# Monitoring and analysis of the behavior of the Salzburg-Clay during the jet grouting works for the S-LINK project

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ABSTRACT: The underground railway line project S-LINK aims for a fast rail connection within the Greater Salzburg Area. The alignment in the first section, starting from Salzburg main station southwards runs underground. The subsoil along the alignment consists of a few meters of fill and gravel in the uppermost section, followed by fine sand-dominated and silt-dominated lacustrine deposits with varying clay and a high water content, which are locally referred to as "Salzburger Seeton". In order to increase the robustness and reliability of the design and optimize the relevant construction parameters, the jet grouting method and its effect on adjacent soil and structures were tested in a test field. The main purpose of these tests was knowledge acquisition for the best possible application of the method under the given geological conditions as basis for design.
In this article, the relevant boundary conditions, objectives and results of the test field are presented.

*Keywords: Monitoring, Data Acquisition, Jet Grouting.*

## 1 THE S-LINK PROJECT

The city of Salzburg is the economic center of an entire region. Today, almost 60,000 people already commute to the state capital every day. In the future, the S-LINK will connect the city of Salzburg with its neighboring regions. The new high-capacity rapid transit connection will offer the possibility of timesaving, comfortable and inexpensive mobility by public transportation. In this way, it will help to reduce commuter car traffic and reduce the volume of traffic jams in Salzburg's central region.

As an extension of the existing local railroad, the S-LINK will connect Salzburg's main station with the south of the state capital and the city of Hallein in four stages. The first stage - the section from Salzburg's local train station to Mirabellplatz – has a length of app. 900 m and runs from Salzburg main station at a low level below Rainerstrasse to the stop at Mirabellplatz.


Figure 1. General Overview of the alignment.

The construction of this section will be realized over large areas along Rainerstrasse using the cut and cover construction method (i.e., top-down).

In the area of the underpassing of the Austrian railway (ÖBB) line, the S-LINK line will cross the railroad line underground in immediate vicinity of the railroad bridge over Rainerstrasse, built in the years 2009 - 2012.

This particular section, with a length of 80 m, will be constructed using NATM. The deep foundation of the two bridge abutments on ductile driven piles, which have to be uncovered and capped in some areas in the course of tunnel driving, represents a particular technical challenge.

In view of the complex technical conditions and the demanding geological-geotechnical conditions in the so-called "Salzburger Seeton", particular support measures are absolutely necessary to improve the foundation soil and to minimize undesirable deformations of the existing bridge structure.

Soil improvement by means of high-pressure cement grouting (jet grouting) was selected as a special measure. The auxiliary construction measures are carried out in advance both from the surface and from the adjacent S-LINK excavation pits using the cut-and-cover method. In this process, a single block is created from a large number of mutually overlapping individual columns. Subsequently, the tunnel drive can be constructed under the protection of this self-contained jet-grouting block.

The jet-grouting method is also used for the cut and cover sections. In these areas, the method is used to produce a stiffening horizon below the base of the structure between the two parallel excavation pit walls as a stiffening base.

## 2 FIELD TEST

The high-pressure grouting method has already been successfully used in many projects for ground improvement, such as in the area of the tunnels in the lacustrine sediments of the ÖBB tunnel chain St. Kanzian in Carinthia. Its correct execution and effectiveness depend on numerous boundary conditions as well as site-specific soil properties. To increase planning reliability and to optimize the relevant parameters, it is important to test the procedure and its effect in a trial field.

In the period from March to May 2022, a jet-grouting test field has been set up with the aim of gaining the knowledge for the best possible application of the method under the given geological conditions as a basis for the tender and execution planning for a safe, robust construction of the S-LINK.

Since the workability of the soil and the system-related effects on pore water pressures and displacements in the vicinity of high pressure grouting works can vary considerably, and the achievable strengths and dimensions of the improved soil column elements can vary greatly depending on the choice of machine parameters in the respective soil layer, the influence of the individual parameters have been investigated and adjusted in the test field. The process and the manufacturing parameters have been varied during the execution of the jet-grouting works and the results as well as the effects on the environment can be monitored and verified online.

Figure 2. Aerial View of the Test Site.

The test field was located directly next to Salzburg's main train station and hence located in comparable geological conditions as the project.

For the verification of comparability, three cone penetration tests (CPTu) and dilatometer tests (SDMT) were carried out at the selected site in advance of the tests. Based on these explorations, the representative test depth of the grouting work was determined with a depth of up to about 15m.

The subsoil in the area of the test field as well as in the project area comprises in the uppermost area of a few meters of fill and gravel, followed by “fine sand dominated” and “silt dominated” lacustrine deposits. Particularly at the depths relevant to the construction project, the "fine sand dominated strata" are a horizontally stratified alternating sequence of sandy silts to fine sands with a high water content. In some areas, lenses with significant clay content as well as well graded fine sands are interbedded. With increasing depth, the clay content increases and the fine sand content decreases or disappears.

These different layers - the “fine sand dominated” and the “silt dominated” soil layers, respectively - exhibit different soil mechanical properties, therefore different geotechnical homogeneous areas were identified for the jet-grouting works and to which uniform jet-grouting production parameters were applied.

## 3 TEST SETUP

For the construction of the grouting columns in this test setup, equipment was used suitable for the jet-grouting works to be carried out in the course of the main construction works. Particularly in the area of the ÖBB railroad bridge due headroom limitations, only smaller equipment can be used in some cases. Hence for the trial columns construction two types of equipment with different size were used. The principal difference is the drilling accuracy to be achieved.

Generally, for the test setup two different settings were chosen.

- Construction of single columns (vertical and inclined) and a column group (total 12 Nos. of columns) in an unconfined setting with detailed instrumentation – indicated in below figure with red and green rectangles.
- Construction of jet-grouting layers as stiffening horizons within the confinement of a sheet pile box – indicated in below figure with a blue rectangle.

The unconfined setup outside the sheet pile box comprised nine single columns at a spacing of 3.0 m and a small jet-grouting block with three nos. of overcut columns. The latter three columns were used to verify the cohesiveness of the jet-grouting body created at the selected column diameter and drilling grid.

To test the design of a stiffening horizon comparable to the conditions in the cut and cover construction method and to explore the excess pore water pressures, horizontal displacements, and potential failures to be expected during construction, overlapped columns were executed within the confinement of a sheet pile box. Two jet-grouting horizons with a thickness of 2 m were constructed at two different depths depending on the geological conditions and separated by a transverse bulkhead consisting of 15 m long intersecting columns.


Figure 3. Test Setup.

Before starting the execution, the suspension formulation and the execution parameters (type, number, diameter and arrangement of the cutting nozzles, composition of the suspension, binder content, w/c ratio, manufacturing process) and the optimum manufacturing sequence were determined on the basis of the experience of the executing specialist company, taking into account the values for diameter, strength and drilling tolerances required in the planning. As a manufacturing process, rods with nozzles in different numbers and sizes were tested using different media with or without precutting.

Three different methods were applied for column construction:

- Single jet grouting with pre-cutting – pre-cutting with water and jetting with suspension
- Single jet grouting without precutting – cutting and jetting with suspension
- Triplex jet grouting - cutting with water and simultaneous jetting with suspension

The relevant nozzle parameters and machine data (cutting pressure and flow rates, drawing and rotating speed of the rods, drilling depth, start and end of the individual drilling/precutting/nozzling operations) were permanently recorded automatically on the drilling rig for the time of execution during the production of the columns and monitored by the specialist personnel on site.

Since the consolidated grouting elements cannot be exposed during the main construction work, reliable methods for verification of the achieved column diameter are of particular importance. An acoustic method was used to determine the diameter at the test site. The results of this indirect test method were compared with direct tests using core drilling on cured columns to verify the reliability of the indirect test method. The mechanical properties (unconfined compressive strength, stiffness) were tested in an accredited laboratory on representative specimens. Core drilling and fresh mortar sampling were used as methods for obtaining specimens.

In the case of top down construction method, different forces act on the stiffening base between the vertical retaining walls (diaphragm walls) as a result of uplift depending on the construction phase. These forces need to be transferred via friction across the interface between jet-grouting body and cast-in-place concrete walls (D-walls). In order to test the load transfer in this interface, a test setup was developed that is intended to realistically simulate the planned interface design. The findings from this test will be used to verify the assumptions made for the structure’s resistances and as a basis for optimizing the structure's size in the course of further design.

## 4 MONITORING THE TESTS

The test site was intensively monitored to enable immediate analysis and interpretation of the results and, if necessary, an immediate operational decision on how to proceed with the construction of the test columns. The following geotechnical instrumentation was permanently provided for the period of execution for early detection of heave/settlement/subsurface deformations and ground reactions to jet grouting activities.

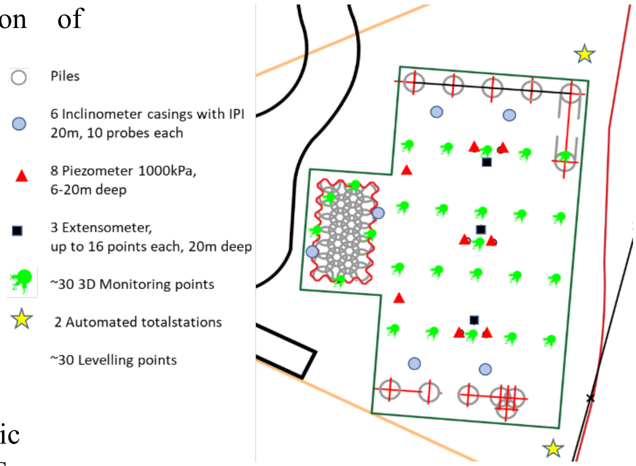


Figure 4. Type and location of instruments.

- 8 vibrating wire piezometers in different depths and distances from the test columns provided continuous data of pore water pressures and temperatures. The sensors were installed in a short filter pack of just 30cm length and a seal with bentonite pellets to obtain a well-defined and short intake zone. Each piezometer is displaced a separate hole to avoid hydraulic connections between the measuring points.
- 3 multiple point extensometers to measuring vertical displacements in the subsoil. Each extensometer installation consisted of a combination of a 20m deep single rod extensometer and a magnetostrictive extensometer. The 20m extensometer with a VW-displacement transducer served as a deep datum point, and the magnetostrictive extensometer represented a 17-fold extensometer to a depth of 16m below ground level. This arrangement allowed the online observation of the vertical displacement profile with a precision of < 0,01mm. The magnetostrictive extensometer is not widely used in geotechnical engineering, although it is mentioned in John Dunnicliff's "Red Book" as the “Sonic Probe”. Today, the flexible probes are available up to a length of 20m and can be operated with up to 20 magnetic anchor parts.
- To monitor horizontal displacements in the soil 8 inclinometer casings with lengths of 20m were installed. In addition to daily manual measurements, two casings closest to the piles just produced were equipped with inclinometer chains (IPIs) comprising of 2m segments.
- Approx. 30 settlement points and more than 40 3D monitoring prisms in the testing area and on nearby buildings were installed. 3D monitoring was carried out by two automated total stations. 10 fixed points, a continuous measurement interval of 7 minutes and the use of dual targets acquired by both total stations allowed measurements with an accuracy of < 1 mm.

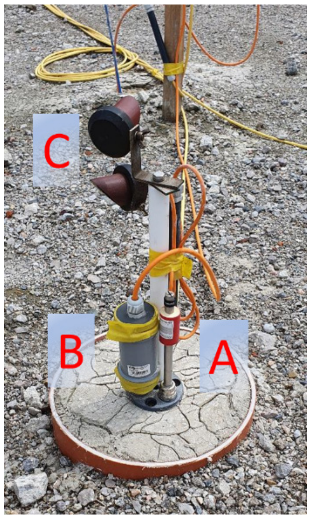


Figure 5. Assembly of a single rod extensometer with VW-displacement transducer (A), magnetostrictive extensometer (B) and 3D monitoring prisms (C).

Data acquisition also played a significant role. The sensors of the geotechnical instrumentation were recorded with data loggers on site. The total stations were remotely controlled via Internet. The measured values were transmitted in real time to a data platform with access for Client, Geotechnical Engineer, and Contractor.

## 5 EXPERIENCE AND MAIN FINDINGS FROM THE TESTS

First, the individual columns in the unconfined area were produced. The manufacturing parameters for the individual columns were varied until the optimum combination was found. For the columns within the sheet pile box (confinement), the quality was especially investigated for the fresh-on-fresh manufactured columns. Important findings on the quantity and quality of the system-related return slurry were collected in the process.

Thanks to the exact temporal logging of the individual work steps and the real-time monitoring, the direct effects of the manufacturing parameters used and parameter changes in the process sequence could be continuously monitored. The knowledge gained from this was discussed at regular intervals together with the client and the client's representative, and the upcoming work was adjusted accordingly if necessary.

The test field was also used to gather knowledge about the most suitable method and frequency of measurements for quality control during and after production of the jet-grouting columns.

Residual samples from different depths were continuously taken and analyzed to check the suspension. Inclinometer measurements were used to check the borehole progress and thus compliance with the drilling tolerances after the drilling rods had reached to the final depth.

From the tests, the following main findings are derived:

- The target column diameter of 1,5 m has been achieved and verified using both an indirect acoustic method and direct method using drillings in all strata using varying machine parameters.
- In the soil in vicinity to the grouting works, significant differences of effects on pore water pressure in fine sand dominated and silt dominated lacustrine deposit due to jet-grouting works have been detected. Measured correlation of change in pore water pressure due to jet grouting and associated settlements measured on surface and with deep settlement points (extensometers) have been successfully quantified.
- The differences of method (single with pre-cutting, single without pre-cutting, triplex) have been evaluated successfully under constrained and unconstrained conditions and its differences in terms of pore pressure build up and reduction have been quantified.
- The area of influence from the production of jet grouting columns in terms of pore pressures and settlements have been quantified successfully.
- The vibration measuring devices installed at buildings in the vicinity of the test field did not show any noticeable impacts.
- During the production of the columns in the lower strata within the sheet pile box, noises from the production process were perceived over distances of several hundred meters.

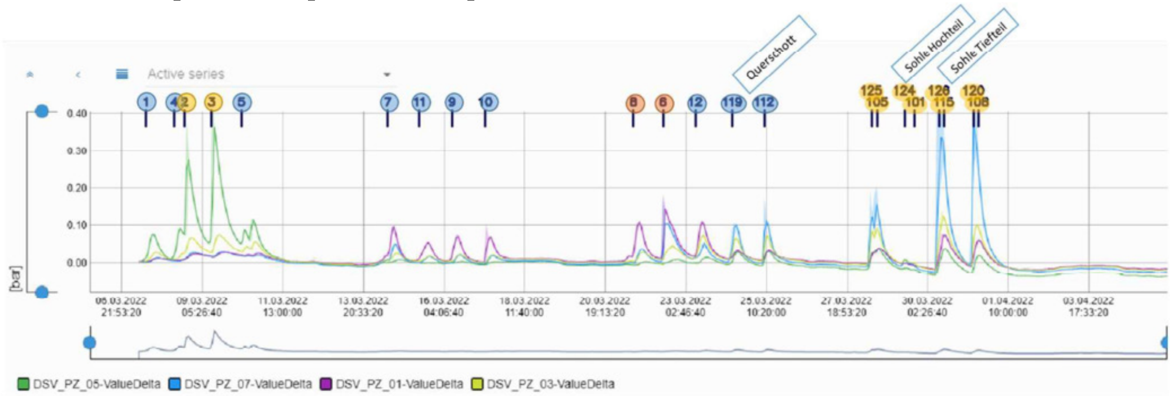


Figure 6. Change of pore water pressure due to jet-grouting works.

## 6 SUMMARY AND OUTLOOK

For the <reliable construction of the S-LINK project, the high-pressure grouting method will be used as a soil improvement measure. The relevant production parameters under the site-specific geological conditions have been tested in the course of a trial field. The results obtained from this will serve as the basis for the robust tendering and execution design of the main construction measure.

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