APPLICATION AND RESEARCH OF SEISMIC INVESTIGATION METHODS TO PREDICT ROCK MASS CONDITIONS AHEAD OF THE FACE

T. DICKMANN[1] and S.K. TANG[2]

[1]*Amberg Technologies AG, Switzerland*
(*tdickmann@amberg.ch*)

[2]*Amberg & TTI Engineering Pte Ltd, Singapore*

Tunnelling works involve high risk and the major influencing factor, the geology, is at best interpolated from data gathered from a minute percentage of the total ground to be excavated. More often, the tunnel alignments are dictated by the requirements of the client and not restricted by the geology or excavation technology. As part of the overall site investigation scheme, geophysical prediction systems can play an important role when used appropriately in the efficient management of risk during the construction process. This paper reviews this additional form of site investigation and proposes some methodology for integrating the process into the overall management of risk and cost control.

Keywords: geophysical ; tunnelling; Gotthard Base Tunnel.

1. Introduction

One of the most important requirements for the realisation of a tunnel is the knowledge of the geology and its physical parameters. Owing to different circumstances more underground projects must be realised in very difficult rock and soil conditions. High costs and the demand for safety, influence the adoption of high excavation rates and the application of the best possible technology for the optimum construction program. This demanding characteristic of underground projects requires a thorough investigation of the ground.

2. Geology

Underground work generally poses intimidating, but not impossible challenges to the geotechnical and tunnel design teams. Tunnelling means construction carried out in an uncertain and often aggressive environment. Geology determines the cost, overall feasibility, and even the application of the completed structure. The relationship between geology and cost is so dominant that all parties involved in the planning and design of tunnels must give serious consideration to the geology of the site. The spatial uncertainties in geotechnical properties are greater in tunneling projects compared to most other engineering projects. It essentially requires expert engineering judgement and experience. In many cases, experience in similar ground conditions may not be available and one has to deal with unique uncertainties in ground conditions. For this reason the regional geology and hydrogeology has to be understood. Typically, groundwater condition is the most difficult parameter to predict and also the most troublesome during construction. Any information about location, depth of the water table and aquifer thickness is an important precondition for the design of the tunnel lining.

Currently, there is no accepted standard for the number of probing boreholes, their spacing, depths, etc. Each project must be evaluated on its own merits. A closer spacing between boreholes may not necessarily result in a more accurate inferred subsurface profile. It is clearly not practical to have extremely closely spaced boreholes along the tunnel alignment in order to have an accurate subsurface profile. However, even comprehensive exploratory drilling programs recover a relatively tiny drill core volume that is less than 1/50000th of the future excavated volume of the tunnel.

A comprehensive and thoroughly conducted geotechnical prediction will enable the most appropriate construction methods along the tunnel alignment. It is absolutely necessary that the actual stratigraphy and groundwater flow observed during tunnel excavation works should be compared to the predictions, so that a knowledge-based experience can be established and contributed for future tunneling methods.

3. Site Investigations

Even though there are many challenges in appreciating complex ground conditions, geotechnical explorations have been fairly successful so far. However, the owner and designer must realize the imprecise nature of geotechnical predictions. At the same time, the geotechnical engineer must appreciate the fact that such imprecision is contrary to the usual data precision a designer deal with, unless they are well-experienced in tunnelling. It is important that these uncertainties and their associated risks are fully appreciated by all parties, especially by the management and the legal staff of the client. Clients and designers already begin to evaluate risk much more comprehensively than in the past, in terms of cost and potential schedule delays, in the planning stage. The identification of the potential risks at the planning stage is important because it gives time for planners and decision makers to understand the uncertainties associated with the project.

A first step of the risk assessment involves identifying all the factors and parameters that could affect the tunnel in order to determine the likelihood of a failure or an unsatisfactory performance in a qualitative manner. Geology establishes one of the major risk categories. Here, exemplary risk factors related to geology are shown:

- Rock type (e.g., Limestone, Shale, Sandstone, Conglomerate),
- Structure (e.g., Discontinuities, Folding, Faulting, Soil/Rock cover),
- Properties (e.g., Permeability, Strength, Deformability),
- Others such as Groundwater, Swelling, Chemical reactions, vertical and horizontal Stress.

It is possible to quantify the uncertainty of geotechnical parameters and estimate the risk of those uncertainties to the project cost and timing. The quantification of this uncertainty can then be included in a framework of a geotechnical investigation and then into the geotechnical baseline report (GBR). The framework suggests that the quantification of uncertainty can be undertaken in the following manner. There are four Geotechnical investigation stages comprising a Desktop study, Preliminary investigation, Detailed investigation and the Construction stage review.

The level of risk in a project is directly related to this uncertainty and this in turn has a relation to the amount of site investigation carried out prior to letting the contract. There is however a limit to the benefit that further site investigation from the surface can bring to a project. Ideally the amount spent on overall site investigation should be approximately 3% of the total project value.

4. Contracts

Within tunnelling projects a significant cause of cost overrun has historically been associated with the contractor claims for ground conditions significantly different from those expected at the time of tender. It has been difficult to assess these claims without a well-defined benchmark conditions agreed at the outset between all the interested parties. The GBR is the tool designed to address this problem.

However the nature of the tunnelling contract greatly effects how the SI data is interpreted and further investigation stages are pursued. In adversarial contracts, some post contract SI work is done retrospectively to prove and disprove claims against the findings from the original SI. In constructive and shared risk contracts, further SI work is done to achieve more positive goals including safety, optimisation of techniques and tunnelling processes and even research for future projects.

5. Construction Stage

Geotechnical assessment should not stop at the end of the detailed site investigation works. A plan to monitor the performance of key design criteria such as ground deformation, groundwater condition, effects of the proposed tunnelling works to existing structures, obstructions, and other potential soil or rock anomalies should be identified as part of the tunnel construction specifications. The observed performances either on the surface or from the instrumentation monitored during the construction are valuable inputs to assess the appropriateness of the geotechnical baseline report prepared during the detailed design. Here the ground characteristics determined during the construction are fed back into the system to confirm / modify the design parameters derived from the initial factual data. Besides exploratory drilling from the tunnel face, non-destructive geophysical methods can detect lithological heterogeneities at distances up to several hundred meters. Geophysics methodologies should be considered at this stage from within the tunnel projecting along the planned axis ahead of the face. Seismic imaging is the most effective method because of its large prediction range and high resolution.

6. Geophysical Applications In Tunnelling

Since the 1980´s, geophysical applications from the surface have been conducted in the field of tunnel construction. Due to the restrictions of overburden, accessibility and resolution etc new methods have been developed and are still in the process of development since the early 1990´s, in order to predict the ground conditions ahead of the face and the surroundings from within the tunnel. At the same time it is crucial how fast the geophysical data can be measured, processed and interpreted in order to deliver the information about the heading conditions already during the tunnel work.

Geophysical systems may provide ambiguous results when used as a once off technique. This is to be expected to a certain extent due to the relative nature of the analysis process. However, when it is used on a regular basis, geophysics not only provides a valuable early warning system but also the basis for the measurement and recording of the actual rock mass parameters encountered through the project in the construction stage. It is especially important with the operation of Tunnel Boring Machines (TBM) that a continuous prediction of the ground is carried out as a critical requirement for a smooth and efficient construction program.

The TSP system from Amberg Measuring Technique is a proven geophysical system suitable for inclusion into the tunnelling process on a regular basis. This includes the production of results on site for immediate evaluation and action as required. However the use of geophysics has to be a continuous process so that the geological engineer can continually confirm the assumptions that have been made in the software parameters. The iterative processes in the software built within the TSP system facilitate this option. A familiarity with the general site geology and confirmation over a number of measurements that matched predictions will develop a confidence in the system and parameters used. When a major discontinuity is identified, preventive measure needs to be taken. The ability to plan ahead the deployment of the correct resources and materials to the tunnel face, will help to mitigate delays and will provide a major cost savings on the project.

7. Case History

7.1. *Introduction to the Gotthard Base Tunnel project*

The 57 km long Gotthard Base Tunnel (GBT) will be the main element of the new Swiss Railways routes crossing the Alps on the Gotthard axis and providing a vital link between the high-speed rail networks of Germany and Italy. The tunnel consists of two parallel single-track tubes. With three intermediate points of attack the GBT is divided into the five sections of Erstfeld, Amsteg, Sedrun, Faido and Bodio. Nearly 90% of the entire GBT length is through three major gneiss zones and is essentially considered favourable for tunnelling. Hence, 53 km can be mined by TBM, whereas the remaining parts, the Sedrun section and the Multifunctional Station in Faido, are being excavated by drill & blast. These sections - Sedrun and Faido - are the most challenging portions of the entire project, encountering fault zones of the Tavetsch Intermediate Massif (TZM), and the two younger sedimentary zones (Urseren Garvera Zone and the Piora Basin). Additionally, over major sections of the tunnel, the overburden will be extremely high reaching more than 2000 m causing high squeezing and deforming rock conditions (fig. 1).

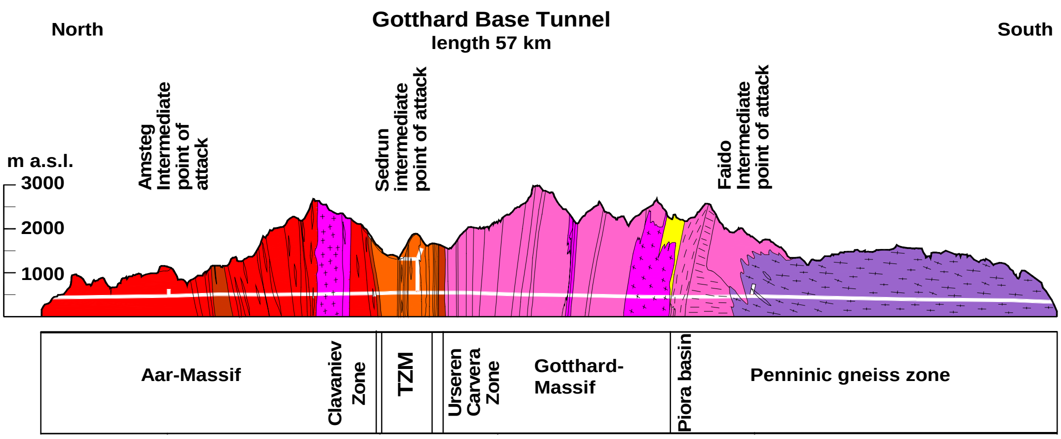

Fig. 1. Geological section of the Gotthard Base Tunnel

7.2. *The Multifunctional Station Faido*

The Faido section includes a Multifunctional Station (MFS) which is located about one third from the south portal. In the event of an accident, they provide safety for passengers and special emergency train stations. The Faido MFS is based at the end of a 2.7 km-long inclined access gallery having a 12 % gradient and a height difference of 330 m. The access gallery was completed in late 2001. Excavation of the MFS Faido started in March 2002 with the cross cavern and the logistics cavern.

During excavation of the cross cavern a downfall occurred in the vault, leaving a cavity about 8 m high. As heading proceeded, the poor material entered the cross-section of the cross cavern, making it necessary to alter the heading and support methods. Because exploratory drill cores showed that the rock would become intact again after a few metres, this event was initially interpreted as a local phenomenon - possibly in the transition zone from Leventina gneiss to Lucomagno gneiss (fig. 2, mark A).

Shortly after the downfall in the cross cavern, the heading of the logistics cavern reached the intersection with the side gallery East. The rock was crumbly, but proved to be manageable with heavier support measures. After the side gallery had broken through at this point, cracks appeared in the northern column, and substantial additional supports were required to stabilise the cavity. When heading work resumed in the side gallery, the material started shifting again and Lucomagno gneiss had been encountered (fig. 2, mark B).

Figure 2 shows supplementary exploratory measures were undertaken to determine whether the two incidents were related and to establish the position of the fault zone that caused them. Numerous advance exploratory drillings (orange) were performed which show that both incidents arose from a fault zone running between the cross cavern and the intersection vault, and that the transition from Leventina gneiss to Lucomagno gneiss lies much further south than expected.

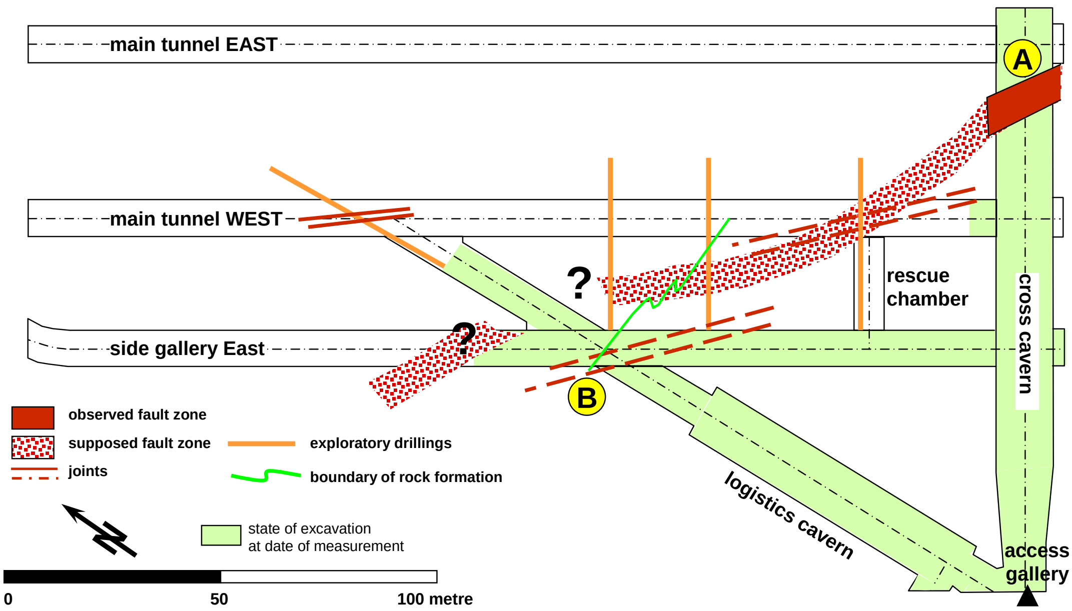

Fig. 2. Northern part of MFS Faido with geological features observed and predicted.

7.3. *The TSP surveys*

Besides percussion drilling, 2 seismic TSP measurements were conducted to explore the rock condition ahead of the logistics cavern crossing the West & East tunnels and the area ahead of the side gallery (fig. 3).

Based on the seismic reflection signals a velocity analysis of compressional and shear waves was performed in order to derive a distribution of rock mechanical parameters in the area ahead of the two headings logistics cavern (2) and side gallery East (1). As seen in fig. 4, colour shadings had been introduced according to dynamical Young's Modulus in order to characterize the rock mass between the reflection interfaces.

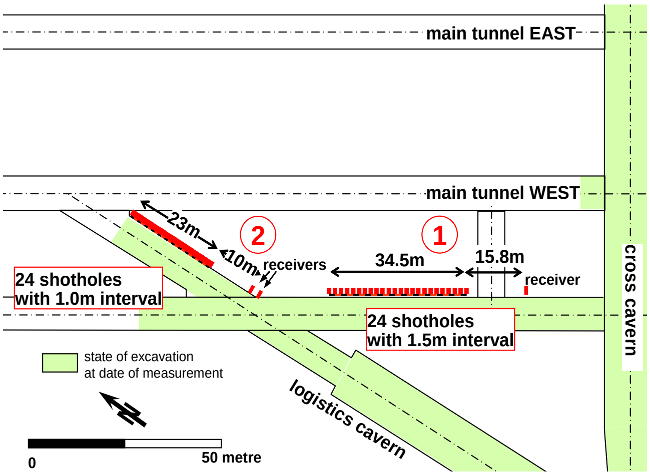

Figure 3. Layout of the TSP measurement 1 & 2 in the MFS Faido

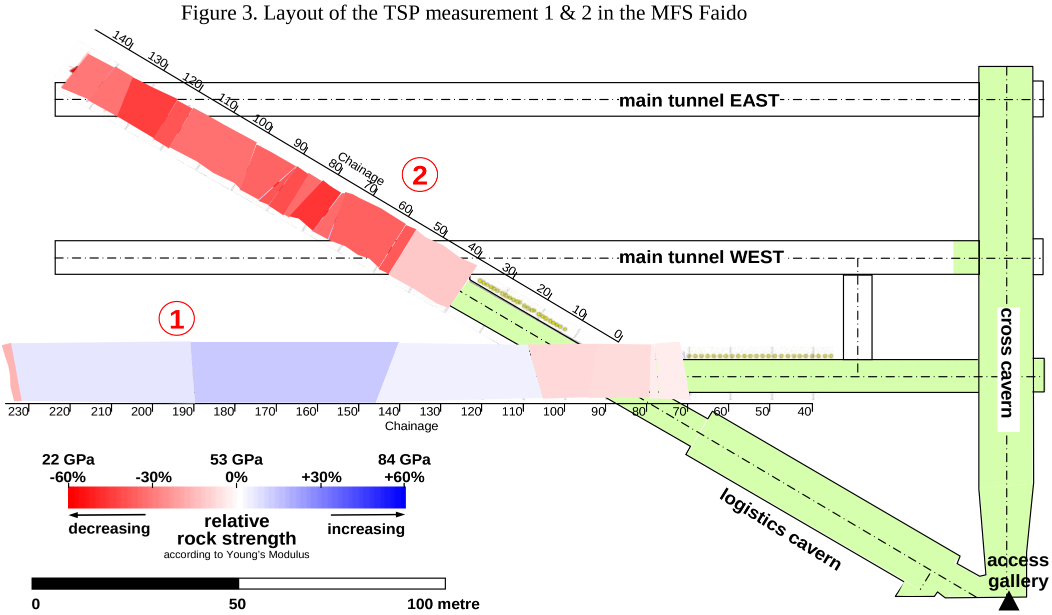

Figure 4. TSP Results indicating relative rock strength according to dynamic Young's Modulus evaluated from the TSP data.

As a result, a clear difference becomes visible between the findings of the two measurements and at the same time between the two areas investigated. Survey 1 shows slightly decreasing rock strength between chainage 70 and 105m being followed by a relative stable rock mass till approx. chainage 235m. A further weakening zone starting at 235m is indicative. By way of contrast, survey 2 illustrates strong rock strength decay from chainage 38m on. In particular at chainage 55m a significant Young's Modulus' drop of more than 30% prevailed till the outermost range of investigation area at chainage 145m.

Both evaluations made it quite evident that the fault zone running between the cross cavern and the intersection vault was thought to strike the MFS Faido with a rather more unfavourable sub-parallel angle to the main tunnel West and side gallery East.

7.4. *Comparison between TSP results and observed geology*

About 2 years after start of excavation in the MFS, all headings shown in the previous detail maps were being excavated. Based on the geological map shown in figure 5, the fault zone runs much more obliquely in relation to the tunnel tubes and stops at the boundary between Leventina to Lucomagno gneiss. However, intensively jointed rock does proceed with the same oblique angle and crosses the western tunnel. In the western tunnel, Lucomagno gneiss has been encountered as expected. In the eastern tunnel, where the expected Lucomagno gneiss has not been encountered, the rock is much complex and still strongly jointed. The rock behaviour in these headings is interpreted as a combination of squeezing and bulking which led to generally slower advance rates. However, the geology encountered differs significantly from the original forecast.

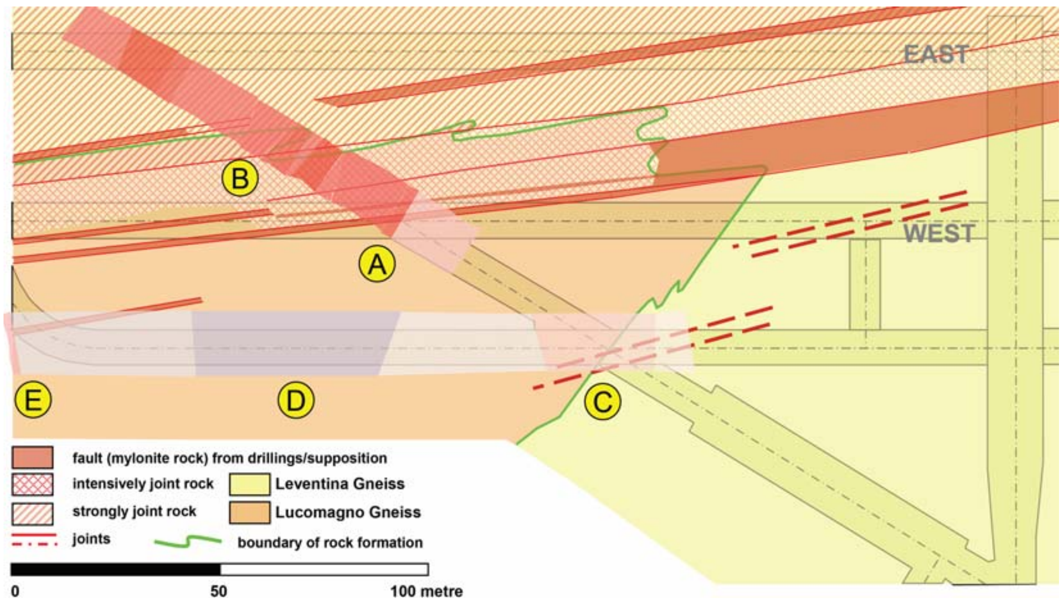

Figure 5. Results of the TSP measurements compared with the observed geology at the MFS Faido.

When comparing the geological findings with the results of the TSP measurements, five areas should be described as follows:

a) The significant drop of Young's Modulus derived from the seismic data exactly coincides with the crossing of the intensively joint rock of Lucomagno gneiss.
b) The curved boundary of Leventina to Lucomagno gneiss that characterizes as well the degree of jointing is well indicated by a further decrease of rock strength in the TSP-data.
c) Shifting rock material at the interface to Lucomagno gneiss characterises the crossing of side gallery and logistics cavern. It is also shown from the seismic section that rock strength decreases.
d) The side gallery further north exhibits no considerable disturbance as seen by slightly raising values of Young's Modulus.
e) When the side gallery turns right to north, it crosses a fault that the seismic receiver indicated as a weakening zone about 210m ahead.

8. Conclusions

Geophysical methods are an essential part of modern tunnelling. They can be applied throughout both the design and the construction stages, and enable continuous risk assessment and management during construction. Geophysical methods will contribute cost effectiveness to the overall project. Even though they do not eliminate all uncertainties, they do contribute to a reduction of them. The comprehension of that is one of the major preconditions for the right communication and validation of the results of geophysical data. Tunnel contractors who use the result of a geophysical investigation as a basis of decision-making may understand and assess the result in a different way than the geophysicist or geotechnical engineer. Hence, a common language should be established to enable the contractor understands the facts and proficiency of geophysical methods such as detectable phenomena, which are at times restricted by survey layout limitations, and secondly how he judges the result with regard to constructional relevance.

We have learnt from the past 10 years how rapidly geophysical methods and their improvement in terms of accuracy have been advanced. Further developments regarding data quality, optimal integration into the tunnelling works flow and sophisticated interpretation methods are still going on and progress has been made in direct cooperation between the tunnelling industry and geophysical research institutes. Geophysical investigations are meaningful and necessary tools in modern tunnelling. When the optimal use of this method has been fully realised, tunnelling works will become more predictable in both costs and risks.

In conclusion, from the moment a tunnel is envisioned, geology strongly affects almost every major decision that must be made in the planning, design, and the construction of a tunnel. All available tools should be employed to reduce the levels of uncertainty encountered.

9. References

Amberg F. and Dickmann T. (2005). "Looking ahead of the face -Benefits of geophys. Methods". Proc. IV UN-ITA Workshop Gibraltar Strait Crossing, Madrid, Spain

Boissonnas, Y. and Jesel T. (2003). "Facing adversity at Faido". Tunnels & Tunnelling International.