International Society for Rock Mechanics and Rock Engineering
Norwegian Group for Rock Mechanics
ISRM International Symposium
Eurock 2025 – Expanding the Underground Space
Trondheim, Norway, 16-20 June
ISBN 978-82-8208-079-8

Investigating the Relationship Between Grouting Response Curves and Stress Measurements at Fornebu Metro Line

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Abstract

Pressure response curves observed during pumping breaks while rock mass grouting at the Fornebu Metro Line project resemble those expected from hydraulic stress tests. Several 3D-overcoring stress measurements have been conducted at the Fornebu Metro Line project. This study compares the observed shut-in pressures from the response curves with the stress measurements.

Keywords

Rock stress, grouting, stress measurement, hydraulic jacking

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1 Introduction

The Fornebu Metro Line project is an extension of the Oslo Metro Line System, linking the Fornebu peninsula to Oslo. The project consists of approximately 8 km of tunnels with 6 new stations, see Figure 1 for an overview.

Figure 1 Oslo Metro overview with the new Fornebu Metro Line extension

The tunnels have been under construction since 2021 and will be completed early 2026. The new line is expected to open in 2029. The station caverns have spans of up to 25 meters. Some with low rock cover. 3D rock stress measurements have been performed in all station areas to confirm the design assumptions. The project has made a large grouting effort to seal the rock mass to prevent ground settlements. During rock mass grouting, pressure curves like those expected from a hydraulic fracturing tests have been observed during pumping stops. This has raised the question if these curves can be used as simple tests to determine if jacking of fractures are ongoing and how they are related to the rock stress.

2 General Geology

The geology around Oslo consists of sedimentary shales and limestones from the Cambrium-Ordovicium period (approximately 540 to 430 million years ago) (Nakrem & Rasmussen, 2013). These formations have been depressed in a graben structure that developed during the opening of the Oslo fjord in Permian time (around 290 to 250 million years ago). The shale is in contact to older gneisses in the east and younger granites to the west. During the rifting magmatic intrusions penetrated the shale forming sills and dykes. The major fault lines follow the graben in a N-S direction. The shale and limestone encountered by Fornebubanen are both folded and faulted. The strike of the bedding is generally in the NE-SW direction with a dip between 20 to 50 degrees. A second general joint set is steep dipping with strike NW-SE. Random fractures of varying lengths are present. Weakness zones with crushed shale of variable thicknesses have been encountered during excavation. Some of the fracture planes have had a thin kaolinite filling. Most of the gauge material has been crushed rock.

3 Rock Stress Measurements

The design of the tunnel geometry and rock support contains assumptions about the rock stress and rock quality. To verify the stress assumptions several rock stress measurements have been performed using 3D-overcoring. This method drills a hole into undisturbed rock mass from the tunnel and inserts a measuring probe at the end of the borehole inside an inner hole with a smaller diameter. This probe is then “overcored” and strain is measured. Combined with laboratory testing of E-modulus the original stress conditions can be back calculated from the measured strain.

The rock stress measurements at Fornebu Metro Line were conducted by SINTEF and presented to the project in the form of a report. Several measurements along the tunnel axis have been performed but this study focuses on the stress measurement carried out about 100 meters before Vækerø Station, see Figure 2.

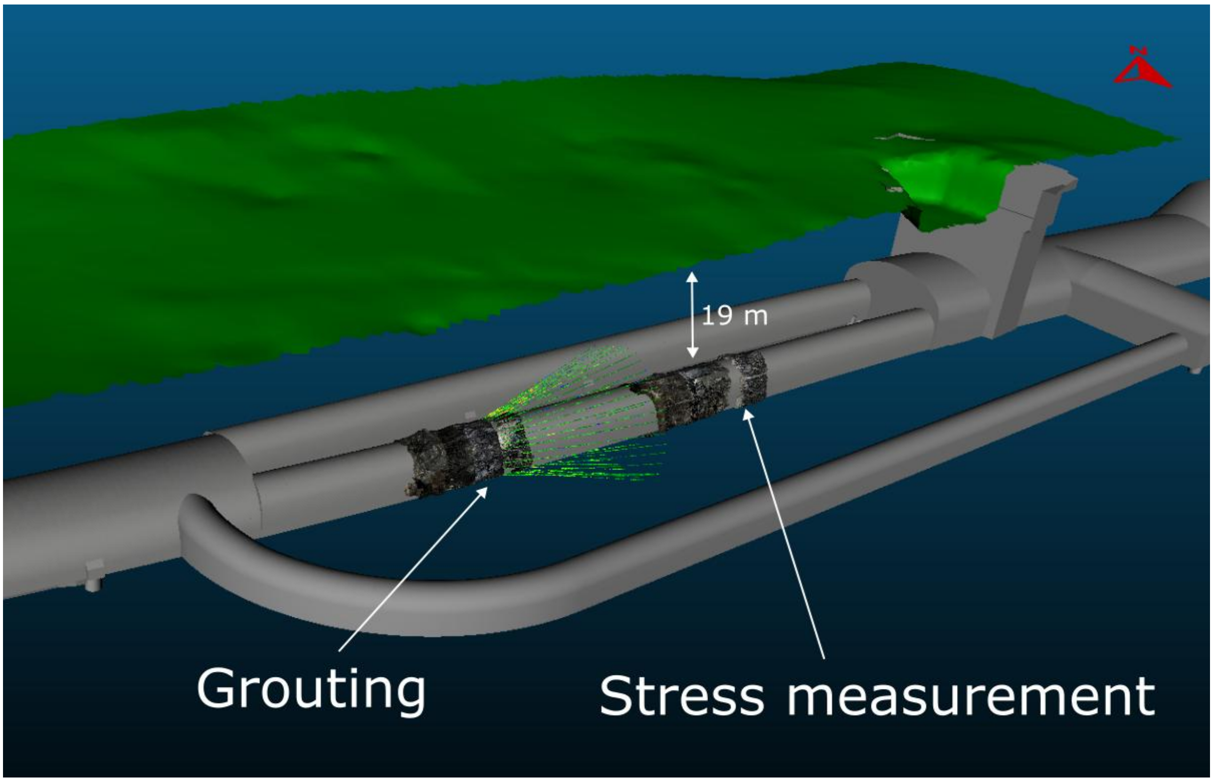

Figure 2 Detailed look of locations of the stress measurement and grout screen with observed shut-in pressures. The green plane represents the top of the rock mass.

Table 1 shows the results of the stress measurement. The largest principal stress is shallow dipping with a plunge of about 30 degrees.

Table 1 Results of in-situ stresses, taken from the SINTEF stress report.

	Mean [MPa]	Average deviation [MPa]	Standard deviation [MPa]	Trend [°]	Plunge [°]
Sigma1	4.60	1.15	1.39	29.60	25.90
Sigma2	2.59	0.43	0.52	124.00	9.00
Sigma3	1.75	0.72	0.89	231.00	62.40

4 Hydraulic Fracturing test (HF)

Hydraulic fracturing test (International Society for Rock Mechanics, 2007) is another method for determining rock stress. The method works by creating or reopen fractures using a pumped liquid. When a fracture is opened, the pump is shut off and the pressure response is measured at the pump. The stop causes the pressure to drop "instantly" before tapering out. The measured pressure where it starts to taper is interpreted as the *shut-in* pressure. This pressure represents the force acting on the fracture by the rock mass itself, i.e. rock stress. An example of a hydro fracturing test is shown in Figure 3.

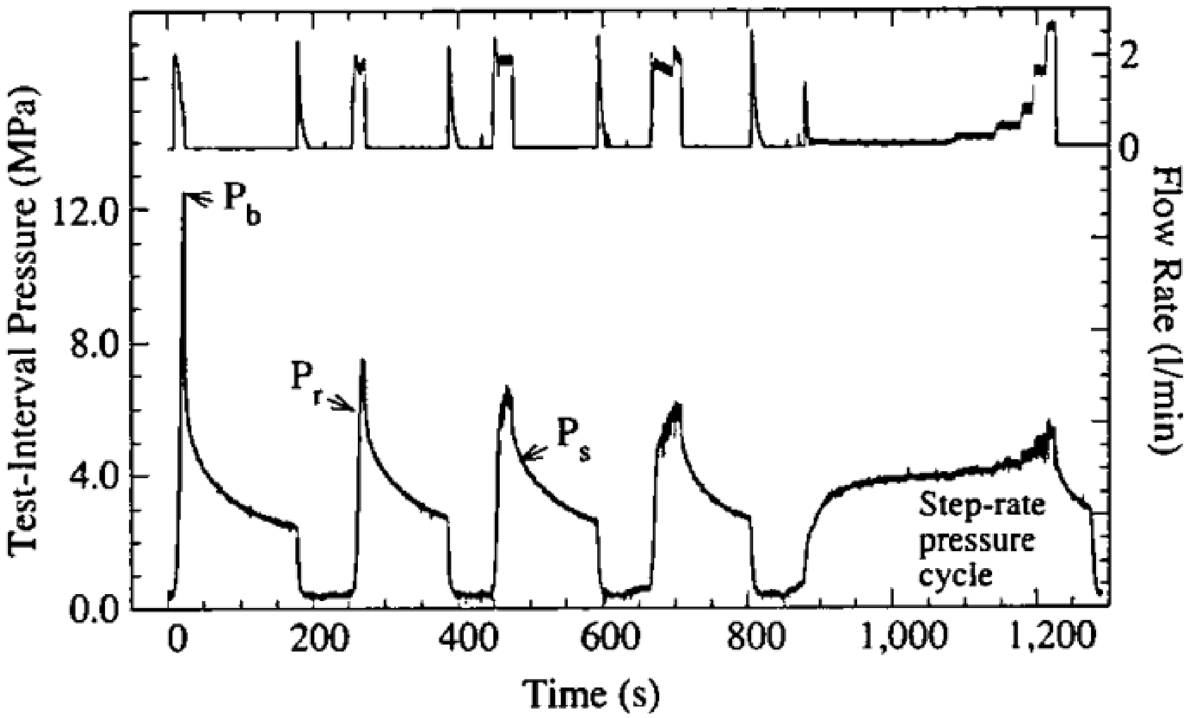

Figure 3 Cycles of measuring the shut-in pressure. Taken from (International Society for Rock Mechanics, 2007).

5 Grouting and hydraulic jacking

Hydraulic jacking is known to occur during grouting. The effects of jacking can be seen as fractures with thick grout filling in the rock mass and/or heaving of the ground above the tunnel. However, determining if jacking occurs during grouting can be difficult.

If no fracture dilatation (jacking) is happening, the grout flow is expected to decrease with grouted volume whilst having a steady grouting pressure. Any deviation from this could be interpreted as ongoing jacking, or grout escaping the rock mass. In practice however, a hole can partly show signs of jacking.

About 2 weeks prior to the stress measurements carried out at Vækerø Station; rock mass grouting was performed at chainage 6030. At this grout screen several pumping stops like those used in a hydraulic fracturing test were performed. The grouting rig was a new "Next Gen" rig from AMV, a Norwegian underground equipment manufacturer. This rig is fitted with a logging software which logs every second. Unfortunately, it does not log when the pump is stopped so digital logs of the pressure tests does not exist. The test data is therefore extracted from the machine's onboard display as seen in Figure 4. The grouting procedure prescribed a grouting pressure ranging from 30 to 15 bars depending on the grouted volume and the rock cover.

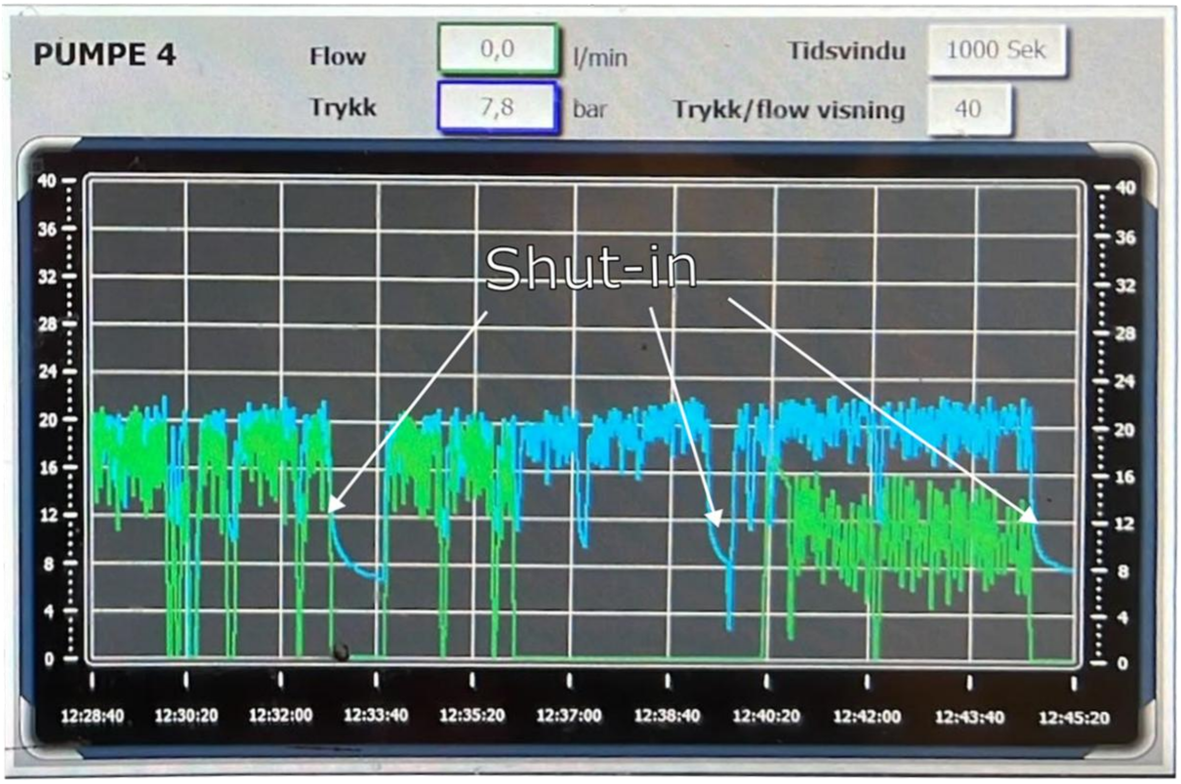

Figure 4. Pressure response curves during grouting when the pump is stopped without venting the pressure

During grouting, hydraulic jacking was suspected when the pressure and flow remained stable, or if the pressure was decreasing with stable or increasing flow. In these holes the pump was stopped without venting the pressure. The pressure response from the rock mass could then be observed on the onboard screen. Figure 4 shows three of these pumping stops with an interpreted shut-in pressure.

A total of 15 pumping stops were performed in 8 different grout holes. The grout holes were placed in the invert and at the tunnel face itself. The shut-in pressure was observed to be between 11-13 bars and 16-18 bars.

6 Geology and measured fractures with grout filling

The tunnel face at chainage 6025, one blast round advance from the grouting face, was mapped with extra attention to fractures with grout filling. Figure 5 show 3D scans of the rockfaces at the grouting and stress measurement location. The rock mass type at both chainages is similar, both consisting of shale. The crown runs along the bedding at both locations, and the right wall runs along a steeply dipping larger fracture. The fracture orientation looks similar, both visually and measured, for both faces. The rock mass was however somewhat weaker at the grouting face with more signs of deformation and less lime content.

Figure 5 Rockfaces at the location of the grouting and the stress measurement

The fracture orientations of grout-filled joints, other joints and the bedding can be seen in the pole plot in Figure 6. The plot also contains the orientation of the principal stresses.

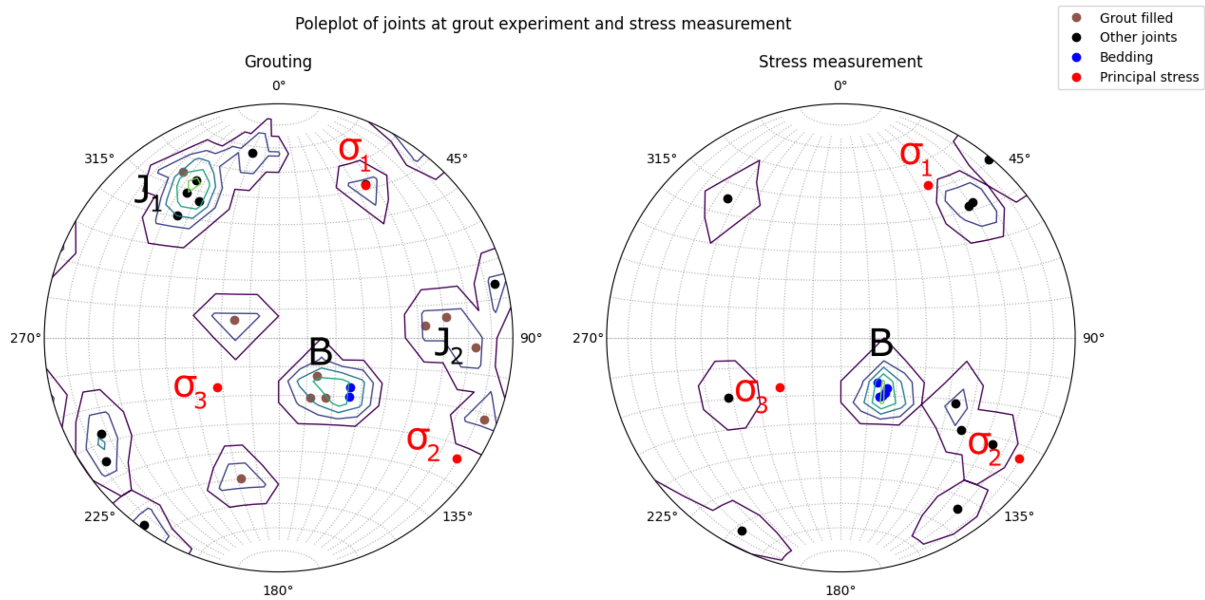

Figure 6 Pole plot of mapped fractures and principal stresses. J = joint set, B = bedding, σ = principal stresses

7 Analysis

The principal stresses given in Table 1 can be used to create a Cauchy stress tensor oriented along the principal stresses. This tensor can then be used to calculate the normal and shear stresses for any direction (Allmendinger, Cardozo, & Fisher, 2012). From the fracture mapping, 3 distinct fracture orientations with an observable grout filling were found. Table 2 show the calculated normal stress acting on these planes. The table uses the standard deviation provided in Table 1 to provide a minimum, mean and maximum value.

Table 2 Normal stress on grout filled fracture planes

Normal vectors for grout filled fractures [°]		Normal Stress [MPa]			Comment
Trend	**Plunge**	**min**	**mean**	**max**	
140	60	1.5	2.2	3.0	Bedding
330	25	2.2	3.1	4.0	J1
80	30	2.6	3.5	4.4	J2

From Table 2 only the bedding has low enough normal stress to provide a shut-in pressure between 11 and 18 bars. Above the tunnel a heaving of about 1 cm has been measured as part of the ground surveillance program.

8 Conclusion

The method of stopping the pump to observe pressure response curves can be used as a simple method to determine if jacking is ongoing during grouting. The response curves can also provide some information about the rock stress if the orientation of the fracture being jacked can be known. In the case of this study the fracture being lifted was most likely the bedding, the most horizontal fracture with the least normal stress acting on it of the fractures found with grout filling. This corresponds well with the measured heaving of the ground.

9 References

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