Geotechnical Aspects of Underground Construction in Soft Ground – Zhou, Guan & Li (eds)

Control of grouting in the bedrock and soil in vicinity of tunnels and construction pits, Case study: E18, Oslo, Norway

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ABSTRACT: Construction of open excavation pits and tunnels below groundwater level in urban areas are continuous geotechnical challenges. Reducing the water ingress to excavations is vital, to limit drawdown of the groundwater head at bedrock level and consequent consolidation settlements in soft clays deposits, which potentially can cause damage to nearby buildings and infrastructure. In connection with the development of the E18 highway near the city of Oslo in Norway, a hydrogeological barrier consisting of sheet pile walls, rock mass pre-grouting and jet column grouting have been designed and executed for a deep excavation in soil and rock. This paper presents the design of the barrier and control of pre-grouting execution which was required to optimize the barrier construction with respect to local ground conditions.

1 INTRODUCTION

Dealing with groundwater during the execution of deep excavations is vital to avoid or reduce damage to nearby buildings and infrastructure. Many studies have been done with respect to rock mass-grouting technology. In some research for example from Rombough et al. (2006); Lombardi (2008); Shuttle et al. (2008); El Tani (2009), the propagation behavior of cement grouting in planar fractures is investigated in detail while other groups such Bremen (1997); Rombough et al. (2006) are more focused on the rheological properties and stability characteristics of cement grout mixed with additives. Besides, safe and sustainable design as highlighted in the Tann (2022 and 2023) paper is key that should be considered in all geotechnical and geological aspects.

Despite many theoretical studies, there are however not many available practical documents showing control documentation, composition and quality of pre-grouting from case studies. In connection with the development of the E18-west corridor highway, near the capital of Norway, Oslo, NGI is engaged to design and quality control of: *a)* The sealing works with rock grouting curtain around the Ramstadsletta deep excavation pit where the abutment for the Høvik-tunnel is going to be established, and *b)* The jet column installation works along the southern area as a sealing measure at the sheet pile toe where the toe is not to be excavated.

This study focuses mainly on the practical process of controlling the rock grouting and jet column installation works. The goal is to avoid or reduce groundwater head draw down of the surrounding areas which may affect the nearby buildings and infrastructure.

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2 BACKGROUND

The first stage of the E18 West Corridor highway is being developed west of Oslo. The location of the project is shown in Figure 1. As is the case with many urbanized areas in Norway, the area around the Ramstadsletta deep excavation is characterized by rock outcrops with intermediary depression zones. Soft marine clay is commonly deposited in these depressions. Layers of more permeable moraine material may be found below the clay above bedrock.

Figure 1. Location of the E18 project in world map and highlighted with red in the local map.

Experience from tunnels and ground water pumping (Langford et al 2016), shows that even small amounts of leakage can result in substantial decrease in pore pressures at bedrock level where the pore pressure reduction triggers settlements on the surrounding areas. During early stages of the design the clay filled depression zones were mapped by ground investigations. Figure 2 shows the extent of the Ramstadsletta excavation pit with the surrounding clay filled depressions.

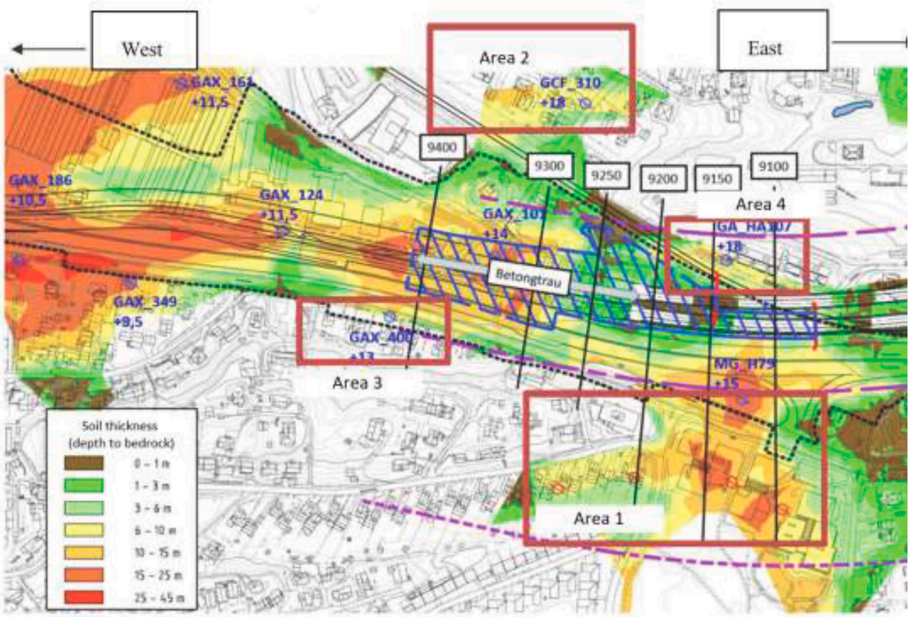

Figure 2. Map of Ramstadsletta, soil thickness to bedrock, areas susceptible to settlement marked with red. The deep excavation is highlighted with the blue hatchet.

As well as investigating depth to bedrock and soil deformation characteristics, the in situ pore pressures were logged over several years prior to the construction work, to determine effects of natural seasonal variations. Based on the thickness of the clay layer and soil deformation characteristics a risk assessment was performed identifying the potential settlements for different groundwater drawdown scenarios in different depression zones. A groundwater barrier as shown in Figure 3 was designed to maintain two different scenarios; *i)* The temporary full drainage of the excavation pit for up to 4 years and *ii)*. The permanent drainage level within the excavation when construction is completed and water levels are reestablished around the water tight concrete structures. The complete groundwater barrier design consists of:

- Steel sheet pile walls to bedrock, including watertight interlocks, corners and anchors
- Concrete beam or jet grouted columns at the sheet pile toe, to seal potential groundwater ingress in the gap between rock and sheet pile through permeable moraine material
- Continuous cement grouting curtain in bedrock below the sheet pile wall down to 10 m under the lowest excavation level and minimum 10m in bedrock.

Figure 3 illustrates the location of the sealing barrier, as well as the recorded level of pore pressure at the rock before the start of construction.

In addition to the groundwater barrier, several water infiltration wells were located in strategic locations around the deep excavation. Wells, where water can be infiltrated into bedrock to counter groundwater head drawdown, temporarily during the construction phase. Furthermore, a large number of piezometers were installed, which all had automatic logging of pore pressures with set limits connected to acceptance criterion for drawdown which would cause damaging settlements. Figure 4 illustrates pore the pressure versus time from one of the closet piezometers to the construction area. This piezometer is installed in the bedrock. Variation on pore pressure is mainly either due to the precipitation (which is plotted in red) or construction activities.

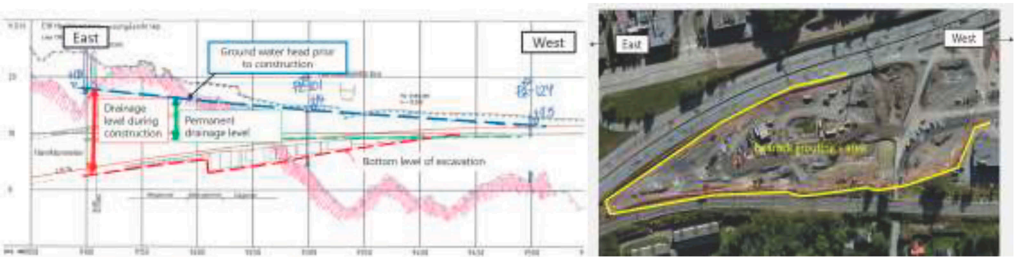

Figure 3. Location of the sealing barrier, as well as the recorded level of pore pressure at the rock before and after the start of construction.

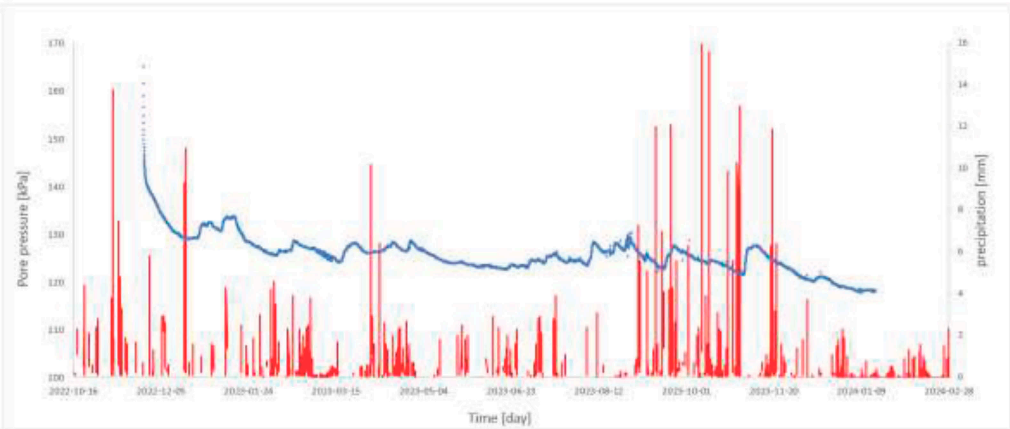

Figure 4. Pore pressure versus time. The left vertical axis shows the amount of rain in mm.

3 ROCK GROUTING CURTAIN

Drilling of grouting holes was performed with a steel casing through soils and typically 0.5 to 1.0 m into rock. In areas where the rock surface was uncovered, the rock hole was drilled directly without any casing. The drilling and pre-grouting works were carried out as a form of “split spacing” as shown in Figure 5. A-holes (center to center- c/c 3.0 m) were first drilled and grouted, then B-holes (c/c 3.0 m). The need for additional drilling C-holes (c/c 1.5 m) between the A- and B-holes was assessed based on reported grouting documentation (volume grouting and grouting pressures) from A- and B-holes.

The holes were drilled to 10 m below the bottom level of the excavation in the relevant profile, and a minimum of 10 m down into the rock. Grouting was performed with packer placement first at approx. 5 m into the rock hole, then at approx. 0.5 m depth in rock, see Figure 5. A grouting procedure with stop criterion for grouting volumes pressure for packer placement 5 m and 0.5 m was suggested. A grouting pressure of 10 bar and 5 bar were used for the packers at 5 m and 0,5 m depth. If the grouting pressure was not achieved, the instruction was to gradually reduce the w/c ratio (water to cement ratio) of the grout and then stop at given volumes injected into the bedrock. The amount stop limits were specified accordingly:

- w/c ratio 1. 0: 100 liters
- w/c ratio 0.7: 200 liters
- w/c ratio 0.5: 200 liters

Grouting was terminated at a total grot-take of 500 liters of grouting if pressure build up was not achieved.

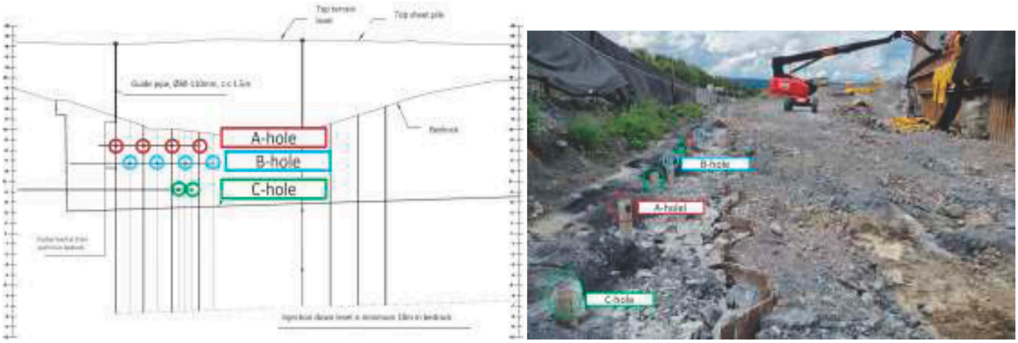

Figure 5. Illustration showing grouting holes with split-spacing procedure and photo of drilled casings for grout holes.

To ensure good progress and rational operation, the contractor was interested to get a specified distance between A-holes where grouting was undergoing, and drilling and grouting of subsequent B-holes. For that reason two criteria were set, both of which must be met. Firstlythe distance between ongoing grouting in A-hole and simultaneous drilling of B-hole

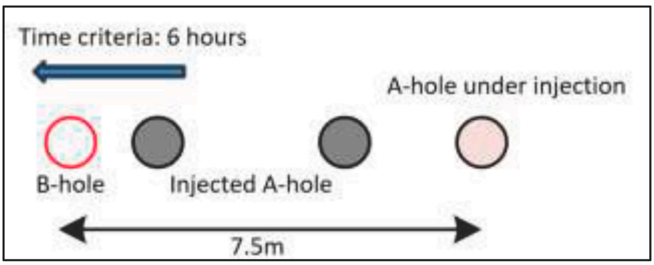

Figure 6. Outline of criteria in relation to distance and time between injected A, and drilling of B holes.

must be large enough to reduce the interaction effects (communication) between holes. The minimum distance from ongoing grouting in A-hole to drilling of B-hole was set to 7.5 m. The second criteria was the time since the nearest A-hole was grouted and drilling of B-hole. It was specified a minimum 6-hour time interval between the nearest A-hole that has been grouted and drilling of B-hole, see Figure 6. Based on following up works in the site, the introduced measures seemed to be working.

4 VISUALIZATION OF DRILLING DATA

All documentation of drilling and injection data was collated through a shared portal with the contractor, NPRA and consulting engineers. With a total of over 700 grouted holes, there was a need to systematize the data. A separate Excel spreadsheet was created where drilling and grouting protocols were systematized and visualized (see Figure 7). The data were sorted based on location coordinates from drilling data. Grouting data was entered and visualized with a color scale based on the completed grouting quantity against set maximum quantities for each w/c ratio. The Excel sheet was used as support for deciding on the need for supplementary grouting holes (C-holes).

In areas where grouting amount is below the stop criteria on volume (liters) on any of the w/c numbers, a color code ''green' has been used. In areas where the stop criteria on volume (liters) of grouting was met, or where back pressure had not been achieved on any of the w/c numbers on either ''A holes'' or neighboring ''B holes'', a color code ''red'' has been assigned and it was deemed necessary to introduce C holes. In any other conditions and depending on amount of grouting compared to the stop criteria, a color shift between lower estimate of ''green'' to upper estimate of ''red'' has been assigned. On a few occasions it also became necessary to introduce D-holes because back pressure was not reached on C-holes. The drilling and grouting data was also visualized in an longitudinal section of the grouting line. This was done both to get an overview of the injection quantities that have passed along the injection line, but also to assess the location of the injection holes against the assumed groundwater level and planned construction bottom, which is visualized in "Grapher" and "bokeh.plotting" (python), see Figure 8.

	Packer at 5 m				Packer at 0.5 m			
BOREHULL	Packer location (kote)	w/c=1	w/c=0.7	w/c=0.5	Packer location (kote)	w/c=1	w/c=0.7	w/c=0.5
L2_A90	10.0	5	0	0	14.5	1	0	0
L2_B89	-4.8	100	102	0	-0.3	7	0	0
L2_A89	-3.2	6	0	0	1.3	3	0	0
L2_C88.1	9.8				14.3	91	0	0
L2_B88	-2.8	100	109	0	1.7	100	200	200
L2_C88	9.8				14.3	100	200	200
L2_A88	-3.2	9	0	0	1.3	4	0	0
L2_B87	-2.8	19	0	0	1.8	20	0	0
L2-A87	-2.5	4	0	0	2.0	4	0	0
L2_B86	-2.2	49	0	0	2.3	104	0	0
L2_A86	-1.6	118	0	0	2.9	3	0	0
L2_B85	0.1	34	0	0	4.6	29	0	0
L2_A85	1.4	100	200	200	5.9	100	52	0
L2_B84	3.7	19	0	0	8.2	6	0	0
L2_A84	4.4	26	0	0	8.9	3	0	0
L2_B83	4.4	21	0	0	8.9	10	0	0
L2_A83	4.4	100	200	200	8.9	100	200	200

Figure 7. An example view of the excel sheet with injection data visualized by color scale.

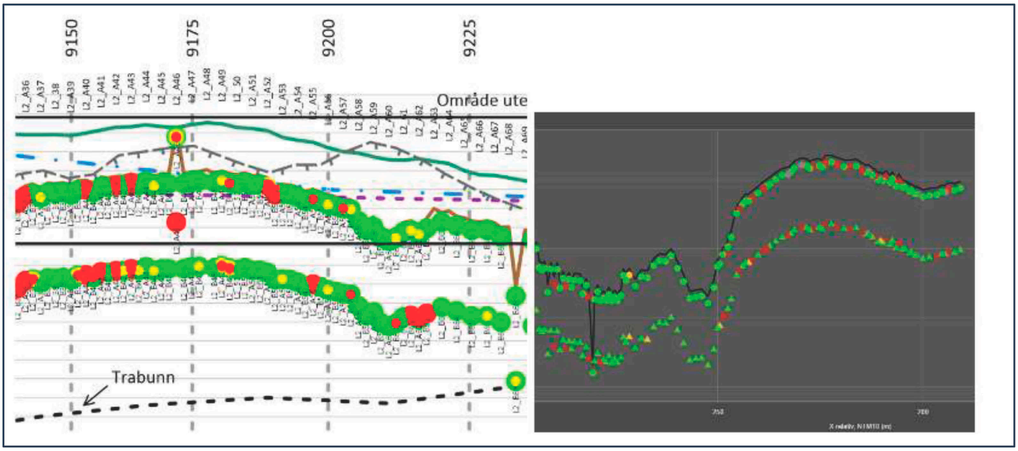

Figure 8. An example of injection data. Left from Grapher, right using bokeh.plotting (python).

5 PERFORMANCE OF GROUNDWATER BARRIER

The risk of obtaining pore pressure decrease due to leakage into an excavation can be reduced by mitigating measures. Combined solutions of sheet pile, grouting in bedrock and jet-grouting are amongst those measures for this project. After finishing the grouting work, very limited leakage (waterproof) was observed in most of the target area which proves a good execution and performance of the grouting work and groundwater barriers. The most leakages observed are through anchors in the sheet pile wall and rock bolt holes. The main reason for such significant leakage was that the anchors were puncturing the grout curtain and opened paths for flow. The introduced measure to stop this leakage is to grout with cement suspension and polyurethane in casings which is still under process.

6 DISCUSSION AND CONCLUTIONS

The following experiences and aspects are gained through the rock grouting work in the project:

i) Systematization of data
Drilling data provides important information regarding the level of the bedrock surface and how high the impermeable barrier ends up in relation to the groundwater level. This is critical information when assessing whether the sealing barrier is acceptable with regard to the requirements in the design. There were cases where the actual rock surface was lower than assumed, so that the sealing barrier ended up at a lower level than designed. This is only recognized when drilling data is post-processed and visualized. It should therefore be specified to the contractor that drilling data should preferably be submitted before the associated injection data.
In other places, it was unclear what level the rock surface actually was, and whether or not casing had been drilled further into the rock than the agreed requirement. For this project, it was agreed that injection data would be sent twice a week, while drilling data would be sent once a week. It is therefore very important that before starting the grouting works, one should investigate the possibilities of achieving a more seamless systematization of drilling and grouting data, by e.g. create a code that acquires data automatically and sorts it, to avoid manual entering of data in spread sheets. Preferably a template could be made for the contractor to use for data documentation and systematization.

ii) Transmission and content of drilling data
During quality control work, rock grouting data were often sent before drilling data. Reentering the correct drilling data (depth to bedrock, length of hole in bedrock etc) afterwards turned out to be time-consuming and a source of error. For example, the rock surface sometimes was discovered to be lower than assumed, and this would affect the intended function of the grouting curtain. Again, a commonly adapted protocol template, improved lines of communication and perhaps utilization of coding for data handling would have benefited the process, reducing hours and errors.

iii) Documentation of w/c numbers and back pressure
It is important that documentation of grouting mass is done according to the w/c number. For grouting work carried out, all mass of w/c=1.0 has been recorded for several holes, with the assumption that quantity criteria for the various w/c numbers have been followed. 500 liters registered at w/c=1.0 means that 100 liters have been grouted for w/c=1.0, 200 liters for w/c=0.7 and 200 liters for w/c=0.5. Data management should then be carried out properly from the start point.

i) Regular site inspection
Regular site visit should always be undertaken by designers if possible. This will help both the designer and the contractor in mutual understanding of different issues which may occur during execution of the drilling and grouting works.

ii) Identification of grouting holes
Hole identification must be consistent through the different manual and electronically kept protocols.

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