Look-ahead seismic investigations during tunneling with shield tunnel boring machines

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ABSTRACT

In order to maintain the economic and safety demand in underground projects, there is a vital necessity of advance geological prediction by using the seismic reflection prediction technique. Tunneling in many projects suffered due to uncertain or even unknown geological problems such as fault and shear zones, cavities and ingress of water and high level of seismicity etc.

By recording the full wave-field of reflected signals, P- and S-waves, prediction of the rock mass quality in terms of physical and mechanical parameters up to 150 m ahead of the face is possible.

Although installing pre-cast segments behind the cutter head of shield tunnel boring machines, seismic investigation become still manageable in hard rock tunneling. They provide an important impact on logistic optimization that could end up in an economic and consequentially time- and cost-effective practice of prediction ahead.

1. INTRODUCTION

Tunnel boring machines are often the only viable option for the excavation of long tunnels with high overburden, due to the impracticalities of opening several faces via adits to enable the application of traditional tunneling methods (Clark and Chorley 2014). However, TBM tunneling encounters unfavorable conditions without warning more frequently than in drill and blast tunneling, which could end up in significant time delays and cost bursts. As unfavorable conditions can be the selection of the wrong TBM type not overcoming the unforeseen unfavorable ground conditions, which can be either a rock mass of very poor quality causing instability of the tunnel or a strong and massive rock mass of very good quality determining very low penetration rates.

For this reason, there have been developments in new technologies of TBM’s in the last decade coping with unfavorable conditions. Today, in many hard rock tunneling projects shielded TBM’s are being preferred to deal with the geological uncertainties and respective ground supports. Among the two types of shielded machines – Single Shielded TBM and Double Shielded TBM – the latter is suitable for application over a
wider range of geological conditions. If it comes to variation in geology from softer to hard rock, ground support regimes can range from pre-cast segmental lining in soft rock to ring beams, rock bolts and shotcrete in more competent rock applying a Double Shielded TBM. However, situations of sudden stoppage still exist due to geological uncertainties, which even more figure prominently in changing rock conditions where a Double Shielded TBM is being preferred.

2. CONSIDERATIONS OF GEOLOGICAL INVESTIGATIONS

The construction of a tunnel never follows the deterministic approach of a design study due to geological, geotechnical, hydrogeological uncertainties and their impact on the construction method used. Barla and Pelizza (2000) stated: “Prior understanding, obtained in a correct manner, of the geological and geotechnical conditions of the site is fundamental for the development of underground works. Up to now, too little money has in general been spent on preliminary investigations. It has in fact been demonstrated that money spent on such investigations is greatly compensated by the savings made in terms of construction cost and time.” Unfortunately, this statement still reflects reality of many tunneling projects today. If it comes to geological investigations during tunneling due to limited access and high overburden above the alignment of the tunnel, the traditional method of probe drilling might be considered as an indicator of water ingress into the tunnel and fault and transition zones ahead of the tunnel. However, it should be also emphasized that in difficult ground conditions and in large diameter tunnels more than one probe drill hole will be necessary. In such cases, the interpretation of the drilling results with TBM operational parameters such as thrust and torque values may be a useful guide for predicting potential hazards ahead of the tunnel (Bilgin et al. 2016). In cases of systematic probe drilling, however, this type of exploration technique is associated to higher costs mainly due to operative downtimes and, short investigation range (< 50 m). Alternatively, geophysical investigations from the face based on seismic methods allow covering a larger range and delivers 3D spatial information about the rock mass properties. Tunnel Seismic Prediction (TSP) technology is a geophysical technique specially developed for tunnelling activities which helps avoid risks associated with poor rock strata (Dickmann 2014). Many TSP surveys had been carried out in TBM tunnel projects worldwide covering a large range of rock types and conditions, e.g. in the Himalayas, the Alps and the Andes.

3. SEISMIC INVESTIGATIONS WHILE TUNNELING WITH SHIELDED TBM

Non-destructive geophysical site investigations while tunnelling are a reliable tool for long range predictions. The TSP technology copes very well this task, since it provides reliable results up to 150 m ahead of the face. In addition, it provides high resolution and allows for the estimation of rock mass mechanical properties based on the seismic wave velocities. Therefore by carrying out comprehensive 3D geological predication using TSP, geological uncertainties can be managed.
If the decision had been made for the use of a shielded TBM for the advance of a long and deep tunnel, the use of precast segments will constitute a crucial point because it shall limit seismic surveys since the rock mass isn't accessible at all. In order to avoid large-scale drilling measures through the precast segments, it is very helpful to use the grouting and lifting inserts of the segments. For example, the hexagonal or honeycomb segmental lining provides a quick and easy layout of the seismic bore line. Regular grouting inserts every 1.2 to 1.5 meters fit perfectly to the regular spacing of the seismic layout (Fig. 1).

The stability safety and the serviceability of segmental elements are guaranteed using explosives for TSP measurements. In case of full backfilling of the segments the blasts could activate settlements with a maximum of 3 mm in worse rock strengths like weathered mudstone. The settlements become less with increasing rock strength. Damage-free blasts can be performed if the blow outs are canalized by installed tubes, while the blow out plane behind the segments is concurrently eliminated. It can be stated that TSP is applicable for TBM advance with segmental lining where any damage to lining elements due to the required explosive charges can be excluded.

4. TSP CASE STUDY WITH SHIELD TBM

The Uma Oya Multipurpose Development Project is a water transfer, hydropower and irrigation project in the south-eastern part of the central highland region of Sri Lanka initiated by the Ministry of Irrigation and Water Resources Management of Sri Lanka and contracted to Farab Company. The main part of the scheme is situated in the south-western part of the Badulla district in the province of Uva (Fig. 2).
The project will transfer water for irrigation purpose and will serve as a power plant producing electricity with a rated capacity of about 120 MW. It consists of two RCC dams, whereof the first is to be built on Uma Oya River at Puhulpola region. The water from Uma Oya River will be linked through an approximately 3.7 km long link tunnel (conveyance tunnel) into the reservoir of the Dyraaba dam built on Mahatotilla Oya River. From this reservoir, a 15.55 km long head-race tunnel and a 628 m high vertical shaft will convey water to the underground powerhouse. The discharge from the powerhouse will be directed into Alikota Oya River through an approximately 3.6 km long tailrace tunnel.

Main geological structures within the project area comprise the occurrence of domes, basins and, anticline and syncline structures. Lineaments identified from aerial photographs suggest that they belong to three different sets running approximately north-south, northwest-southeast and northeast-southwest.

Fig. 2  Overview of the Uma Oya Multipurpose Development Project area, modified from Rahbar and Rostami (2016).
These features could be either major fractures or faults; however, there is not enough evidence of displacement to identify them as faults. Experience elsewhere in the central part of Sri Lanka strongly suggests them to be prominent fractures or narrow shear zones (Rahbar and Rostami 2016).

Due to the construction methodology of the HRT with installation of segmental lining right after excavation and limited access to the face (Fig. 3), a continuous geological mapping is limited. For the subsequent discussion, one TSP campaign is presented (Campaign #21), for which a complete geological profile is available. Additionally, information of probe drills, particularly related to water presence, is also available. Fig. 4 shows the location of campaigns #21 upon the geological profile forecast. Note that the heading follows a decreasing stationing. The objective of this case study is to compare the geological prediction of at least 130 m ahead of the face obtained from one seismic investigation with the encountered geology after excavation. Due to the known high risk of water ingress, particular emphasis is made on the analysis of derived parameters that could help identifying such zones.

In the TSP layout, reference P- and S-wave velocities are estimated as $V_p = 5,680$ m/s and $V_s = 3,280$ m/s, respectively. The prevailing geology within the layout corresponds to interlayering of biotite gneiss and garnet with garnet quartz feldspar gneiss varying from fresh to very slightly and moderately weathered rock at some sections and a zone with water seepage. A reference Young’s Modulus $E_{dyn} = 78$ GPa is estimated. This value is still a little low in comparison to some previous campaigns. According to the face mapping, some jointing and moderate rock conditions are also found. Based on estimated $V_p$ and $V_s$ and geomechanical parameters ahead of the face, four major sections were identified as shown in Fig. 5.
Fig. 4  Location of TSP campaign #21 upon the geological forecast section between TM 10+000 and TM 9+000. Previous and later TSP campaigns are indicated.

Fig. 5  Rock Property charts (top) and reflectors’ longitudinal view (bottom) with colour shading according to P-wave velocity of Campaign #21.
• Section 1 (TM 9+683 to 9+625): This section represents the conditions along the TSP layout and spans until approximately 6 m ahead of the face. Compared to the previous campaign (#20), increased $E_{dyn}$ (78 GPa) and seismic waves velocities are found. These higher values reflect the fresh rock mass found at some areas along the layout. However, still jointed, weathered rock and partly water bearing rock occurs.

• Section 2 (TM 9+625 to 9+604): Similar values for Edyn and S-wave velocity ($Edyn = 79$ GPa, $Vs = 3,385$ m/s) as in reference, however $Vp$ drops to 5,280 m/s towards the end of the section resulting in slightly decreased $Edyn = 74$ GPa. The latter indicates a slightly decrease in rock stiffness likely due to a higher joint density.

• Section 3 (TM 9+604 to 9+563): Throughout this section an increment of $V_p$ is observed (up to 6,250 m/s), which also results in an increment of $E_{dyn}$ (up to 88 GPa) indicating improving rock stiffness. Since $E_{dyn}$ is higher than 80 GPa, it can be inferred that this section most likely comprises moderate to good rock mass. However, in spite of the moderate increment of $V_s$, from TM 9+593 to 9+580, it drops afterwards with a Poisson ratio larger than 0.32 indicating possible water occurrences, likely due to the presence of single fractures.

• Section 4 (TM 9+563 to 9+490 end of prediction): A decrease in both waves velocities and Edyn is found ($Vp = 5,755$, $Vs = 3,350$ m/s, $Edyn = 81$ GPa), indicating decreasing rock stiffness. From TM 9+534, $Vs$ and $Edyn$ further drop indicating a possible fracture zone of about 12 m. Since the Poisson ratio reaches 0.29 at this zone, possible water presence can be expected. From TM 9+522, velocities and Edyn slightly increase again. Towards the end, a similar drop in $Vs$ and Edyn is observed, however, since this area corresponds to the end of prediction interpreting such changes in term of rock conditions is not advisable due to the loss of seismic resolution.

Fig. 6 shows the geological profile based on face mapping and the TSP charts $Edyn$, $Vp$ and $Vs$ of Campaign #21. The first two descriptions indicate fresh to slightly weathered and completely weathered rock conditions, massive to locally blocky and blocky rock mass. As shown by the estimated $Edyn$, both descriptions are in good agreement with the TSP prognosis in Sections 1 and 2, moreover, the borders of the sections fits very well with those of the descriptions. Compared to Campaign #20, seismic velocities are rather higher, however, changes in the velocities still reflects the rock condition variations along this segment. Hence, the higher joint density is reflected in the lowering of $Vs$. The following description starting at TM 9+600 denotes fresh to slightly weathered rock for the next 55 m approx. which is in good agreement with Section 3 and approximately the first 10 m of Section 4 of the TSP prognosis, where an improvement in the rock stiffness was predicted. The next description starting at TM 9+546 points out slightly to highly weathered and highly blocky rock, characterised by a very high joint density in the middle of this segment. In this case, a satisfactory agreement with Section 4 is observed. TSP results indicate slightly changes (decreasing rock stiffness) with a possible fracture zone starting at TM 9+534. This zone fits very
well the area with the highest joint density where Vs response to the jointing is apparently more sensitive than Vp. The agreement at the end of the prediction is also satisfactory; however, it should be considered that the seismic resolution at this distance has reduced considerably.

![Fig. 6](image)

The result and their comparison with excavated geology proved TSP 303 a more efficient and more reliable tool to obtain the advance 3D geological investigation. Data acquisition does not delay or effect the tunnel operation and can be performed on a continuous basis even in shielded TBM’s. As shown in the case study, TSP results delivered prognosis that are in good agreement with observed geological conditions after excavation. However, the low rock physical property contrasts, in particular acoustic impedance of the rock (i.e. product of rock density and seismic velocities) and the spatial disposition of layering and of some fractures (parallel to the tunnel) have posed a challenge when interpreting the TSP data.

5. CONCLUSIONS

The result and their comparison with excavated geology proved TSP 303 a more efficient and more reliable tool to obtain the advance 3D geological investigation. Data acquisition does not delay or effect the tunnel operation and can be performed on a continuous basis even in shielded TBM’s. As shown in the case study, TSP results delivered prognosis that are in good agreement with observed geological conditions after excavation. However, the low rock physical property contrasts, in particular acoustic impedance of the rock (i.e. product of rock density and seismic velocities) and the spatial disposition of layering and of some fractures (parallel to the tunnel) have posed a challenge when interpreting the TSP data.
REFERENCES


