Sensitive Passages during Construction of the Norra Länken Road Tunnel System in Stockholm

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1. Introduction

The Norra Länken (Northern link) is an underground road tunnel system connecting the port areas near Värtan (east) to the hospital area Karolinska (west). The extent of Norra Länken is shown in red in Figure 1. The Norra Länken is included as the northern part of the ring road around Stockholm. The construction of the Norra Länken will continue until 2015 when opening is planned. The construction works comprise rock tunnels, concrete tunnels and traffic interchanges that connect to existing road networks. The stretch of the tunnels is mainly below forest and park areas. Only a few residential areas are affected by the construction works. Among the sensitive passages are the crossings with the Metro system, two rail systems Värtabanan and Roslagsbanan, as well as the tunnel entrances. In addition there are a number of areas with low rock coverage. It is however common that areas with low rock coverage coincide with the passage of an above railway; which is of course because the rail was intentionally designed at the low point between the hills to avoid slopes on the railway.

Figure 1. The Norra Länken as part of the ring road around Stockholm.

2. The Passage between the Norra Länken and the Metro

The Norra Länken crosses the Metro six times between the Royal Institute of Technology and the University. In four of these passages the Norra Länken is situated above the Metro and in the other two the Norra Länken is below the Metro, as shown in Figure 2.
Figure 2. Profile of intersection between the Metro (Tunnelbana) and the Norra Länken tunnels.

The large scale geology of the area for the intersection is characterized by the typical fractured crust of Stockholm where deep weathering and erosion has created valleys between blocks of intact rock. The rock mass consists of gneiss, granite and pegmatite and is dominated by a grey and red granite with medium grained texture. A few zones of structural weakness intersect the Metro with directions of NW-SE to WNW-ESE, but they coincide with the passage of road tunnels only where Tunnel 302 passes over and where Tunnel 313 passes under the subway. Mentioned road tunnels pass the same stretch of subway in a 3 level crossing and are thus both intersected by the same minor weakness zone.

The Q-indexed parts of the subway and all the road tunnels have a characteristic value of 10. The rock mass is composed of 2 to 3 joint sets with smooth and planar joints. Joints are typically lacking in mineral coatings and weathering, however exceptions of soft clay have been noted. The excavation was dry and showed only minor ground water inflow.

2.1 Preparation Works and Rock Excavation

At all crossings between the Norra Länken and the Metro, additional rock support was installed in the Metro prior to the construction of the Norra Länken. The additional rock support consisted of net mesh, rock bolts and sprayed concrete. Where the Norra Länken tunnels are situated below the Metro, temporary steel bridges were placed in the Metro tunnel. The temporary bridges will later be replaced with permanent concrete bridges which will be cast in the Norra Länken tunnels.

A sensitive passage during construction was the intersection between Tunnel 302, the Metro and the Physics Centre (see Figure 2) as the distance between the nearby structures was only between a few metres. The rock coverage to the physics centre was calculated to be 4 metres and the rock coverage to the Metro was calculated to be 5 metres. The additional support at this section consisted of double layers of welded mesh (Φ5 mm, pitch 150*150 mm) which were covered with 160 mm of sprayed concrete. Rock bolts Φ22 mm with distance S = 1.0 metre in the ceiling and with S = 1.4 metre in the walls. The bolt length varied according the local situation to between 2.4 and 4 metres.
During excavation, when a tunnel face approached a distance of 50 metres from the Metro and when the vibration levels were expected to exceed 10 mm/s, representatives from the Metro were called to review the planned activities close to the Metro. If the expected $v_{\text{max}}$ was less than 10 mm/s no limitations of the Metro traffic were necessary. If the expected $v_{\text{max}}$ was greater than 10 mm/s Metro traffic should be temporarily halted during the blasting. As 10 mm/s is a very small vibration for blasting at a short distance, the traffic was always halted for a short time during blasting.

Tunnel 302 crosses the Metro at section 2/275. To keep the vibrations at a lower level in the area of the crossing the excavation was carried out by first blasting the gallery and later the bench. In addition the blasting rounds were reduced to 1.5 metres. Based on blasting trials, the agreed maximum vibration level with traffic halted was 92 mm/s. In figure 3 the recorded vibrations from section 5/450 in the Metro are shown. For all blasting events, except for two, the vibration levels were kept below the agreed maximum level. In the figure higher vibration levels are noted in June 2008, which represents the passage of Tunnel 302. Another area with higher vibration levels is noted during October 2008, which represents the passage of tunnel 313. The single recording of 112 mm/s from August 2009 is caused by a simultaneous blasting in both tunnels 313 and 315.

Figure 3. Recorded vibration levels in section 2/275 of the Metro tunnel.

2.2 Adjusted Grouting Concept

The grouting concept at Norra Länken is different from all previously performed grouting concepts in that a continuous updating for different geological situations is performed based on analysis of MWD data (measurement while drilling). The normal grout fan at Norra Länken consists of 35 ordinary grout holes. Initially half of them are drilled and then the MWD data is sent to the client for analysis. During the time the client is analyzing the data, the contractor completes the other half of the ordinary grout holes. Before the drilling is completed the client returns with an order with supplementary grout holes. Additional drilling of grout holes for the grout fan is then performed in necessary areas.

The decision for supplementary holes is based on surveyed geology, previously performed grout fans and analysis of MWD data. The MWD analysis results in three primary data series related to rock strength (ratio scale), fractures (ordinal scale) and water content in fractures (ordinal scale), which can be presented graphically. In Figure 4 the rock strength of an area near the crossing of
Tunnel 302, tunnel 313 and the Metro is shown. Similar images can also be presented for fractures and water. The analysis of the various properties, and identification of irregularities, requires a carefully performed calibration of the MWD analysis tool [2].

![Image](image1)

**Figure 4.** Graphic presentation of rock strength based on interpreted MWD data. In the lower tube the so far unexcavated part surrounding the Metro tunnel can be seen. Grey is low strength, purple is high strength.

The calibration of the MWD analysis tool was performed on the first ten grout fans drilled by each individual drill rig. In each grout hole in the first ten fans the water loss is recorded. The model was then adjusted to give the same recommendation for additional grout holes that a group of geologists and grout engineers estimated based on the water loss, geological survey and previous grouting results. In Figure 5 the additional grout holes, based on the MWD analysis tool, that are required to fulfill the requirements for limitation of water in-flow, are indicated in red.

![Image](image2)

**Figure 5.** Additional grout holes based on the MWD analysis tool are shown in red.

Crossing close to existing tunnels put high demands on the grouting works. As shown in Figure 6, the geometry of the grout fans was adjusted to maintain a minimum distance from the end of the drilled hole to both the Physics Centre foundations above, and to the below Metro.
In addition the amount of grout was adjusted to avoid flow of excess grout into the drainage system of the building above or to the Metro tunnels.

The grout spread in rock takes place in the discrete open fractures of the rock mass. The fracture location and the fracture aperture can be calculated; however the level of uncertainty is often quite high. During grouting work at these sensitive locations, close to the Metro and the Physics Centre, observers were posted to report any excess grout spread. No excess grout spread was noted during the grouting.
To be able to adjust the grouting the rock mass was examined with water loss measurements and MWD. The hydraulic conductivity of the rock mass was calculated to $2.3 \times 10^{-6}$ [1]. The transmissivity $[m^2/s]$ for each fracture was calculated assuming plan parallel geometry of the fractures according to Equation 1:

$$T = \frac{Q \cdot \ln \left( \frac{L_b}{r_w} \right)}{2 \cdot \pi \cdot \Delta h} \tag{1}$$

With:
- $T$ transmissivity $[m^2/s]$  
- $Q$ waterflow $[m^3/s]$  
- $\Delta h$ pressure difference $[-]$  
- $L_b$ length of measurement $[m]$  
- $r_w$ radius of hole $[m]$  

The hydraulic aperture $b_{hyd} [m]$ is then calculated according to equation (2):

$$b_{hyd} = \left( \frac{T \cdot 12 \cdot \mu_w}{\rho_w \cdot g \cdot N_w} \right)^{1/3} \tag{2}$$

With:
- $\rho_w$ density of water $[kg/m^3]$  
- $g$ gravitational acceleration $[m/s^2]$  
- $\mu_w$ viscosity of water $[N/m^2s]$  
- $N_w$ number of fractures with equal aperture $[-]$  

The typical rock mass could then be described by a fracture aperture distribution as shown in Figure 8.

Out of the measured sections, 35 % show no water loss, resulting in an aperture equal to zero. The grouting should then be adjusted to be able to seal fractures with a hydraulic aperture in the range from 0.15 to 0.65 mm. With these values, the rock mass could be regarded as quite open, which was expected due to the shallow location of the tunnel and the blasting and excavation of earlier adjacent tunnels.

![Histogram](image)

Figure 8. Fracture aperture distribution for the rock mass.

The water sealing requirement was stated to a maximum of 2.5 litres over a tunnel length of 100 metres of tunnel. With the existing conditions this requirement results in a demand for sealing of 93% of the initial water in-flow by grouting. If the in-flow for each individual fracture aperture in Figure 8 is accumulated, 93% is equal to seal fractures down to an aperture of 0.2 mm. The maximum allowed grout volume per grout hole was calculated to 115 litres.
2.3 Measurement of Rock Mass Movements by Extensometer

Ten years before the passage between the Norra Länken tunnels and the Metro, 32 extensometers were placed in 16 holes drilled in the ceiling of the Metro tunnel to record any possible rock movements. The locations of the extensometers are shown in Figure 9.

![Extensometer location in the Metro.](image)

Since the additional support installed in the Metro tunnel was calculated with very high safety factors, no significant movements were expected in the Metro tunnel due to excavation of the Norra Länken tunnels. By way of precaution, the 32 extensometers were installed anyway. Tunnel 302 crossed the alignment of the Metro in June 2008. In Figure 10 the recordings from the extensometers are shown. In total ten extensometers were active and the initial values before the crossing began are shown on the y-axis. The values decreased when the tunnel front approached. A decreased value represents an extension of the extensometer rod. Tunnel 302 is located above the Metro, which means an extension of the rock mass between the tunnels. As the newly excavated Tunnel 302 is unsupported, it might be more probably that the floor of Tunnel 302 was lifted. The movement is in accordance with what could be expected. The movement is small, less than 0.5 mm, and the movement is halted within a period of one month. The time period is equal to the time used to excavate the crossing. Based on the movements recorded from the extensometers the rock mass at the crossing was regarded as stable.
3. Discussion

The grouting and blasting operations were adjusted for the six sensitive passages between the Norra Länken and the Metro. The crossings were performed without any interruptions in the operation of the Metro, so far. The movements recorded by the extensometers were very small. The movement was halted after completion of support work. The maximum accepted vibration level was exceeded a few times and the support in the Metro was inspected. No damage to the support system of the Metro could be detected. The accepted maximum level for vibrations was adjusted according to the onsite experience as an agreement between representatives from the Metro and the Norra Länken. The need for cement grouting was adjusted to the local geological situation. The area around the Metro was most probably already affected by the drainage system of the Metro, which made it easier to fulfil the demands on water in-flow to the Norra Länken. Construction of a tunnel that fulfils the requirements for water-tightness was accomplished without affecting surrounding structures. With an adjusted execution of the different activities it was possible to construct crossings at the Metro tunnel at a very short distance without any delays in the Metro traffic.

4. References