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Shotcrete – sustainable design for underground structures facing challenging ground conditions

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ABSTRACT

The Koralm railway line is a new high-speed railway line of ÖBB (Austrian Federal Railways), which will connect the two cities Graz and Klagenfurt in the south of Austria. In the western part of the line, six double-track tunnels with an excavation area of about 130 m² and lengths between 250 m and 2,100 m form the St. Kanzian string of tunnels. Two of the tunnels, the Srejach tunnel and the Untersammelsdorf tunnel, each slightly more than 600 m long, will be excavated in challenging ground conditions composed of silty to sandy lacustrine sediments.

The Srejach tunnel is to be constructed using the cut-and-cover method. For the Untersammelsdorf tunnel with a maximum overburden of 30 m (above rail-level), a special mining method using bored piles, jet grouting and shotcrete has been developed. A test field was used to test parameters of jet grouting, bored piles, dewatering measures and a small-scale tunnel drive. The evaluation of the tests resulted in the need to carry out additional studies with regard to dewatering and disposing of the spoil arising from the jet grouting works.

As experience gained by owners of NATM tunnels during the last two decades shows, removing hardened scale deposits from the drainage pipes can be one of the most relevant factors in keeping maintenance costs and traffic interruptions to a minimum. The main factor influencing scale formation behaviour is the chemical composition of the groundwater. Cement-bound material, especially shotcrete, may increase the scale formation behaviour. This is why in Austria special focus is laid on optimising the drainage system as well as producing shotcrete which minimises scale formation behaviour. Regulations and a special test for the scale formation behaviour have been developed.

PROJECT OVERVIEW

The 127 km long Koralm railway line is part of the international rail corridor from Bologna in Italy to Gdansk in Poland (Baltic-Adriatic Corridor). Together with the tunnels it is designed for a maximum speed of 250 km/h and is meant to reduce the travel time between Graz and Klagenfurt from currently three hours to 60 minutes. The opening of the line is scheduled for 2023.

Figures 1 and 2 show the location of the St. Kanzian string of tunnels in a zone that is sensitive in terms of landscape and ecology between the Völkermarkt hydropower dam and Lake Klopein. The tunnels are executed as twin-track structures with a distance between tracks of 4.70 m. Rectangular cross sections and vaulted cross sections will be constructed. The clear cross sectional area is between 76.6 m² and 84.8 m².

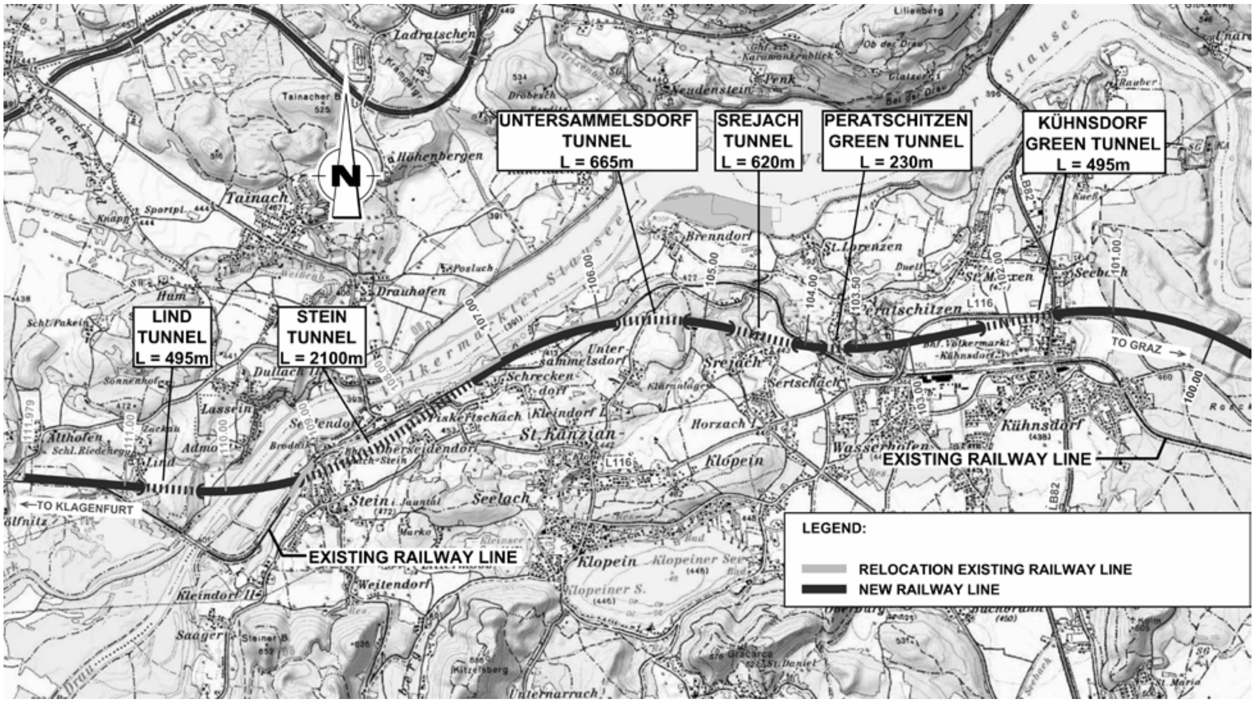

Figure 1: General Layout of St. Kanzian string of tunnels

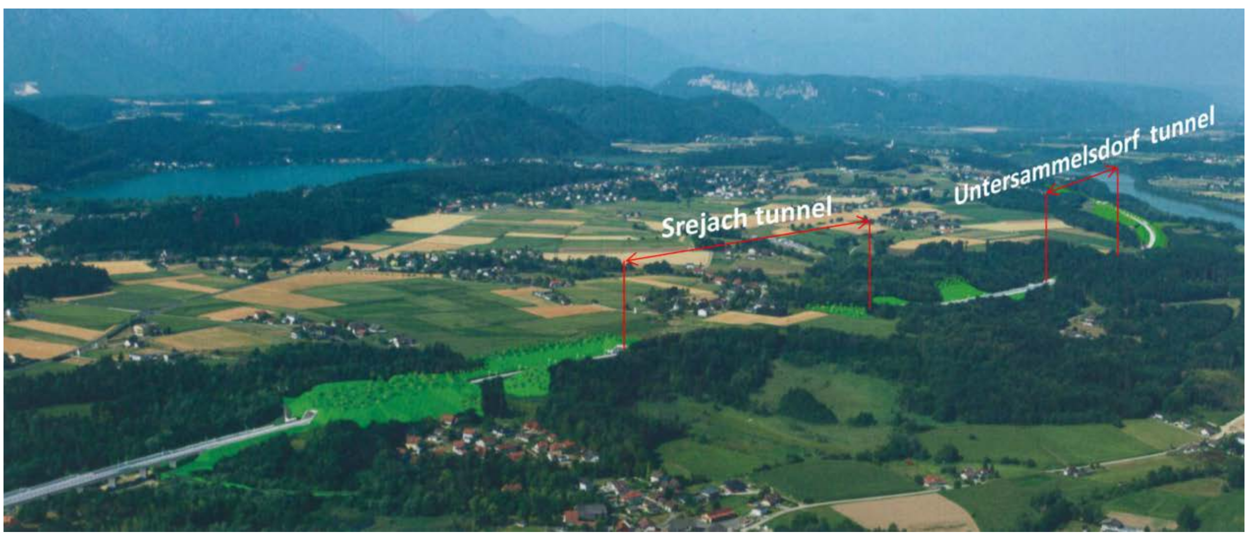

Figure 2: Visualisation of St. Kanzian string of tunnels with Srejach tunnel and Untersammelsdorf tunnel

GEOLOGICAL OVERVIEW

The string of tunnels is situated in the eastern part of the Klagenfurt Basin. The subsurface consists of the paleozoic basement of the Magdalensberg series (quartz phyllites) and overlying, partly redeposited ground moraines and end moraines. They are overlaid by alternating sequences of gravels and thick stillwater sediments (lacustrine clay) deposited in glacial lakes. At the surface coarse-grained, post-glacial gravel terraces are encountered.

The fine lacustrine sediments occurring at the Srejach and Untersammeldorf tunnels are challenging in terms of engineering works. With a view to the geotechnical behaviour they are subdivided into sand- and silt-clay-dominated sections. The sand-dominated sediments are composed of silty to highly silty fine sands and show a high to very high density. The silty clay-dominated fine-grained sediments consist of mainly medium plastic to very plastic silts and/or silty clays (lacustrine clay, see Figure 3) with mostly only low fine sand content. The consistency of these soils ranges from soft and soft to stiff, frequently it can also be very soft, or very soft to soft. The lacustrine sediments occur in alternating sequences, which are characterised by partly intensive interfingering. Partly, thin layers of fine sand are intercalated in the silts/clays.

Figure 3: Soft clays (Lacustrine sediments)

SREJACH TUNNEL

The Srejach tunnel will be located in sandy lacustrine sediments in the eastern part of the tunnel and in very soft (silty clay) lacustrine sediments (see Figure 4) in the western part of the tunnel. Here, these sediment layers are very thick (> 40 m, bottom edge not reached during the investigation), which means that the tunnel structure "floats" in this geological formation. Quaternary sands and gravels with varying thickness are encountered in the crown area and above.

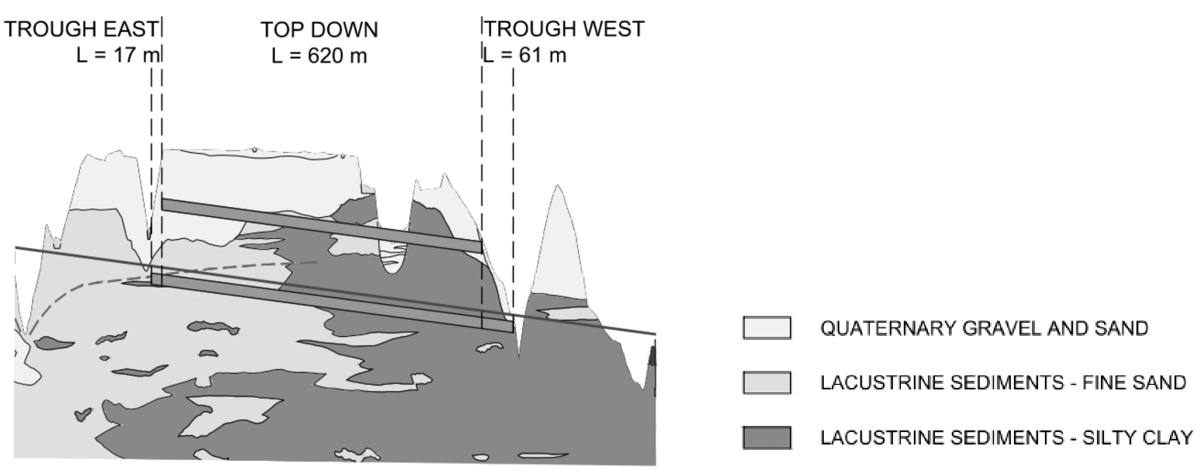

Figure 4: Geological longitudinal section of Srejach tunnel

For the Srejach tunnel a top-down construction method with an intermittent bored pile wall is planned (see Figure 5). The approx. 1.5 m thick base slabs and top slabs are part of the final lining in conjunction with the 0.9 m thick sidewalls that are arranged inside the bored pile walls form a rectangular pressure-tight tunnel cross section. The clearance of 7.25 m between rail level and lower edge of the tunnel roof takes account of a reserve of 25 cm due to the long-term deformation behaviour that is difficult to predict. Adjacent to each portal a continuous concrete structure with a length of 17 m and 61 m respectively consisting of bored pile walls is to be constructed.

To achieve sufficient bracing of the bored piles during the construction of the base slab, the ground below the slab is to be improved by jet grouting. Sealing of the gap between the bored piles by means of jet grouting columns prevents the sand layers that are under water pressure from flowing into the tunnel. There are plans to lower the groundwater level by means of a drilled well in the eastern portion of the tunnel in the zone of the sandy lacustrine sediments.

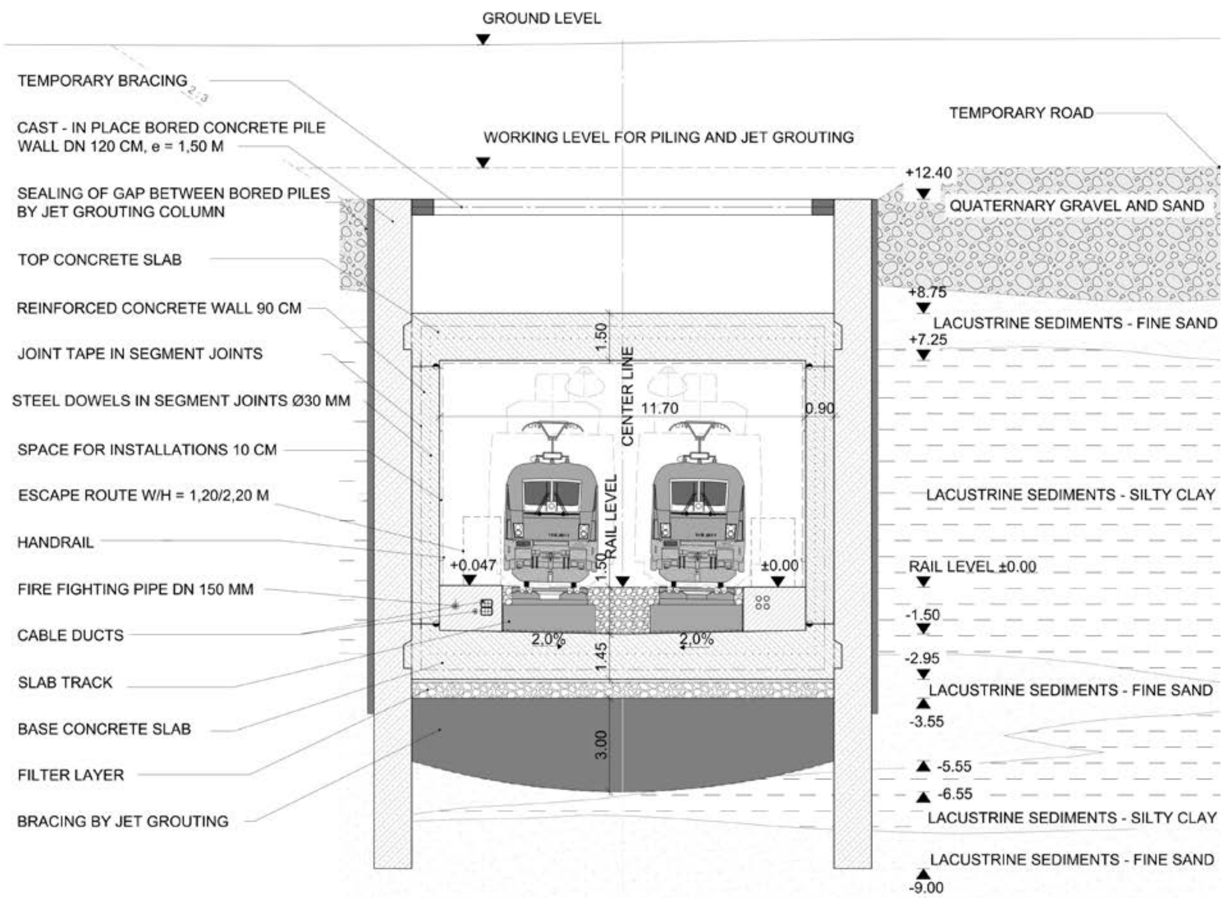

Figure 5: Cross section of Srejach tunnel

Currently the works for the bored pile walls and the jet grouting are underway at the Srejach tunnel.

UNTERSAMMELSDORF TUNNEL

Due to an overburden of up to 33 m above rail level the Untersammelsdorf tunnel is mainly constructed using the mining method with a vaulted cross section. In the portal areas, over a length of 24 m, the top-down construction method with a rectangular cross section will be used.

The Untersammelsdorf tunnel will be mainly located in silty-clayey lacustrine sediments (see Figure 6). In the bench and invert area as well as underneath the tunnel invert, quaternary gravel and sand, coarse fluvial deposits accumulated during glacial advances (German “Vorstoßschotter”) and moraine sediments are encountered. These gravel dominated soils show a high to very high degree of compactness. Together with the phyllite bedrock occurring several meters below the tunnel invert, these layers provide the opportunity to construct the tunnel foundations without significant ground subsidence.

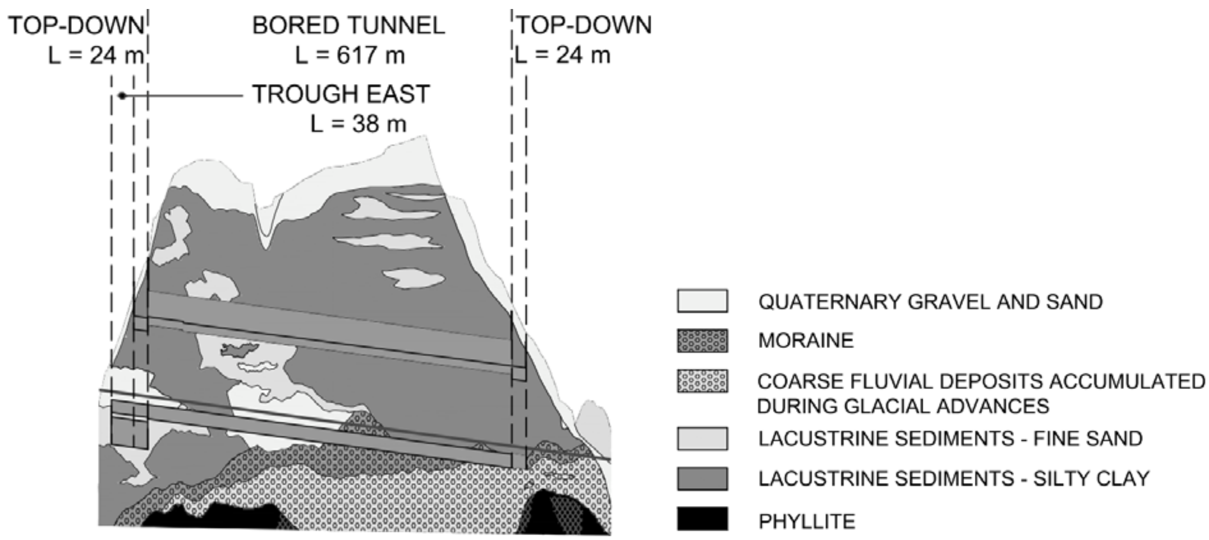

Figure 6: Geological longitudinal section of Untersammelsdorf tunnel

The construction of a tunnel with an excavation cross section of 137 m² in soft lacustrine clay is a technical challenge both for sequential and TBM excavation. A TBM excavation was investigated but due to economic and technical criteria (short length of tunnel, low overburden, large diameters, bedding conditions, risk evaluation etc.) was not pursued further. For the solution using the sequential excavation method a support concept with the special measures described below was developed.

In order to ensure a protective arch above the crown and to avoid any inflow of sand from the crown to the excavation area, ground improvement in form of a jet grouting arch is required (see Figure 7). In order to ensure interlocking and support of this jet grouting arch, on both sides the sidewalls are designed as bored piles that reach down to the load-bearing ground.

The cross section is divided into top heading and bench/invert. To support the top heading during construction (prior to invert closure), a shotcrete lining is foreseen, which connects to the bored piles by means of a notch. To ensure the stability of the tunnel face during excavation of top heading and bench, individual jet grouting columns are constructed in the heading face from the jet grouting arch down to rail level. The length of round for the top heading depends on the pertinent grid array of the jet grouting columns in the heading face and is approximately 2 m.

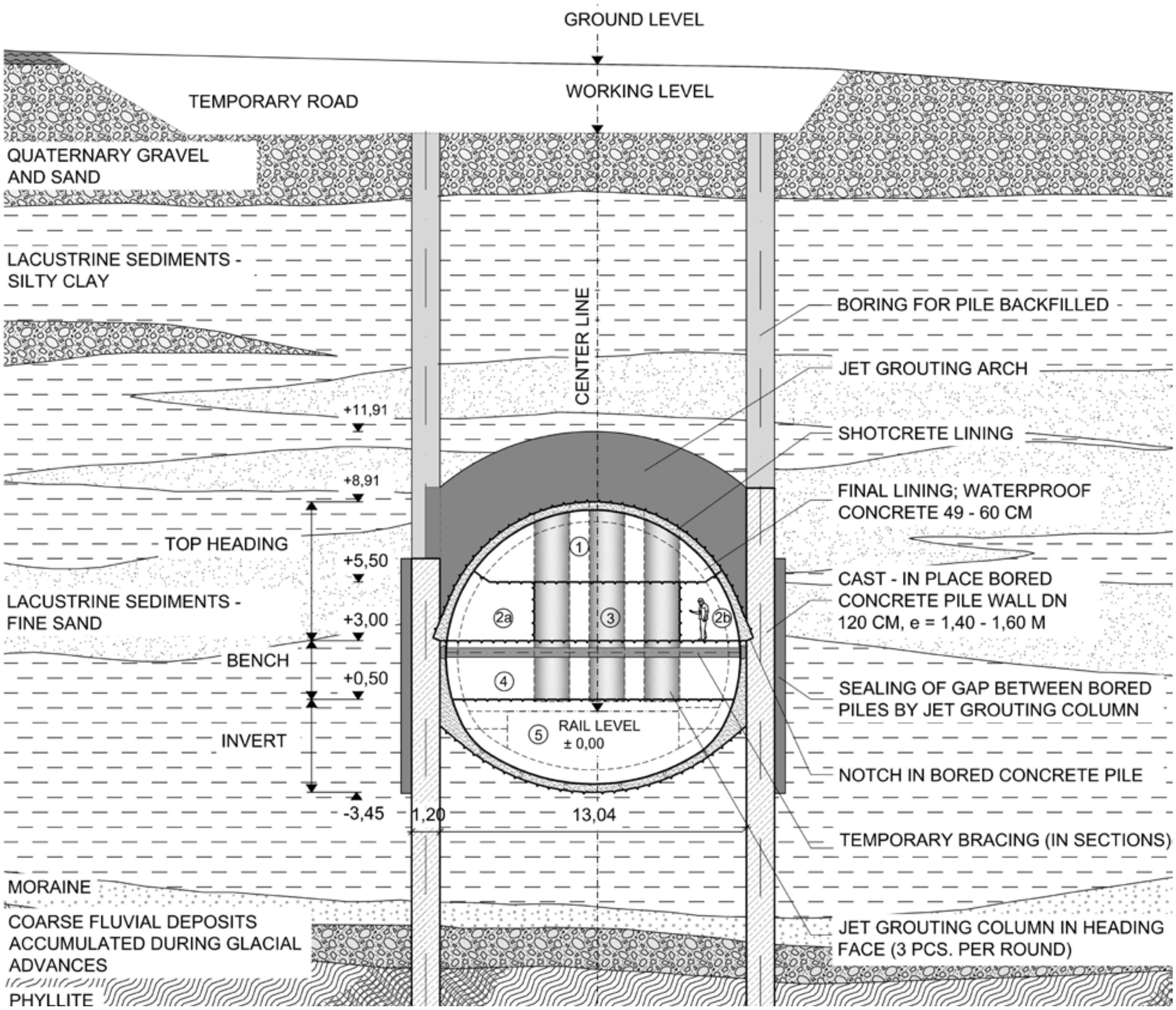

Figure 7: Cross section of Untersammelsdorf tunnel

Due to the intended support measures the top heading can run ahead without restrictions. For the subsequent bench/invert excavation, depending on the overburden conditions and stiffness of the soil underneath the shotcrete invert arch, it is planned to use temporary bracings to bridge the excavation area before invert closure (see Figures 7 and 8). The length of round for bench and invert is between 1.4 m and 3.2 m, with the invert closure distance being limited to about 10 m.

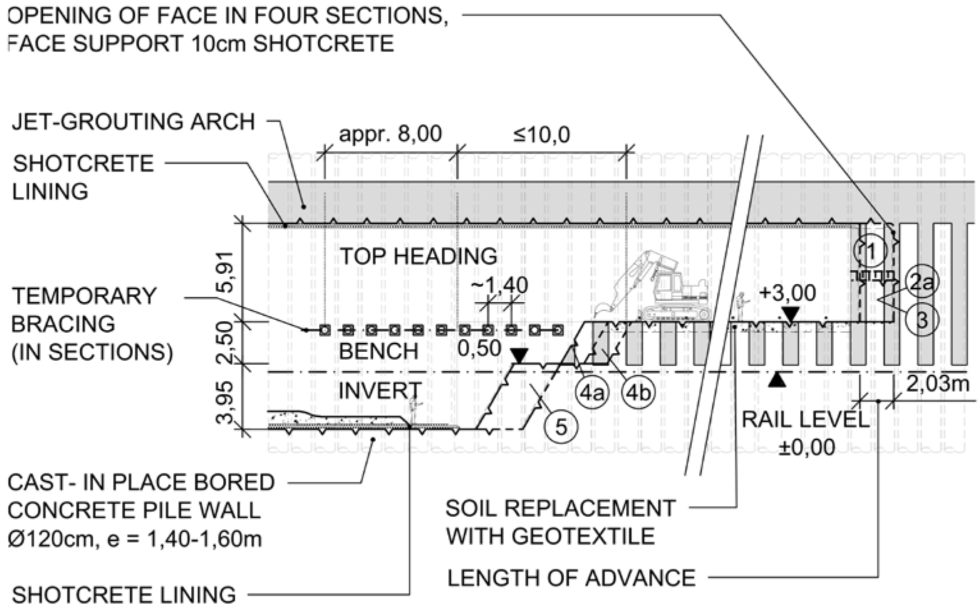

Figure 8: Concept for excavation - longitudinal section

Start of construction of the Untersammelsdorf tunnel is scheduled for spring 2016.

UNTERSAMMELSDORF TEST FIELD – JET GROUTING

In order to answer specific questions on jet grouting, on planned excavation and on bored pile construction, a test field with three compartments (C1, C2 und C3) was set up (see Figure 9, see also Schachinger T., Gaube H., Krainer G. (2010) and Heissenberger R., Benedikt J., Mauerhofer G. (2014)).

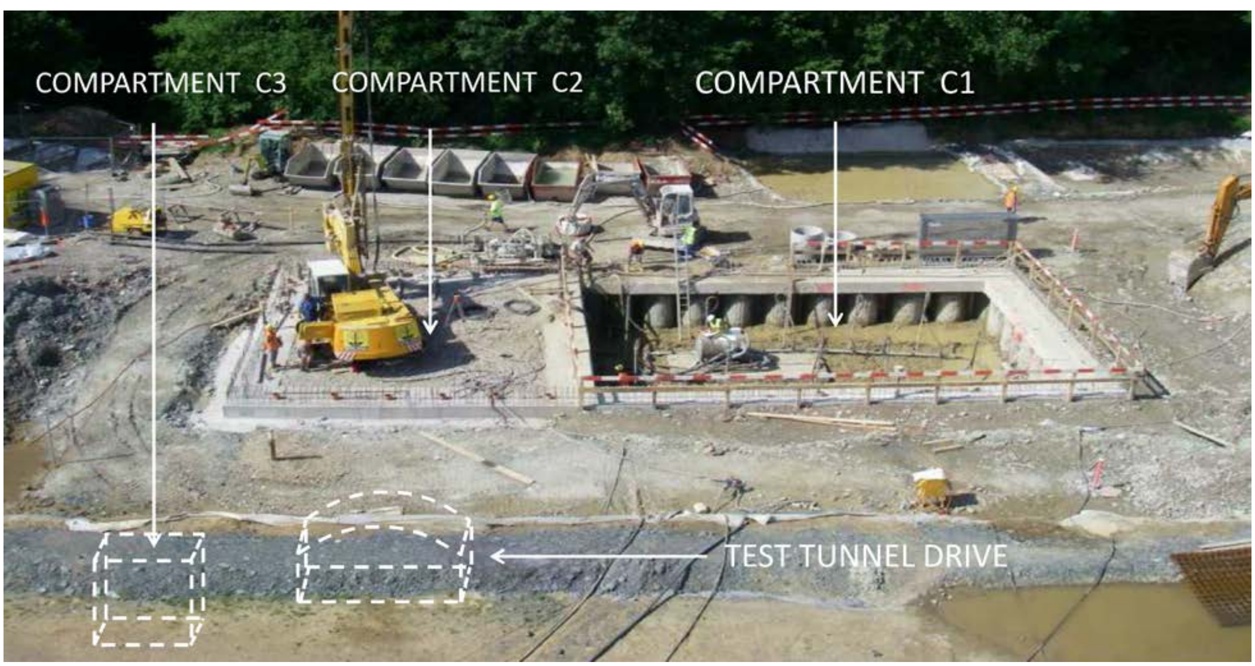

Figure 9: Untersammelsdorf test field

In **compartment C1** a total of 28 individual jet grout columns were constructed by means of the single fluid system (cement slurry), double fluid system (cement slurry + compressed air) and triple fluid system (cement slurry + water + compressed air) at depths of 6 to 10 m. Among other parameters, the achievable diameters of the columns, strength, drilling accuracy, uniformity, amount of spoil return, disposal of spoil return and consumption of binder depending on the production method with varying production parameters were to be clarified.

In **compartment C2** jet grout bodies were produced from individual jet grout columns in order to verify the quality of the jet grouting arch at depths of 6 to 10 m and 12 to 15 m. For this purpose various grid arrays (triangular or square grid array), overlapping and various production sequences (fresh-on-fresh, fresh-on-solid) were used.

The objective of **compartment C3** was to examine the feasibility of the jet grout columns at depths >20 m with pertinent drilling deviation and flow of the spoil to the surface. Both the single and the double fluid system were applied.

The following important findings were obtained from the test field:

- Production method: The triple fluid system did not deliver any satisfactory results, and the single and double fluid system require pre-cutting with water
- A Diameter of 1.5 m for jet grout columns is achievable
- A strength of 4 MN/m² for the jet grout columns is achievable
- The volume of return spoil is approx. 3.5 times the volume of the jet grout columns
- Production sequence: fresh-on-solid
- A drilling deviation < 1 % is achievable
- Conditioning (dewatering) of spoil return is required prior to its disposal

With regard to the dewatering of the spoil return it was found that dewatering is not possible to a sufficient extent by means of sedimentation in basins.

Therefore different dewatering tests using slurries with varying cement and soil content were carried out at the Montanuniversität Leoben where the following findings could be obtained (see Moser A. 2012):

- The addition of a flocculant does not significantly improve dewatering using sedimentation basins
- Dewatering using hydrocyclone is not possible or only possible to a limited extent because of the expected composition of the spoil return
- The spoil return achieves an apparent strength under specific compositions, which is lost when subjected to dynamic stress
- Dewatering using filtration is possible

Based on these results, subsequently large-scale tests for conditioning were conducted at 4 manufacturers of treatment plants, with the following outcome (see Heissenberger R., Benedikt J., Mauerhofer G. 2014):

- Dewatering is possible both with a chamber filter press and a decanter centrifuge
- Residual moistures w_A (with regard to total mass) of between 20 % and 35% can be achieved
- If the spoil return contains cement, flocculants do not have any significant effect on dewatering
- If chamber filter presses are used a significant effect on the dewatering time can be detected because of the cement in the spoil return

UNTERSAMMELSDORF TEST FIELD - REVIEW OF TUNNEL EXCAVATION

The test field was also used to simulate a tunnel excavation at a reduced scale (excavation cross section of 12 m²) utilizing the same support measures (bored pile wall, jet grouting arch, jet grouting columns in the heading face, shotcrete support) and to investigate the behaviour of the heading face in the lacustrine sediments (see also Heissenberger R., Benedikt J., Mauerhofer G. 2014). The tunnel trial excavation consisted of 4 rounds of advance with the ground being excavated using a small excavator and, within the jet grouting zone, a small excavator with an attached cutter head.

Figure 10: Tunnel trial excavation

The following findings were obtained during monitoring of construction and evaluation of measured data:

- Excavation of lacustrine sediments with an excavator is possible without additional measures
- Sufficient interlocking of the jet grouting arch with the bored pile walls was observed
- No significant displacements of the jet grouting arch were measured
- Profiling of the jet grouting arch is possible using an attached cutter head
- After the excavation a measureable short-term pore water vacuum occurs
- The stability of the heading face with jet grouting columns in the heading face can be ensured
- A considerable heat development can be observed in the excavation area resulting from hydration (up to 42°C).

SHOTCRETE AND POTENTIAL FOR SCALE FORMATION

For the three NATM tunnels of the St. Kanzian string of tunnels (Untersammelsdorf, Stein and Lind tunnels) a dual lining system is planned utilizing a primary shotcrete lining and a secondary reinforced in-situ concrete lining. The tunnels are constructed as watertight structures. An essential criterion for this decision, in addition to environmental protection, was the objective of ÖBB to reduce the maintenance costs and any interruption of operation as far as possible. Extensive experience shows that the required cleaning (flushing) of the tunnel drainage pipes to remove (hardened) scale deposits accounts for a significant portion of the maintenance costs for drained tunnel tubes and that cost savings are possible in the long run when constructing tunnels as watertight structures.

However, many tunnels cannot be constructed as watertight structures due to the existing overburden conditions and the resulting high groundwater pressure and therefore have to be constructed with drainage facilities. Great efforts are still being made to gain a comprehensive understanding of the complex mechanisms involved in the formation of scale, to predict them accurately based on hydrochemical modelling and to develop effective countermeasures.

The following chemical mechanisms are essentially responsible for scale formation processes in tunnel drainages (see ÖVBB 2010, tunnel drainage):

- Scale formation resulting from lime-oversaturated groundwater due to a pressure drop and temperature increase when the water enters the tunnel drainage
- Scale formation due to an increase in the pH value of the groundwater as a result of its contact with alkaline substances and formation of calcium due to neutralisation of the hydroxides
- Scale formation due to corrosive groundwater which dissolves calcium hydroxide from cement-bound construction materials and deposits it as calcium in the tunnel drainage due to the neutralisation of carbon dioxide
- Scale formation due to water containing dissolved calcium hydroxide and contact of CO_2 with air
- Scale formation due to the occurrence of lime-secreting water when waters with different composition meet

Figure 11: Example of scale formation in tunnel drainage and maintenance manhole

The main reason for scale formation is thus the chemical composition of the groundwater. Cement-bound construction materials are among many other influencing factors that may speed up the scale formation behaviour.

In conjunction with the problems of scale formation the following measures are considered expedient for the design of tunnel drainages and the specification of appropriate construction materials:

- Local catchment of separately occurring sizeable water ingress at the tunnel intrados and permanent transport into tunnel drainage pipes by means of hoses, pipes or centre-split pipes

- Minimising the contact of the groundwater with cement-bound construction materials (drainage drilling through shotcrete, shotcrete-free contact zones between rock mass and drainage fill)
- Installation of drainage mats with increased drainage capacity (> 0.10 l/ms at 200 kPa and a hydraulic gradient of i=1) behind the waterproofing membrane.
- Unsophisticated and straightforward concept for drainage system with calm water flow (no sudden drops, no lateral discharges, no turbulences), only 15° pipe elbows
- Use of impact-proof, single-layered, solid-walled circular pipes, minimum diameter 250 mm, pipe stiffness at least SN 8; Due to greater dimensional stability (as compared to high-density polyethylene (PE-HD) pipes) and impact strength (as compared to polyvinyl chloride (PVC) pipes) polypropylene (PP) pipes are recommended.
- Opening width of drainage slots in pipes ≥ 5 mm to ≤ 10 mm.
- Easy accessibility of pipes via sufficiently dimensioned maintenance manholes at intervals of < 100m
- Hardness stabilisation by adding solid or liquid agents in the drainage pipes (polyasparaginic acid, diluted muriatic acid etc.) *Note: Environmental compatibility, ecotoxicity and interaction with microbiology shall be taken into account.*
- Use of modified cement-based construction materials (shotcrete, anchor grout, grouting, mortar bed for drainage pipes, drainage fill)

Cement-bound construction materials are characterized by a calcium hydroxide content (about 20% of the cement clinker) which is initially leached close to the surface and subsequently due to diffusion resulting from contact with water and may eventually lead to scale buildup in the tunnel drainages.

According to current knowledge the scale formation potential of cement-bound construction materials can be reduced by the following measures:

- a low water/binder ratio (low porosity)
- the use of binders/cement with low clinker content
- by substituting the cement and/or adding treated hydraulically effective additives (ground granulated blast furnace slag, fly ash, silica fume)

Adding additives shall provide a bond of the calcium hydroxide ($Ca(OH)_2$) that is released during the hydration of the cement clinker.

In the absence of a standardised method for investigating the calcium release in cement-bound construction materials, a test method was defined in the Austrian öbv leaflet "Festlegung des Reduzierten Versinterungspotentials" (2012) for determining the scale formation potential of shotcrete. It provides comparative values for assessing the leachability of calcium from shotcrete. In this test method two test specimens, each with a diameter of 50 mm and a length of 100 mm, are stored in airtight containers with de-ionized water (eluent) in three cycles of 24h, 48h and 120h. The mass ratio of water to the test specimen is defined at 4.0. After completing each storage cycle the extracted eluent is acidified to a pH value of 3.0 to 4.0 for determining the dissolved calcium in mg/l. The released calcium is subsequently converted into kg Ca per tonne of shotcrete.

A currently ongoing research programme shall yield more accurate results about impacts on the test method (see Thumann M.; Hartmaier M.; Saxer A., Kusterle W. 2015) by conducting studies of test parameters (such as temperature, conductivity and movement of the eluent, air volume in the container, additional storage cycles).

Practical experience with a required value for the leaching behaviour of shotcrete of ≤ 0.70 kg Ca per tonne of shotcrete on several construction sites in Austria has shown that this value is met for wet mix at 280 kg/m³ CEM I 52.5 R and 140 kg/m³ of processed, hydraulically effective additives. However, test results on construction sites occasionally showed comparatively large fluctuations, the causes of which are assumed to be fluctuations in the base materials, fluctuations in the mixture and dosage of the accelerating admixture or varying compaction during the grouting procedure. Further investigations shall address this problem and may lead to an optimisation of the test method (see Thumann M.; Hartmaier M.; Saxer A., Kusterle W. 2015).

CONCLUSION

The challenging subsurface conditions of the Srejach and Untersammelsdorf tunnels called for the development of specialized construction methods, which not only involve the use of shotcrete as support measure, but also the use of specific measures such as jet grouting, bored piles and temporary bracings. The project implementation in the coming years will show whether the concepts developed and the investigations carried out will stand the test of time.

As shotcrete is essential in providing support measures for NATM tunnels, but as it also tends to contribute to promoting scale formation in tunnel drainage systems, continued research and further development aimed at reducing the scale formation potential of shotcrete and at providing reliable test methods will be of key importance.

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