A new approach to engineering geological documentation of slurry shield drives

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**ABSTRACT:** A new way of engineering geological documentation of slurry shield drives with an inaccessible tunnel face was established on two tunnel projects in Austria. Both tunnels with a diameter of 13.03 m are situated in different quaternary soils and run beneath groundwater surface. During the tunnel drive the engineering geological documentation was concentrated on the excavated material and is therefore specified as *indirect documentation*. The main aspects, which were taken under consideration were: grain size distribution, sphericity and grain surface, petrography, consistency of cohesive soils, appearance of other materials in the excavated material as well as the properties of the bentonite slurry. In special cases also the tunnel face could be inspected under hyperbaric air conditions. The combination of the results of indirect and direct documentation leads to a complete and detailed geological documentation as well as to a better understanding of the interaction of building ground and slurry shield drive.

1 INTRODUCTION

One characteristic of slurry shield drives is the inaccessible tunnel face while tunnelling due to the need of active face support, which is mostly performed by a bentonite slurry. Compared to the documentation of conventional tunnel drives the geologist at the site has to cope with limited opportunities for geological documentation of the ongoing tunnel drive.

For control and maintenance of the cutter head the tunnel drive must be interrupted time by time and the operation mode is changed from fluid support of the tunnel face to hyperbaric air support. During these maintenance stops the geologists have the opportunity to get to the tunnel face. The bentonite cover can be removed in small areas of the face so that the soil at the tunnel face can be recorded. Under stable face conditions it is also possible to take samples of the soil for further investigations. In general control and maintenance stops are set in distances of 50–200 m. The geological information gained out of that comparatively rare face investigations are not enough for continuous geological tunnel documentation, which is important for optimization of current tunnelling works as well as for comparison of target and actual conditions. For that reason the excavated soil material, which is encountered during tunnel drive, must be taken into account in the geological documentation. This material—when coming out of the separation plant—is mixed up and modified, but the documentation of this material is the only chance to collect some information about the soil at the tunnel face during active tunnel advance. This paper presents the continuous engineering geological
documentation of slurry shield drives which was performed for the first time at two slurry shield drives in Austria.

2 PROJECT OVERVIEW

In the lower Inn valley in Tyrol, Austria, the new approach route to the Brenner Base Tunnel is presently under construction. The main lots H3-4 (Tunnel Münster—Wiesing) with a tunneled length of 5.77 km and H8 (Tunnel Jenbach) with a tunneled length of 3.47 km are parts of the first 40 km long section of the two-track railway line. Both tunnels are situated in loose quaternary soils mainly consisting of sandy gravel with varying content of fine grain material as well as interstratified stones and blocks. The hydraulic conductivity of these gravel deposits can reach up to $3 \times 10^{-2}$ m/s. Subsidiary fine grained sediments as fine to medium grained sands and cohesive silts and clays occur in some tunnel sections. Partly the gravels and sands of the so called Inn gravel intersect with silty gravels of alluvial fans. These fans originate from the northern flank of the Inn valley and contain mudflow deposits with a high amount of stones and blocks. The start and target areas of the tunnel alignment were characterised by mixed-face conditions with hard rock (dolomite and limestone) and soil coexisting in the tunnel cross section. Due to the homogenization of ground conditions, the soil was improved by jet grouting before tunnel drive.

The overburden over the tunnel section varies from 5 to 44 m. Different existing infrastructure facilities as railway lines and highway as well as the river Inn had to be passed under. Furthermore the tunnel alignments run totally beneath the groundwater surface, whereas water pressure at the crown level mostly ranges between 1.0 to 2.0 bar (maximum 3.6 bar). During June 2007 and April 2009 the total tunnel length of about 9.2 km was driven by using two slurry shield machines of nearly identical construction. The diameter of the cutter heads was 13.03 m. As shown in Figure 1 the cutter heads were equipped with different kinds of extraction tools like disc cutters, scrapers and reamers.

Emergency exits were arranged at intervals of about 500 m along the tunnel alignment. These emergency exits consist of an emergency shaft in diaphragm wall method or bored pile method and an emergency tunnel in pipe-jacking method. In the connection area between main tunnel and emergency tunnel sealing blocks were prepared either by using jet grouting method or diaphragm wall method to ensure stable and water tight ground conditions while connecting the tunnels. In general the construction of the emergency shafts was completed before the TBM passed by.

Figure 1. Slurry shield machine with 13.03 m diameter of the cutting wheel at the main lot H3-4 Tunnel Münster—Wiesing.
To support the loose ground at the tunnel face the extraction chamber of a slurry shield machine is completely filled with bentonite suspension, which is pressurized according to the support pressure calculation. Neither the geological ground conditions nor the process going on while excavation can be seen directly during tunnelling works. Therefore the geological documentation of the tunnel drive must concentrate on the excavated material. After the soil components were removed from the tunnel face by the extraction tools, they were transported out of the tunnel together with the bentonite slurry. Simultaneously the same amount of fresh bentonite slurry is delivered back to the extraction chamber. The bentonite slurry acts as supporting medium as well as transporting medium. In the separation plant the soil components are divided from the bentonite suspension, which goes back into the fluid circuit. After separation in different fractions (in general: gravel, sand and fines) the geologist can describe the excavated material. Of course the excavated material is, in comparison to the soil on the tunnel face, mixed up and also altered due to the whole excavating and transporting process. Nevertheless it still contains a lot of information about the composition of the soil at the tunnel face and also about the actual situation in the extraction chamber (e.g. material accumulations, see chapter 3.1). Therefore the analysis of the excavated material is an indirect way of geological documentation of the tunnel drive. During the documentation of the two tunnel drives the following aspects were taken into consideration:

- Grain size distribution of excavated material
- Grain sphericity of gravel and sand components
- Grain surface of gravel components
- Petrographic content—mainly of gravel fraction
- Consistency of cohesive soils
- Appearance of other material such as wood or metallic fragments of tools
- Properties of bentonite suspension
- Operation mode of the separation plant

Normally the tunnel progress of slurry shield machines averages from 10–20 m/day. The experience gained during engineering geological documentation at the two tunnel drives in Austria shows that an interval of the regular indirect documentation of 15–25 m of tunnel length is adequate. This documentation rate turned out to be reasonable due to the geological surroundings that do not vary significantly over short distances and due to the fact that little differences in the soil are blurred during excavation and transporting process. Therefore at normal progress rates one geological analysis of the excavated material in the separation plant per day is recommended. In special cases e.g. extraordinary contents in the excavated material or unusual TBM data, a shortening of the investigation interval is advisable.

Figure 2 (a) and Figure 2 (b). Impressions from the separation plant were indirect documentation of excavated material takes place: Figure 2a shows the excavated material being discharged at the dump. Figure 2b shows medium to coarse gravel passing by a sieve in the separation plant.
As mentioned above, there are emergency exits arranged along the main tunnel alignments at a distance of around 500 m. The construction activities at these sites started several months before the main tunnel passed by. The geological documentation of the different construction activities at the shafts and at the sealing blocks as well as investigation drillings also brought information about the geological ground conditions (e.g. maximum grain size of soil components, loss of drilling suspension, occurrence of cohesive layers). Because the shafts were constructed chronologically before the main tunnel drive, geological information out of these settings improved the predicted conditions for the main tunnel. Therefore the documentation of geological settings near the tunnel alignment can contribute to the indirect geological documentation and additionally to the detailed subsoil prediction of tunnel drives.

3.1 Appearance of so called pseudopebbles

In some tunnel sections lumps of cohesive soil occurred beside the hardrock pebbles in the gravel fraction of the excavated material. The surface of these well rounded pebbles, were coated with gravel fractions, whereas inside they consisted either of silt and clay or of a cohesive mixture of gravel, sand, silt and clay. These pebbles were called pseudopebbles because they are, like the hardrock pebbles, well rounded and in the same grain size, but consist of soil material. Figure 3 shows such pseudopebbles which emerged in the excavated material of lot H3-4 at station TM 4012. In the inside of the silty to clayey pebbles often a fine sedimentary stratification was preserved, which identified them as original parts of cohesive layers at the tunnel face. These pseudopebbles arose when parts of cohesive soil were peeled off from the tunnel face by the excavation tools and were rounded during the transportation process. Other pseudopebbles without preserved sedimentary structures were identified as parts of accumulations in the extraction chamber. The appearance of pseudopebbles gave clear evidence (without a direct inspection of the face) that partly cohesive layers existed at the tunnel face. During tunnelling in cohesive material, the risk of material accumulation in the extraction chamber and on the extraction tools exists. Such accumulations hinder the tunnel drive by increasing machine data such as total force and torque, thereby decreasing advance. An early cognition of cohesive layers by indirect geological documentation gives the chance of an immediate response like adapting the supply of slurry and adjusting the progress parameters to the actual conditions within the current heading. Thereby the formation of accumulations can be reduced and an interruption of the tunnel drive with a compressed air inspection for cleaning can be avoided.

3.2 Recognition of block components

First it has to be mentioned, that the grain size that is able to pass the transporting circuit is limited by a grill that is arranged in front of the suction line. The grills at H3-4 and H8 had

Figure 3 (a). Pseudopebbles consisting of fine-grained material. Gravel clings on the outside of these pebbles. Figure 3 (b): Pseudopebble (broken apart) with preserved sedimentary stratification inside.
spacings of 15 cm. Larger material (stones and blocks) is broken apart by a stone crusher before entering the circuit.

This meant that the block components that exist at the tunnel face cannot pass the transporting process and therefore can not be documented directly in the excavated material. It is possible however to recognize block components by the appearance of numerous sharp-edged, relatively large pieces of the same rock type in the excavated material. The existence of single blocks at the face generally can’t be observed in the machine data. Hence the only opportunity to detect blocks at the face during running tunnelling works is via indirect observation through continuous surveying of the excavated material.

Besides the petrographic composition of gravel and stone fraction, the surface and the sphericity of the pebbles was surveyed as well. It was observed, that a lot of components in sand and gravel fraction had fresh fractures resulting from the mechanical impacts during the excavating and transporting processes.

4 DIRECT GEOLOGICAL DOCUMENTATION

At regular intervals an interruption of the excavation works is necessary in terms of checking and maintenance of the TBM. To enter the extraction chamber, the operation mode of the machine is changed into compressed air support of the tunnel face. The interval of these inspection stops depends on several factors, such as actual machine data, surrounding conditions on the ground surface as well as experience out of the already driven tunnel length. The interruptions in compressed air mode provide the only opportunity for the geologist to see the tunnel face. During the tunnel drive of H3-4 and H8, there were several compressed air interruptions with stable face conditions, that offered the possibility of opening the tunnel face in small areas of max. 2 m × 1 m by removing the bentonite cover and investigating the soil composition directly (see Figure 5). Geological factors as composition, structure and compactness of the soil as well as penetration depth of the bentonite suspension were recorded. For further investigations samples from the soil at the face were taken. Similar to the documentation of the excavated material the grain size distribution, the petrography, the grain surface and sphericity was determined for these soil samples. Thereby a comparison of properties of the in-situ soil and the excavated material can be drawn. For example, the amount of soil components with fresh fractures is much higher in the excavated material than

Figure 4. Sharp-edged pieces of carbonate rock in stone fraction in the excavated material. These pieces originate from a single block at the tunnel face.
in the in-situ soil samples. This is obvious because there is a lot of mechanical damage to the excavated material while passing the excavation and separation process. As generally known, sharp-edged components lead to a higher abrasion of TBM components (e.g. tools) as well as other TBM utilities like delivery lines, pumps and separation plant. This fact has to be taken into consideration when evaluating the observed abrasion and wear. The proportion of sharp-edged components in the excavated material in comparison with the soil at the tunnel face can be quantified by indirect and direct documentation.

Once more it has to be pointed out, that the direct documentation of the tunnel face is only possible at stable face conditions with minor leakage of compressed air. Another restriction is, that only a small part of the whole tunnel section can be observed during an inspection. Furthermore the inspections mostly run under high time pressure because of the limited exposure time under compressed air conditions for inspection personal. Due to these circumstances the direct documentation is infrequent but is a very important part of investigating the in-situ soil conditions.

Beside the documentation of the soil, the surface of the tunnel face and the condition of the extraction tools were observed during the compressed air interruptions. Figure 6 shows a view between the cutting wheel with a disk cutter on the left side and the tunnel face on the right side. The gathered information about tool wear in consideration of present geological conditions including surface and tightness of the tunnel face as well as the machine data can give useful data regarding the ongoing processes during tunelling. The knowledge of these interactions between soil and excavation tools enables the constructor to improve tool equipment and operation mode of the slurry shield machine continuously.

5 SYNOPSIS OF GEOLOGICAL AND TECHNICAL DATA

During the geological supervision of the two tunnel headings it turned out to be very useful to summarize the gathered geological and technical data in a graphical way on one sheet of paper for further analysis. Therefore the longitudinal section of the tunnel was complemented with the following data:

- Petrographic content of coarse and medium-grained gravel
- Grain size distribution of excavated material and/or face samples
- Ground surface deformation
- Chainage of compressed air interruptions including tool management data
Machine data (total force, torque, cutting wheel force, speed rate, penetration and rotation speed)
- Advance rate per day
- Information about special events
- Data of groundwater level in the immediate vicinity of the tunnel

For illustration Figure 7 shows a detail of such a longitudinal section. The graphic combination of the geologic information gained out of indirect and direct documentation and the technical data of the slurry shield drive enables an all-embracing analysis of the tunnel drive.
This is required for comparison of target and actual conditions and also for the steady improvement of slurry shield drives by recognizing the interaction between soil and slurry shield machine.

The list outlined above does not necessarily be applied for all tunnels and the listed parameters are specific on the tunnel headings of the tunnels Münster—Wiesing and Jenbach. Every slurry shield drive has it’s own challenges and specific demands on which the geological documentation must be adapted.

6 CONCLUSION AND PERSPECTIVE

While supervising the two slurry shield headings in Austria, the authors came to the conclusion that an engineering geological documentation is definitely practicable even though it differs significantly from the “classical” geological documentation of conventional tunnel drives. Despite the restrictions of the mostly inaccessible tunnel face, an engineering geologist supervising a slurry shield drive should take every chance to collect information about the soil conditions. The decisive fact is the division into indirect documentation (excavated material) and direct documentation (tunnel face). Each type of documentation provides information about the subsoil but only the combined consideration leads to a continuous, detailed and reasonable engineering geological documentation of a slurry shield drive. It was found out that such a detailed documentation required a daily supervision of the tunnel drive and can only be performed with more than two geologists at the construction site. The collection, processing and all-embracing analysis of data concerning geology, machine data, cutter wear and surface settlements is extensive work. But it provides the opportunity to understand the ongoing interaction between subsoil and slurry shield machine. Furthermore it obtains data which is needed for factual determination of matters of dispute between different parties.

Furthermore it should be mentioned that for drawing accurate conclusions out of the collected geological and technical data, the geologist should have an idea how the complete tunnelling method works (from excavation to deposition of the soil material). The geologist can’t draw his own conclusions without taking into consideration the functionality of the tunnelling machine and the registered machine data. And on the other hand, the engineer needs to know the geological conditions to adapt tools and operation mode of the TBM. Therefore a close collaboration of all involved personal at the construction site is essential. It is the authors view that the detailed engineering geological documentation, carried out in the described method above, should become state of the art for supervising slurry shield drives.