Passage under Lövstavägen at Bypass Stockholm – From Design to Realization

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ABSTRACT

The passage under Lövstavägen within the Stockholm Bypass Project has been the first real critical and sensitive area excavated during the construction phase of this important project. In this area, two access ramp tunnels pass under the four-lane road named Lövstavägen.

Above the tunnel crown, 7-10 m of soil and no rock cover had been verified by several investigations. From the top down, the soil consists of man-made ground, a soft clay layer and a water-bearing moraine, followed by the bedrock with varying quality of the rock mass. These circumstances resulted in a very complex tunneling situation with mixed face conditions – competent rock together with soft soil and water. The design phase started in 2013 and resulted in a technical solution including a treatment of the soil with jet grouting from the surface prior to the tunnel excavation and the installation of a pipe umbrella. The temporary support in the tunnel consisted of rock bolts and fibre reinforced shotcrete and was planned to be applied immediately after every blasting round. Finally, a cast-in-place concrete lining was to be installed acting as the permanent ground support with drainage and waterproofing layer behind.

Since the realization of the jet grouting from the surface began in early 2016, several adjustments and improvements to the design solution have been made in order to better fit the real situation met on the site and to allow a faster construction process. In March 2017, the excavation of the ramp tunnel finally reached the Lövstavägen area.

This paper presents the evolution of the technical solution from the design to the as-built situation. In particular, an unexpected fault zone with low rock mass quality together with the 3D implementation of the real rock cover data from the jet grouting led to a partially new evaluation of the temporary rock support. Together with monitoring in and above the tunnel, this allowed a safe crossing under the road Lövstavägen.

Key Words: Monitoring, Jet grouting, Tunnel excavation, Mixed face, As-built, Pipe umbrella

1. INTRODUCTION

The Stockholm bypass – Förbifart Stockholm – is a new motorway linking southern and northern Stockholm resulting in a new route for the European highway E4. To reduce the impact on sensitive natural and cultural environments, just over 18 km of the total of 21 km leads through tunnels and after opening for traffic, it will be one of the longest road tunnels in the world.

The ramps 411 and 412, part of contract FSE403 – Johannelund built by Implenia, which connect the main tunnel and the Vinsta roundabout, pass under the road named Lövstavägen with very little or no rock cover. Above the rock surface, a soil cover with varying thickness from around 7 to 10 meters has been identified by various investigations and confirmed during the construction work. For a successful underpassing of Lövstavägen, auxiliary ground support measures have been considered necessary since the beginning of the design phase. Before the tunnel excavation, a jet grouting body has been performed in order to reduce the permeability of the moraine material and

to increase the strength and stiffness of the moraine material and the overlying soft clay material. A pipe roof umbrella has been installed as an additional support measure. Shotcrete and bolts were applied as temporary rock support to this passage.

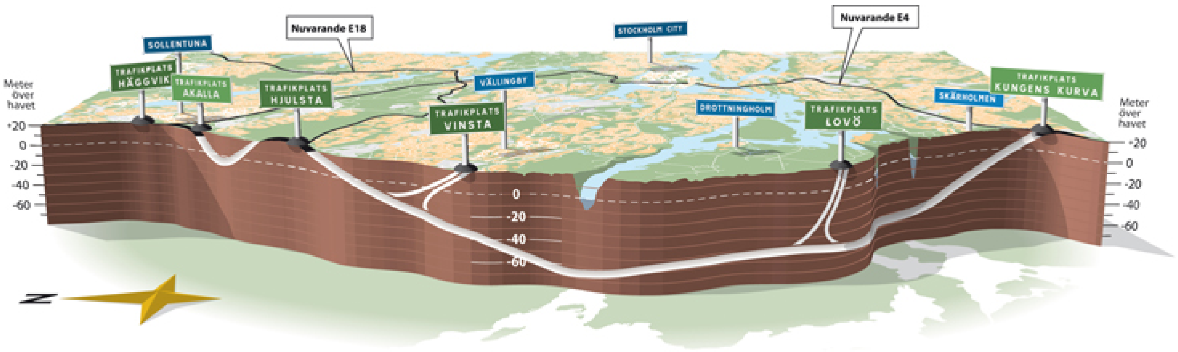

Figure 1. Förbifart Stockholm - Situation

2. PREDICTED GEOLOGICAL CONDITIONS

During the design phase, the rock condition in the area has been predicted to be very good, with a Q_{bas} higher than 10. This assumption was based on the preliminary design studies and extrapolated from the mapping of the area and the Johannelund metro station already built in the vicinity.

On the other hand, the non-cohesive soil located above or at the tunnel crown level was considered highly problematic due to its high permeability and to the related risks for both temporary and permanent support.

3. ORIGINAL DESIGN AND CONSTRUCTION CONCEPT

For a successful underpassing of the road Lövstavägen, several auxiliary measures have been considered during the design phase and they could be divided into two groups – prior to and during the tunnel excavation.

Prior to the tunnel excavation, the soft soil should be treated by jet grouting, executed from the ground surface with vertical drillings. The main reason for jet grouting was to reduce the permeability of the water-bearing moraine material and to increase the strength and stiffness of the moraine. The jet-grouted surface area was planned to be approximately 1100 m^2 and contain 1070 columns with a diameter of 1.5 m. The total estimated grouted length was about 3’600 m. During the tunnel excavation, additional rock grouting ahead of the tunnel was considered to reduce the permeability of the competent rock around the tunnel. To overcome local instabilities, a pipe roof umbrella should be installed in the roof area where the rock cover was lower than 3 m. The pipe umbrella was designed as Ø114 / 6.3 S355 tubes, c/c 33 cm, a length of 15 m with an inclination of 4 degrees offset from the tunnel axis and an overlap of 3 m. The temporary ground support should consist of fiber-reinforced shotcrete with 300 mm thickness applied over the whole tunnel perimeter and rock bolts which should be installed only in the sidewalls with 2m spacing.

Finally, to guarantee 120 years durability a cast-in-place concrete lining with drainage and a waterproofing layer should be installed as the permanent ground support. The thickness of the lining was considered 480 mm and it was designed with standard steel reinforcement. The sealing system should consist of a drainage layer, sheet membrane, and a protective layer along the shotcrete perimeter and a drainage pipe at the wall base.

3.1.1. Jet Grouting and ground improvement

The design of jet grouting was mainly focused on reducing the permeability of the water-bearing moraine material and increasing its strength and stiffness..

- The first task was to determine the grouting scheme and the nominal diameter of each column.
- Secondly, it was necessary to obtain the drilling and grouting length of each individual column.
- Thirdly, it was necessary to prepare a pre-construction test program, which should verify the design assumptions for column diameter and in-situ characteristics such as strength and permeability of the jet grouting treatment zone.

3.1.2. Numerical analysis for ground support

The original check of ground support and the overall stability of the tunnels were carried out by performing a numerical analysis. A 2D plane strain continuous model was used, representing a 175 m wide and 50 m deep section of the ground. The rock and soil masses were modelled using a linear elastic-perfectly plastic Mohr-Coulomb constitutive model. The rock mass and moraine were modelled as fully drained materials while the clay was modelled as an undrained material due to its low permeability. For modeling purposes, it was assumed that the vertical in-situ stress is based on the weight of the rock mass above and the horizontal in-situ stress equals the value $\sigma_h = 0.75^* \sigma_v$ in all directions. The result of the numerical analysis was the response of the ground in terms of the surface settlement, tunnel convergence and the check of internal forces in rock bolts and shotcrete.

3.1.3. Pipe umbrella

For the pipe umbrella analysis, a simple structural model was adopted. The model consisted of a beam with one end simply supported and the other end fixed [1]. The span was chosen to be 1.5 m. The ground load and water pressure was acting on the beam and the contribution of the jet-grouted body is disregarded. This choice can seem overly conservative but was based on the possibility that the jet-grouted material would completely degrade in the long-term, resulting in the pipe umbrella working in an non-cohesive material.

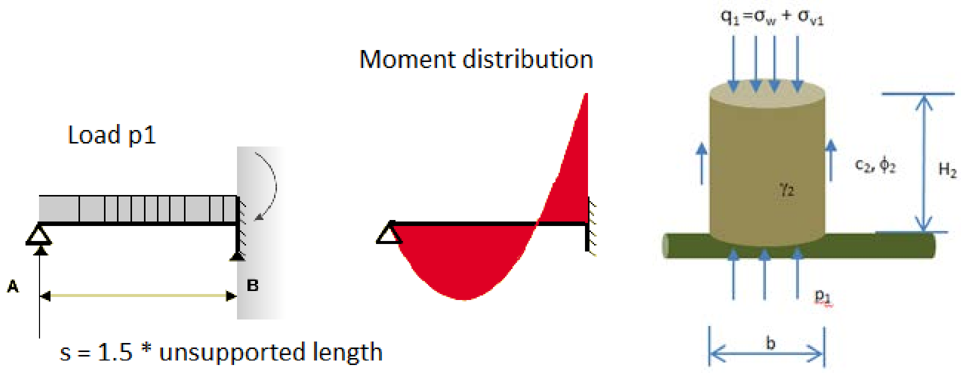

Figure 2. Simplified model for pipe umbrella analysis

3.1.4. Permanent support

The structural analysis of the permanent lining was carried out by using the continuously supported beam-spring model. The interaction between the inner lining and the surrounding ground was simulated by non-linear springs (reacting only to compression). Moreover, in the analyzed case, a full shear slip was simulated between the temporary and permanent lining which led to the situation where loads were transferred only in the radial direction via the radial springs between the permanent lining and the surrounding groundmass.

4. ON-SITE GEOLOGICAL CONDITIONS

Thanks to the jet grouting operation in the area, it has been possible to gather very precise information regarding the rock surface and identify possible critical sections for the upcoming tunnel excavation. The results obtained from several core drillings in the grouted area, extending several meters into the rock mass, showed that the geological prediction made during the design phase would not be met for whole Lövstavägen passage, and that a weakness zone would most likely cross both ramps.

Since the Q_{bas} predicted from the drilling was expected to reach a value of ca. 0.1 in the weakness zone, the basic assumption made in the design for both temporary and permanent support were not valid anymore and a updated verification was required.

Figure 3. Core drilling of the grouted material and rock mass

5. ADJUSTED DESIGN BASED ON REAL CONDITIONS

Taking into account the worse rock mass condition, lower position of rock cover and better strength parameters of the jet grouting, several adjustments and improvements to the design solution have been made in order to better fit the real situation met on the site.

5.1.1. Jet grouting

The lower rock surface above Ramp 411 unfortunately led to the need of an enlargement of the jet grouting area. It was necessary to perform additional jet grouting columns above another 10 m of the tunnel. This also had a direct impact on the pipe umbrella and the permanent lining, which also had to be extended. Additionally, the first round of pipes had to be moved in the direction of the portal as well.

On the other hand, in order to not significantly increase the number of columns, an optimization of the jet grouting was performed, discarding the columns originally positionned between the two ramp tunnels. Together with a reduction of the jet grouting above Ramp 412 due to higher rock cover than predicted, this finally resulted in a total of 1094 columns (1070 were originally designed) with 3’448 m of performed jet grouting.

The results from the core drillings also showed that the quality of the jet grouting was much better (compressive strength 6.0 – 16.5 MPa) than predicted during the design phase (approx. 2 MPa) and this allowed to increase the parameter for the numerical analysis and analytical calculation, balancing, in some way, the worse rock mass conditions.

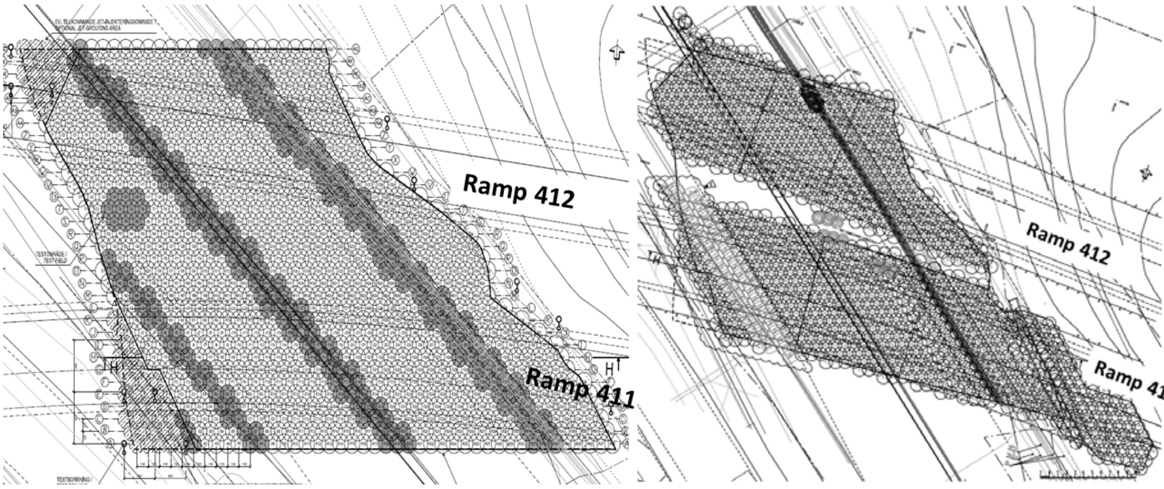

Figure 4. Area of jet grouting in Lövstavägen area (left – original design, right – adapted design)

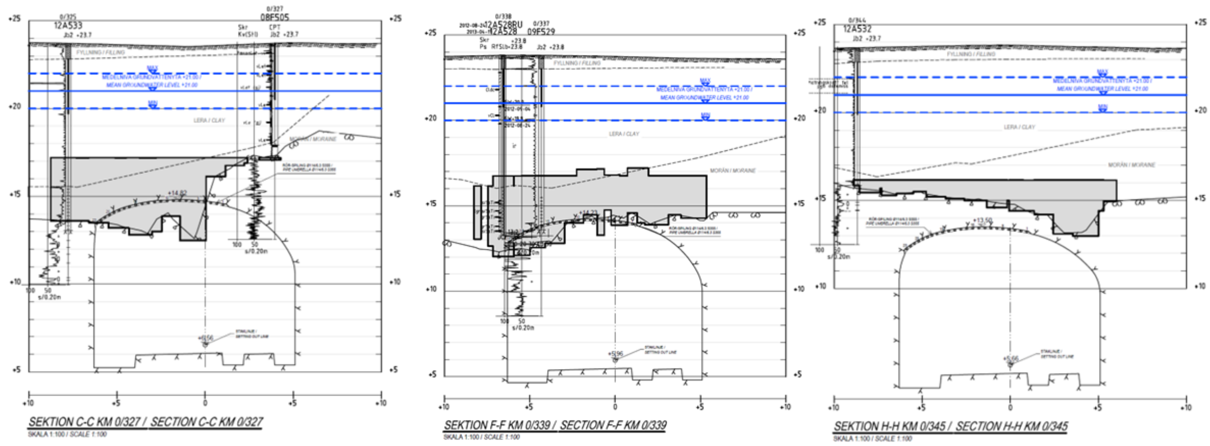

Figure 5. Cross section of the executed jet grouting, ramp 412

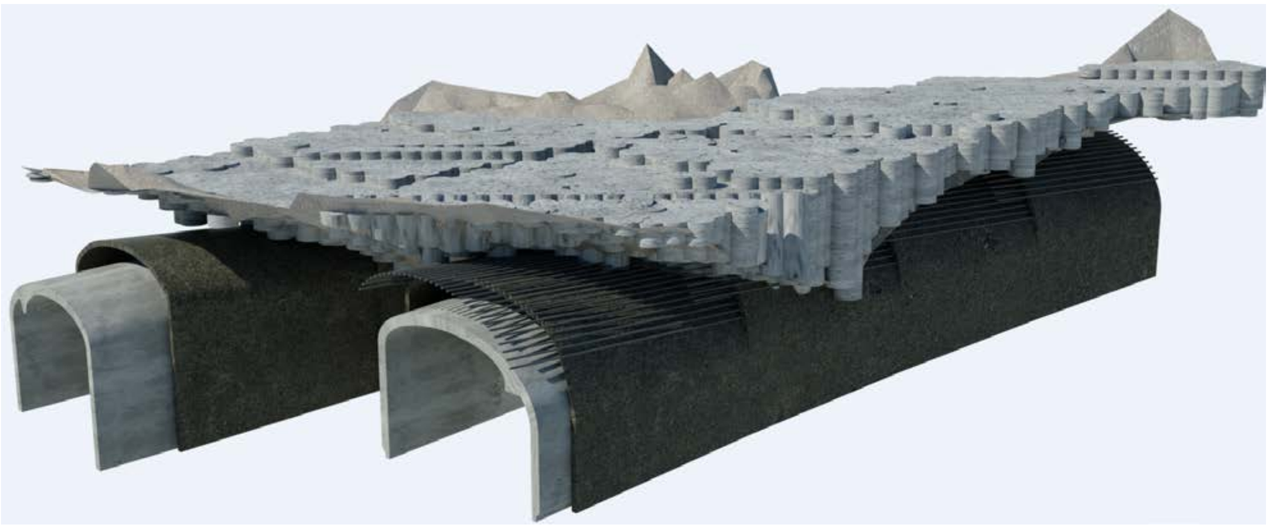

Figure 6. 3D representation of the passage under Lövstavägen

5.1.2. Numerical analysis for ground support

Due to the worse rock conditions and lower rock cover it has been necessary to perform a new numerical analysis to verify the ground support and overall stability of the tunnels with the conditions met at the construction site. Unlike in the original numerical calculation, the discontinuum model has been utilized, in order to better understand where the potential rock stability issues, related to the mapped discontinuities, could lie.

Based on the real conditions mapped on the construction site, the ground and jet grouting parameters have been modified as shown in Table 1 and an interface between jet grouting and soil / rock has been implemented with cohesion c = 0 MPa and friction angle φ = 25°. Moreover, the initial in-situ conditions have been based on a gravity stress field and are described by the following formula:

$$\sigma_h = k_0 \sigma_v \tag{1}$$

Where k_o is the coefficient of lateral earth pressure which can be estimated by ν /(1- ν).

Table 1. Geotechnical ground parameters for the numerical analysis

	Q_{bas} - value	Weight density	Cohesion	Friction angle	Undrained shear strength	Poisson's ratio	Young's modulus
	[-]	γ [kN/m³]	c [MPa]	Φ [°]	c_u [MPa]	ν [-]	E [GPa]
Rock – Case# 1	1-4	26.5	1.0	45	-	0.25	10
Rock – Case# 2	0.1-1	26.5	0.5	30	-	0.25	3.0
Clay	-	19.0	0.003	30.0	0.03	0.4	0.012
Moraine	-	19.0	0.0	35.0	-	0.3	0.025
Jet grouting	-	21.0	1.0 *	35.0	-	0.3	1.8

* The adopted cohesion of 1 MPa for the jet grouting is equivalent to a compressive strength of 4 MPa and in line or even conservative if compared with the results on core drilling

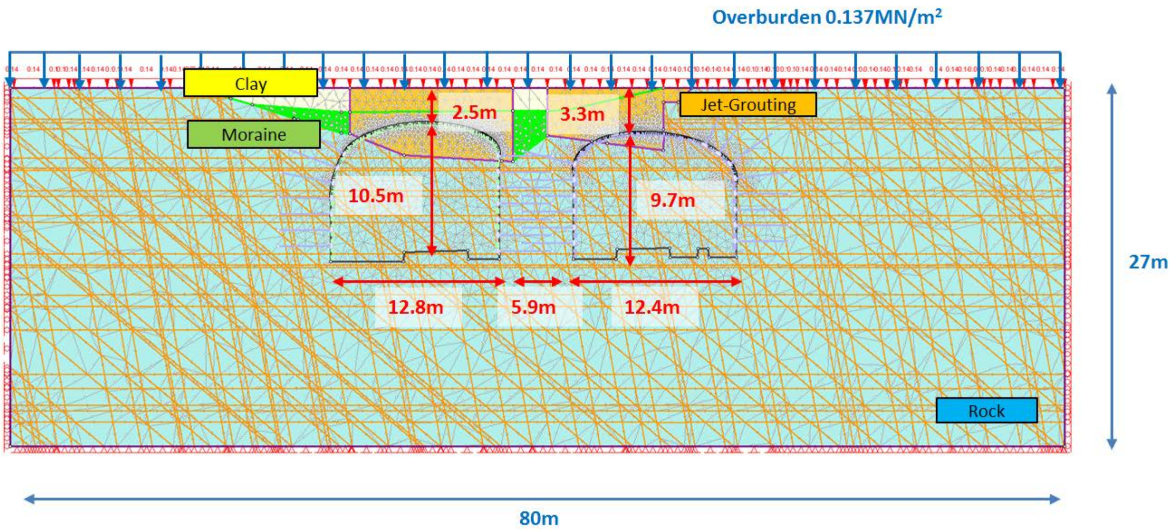

Figure 7. Cross section analyzed during the construction phase

The results of the numerical analysis led to a slight modification of the temporary rock support for ramp 412 and ramp 411 compared to the original design:

- Pipe umbrella in the crown - diameter 114mm, thickness 6.3mm, S355, c/c distance from 350 to 500mm (original c/c was 330mm)
- Sprayed fibre reinforced concrete – thickness 300mm, C32/40 (unchanged)
- Rock bolts in walls and haunch – 4m length, systematic bolting 1.3m x 1.3m for 0.1 < Qbas <1,
- Rock bolts in walls and haunch – 4m length, systematic bolting 1.5m x 1.5m for 1 < Qbas <4
- Rock bolts in walls and haunch – 3m length, systematic bolting 2.0m x 2.0m for Qbas > 4

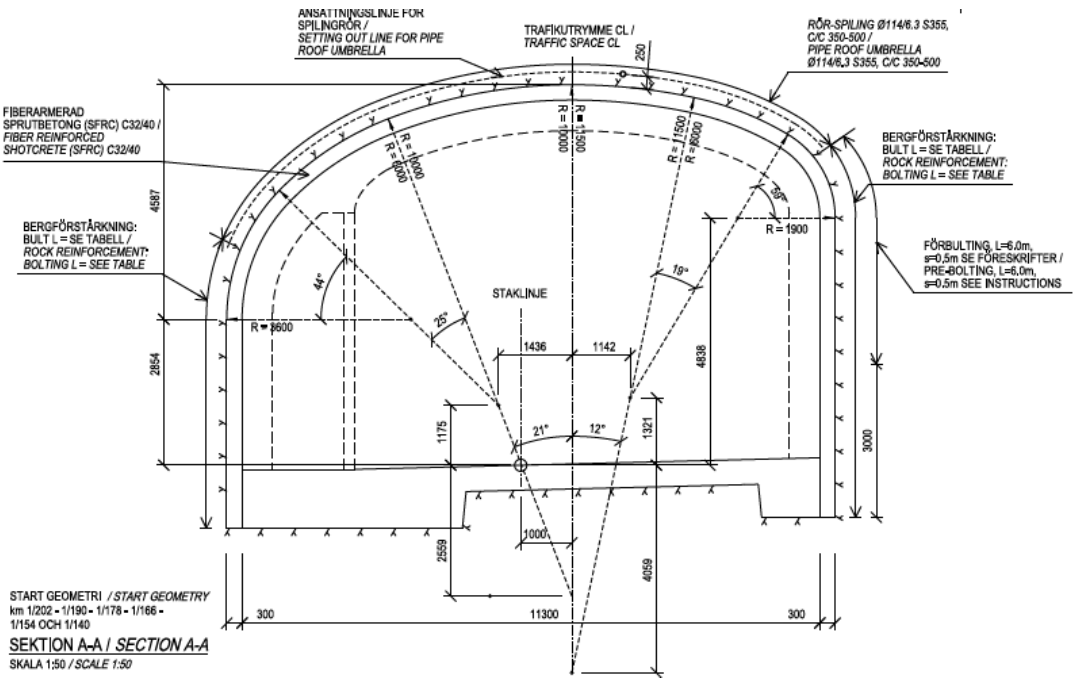

Figure 8. Ground support - Adapted design solution

5.1.3. Pipe umbrella

One of the questions from the Contractor during construction, was to increase the excavation round length up to 4.0 m. For this reason, additional analyses regarding the pipe umbrella have been carried out with the conclusion that under some conditions related to the rock parameter and the already installed rock support , this would be possible. The same model was used as in the original design but in this case the jet grouting was considered with at least 1 MPa cohesion and a 35° friction angle due to the fact that these values had been confirmed by the core drillings done on the performed jet grouting.

Table 2 summarizes the results of the analysis and provides a clear indication regarding the allowed excavation round for different thicknesses of jet grouting and properties of the rock mass.

Table 2. Summary of analysis of pipe umbrella bearing capacity

	Jet grouting		Rock mass properties		Verified excavation length [m]		
	Thickness [m]	c [kPa], Φ [°]	Thickness [m]	c [kPa], Φ [°]	2 [m]	3 [m]	4 [m]
Case# 1	1	1000, 35	-	-	yes	yes	yes
Case# 2	1	1000, 35	1	1000, 45	yes	yes	yes
Case# 3	0.5	1000, 35	2	40, 17	yes*	no	no
Case# 4	0.5	1000, 35	2	150, 21	yes	yes	no

*distance between pipes reduced to 350mm. If the jet grouting thickness is 1m or more the n 500mm can be also utilized

5.2. Permanent support

Under the new geological conditions, it has also been necessary to adjust the design of the permanent lining, since the rock mass was not able to transmit the forces from the lining to the ground. Finally, taking into account the real geometry of the excavated tunnel and the overbreak measured, it was possible to move the drainage pipe outside the lining footing and increase the contact area along the whole permanent lining section, with immediate benefit to the whole bearing system.

The rock mass conditions also required a reevaluation of the amount of reinforcement to be installed, and the original beam-spring model used had to be adjusted to the new situation.

This adjustment of the footing made it possible to verify the permanent lining for different rock mass conditions, without any major adjustment of the ramp geometry but simply by using the available space in the tunnel after the rock excavation.

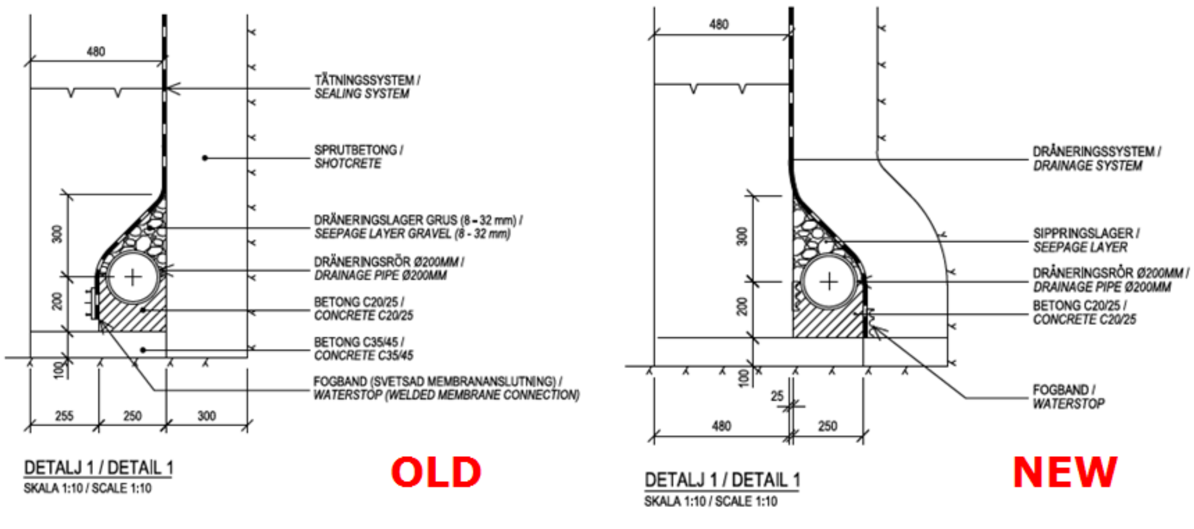

Figure 9. Adjustment of the footing

6. REALIZATION AND MONITORING DURING CONSTRUCTION

In March 2017, the excavation of the ramp tunnel finally reached the Lövstavägen area. Since the previous construction of jet grouting columns confirmed that better conditions were to be expected in Ramp 412, it was decided to start the excavation there to verify all assumptions considered in original and adapted design and to optimized excavation process before excavation of more critical Ramp 411.

During the excavation of Ramp 412, the round length has varied between 2 – 4 m based on the actual rock conditions. The contractor optimized the process and was able to perform one round of pipe umbrella in 2 – 3 weeks. In general, 1 week was necessary for drilling, installation of pipe umbrella and pre-grouting. After that, it was possible to blast and support one round length within 2 – 3 days. The temporary rock support was applied immediately after every round length. The shotcrete has been sprayed in 100 mm thick layers, which meant that the final thickness of 300 mm could only be reached two round lengths behind the tunnel face. The only exception was the shotcrete arch at the beginning of every pipe umbrella round where the 300 mm were installed immediately, working as a support for the pipe umbrella. During the excavation of Ramp 412 under the Lövstavägen area, no serious problems have been detected and the tunnel had passed the critical area in June 2017.

A more challenging situation was expected in Ramp 411. The area with low rock cover was larger than in Ramp 412 and the rock cover in some sections was expected so low that the jet grouting was covering the tunnel crown and haunches. The same working procedure as in Ramp 412 was used. Due to some difficulties with drilling and installation of the pipe umbrella (some pipes could not be installed), it was decided to reduce the round length to 2 m. The excavation started in June 2017 and was successfully finished in October 2017, also with no serious problems.

Figure 10. Pipe umbrella and jet grouting in Ramp 412

Figure 11. Pipe umbrella and jet grouting in Ramp 411

Figure 12. Detail of pipe umbrella and jet grouting

During the whole excavation process, an extensive monitoring system has been set up with three different types of instrumentation:

- Extensometers from the surface down to the jet grouted body;
- Convergence measurement in the tunnel;
- Inclinometers in the pipe umbrella.

The aim of the monitoring was to control the surface settlement in advance, by means of the extensometer and to have a clear picture of the system reaction at tunnel level during the advance of the face.

The measurements were periodically controlled and confirmed the results obtained from numerical and analytical calculations. All measurements were within the given alarm values with a maximal deformation at the tunnel level of 11mm and another 11mm of settlement at the surface as well.

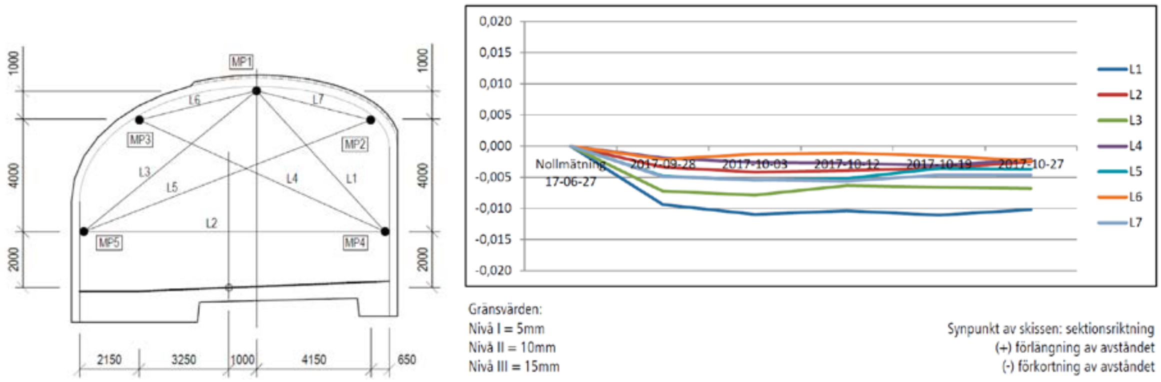

Figure 13. Monitoring of convergence in ramp 411, km 1/198.

7. CONCLUSION

The data coming from the jet grouting operation played a crucial role in identifying deviations from the design scenario and helped to better calibrate the numerical models which defined the rock support and the excavation restriction in the Lövstavägen area.

The jet grouting itself has been a key factor in the following aspect:

- Precise mapping of the rock level in the whole area;
- Rock mass quality definition prior the excavation thanks to the core drilling;
- Good quality of the jet grouting balanced the worse rock mass quality.

The original design had considered a good rock quality and in fact disregarded the positive stabilizing effect of the jet grouting. For this reason, a pipe umbrella was as well designed in order to allow tunneling under the non-cohesive soil with 1m round length.

During the construction phase, the recognition of the higher jet grouting quality than predicted, opened to the possibility to reach a longer excavation round length, even in poor rock mass conditions, once the 300mm shotcrete and a sufficient number of rock bolts had been installed at the tunnel contour.

A close collaboration among all the actors involved in the construction process was also required due to the limited time available, during construction, to adjust and optimize the excavation preocess.

The combination of all the above, made it possible to speed up works compared to the original design, with advantages for both the owner and the contractor.

8. ACKNOWLEDGMENTS

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9. REFERENCES

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