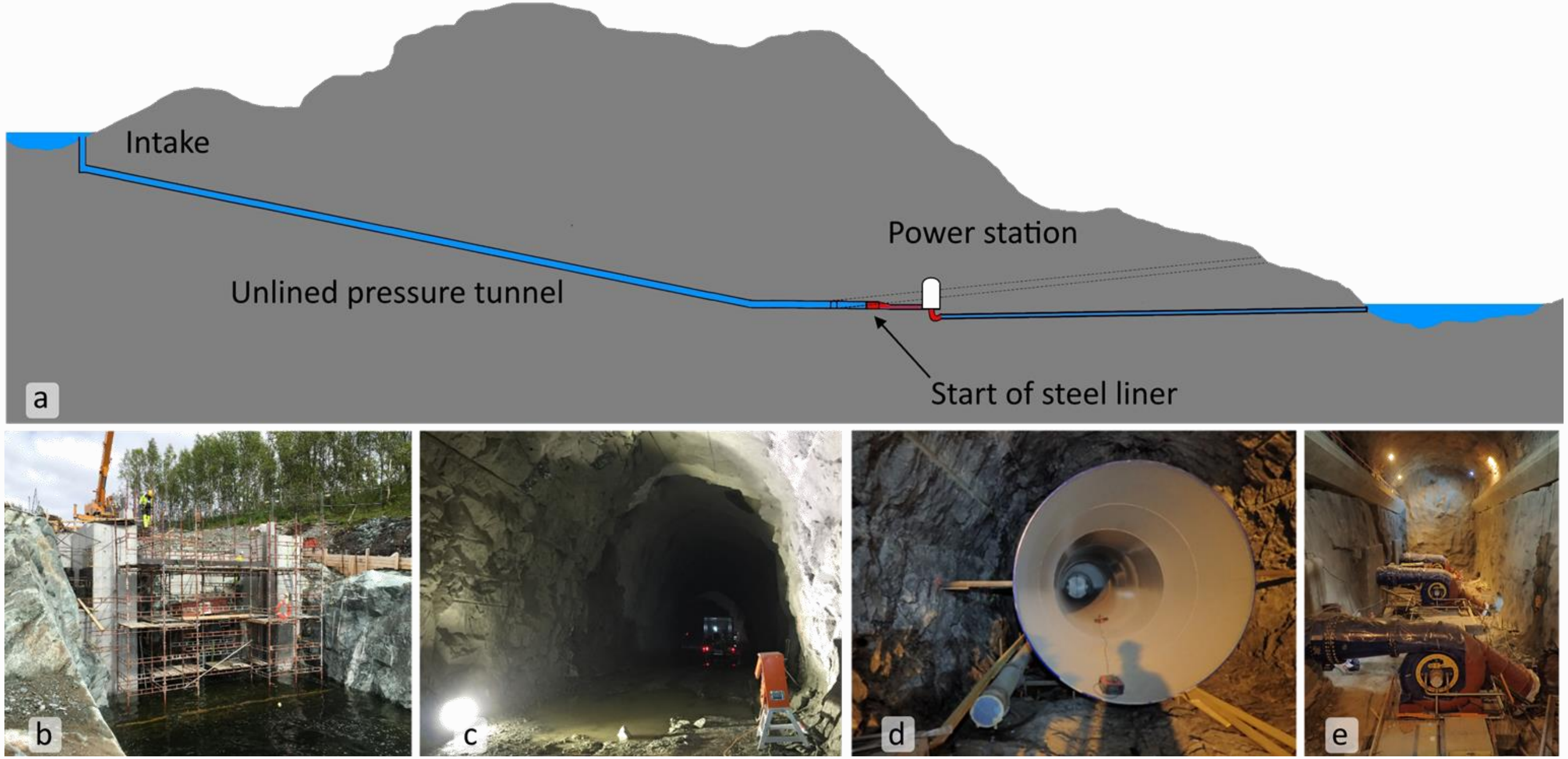
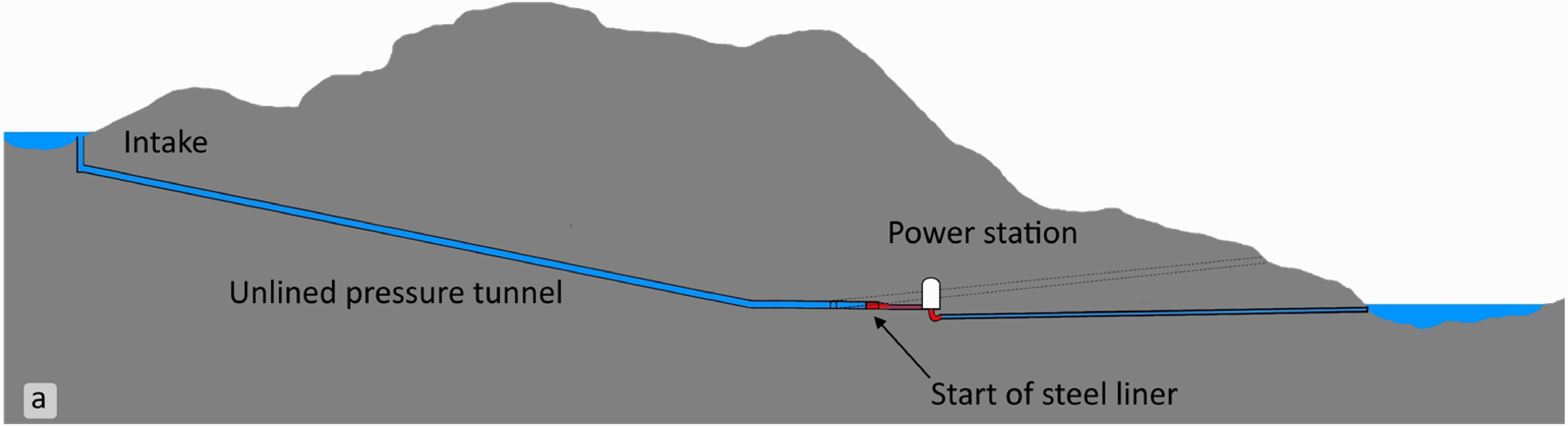


Figure from Ødegaard (2021)

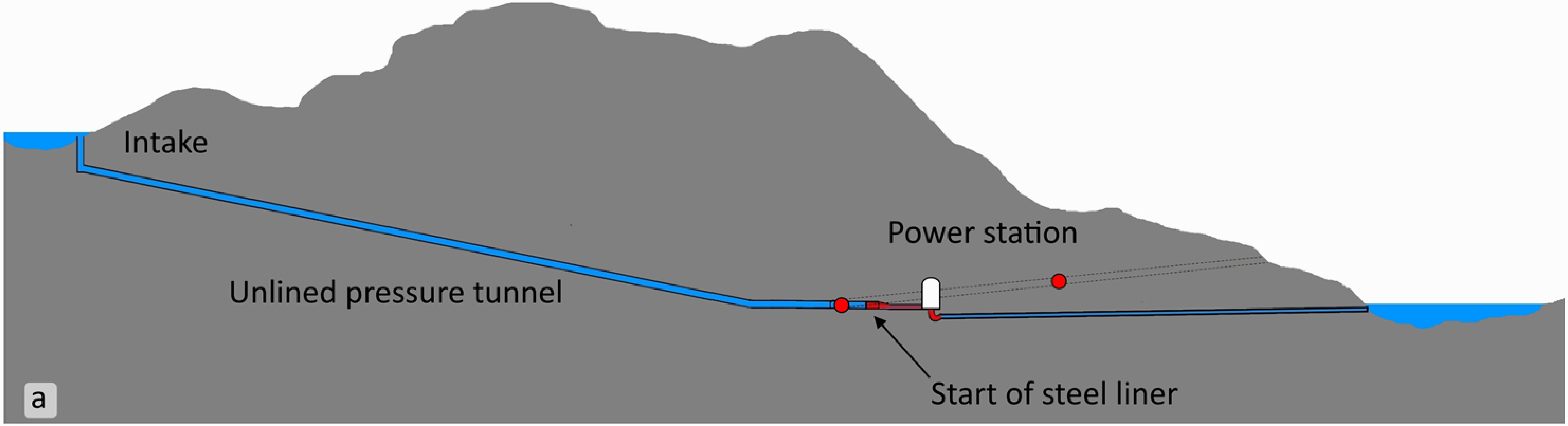
Unlined pressure tunnels - requirements

- Suitable rock mass that is long-term durable
- Water leakage within acceptable limits
- Sufficient *in-situ* stress



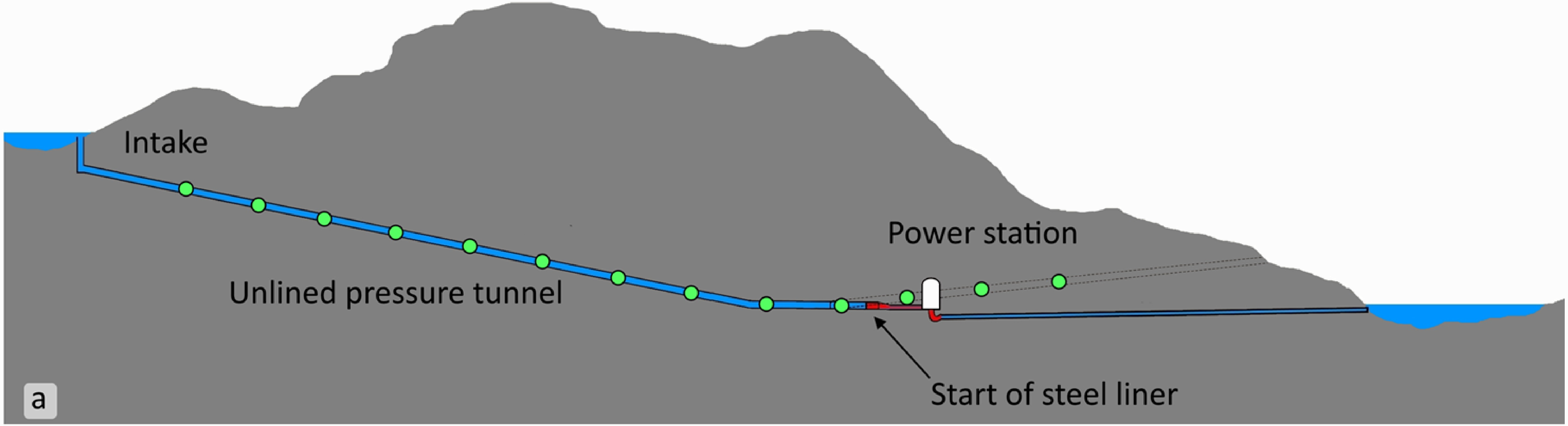
Unlined pressure tunnels – stress estimation

- Current practice based on relatively few test locations (red dots)
- Presumption: Stresses away from measurement location can be predicted to a satisfactory degree of certainty



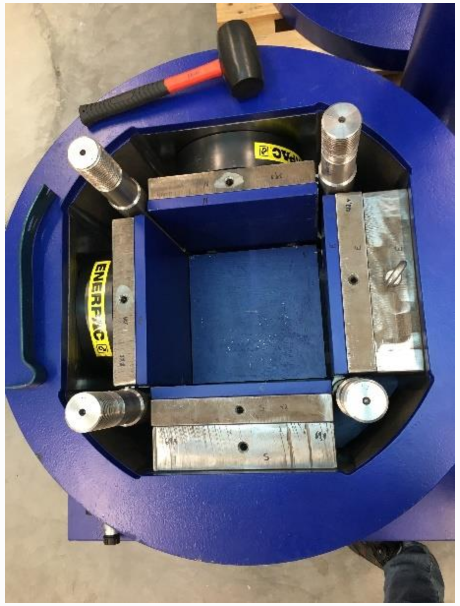
Unlined pressure tunnels – stress estimation

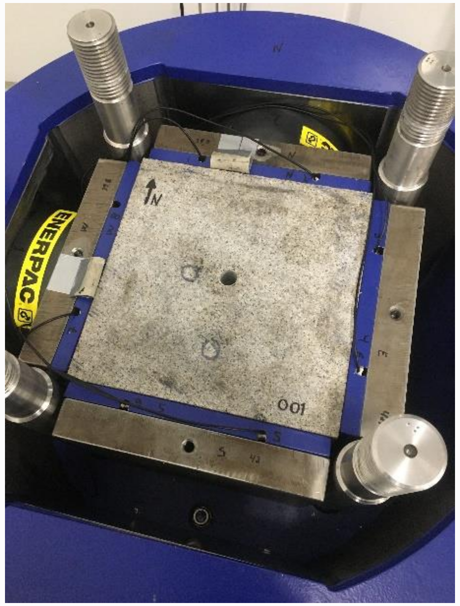
- Point measurements should be replaced by distributed measurements (green dots)
- Can reduce risk of undetected regions of inferior stresses
- This will require rapid and cost-effective measurements



Developing a new test protocol

- Laboratory experiments using custom-built true-triaxial test rig
- Enabled laboratory controlled hydraulic jacking experiments

Test rig - setup

A. Rigid test frame
B. Hydraulic crane
C. Granite specimen
D. Hand pumps
E. Injection pump

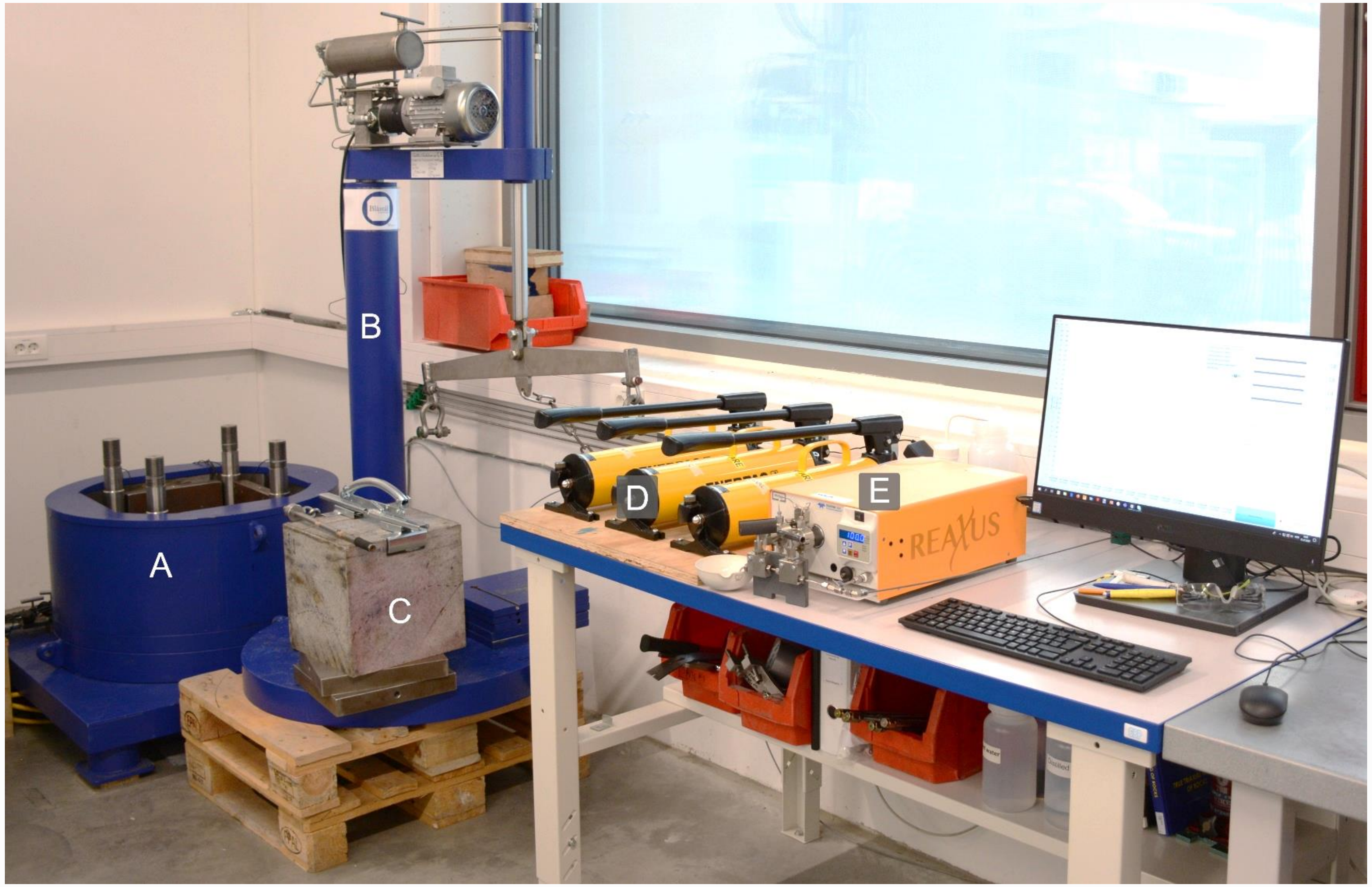
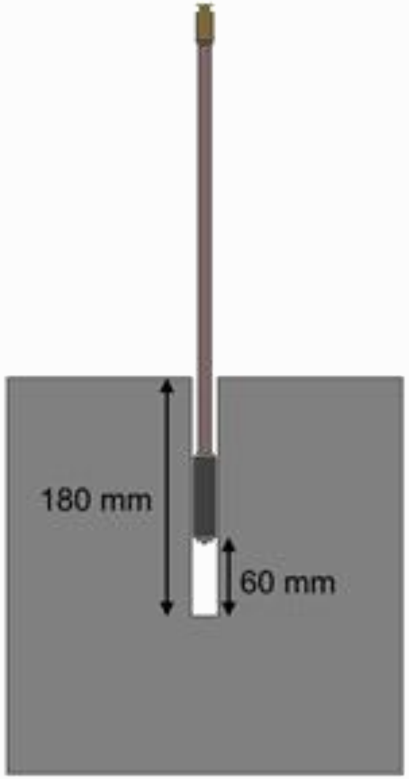


Figure from Ødegaard and Nilsen (2021)

Boreholes and packer

- Specimens hydraulically fractured to create a planar fracture for later testing



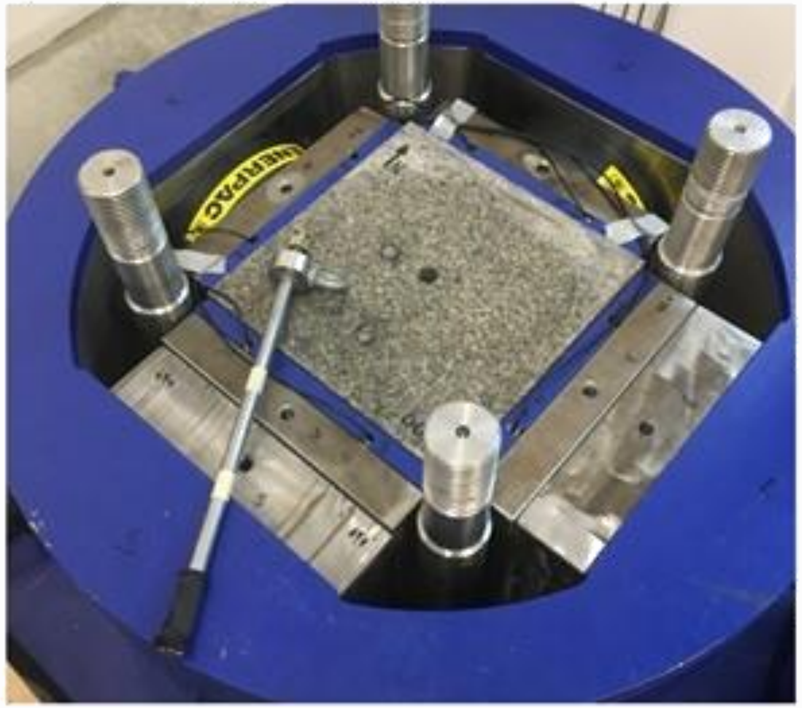
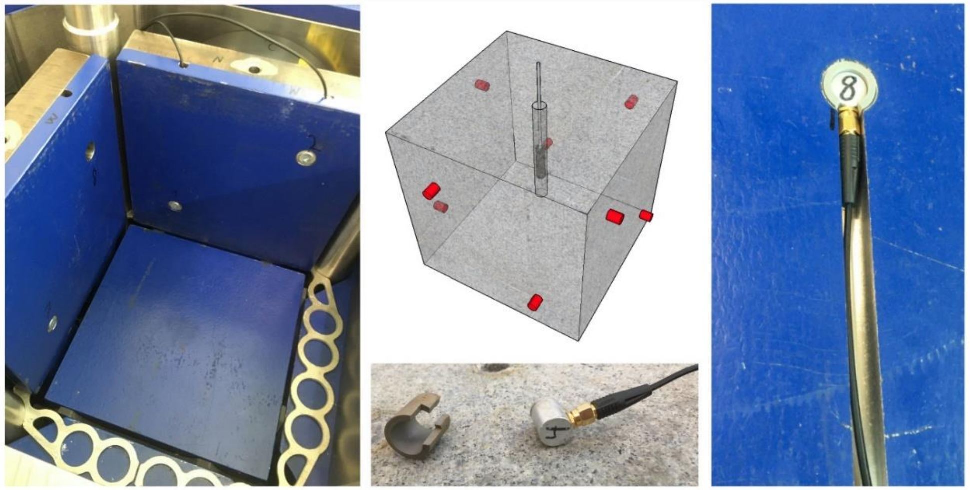
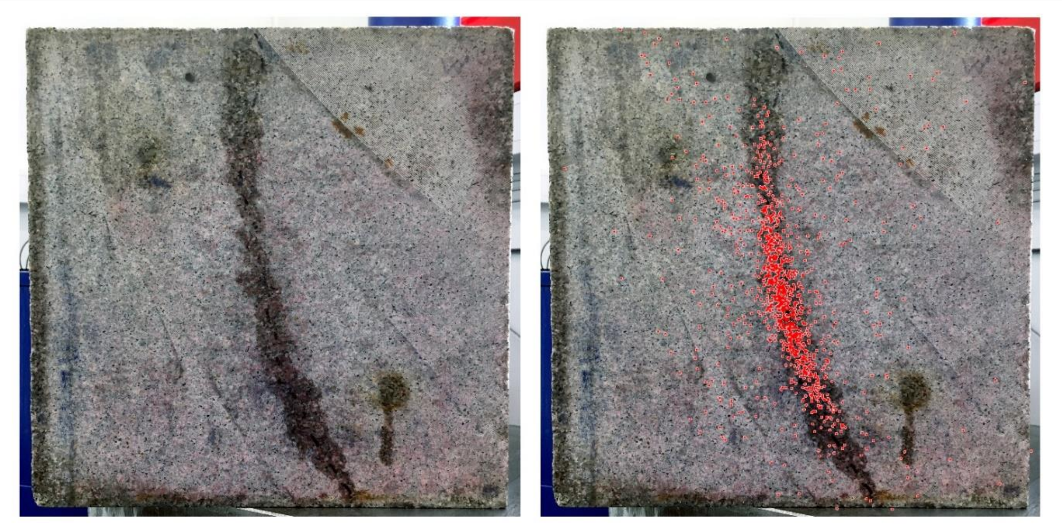


Figure from Ødegaard and Nilsen (2021)

Acoustic Emission Monitoring

- Used to investigate fracture behavior
- Enabled mapping of fracture geometry





Figures modified from Ødegaard and Nilsen (2021)

Laboratory controlled hydraulic jacking tests

- Known fracture geometry
- Stresses are controlled
- σ_n can be calculated
- Enables efficient testing of various testing protocols

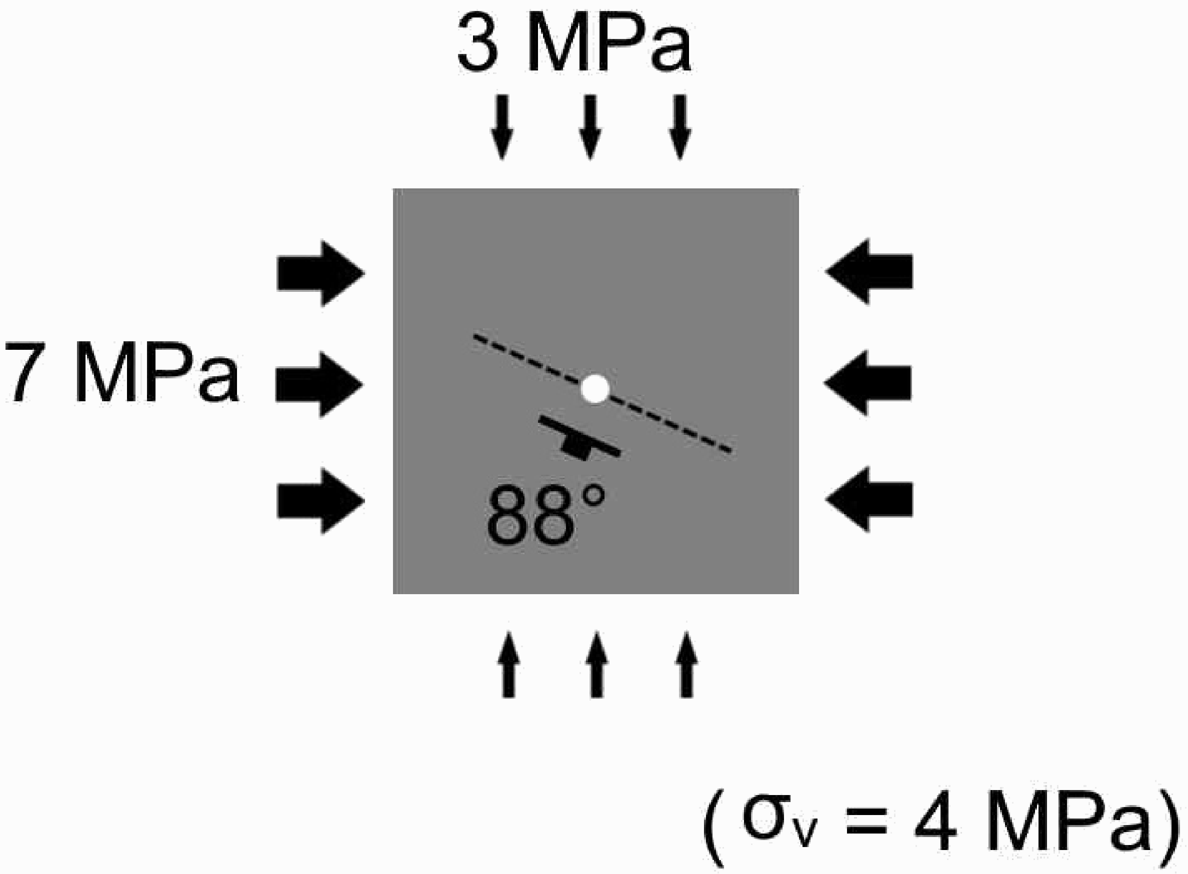
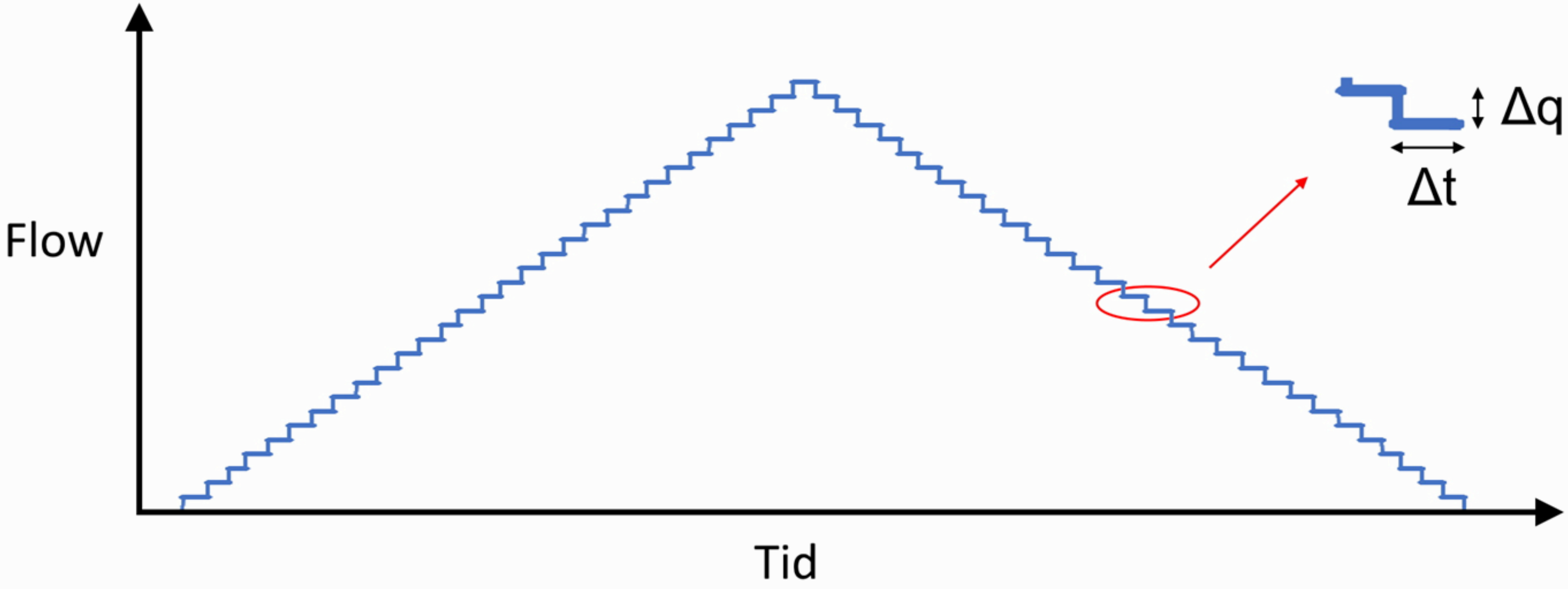


Figure modified from Ødegaard and Nilsen (2021)

Rapid Step-Rate Test (RSRT)

- Forward-step: Flow increased in equal steps, each of the same duration, until jacking (or fracturing)
- Backward-step: Flow decreased in same steps down to zero flow



Rapid Step-Rate Test (RSRT)

- Step height (Δq) and duration (Δt) adapted to local conditions
- Once set, (Δq) and (Δt) are kept unchanged throughout each test cycle

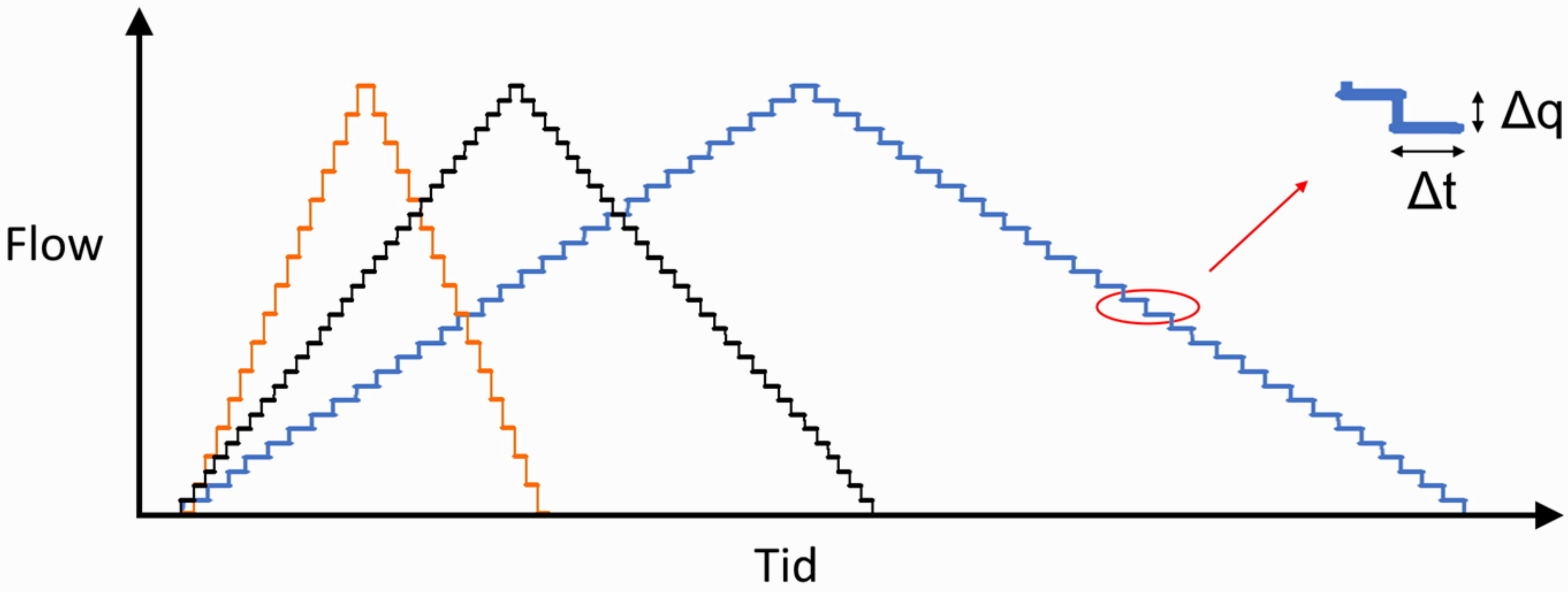
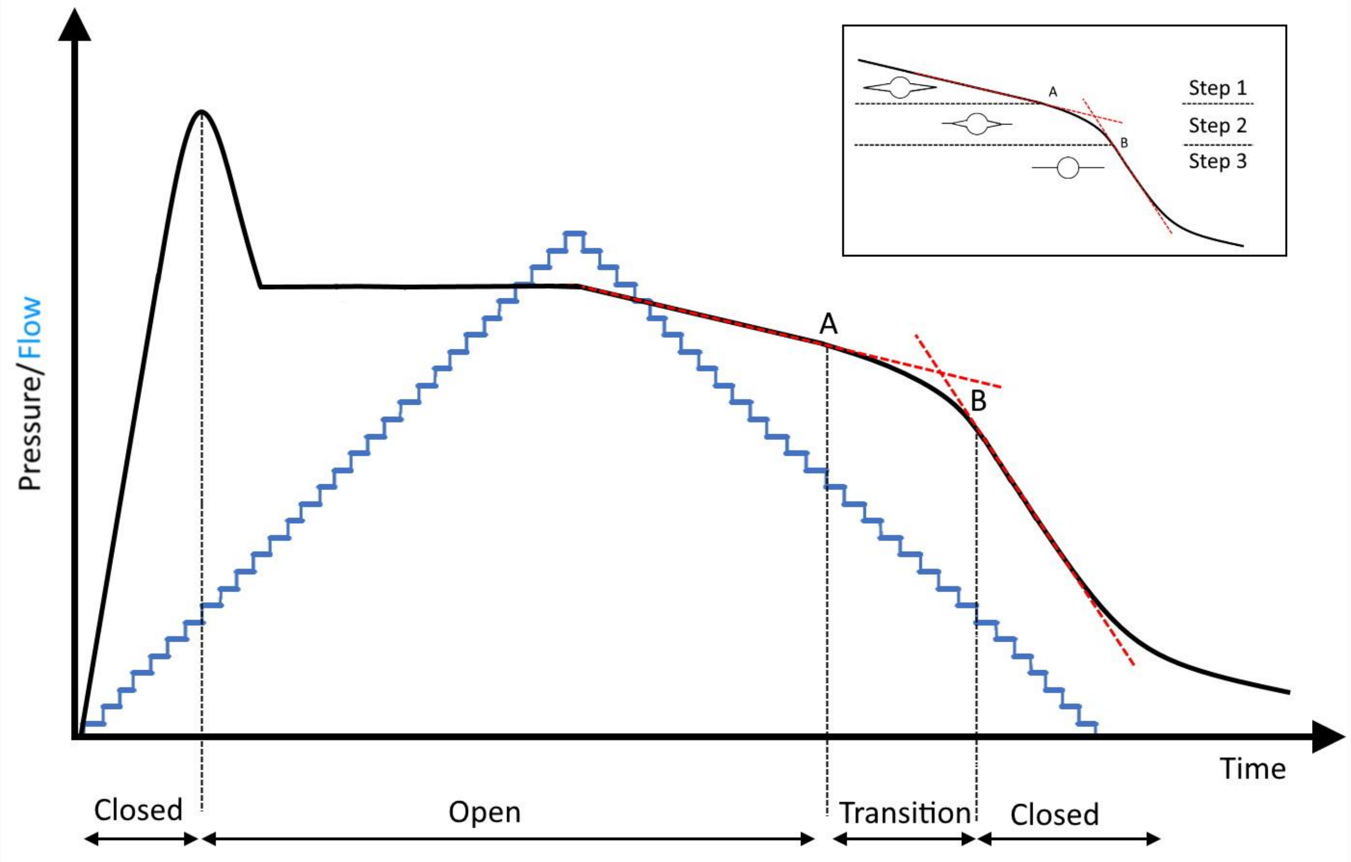


Figure from Ødegaard (2021)

Rapid Step-Rate Test (RSRT)

- The resulting pressure development used to estimate normal stress
- Interpretative technique derived from works of Hayashi and Haimson (1991) and Raaen et al. (2001)



Interpretation of pressure data

- Changes in the hydraulic “stiffness” is detected in pressure data
- Change of stiffness caused by stages in fracture closure:
    1. Hinge-like closure (const. stiffness)
    2. Fracture starting to close by length-reduction
    3. Full (mechanical) closure
- Pressure at end of Stage 1 taken as measure of normal stress across stimulated fracture

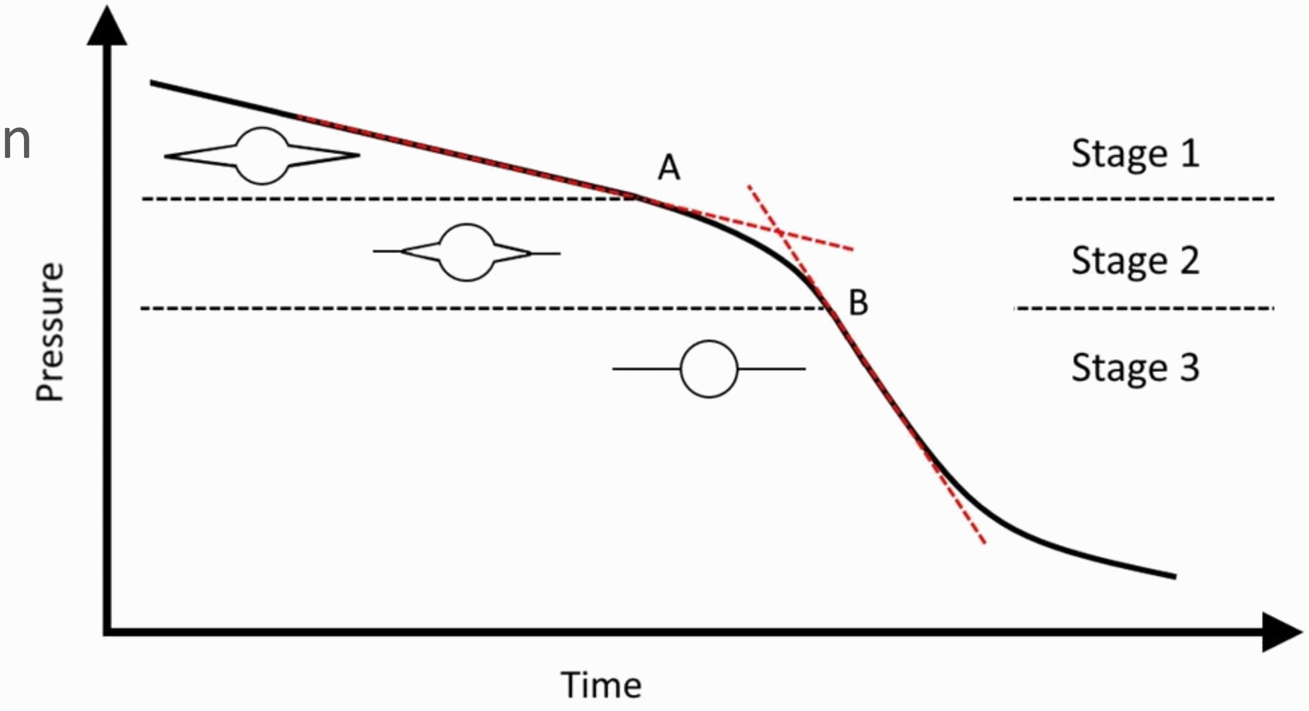


Figure modified from Savitski and Dudley (2011) and Raaen et al. (2001)

Examples from laboratory experiments

- Red line is calculated normal stress

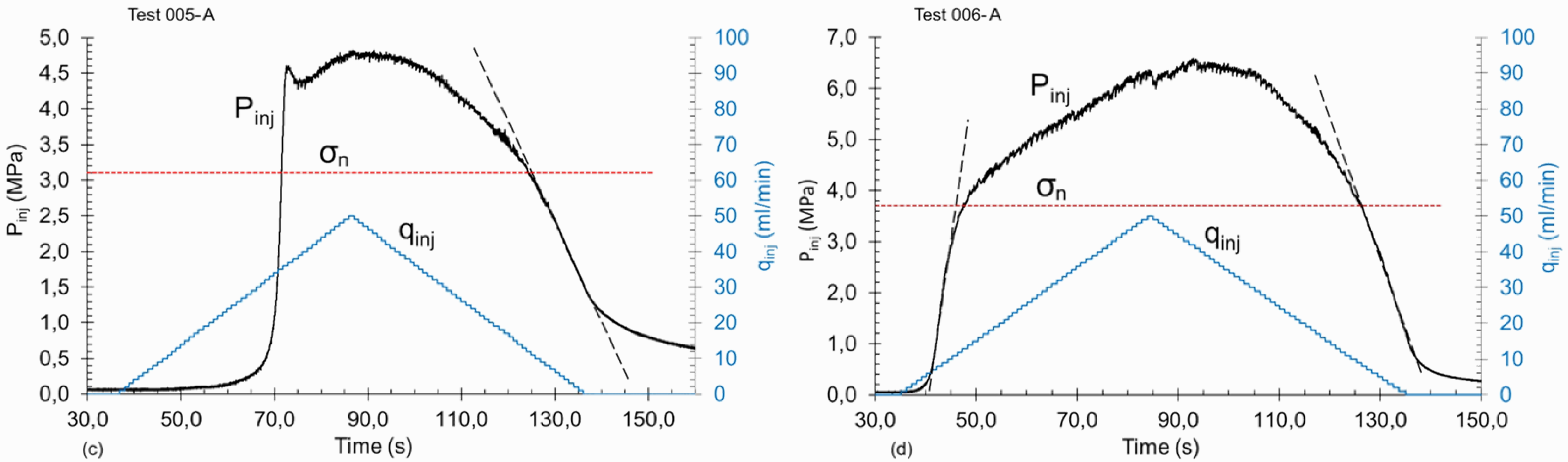


Figure modified from Ødegaard and Nilsen (2021)

Examples from laboratory experiments

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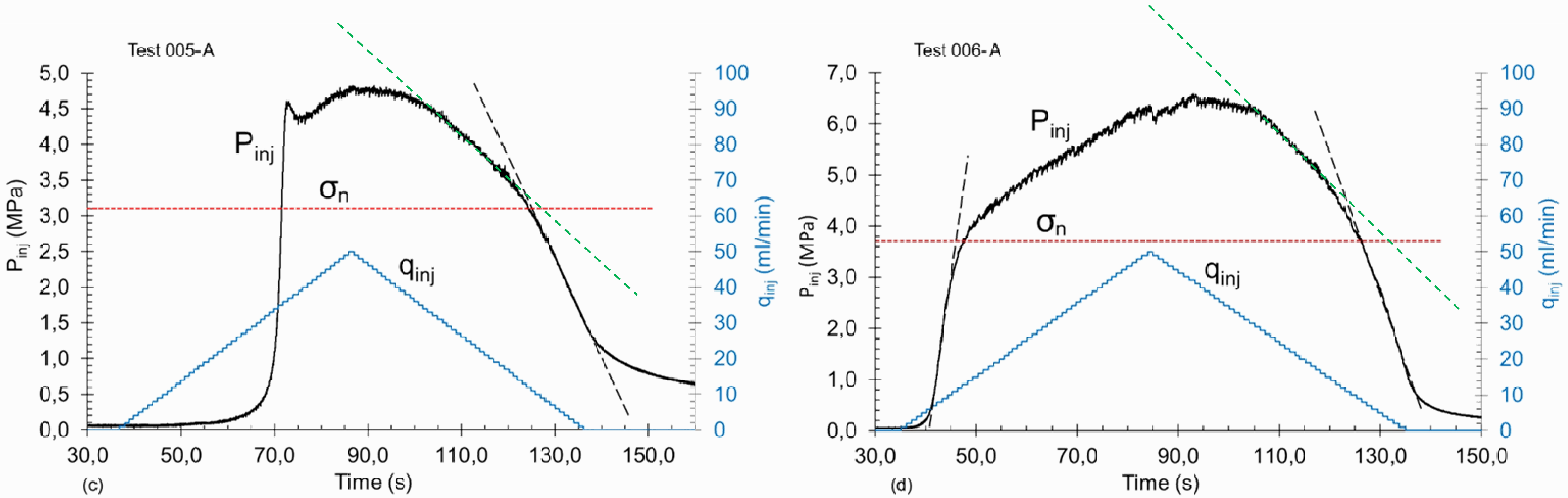
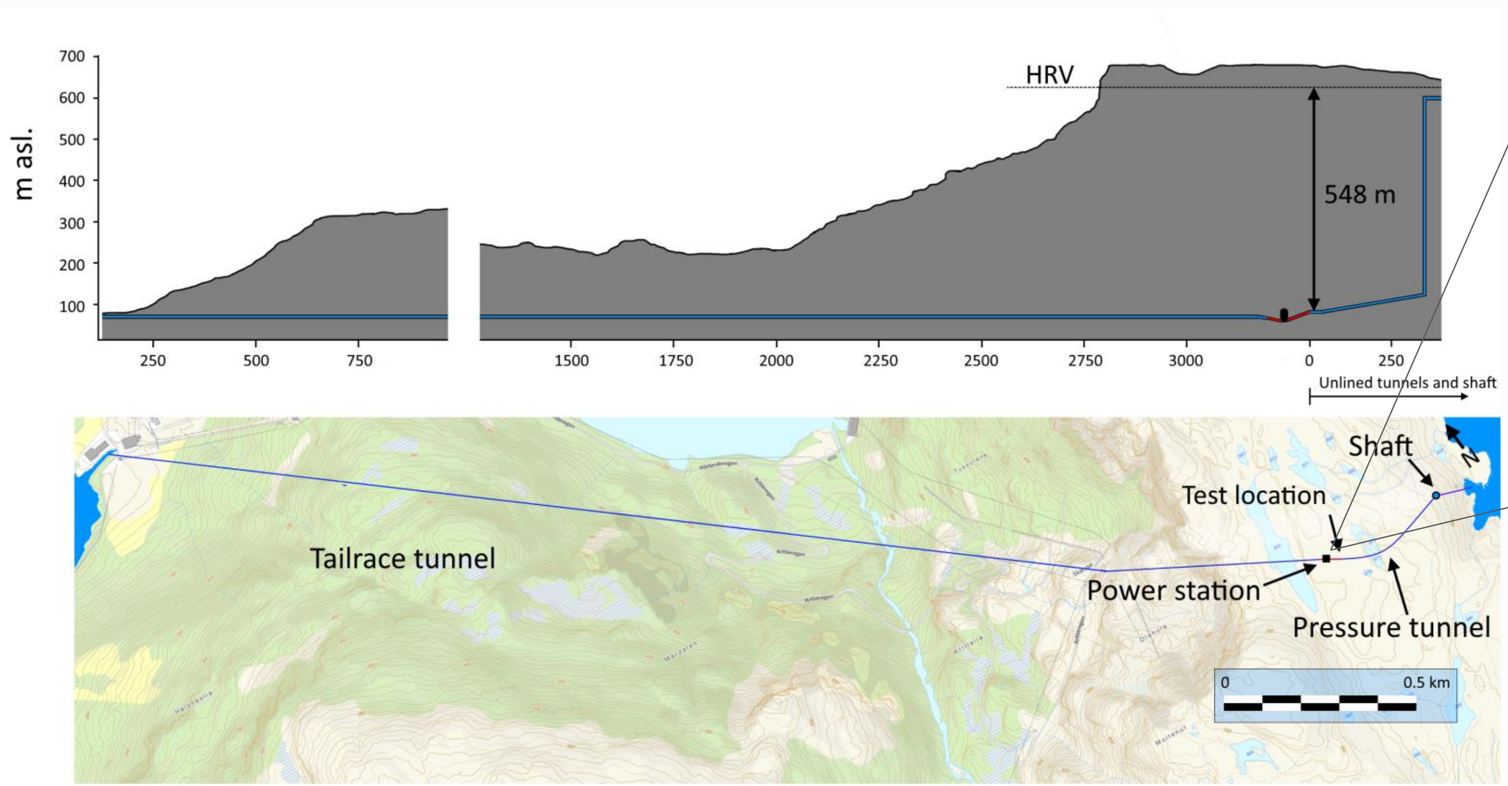
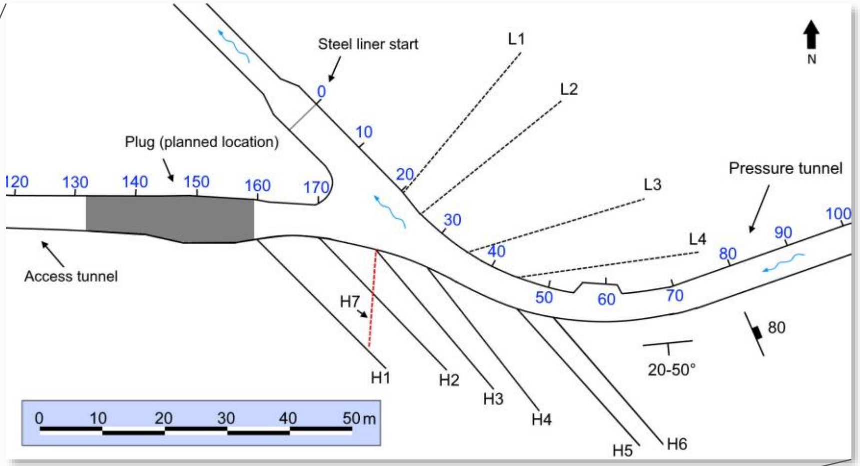


Figure modified from Ødegaard and Nilsen (2021)

Field experiments at the Løkjelsvatn HPP

- 29 test cycles in 7 boreholes





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Field experiments at the Løkjelsvatn HPP

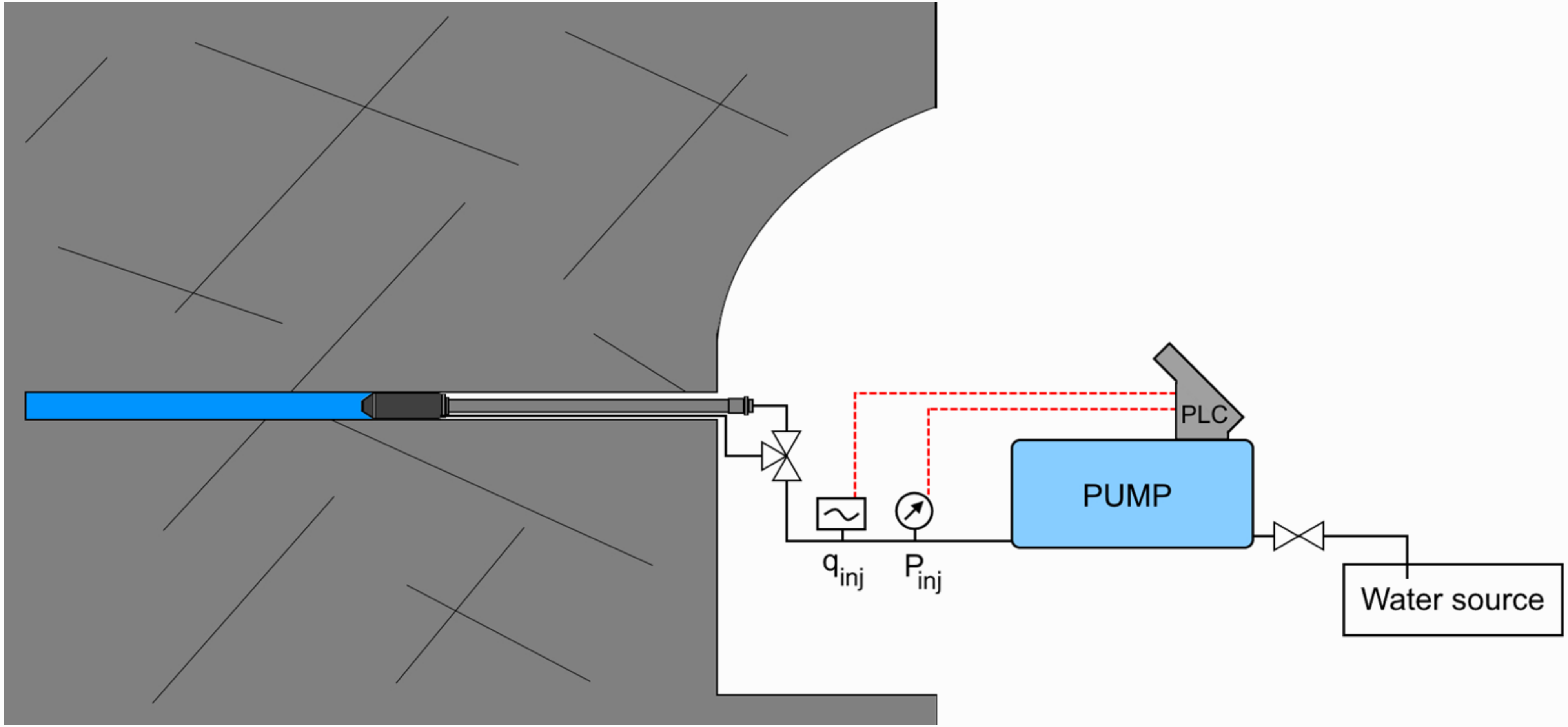

Figure from Ødegaard (2021)

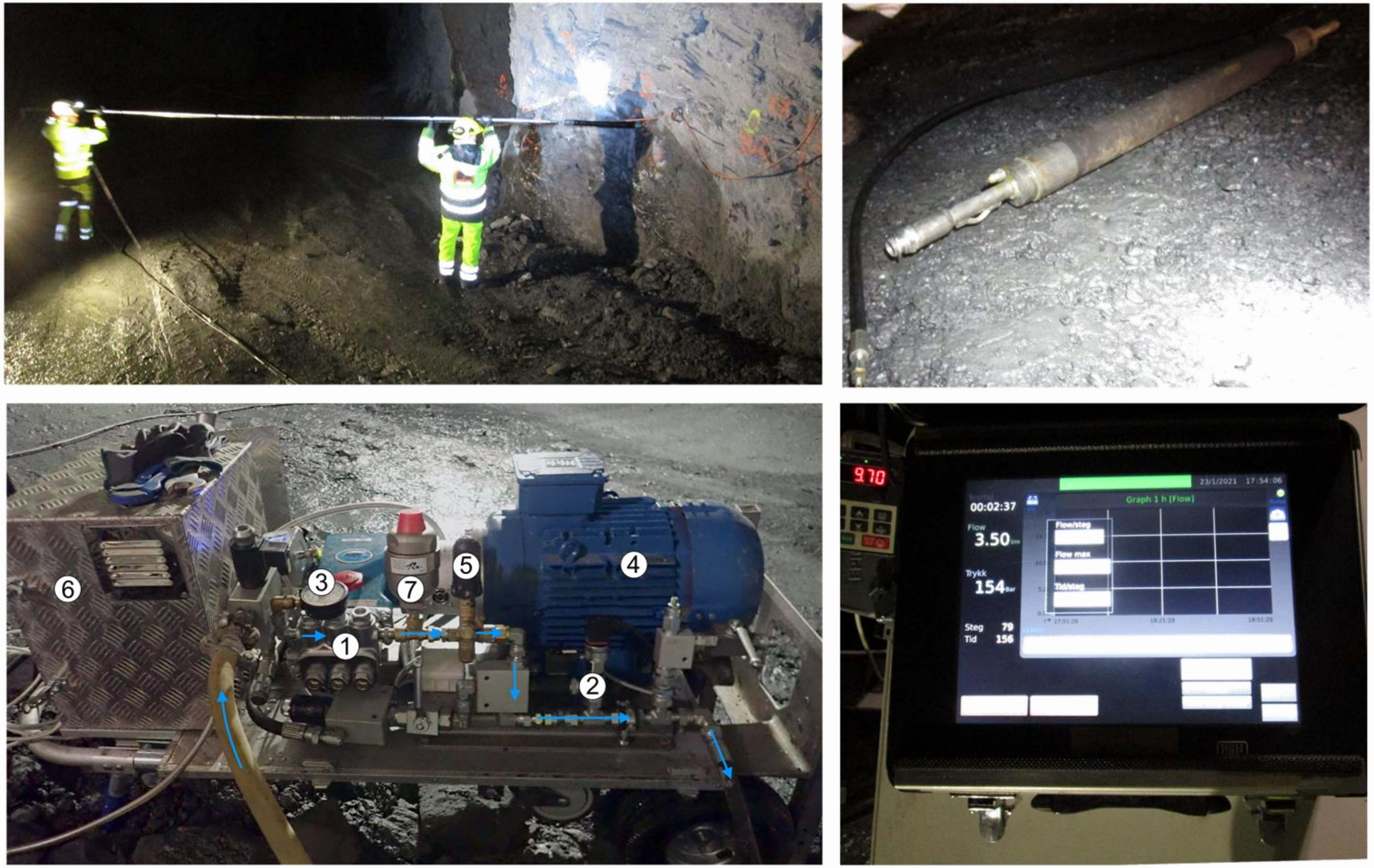

Figure modified from Ødegaard (2021)

RSRT – example of pressure development

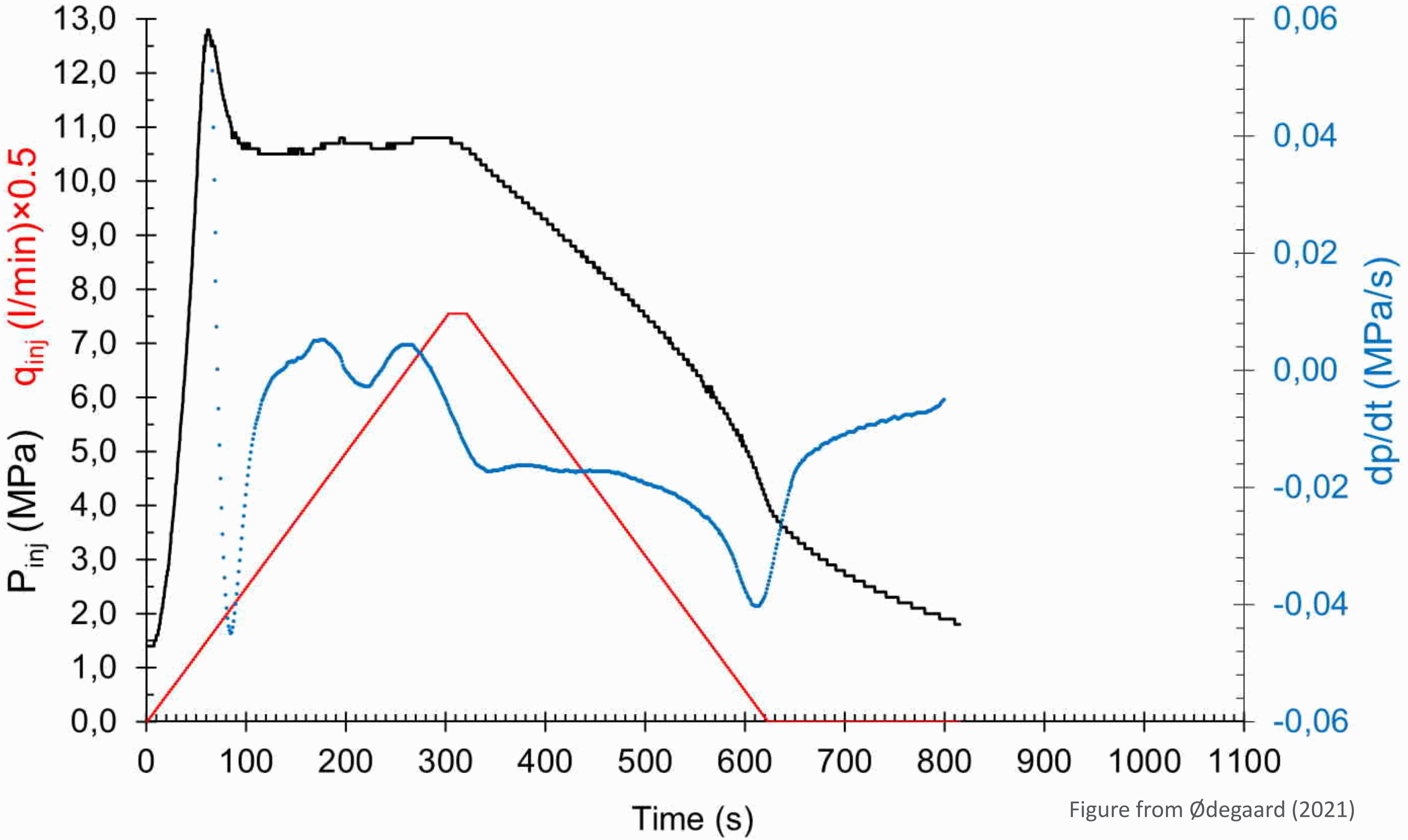

Figure from Ødegaard (2021)

RSRT – example of pressure development

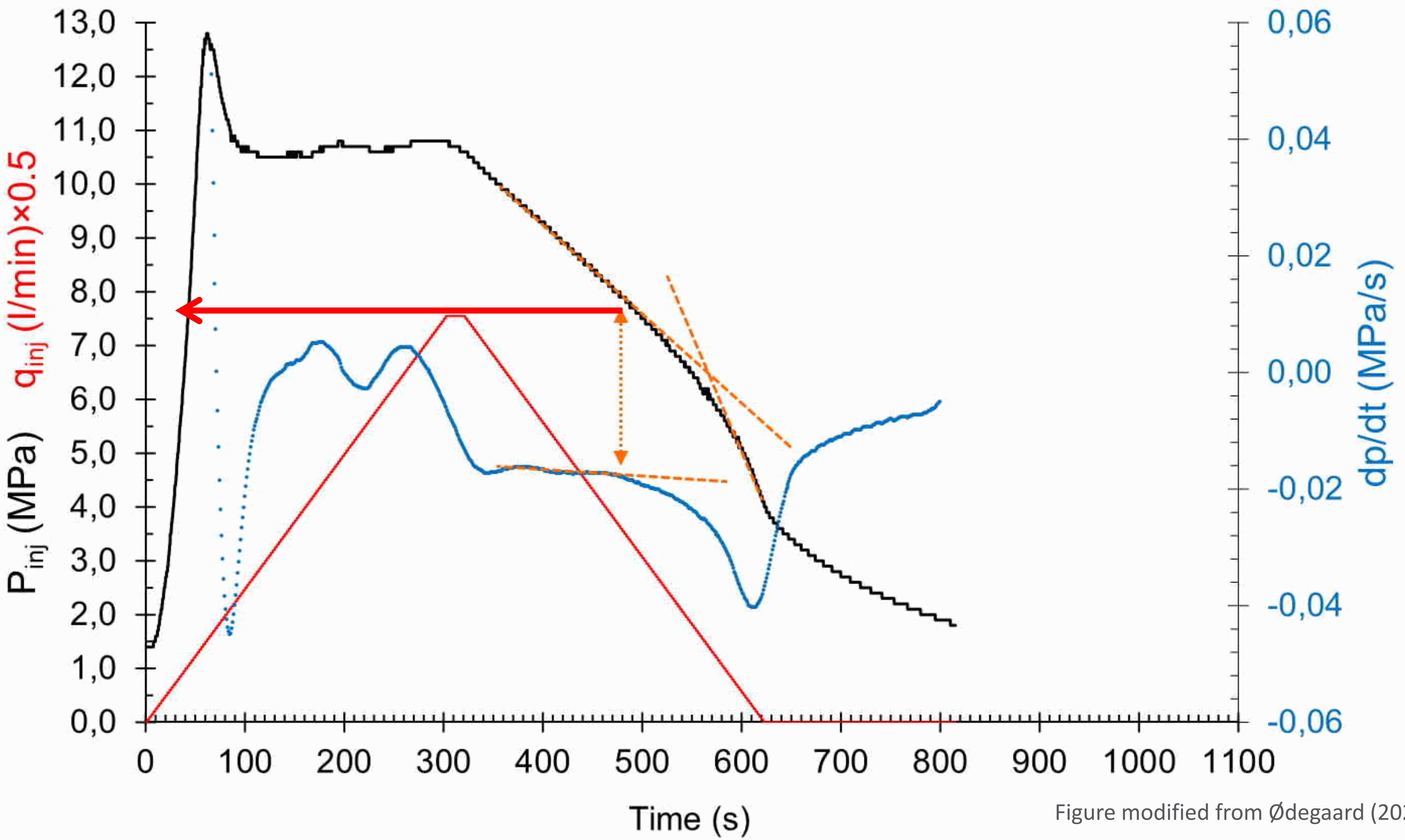

Figure modified from Ødegaard (2021)

Results from field tests at the Løkjelsvatn HPP

- Pressure development very similar to what was seen in lab – fracture closure can be detected
- Result from RSRT correlate reasonably well with values found from preceding HF and OC tests at the same location:
  - σ_n values from RSRT: **7,2 – 8,7 MPa**
  - σ_3 values from HF and OC: **7 – 9,5 MPa**

Summary

- The RSRT test protocol is simple and robust – enables rapid and cost-effective stress estimation
- Interpretative technique is “transparent” – can be done visually in plots of pressure versus linear time
- The term “hydraulic jacking” might be somewhat misleading – many tests are believed to involve initial fracturing
- Where the stimulated fracture is oriented normal to the minimum principal stress can the RSRT estimate σ_3 directly

Thank you!

References

Ødegaard, H. (2021). *Rock Stress Estimation for Unlined Pressure Tunnel Design*. Department of Geoscience and Petroleum. Trondheim, Norway, NTNU. PhD thesis.

Ødegaard, H. and B. Nilsen (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**(6): 21.

Hayashi, K. and B. C. Haimson (1991). *Characteristics of shut-in curves in hydraulic fracturing stress measurements and determination of in situ minimum compressive stress*. Journal of Geophysical Research: Solid Earth **96**(B11): 18311-18321.

Raaen, A. M., et al. (2001). *Stress determination from hydraulic fracturing tests: the system stiffness approach*. International Journal of Rock Mechanics and Mining Sciences **38**(4): 529-541.

Savitski, A. A. and J. W. Dudley (2011). *Revisiting Microfrac In-situ Stress Measurement via Flow Back - A New Protocol*. SPE Annual Technical Conference and Exhibition.