On the role of the Engineering Geologist in the Construction Phase of Challenging Tunnel Projects

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ABSTRACT: Independently, if hardrock or soil conditions, conventional or mechanized tunnelling - the role of the engineering geologist as an „interpreter“ of the naturally formed subsurface conditions is undergoing significant changes in the course of the planning and realization process of any tunnel project. Even with the most detailed and most competent site investigation risks for adverse subsurface conditions will still remain. The remaining uncertainties regarding ground behaviour and the interaction of ground and structure and the implied risks for the technical and contractual aspects of underground construction do indeed require further involvement of engineering geological expertise in the course of project realization. The proposed paper is intended to analyse the roles and tasks for engineering geologists involved in a tunnelling project either as a representative of the builder / client, the authorities or the contractor.

1 INTRODUCTION

1.1 *Ground Risks in Tunnel Construction*

In tunnel construction, insufficiently recognized or inadequately considered ground conditions can lead to considerable construction time prolongation, cost increases or even damage such as collapses or damage to existing infrastructure. According to an analysis of international reinsurance companies, tunnel construction is regarded as the only sector in the construction industry, where possible damage can exceed the costs of the construction project itself several times (Lombardi, 2004; Wannick, 2007).

Challenging tunnel projects have therefore always placed great demands on the ability of the engineering geologist and geotechnical engineer to properly explore, describe and predict the geological circumstances and interactions between the ground and the tunnelling method.

1.2 *Project phases*

From the view of the engineering geologist, the following project phases may be distinguished during the realization of a tunnel construction project:

- the preliminary site investigation phase(s), in which the geologist is usually responsible for the planning of the investigation measures and the identification of relevant project risks,
- the tender preparation phase for the main construction works,
- the project execution phase in which the geologist(s) may have different roles depending on their individual task and affiliation,
- as well as a post-project phase, where experiences gained during the execution are either processed for documentary background or within the framework of ongoing litigation procedures.

1.3 *Roles within the project*

The role of the geologist is defined by his position within the project group and the project phase (Poscher, 2004). Usually it refers to one of the following positions and functions:

- Geologist, representing the client (transport authority, energy supplier, etc.);
- Geologist representing the contractor, taking over tasks within the scope of the construction company´s chances and risk management, either during the tendering phase and / or in the execution phase of the project;
- Geologist, representing public authorities (for example in the area of Health, Safety or Environmental Protection).

In the following paragraphs the involvement and usual core tasks of the engineering geologist during the construction phase of larger tunnel projects will be discussed.

2 DOCUMENTATION – THE "VIEW BACK"

2.1 *Objectives*

A comprehensible and objective documentation of the encountered geological and geotechnical conditions during excavation is a basic element for answering any ground-related question. Such documentation on the one hand serves as a tool for controlling the tunnelling works, i.e. adapting excavation sequence and support to the actual ground conditions (→ Section 3.2) and on the other hand serves as evidence for objective discussions on contractual topics between client and contractor.

Unquestionably, the preparation of such documentation is one of the core tasks of the involved engineer geologist(s), regardless of their role and affiliation in the project. However, for especially challenging or conflict-prone projects, the implementation of the so-called "two man rule" has proven as a valuable method for enhancing objectivity and credibility of the work. Such procedure includes the joint inspection of tunnelling works, joint assessment of relevant rock and rock mass parameters and mutual acceptance of documents by geologists acting on behalf of different parties in the project (Figure 1).

Figure 1. Executing the "two man rule" during geological documentation: A close cooperation between geologists of client and contractor contributes to an objective and reliable geological documentation (Photo: Vigl).

2.2 *Documentation for conventionally mined tunnels*

For conventional excavation, mapping of the excavation face is still the main tool of geological assessment. The favourable conditions for direct examination of rock and rock mass properties and the possibility to directly measure the orientation of relevant discontinuities contribute to a generally high level of quality for geological and geotechnical documentation. Additionally, usual advance rates of some meters to dekametres per day provide a sufficient density of observation. Figure 2 shows an example for such full-face mapping of the crown section of a road tunnel.

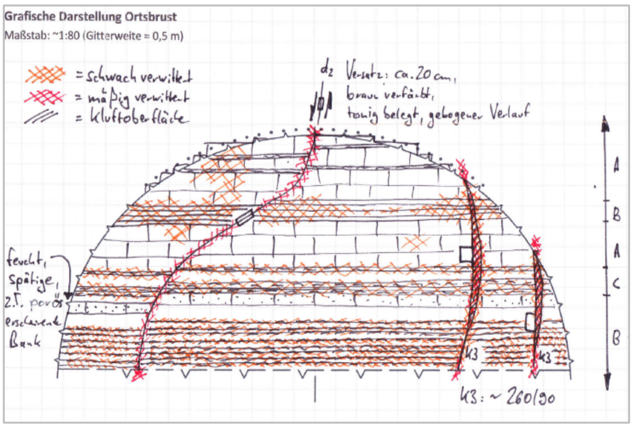

Figure 2. Example for geological face mapping in the crown section of a road tunnel including generalized information on lithological units and discontinuities.

2.3 *Documentation for TBM tunnels*

Under favourable conditions, for instance during open gripper TBM operation, partial mapping of the face might be supplemented by documentation of even larger scale outcrops in the perimeter of the tunnel.

Under unfavourable conditions, for instance operation of a double shield TBM with precast segmental lining and largely closed cutterhead design, limited access to the rock mass, the impossibility to take proper readings with a magnetic compass and the usually high advance rates achieved might significantly limit the possibilities for proper direct documentation at appropriate intervals. Under such circumstances, it might even be useful to distinguish between a "mapping" of the actually visible areas at the face and a larger-scale "interpretation" of the geological conditions in order to equally meet both mentioned requirements of the documentation, excavation control and filing of evidence (Figure 3).

However, a continuous acquisition of relevant machinery data and subsequent data back-analysis might be used as a tool to overcome some of these problems and to derive a sufficiently detailed and sufficiently dense interpretation of the encountered conditions. As recently presented by Radoncic *et al.*, 2014, daily comparison of geological documentation, observed rock mass behaviour and analysed machinery data can provide interpretations on relevant rock mass-TBM-interactions like:

- steerability of TBM,
- stability of rock mass at the face,
- blockiness in the cutter head area,
- general degree of fracturing of the rock mass,
- overall intact rock strength,
- or the state of the annular gap.

For the application of such methods (Figure 4), a close interdisciplinary cooperation of geologists, geotechnical engineers, civil engineers and surveyors is mandatory in order to provide more or less real-time interpretation and to allow adjustment of excavation and additional measures to the actual geological and geotechnical prognosis.

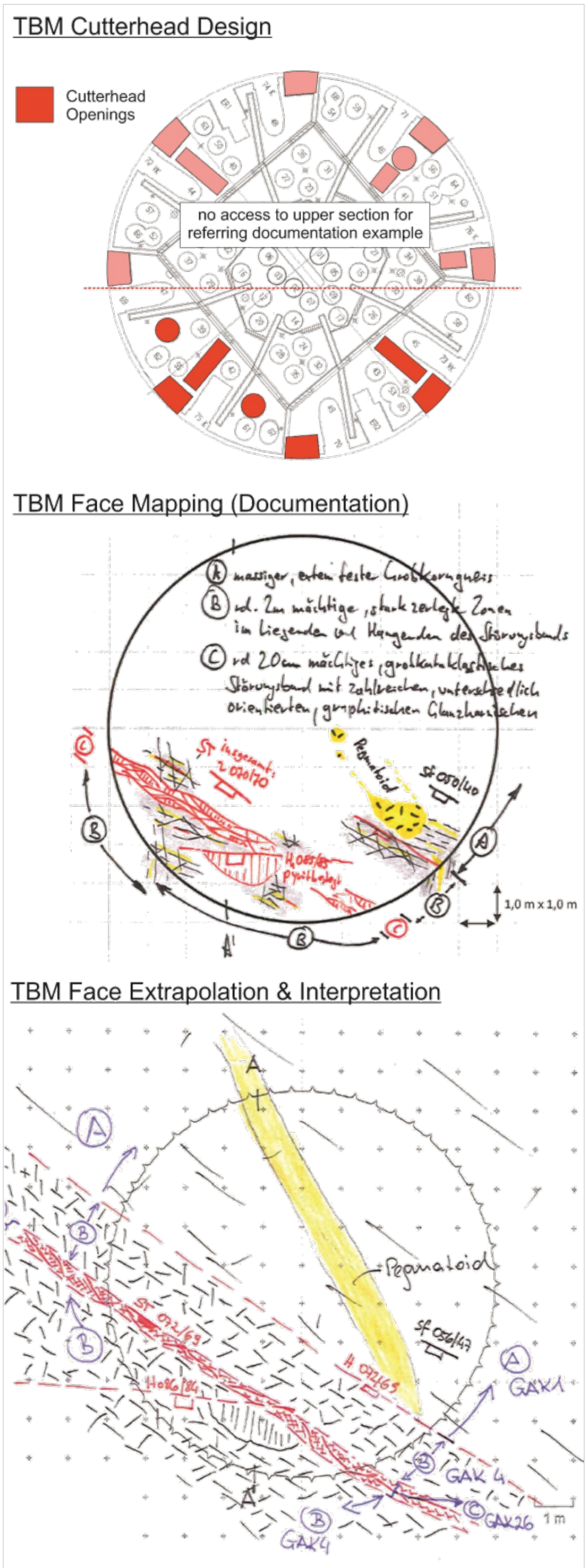

Figure 3. Example for TBM Face Mapping (middle figure) and TBM Face Interpretation (lower figure) under the limited possibilities of a more or less closed ∅ 10 m TBM cutterhead (upper figure).

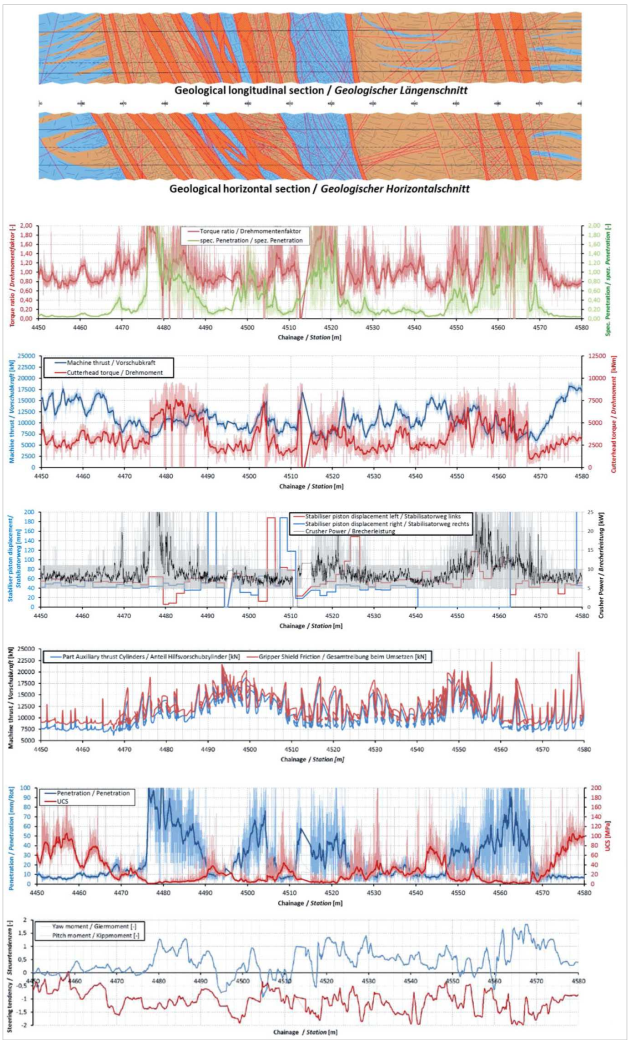

Figure 4. Example for the comparison of geological data and various machinery data sets for an alpine TBM tunnel (from: Radoncic et al, 2014, Figure 6, page 574).

2.4 *Visualization and Data Management*

In order to provide data for computer-assisted communication and analysis, database-supported documentation software is increasingly used, especially in large projects. In addition to the mere distribution of rock units at the face, additional data on the orientation of relevant discontinuities, rock properties, rock mass parameters and displacement measurements can also be filed in such database systems.

Based on these raw data sets, such programs allow computer-assisted visualization of the conditions encountered (Figure 5) as well as easy evaluations of the recorded parameters (for instance comparisons between predicted vs. encountered conditions).

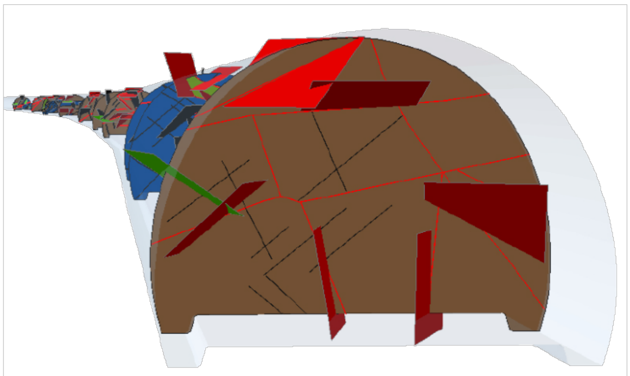

Figure 5. Example for the three-dimensional visualization of several face mappings in a conventional drill and blast excavation by use of GIS-based software.

3 PROGNOSIS – THE “VIEW AHEAD”

3.1 *Objectives*

Ground exploration in front of the current tunnelling station represents a highly relevant and highly dynamic task, which is strongly influenced by the further improvement and development of technical possibilities. However, the procedures outlined in the sections below are only a selection of relevant methods. Usual practice includes a combination of several different methods, often applied according to a predefined stage concept.

3.2 *Improvement of the Geological Model*

In the course of tunnel excavation, there are generally far better possibilities for observing rock and rock mass and for assessment of the interactions between excavation and ground than during any preliminary site investigation. Therefore, the findings of the geological-geotechnical documentation as described above will usually allow further improvement and detailing of the existing geological-geotechnical model. The complementation of the geological model and the combination of geological and geotechnical observations is therefore an essential component of any risk management in tunnelling (Schubert, 2001).

3.3 *Core Drilling ahead of the face*

The execution of horizontal or flat inclined core drilling methods for ground investigation ahead of the face definitely represents the highest quality possible to obtain information on the lithology, the structure and the rock characteristics of the ground ahead. Especially for TBM application, conventional core drilling with single or double coring tubes is practically ruled out as a result of the required handling time for rods and missing borehole support during those roundtrips, so wireline systems are frequently used there (Kogler & Krenn, 2014). However, even for these systems the usually high efforts for machinery setup, related downtimes and costs do in fact conflict with the frequent application of this high-level investigation method (Figure 6).

Figure 6. Subhorizontal Core Drilling ahead of the TBM advance from the upper deck of a ∅ 10 m doubleshield TBM using an Atlas Copco DIAMEC U6 Drill Rig.

3.4 *Hammer drilling ahead of the face*

Due to their usually good availability, relatively low cost and high drilling performance, rotary-percussive drilling methods (also referred to as “hammer drillings”) without extraction of cores can more easily be integrated into the working cycle of both, conventional and TBM excavation. Although only small drill cuttings can be used for direct geological observation, a large number of other relevant information on rock and rock mass composition can be determined indirectly, with corresponding recording of drilling data. This allows relatively accurate predictions on the occurrence of larger cataclastic fault zones, loose soil, or zones with increased ground water inflow.

Figures 7 and 8 show examples for the evaluation and visualization of such drill data. In the referring case, the data is derived from standard blasthole drilling, with the data being recorded using Atlas Copco´s MWD (“Measure While Drilling”) system and being evaluated with the referring "Underground Manager" software.

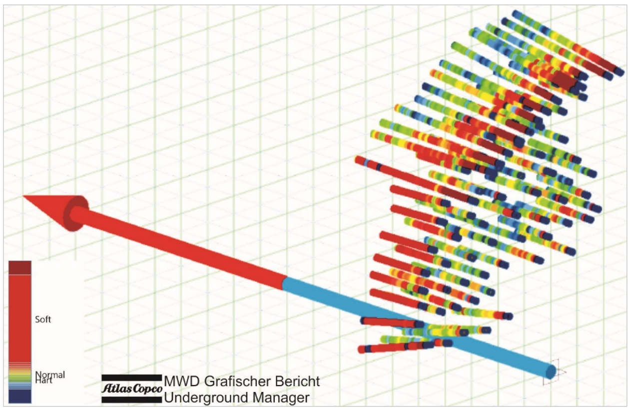

Figure 7. Example for the interpretation of rotary percussive blasthole drilling for a conventional tunnel drivage using the Atlas-Copco MWD and Underground Manager.

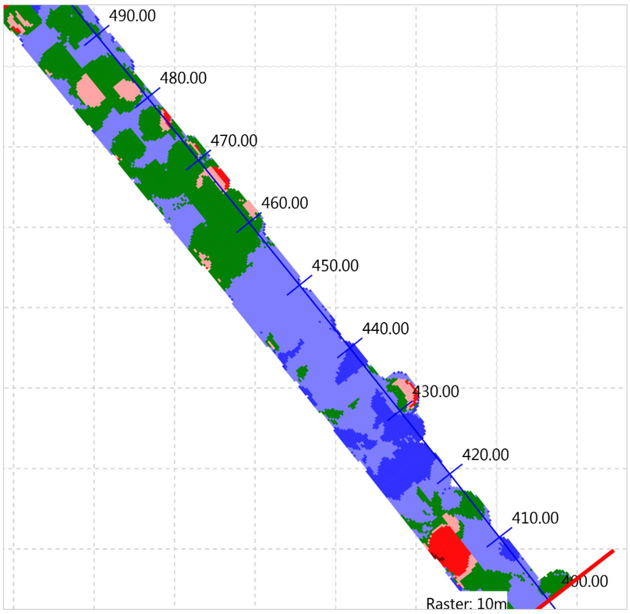

Figure 8. Example for the interpretation of rotary percussive blasthole drilling using Atlas-Copco´s MWD and Underground Manager software.

3.5 *Application of borehole video inspection*

Dropping prices for miniaturized video systems with cable lengths of ≤ 100 m have in the past few years allowed an increasing use of optical inspection systems for boreholes with a minimum diameter of approx. ∅ 40 mm. If interpreted by a skilled geologist, such optical inspection opens up a large number of additionally relevant geological information, in particular if used in combination with rotary percussive drillings, where no core is available.

Figures 9 and 10 give a lucid example for the images and interpretation.

Figure 9. Example for video image in a folded quartz phyllite series in a ∅ 75 mm drillhole used for ground investigation ahead of a TBM.

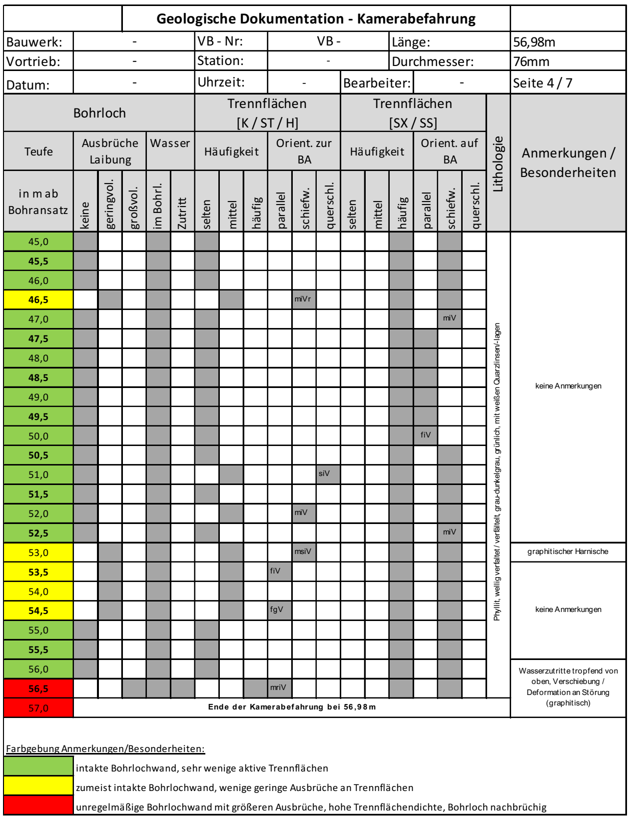

Figure 10. Example for the interpretation and documentation of a borehole video inspection using project-specific classifications of geological observation.

3.6 *Application of geophysical methods*

In addition to direct investigation methods, as described in the sections above, indirect geophysical methods, e.g. seismic, geoelectric or georadar methods can also be used from the undergoing advance. A number of case studies recently published (Brückl *et al.*, 2008; Kaus & Boening, 2008; Radinger *et al.*, 2014) do on the one hand summarize on a useful application of these methods within the referring projects, but on the other hand also give hints towards the still existing uncertainties in the interpretation of these data (see Figure 11).

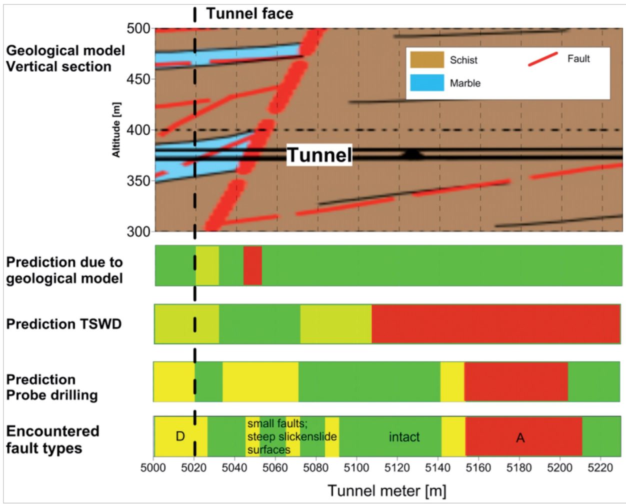

Figure 11. Comparison of different stages in the evolution of the geological model, from top to bottom: Prediction from preliminary site investigation) – Geophysical Forecast (Tunnel Seismic While Drilling) – Percussive Drilling – Encountered Geology (from: Radinger *et al.*, 2014, Fig. 7, page 574).

4 INTERDISCIPLINARY COOPERATION ON SITE

As shown in the previous sections of this paper, state-of-the art documentation and prognosis includes a vast number of different data sets gained from various sources. In order to understand the interactions between ground and tunnel and to provide optimum solutions, the engineering geologist on site has to be implemented into a competent team of neighbouring expertise. Usually, the main interactions exist with the following disciplines:

- Civil engineers (planning, realization),
- Geotechnical engineers,
- Surveyors,
- Geophysicists,
- Hydrogeologists and engineering geologists with other affiliation.

The following typical examples from the daily on-site schedule of an engineering geologist give an idea of the required interdisciplinary cooperation:

- Documentation of drill cuttings during rotary percussive drilling ahead of the face (→ Driller, Civil Engineer),
- Evaluating and geological interpretation of drilling data for hammer drilling (for instance MWD) (→ Civil Engineer),
- Geological interpretation of TBM operational parameters (→ Civil Engineer, Geotechnical Engineer),
- Geological interpretation of deformation monitoring (→ Surveyor, Geotechnical Engineer),
- Geological interpretation of geophysical investigations (→ Geophysicist),
- Actualization of ground water model (→ Hydrogeologist),
- Adjusting support and excavation sequence to the actual geological and geotechnical prognosis (→ Civil Engineers),
- Judging technically on contractual impacts of encountered ground conditions (→ Civil Engineers).

5 CONCLUSION

In challenging tunnel projects, the geological model is inevitably undergoing a process of increasing detailing and sharpening with an increasing density and quality of observations from the preliminary site investigation phase to the actual excavation. This process also applies to the understanding of the interactions between tunnel advance and ground conditions.

While the involvement of the engineering geologist in the preliminary site investigation phase is hardly ever doubted, an intensive and competent on-site support of the construction works by engineering geologists is from the authors point of view still not common standard. However, actual experience shows, that the on-site employment of engineering geologists as part of an interdisciplinary team of skilled experts can significantly contribute to the reduction of remaining residual risks within the project. This not only applies to an increased health and safety aspect by adjusting support and excavation sequence to an actualised prognosis of the conditions ahead, but also contributes to objective discussion of contractual impacts between client and contractor.

State-of-the-art methods like detailed geological documentation, hammer drillings ahead of the face, borehole video inspections or back-analysis of TBM machinery data are only some of the core issues, where the engineering geologist is able to provide specialist knowledge for the project team.

Vice versa, the authors are convinced, that neglecting the engineering geologist's expertise in the project phase does indeed despise the remaining residual ground risks and will definitely reduce the possibilities to sharpen the geological model and to fully understand the complex interactions between tunnel excavation and rock mass.

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