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Uninterrupted continuous forecasting in mechanized tunnelling in rock

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ABSTRACT: The history of seismic exploration in tunnelling began in the early 1990s and continues until today. Especially in mechanised tunnelling, technologies are advancing. Digital construction requires a digital ground model that must be adapted during the construction to reassess newly gained knowledge about the ground risk. In fast tunnelling with average daily rates of 20-30 metres, geological surprises must no longer play a significant role. The innovative TSP 603-Impact system ensures seismic exploration wirelessly in the TBM area. With TSP-Impact, a mechanical source rapidly transmits high-energy seismic waves from the TBM's shield into the rock mass, enabling a prediction range of 100 metres or more. Wireless transceivers convert the signals into digital data and send them to a tablet. This procedure is carried out at the end of each stroke of the TBM. Thus, reflection-seismic data from different spatial positions on a possible fault can be collected and analysed. Flexible and subsequent installation of the system in the TBM makes it independent and yet easy to operate. Once the data from 20 strokes has been collected, it can be uploaded to the cloud with a unique encrypted identifier for data protection. If no trained site personnel are available to process the data, the data can very quickly reach an authorised expert who will process it and return with a geological forecast after 2 to 3 hours. The 3-D velocity distributions of P- and S-waves can be surface rendered to focus particularly on anomalies characterised by low-velocity zones. A geological model of the predicted area completes the picture. This allows the size and extent of the anomaly to be determined, preventing the risk of failure and collapse in the tunnel with an accuracy of 85-90%. With such a TSP operation once a week, continuous geological prediction can ensure smooth tunnelling.

Keywords: TSP, In-tunnel seismics, geological characterization, risk mitigation

1 INTRODUCTION

During the last three decades, the use of seismic techniques for geological characterization in tunnelling has established as a suitable and reliable methodology. By integrating data obtained from in-tunnel seismic surveys with targeted probe drillings, the existing digital geological model can be improved by reassessing information about the rock mass condition as the excavation moves forward (Dickman et al., 2018). In-tunnel seismics can be applied in all types of tunnelling methods. However, in case of mechanized tunnelling in rock, some special requirements should be fulfilled to apply these techniques with minimum to no impact in the production cycle.

Modern mechanized tunnelling using Tunnel Boring Machines (TBMs) may achieve advance rates of up to 20-30 meters per day, or even more. These high advance rates pose challenges for geological investigations. Firstly, the excavation may reach hazardous zones without sufficient early warning. Secondly, the limited available time for geological investigations adds to the complexity.

Current TBMs are equipped with rigs for probe drilling the rock mass ahead while the TBM is in standstill. This process is commonly integrated in the project execution. In many cases, probe drilling is carried out on a regular basis, even if the geological baseline report does not indicate a hazard zone nor the rock composition does change. These boreholes are time-consuming and give a rather limited view of the dimension of the geological conditions ahead of the cutter wheel. In order to profit from in-tunnel seismics in the TBM environment, an execution with an uninterrupted production cycle becomes necessary. Moreover, due to the high advance rates, the prediction of the rock condition should cope with the speed of excavation. This challenge can only be met, and the process can only be appropriate to the TBM environment if rapid seismic data acquisition procedures and continuous interpretation and prediction for the job site are put in place.

2 TUNNEL SEISMIC PREDICTION (TSP)

The TSP method is based on the principle of reflection seismics. It is used to image the structural features of the surrounding rock from inside the tunnel by excitation, reception and evaluation of elastic

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body waves. The method requires a controlled seismic source, which usually consists of small explosive charges in conventional tunnelling. They are blasted in 1.5 m deep boreholes drilled into a tunnel wall. As a rule, 24 boreholes are used (Figure 1).

Figure 1. Schematic visualisation of a standard TSP layout in conventional tunnelling.

The wavefronts initiated by the blasts are travelling through the ground as compressional or P-waves and as shear or S-waves. They are partially reflected at and partially transmitted through interfaces of different physical properties. The wave and its type are measured with 3-component sensors (accelerometers) installed on both tunnel walls, commonly 4 receivers. By capturing the reflected elastic waves and their corresponding travel time, information about the rock mechanical parameters of the ground can be derived and important technical parameters such as the dynamic Young's modulus (Edyn), Poisson's ratio, shear modulus and bulk modulus can be determined.

2.1 *TSP 603-Impact system*

The TSP 603-Impact system comprises two main elements. One is the TSP 603 wireless system that acquires and processes seismic data in the tunnel. The other is the TSP-Impact as a seismic wave source. The TSP 603 wireless system includes special transceivers which convert the analogue signal picked up by the sensors installed in the rock mass into digital data achieving microsecond accuracy of sync among the transceivers. The data is then transferred to a field tablet where it can be immediately visualised for quality control. The use of wireless transceivers enables easier and safer operation of the TSP system in the TBM environment. At the same time, the use of more receivers/transceivers ensures higher data density. The receivers are additionally equipped with an electronic compass sensor (MEMS) to detect and measure the precise spatial position of the 3-component accelerometers once installed (Figure 2).

The TSP-Impact is a pneumatically driven impact hammer, which has been specially designed for the high-energy excitation of seismic waves in the underground. It replaces the use of explosives as a seismic wave generator and saves the drill holes where the small explosive charges were otherwise detonated. This means an enormous advantage for TBM tunnelling. For its operation, the controlled impact hammer source simply needs a mains power supply of 230V and compressed air supply of 7 bar. The impact hammer can be easily installed into a TBM's framework.

Figure 2. Two TSP 603 wireless transceivers attached to TSP receivers deployed 1.5 m deep in boreholes through the grout hole of precast segments.

Figure 3. Controlled impact hammer of TSP-Impact. The impact cylinder, in which the impact mass is accelerated, is coupled to the lateral rock wall through an opening in the TBM's shield shell by the feed cylinder below.

The hammer can be mounted directly on the framework of the TBM or on a bracket. In any case, a minimum clearance for proper operation of the hammer is necessary. It must be ensured that the hammer's impact cylinder can couple to the bare rock wall through an opening in the TBM's shield

(Figure 3). Once the hammer is mounted, it remains there for the duration of the complete excavation or exploration section.

The hammer works according to the Stretch-Shot-Relax pattern once the TBM has completed its stroke and come to a stop. From its rest position it stretches into the striking position up to the lateral rock wall, where its impact head is prestressed to the rock mass (Stretch). In the striking position, the impact mass is accelerated inside the cylinder and hammers against the prestressed impact head (Shot). 3 to 8 shots are taken in the same place, each recorded individually. The digital data traces of the repetitions at the same point are later vertically stacked to improve the signal-to-noise ratio. The nominal energy of each shot is about 130 Joule. With help of an intelligent routine, the user can evaluate the data quality after each shot and finish the data acquisition at this position. Next, the hammer is decoupled from the tunnel wall (Relax). The entire Stretch-Shot-Relax procedure takes maximum five minutes, while it is completely operated and controlled remotely from a field tablet using a dedicated data acquisition and control software.

Figure 4. Easy to use data acquisition and control software on a field tablet.

2.2 *The seismic source – Explosives vs TSP-Impact*

With TSP, the seismic waves must be generated by a point source. Both, explosives, and TSP-Impact satisfy this requirement. However, the energy transferred by the explosives to the media is larger. Repeated hammer blows on the same spot help indirectly increase the energy transferred to the ground. The difference in energy leads to a more rapid attenuation of the waves as they pass through the medium, so that the penetration depth is lower when using TSP-Impact. When using TSP-Impact, prediction ranges of up to 100 m ahead of the face can be achieved, while up to 250 m are possible when using explosives.

Another difference is the signal bandwidth. Normally, explosives have a wider bandwidth from 100 Hz to 3,000 Hz, whereas with TSP-Impact the bandwidth can be between 100 Hz and 1,750 Hz. The frequency range of the useful signal has a major influence on the spatial resolution. The higher the prevailing frequency, the higher the resolution, i.e., the ability to identify successive reflectors depending on the wavelength.

Figure 5 shows the amplitude spectrum of data recorded with explosives and TSP-Impact (left and right, respectively) with the same receiver at the same location in Switzerland's Hagerbach Test Gallery. Here, the lithology consists of competent schist. The bandwidths of the significant signals are 100 - 1,150 Hz and 100 - 850 Hz, respectively, with most of the energy around 500 Hz for both source types. Given the anelastic attenuation or absorption of seismic waves, the high frequency component of the signal generated by explosives may be rapidly attenuated by the medium, so the signal frequency of reflections from distant areas (e.g. > 20 - 50 m from the face) is likely to be in a similar range, i.e. 100 - 250 Hz. Therefore, a similar spatial resolution can be expected for both data sets, resulting in very similar results.

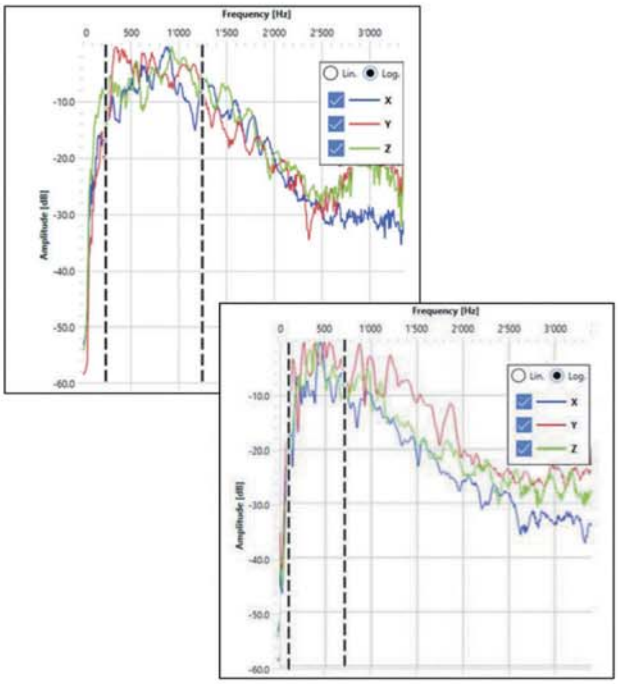

Figure 5. Amplitude spectrum, left: explosive; right: TSP-Impact.

2.3 *Uninterrupted data acquisition and processing*

To fully integrate geological prediction into mechanised tunnelling, the deployment of the measurement system and data acquisition must be carried out quickly so that the tunnelling cycle is not delayed. The use of a pneumatic impact hammer not only fulfils time and safety requirements, but also the demands for efficiency and prediction quality. Full integration of the system into the production cycle is achieved by installing the receivers at a specific location and using the TSP impact hammer during short breaks between each stroke (Figure 6). After a number of shot points have been recorded, the back receivers can be moved forward in a roll-along fashion. This continuous use of the hammer in short breaks after each stroke always ensures a consistent geological prediction. Any downtime is reduced to a minimum.

As soon as twenty shot points have been recorded, the data can be sent to the processing centre via the cloud. Processing takes place immediately so that initial results are quickly available. If further data is collected at more shot points, it can be sent for processing and merged with previous data. In this way, the results are constantly regenerated, and the accuracy of the results is continuously improved.

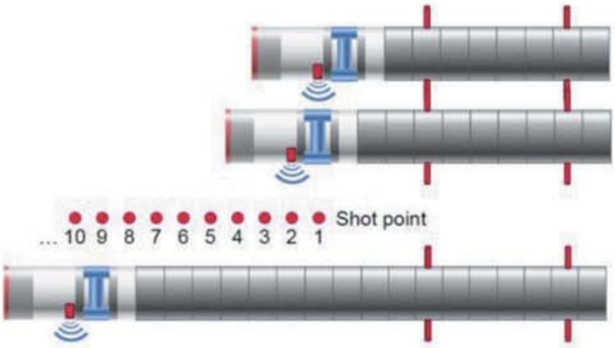

Figure 6. Continuous data recording using TSP-Impact.

3 THE USE OF TSP 603-IMPACT IN THE RISHIKESH – KARNAPRAYAG RAILWAY LINE PROJECT

3.1 *Project description*

The Rishikesh - Karnaprayag Railway Line Project is a 125 km single-track railway line under construction in the Uttarakhand state of India (Figure 7). The project was commissioned by the national enterprise Rail Vikas Nigam Limited (RVNL) and it comprises the construction of 17 tunnels, 35 bridges and 12 stations. Tunnel Package 4 includes the excavation of two main tunnels of about 15 km and an escape tunnel of 0.7 km. 10.5 km of tunnels are currently under construction by two single shield TBMs for hard rock with a 9.1 m diameter each. The construction work is done by the Indian contractor Larsen and Toubro.

Figure 7. Project location overview.

3.2 *Campaign selection and local geology*

To date, more than 25 TSP campaigns have been carried out with the impact hammer source. The TSP hammer was installed in a special niche behind the TBM shield (see Figure 3). In this article, campaigns no. 7 and no. 8 are selected for further discussion. The face positions of those campaigns are at chainage 49,376 m and 49,445, respectively.

According to the Geotechnical Baseline Report and previous field work, a sheared/fault zone was expected along these chainages. The rock mass rating was estimated at RMR< 20 resulting in rock mass class V.

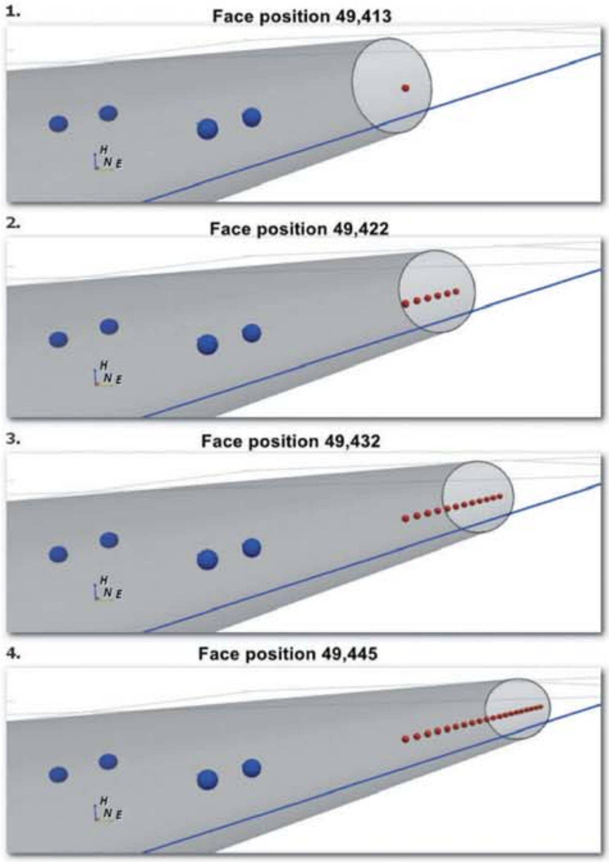

Figure 8. Tunnel model at 4 different face positions. Blue and red dots are receivers and shot points, respectively.

The inspection of the tunnel face during the excavation, which was carried out at two different stations before the problematic zones were encountered, revealed that it was a highly jointed and slightly weathered quartzite phyllite with strong to medium strength.

3.3 *Tunnel definition in Amberg TSP Ease software*

The TSP software makes it possible to take into account both planning information and the current tunnelling status. As soon as the tunnel axis has been entered in project coordinates, the tunnel model can be defined. Data acquisition begins at a specific position with the first blow of the hammer. The impact position refers to the current position of the tunnel face. Figure 8 shows the tunnel model in various positions of the tunnel face as the TBM moves forward.

After each TBM stroke of 1.7 metres, the next shot position is reached and the impact source can be coupled and seismic data recording proceeds. As segments are installed by the TBM or other tasks are carried out between each lift, seismic data acquisition does not cause any additional downtime, which means that the geological investigations are fully integrated into the production cycle.

3.4 *Results*

Seismic results can be obtained as tables, charts, and 2D/3D figures. Figure 9 shows the property charts of the seismic P- and S-wave velocities, Vp and Vs, respectively, and dynamic Young's Modulus (Edyn) of campaign #7. The position and the extent of the changes in the individual parameters are determined by the spatial position of the reflectors extracted by the software. The seismic reflectors correspond to boundaries at which a high acoustic impedance contrast exists. Hence, a large part of the wave energy was reflected to the receivers. The plane representing the boundary intersects with the tunnel axis. This correspond to the position where the change is expected along the prediction range. Decreasing values in seismic velocities or in the elastic parameters are commonly associated to weakness zones were for instance increasing fracturing, fault zones, cavities or any unfavourable ground condition might be expected.

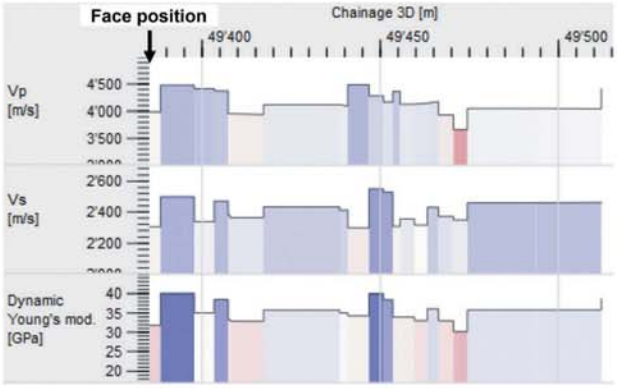

Figure 9. P and S-wave velocities and dynamic Young's modulus of campaign #7.

Figure 10 depicts longitudinal and horizontal planes from the 3D models of the Vp distribution for campaigns #7 and #8, top and bottom, respectively. On the upper part of each figure, Edyn charts are shown indicating the changes in GPa of the modulus. In campaign #7, Edyn values between 35 and 40 GPa dominate throughout most of the model. These values are related to the medium strong rock mass. Two anomalies in the velocity field are observed at the left-hand side of the tunnel axis, starting around 19 m from the axis, and extending for about 20 m, laterally. The reflectors defining the start of these two zones intercept the axis at chainage CH 49,407 and 49,466. The second anomaly has the lowest Vp and Edyn values: 3,630 m/s and 30 GPa, respectively. Lower Edyn values are associated with decrease in rock mass stiffness due to increasing fracturing, fault zones, etc.

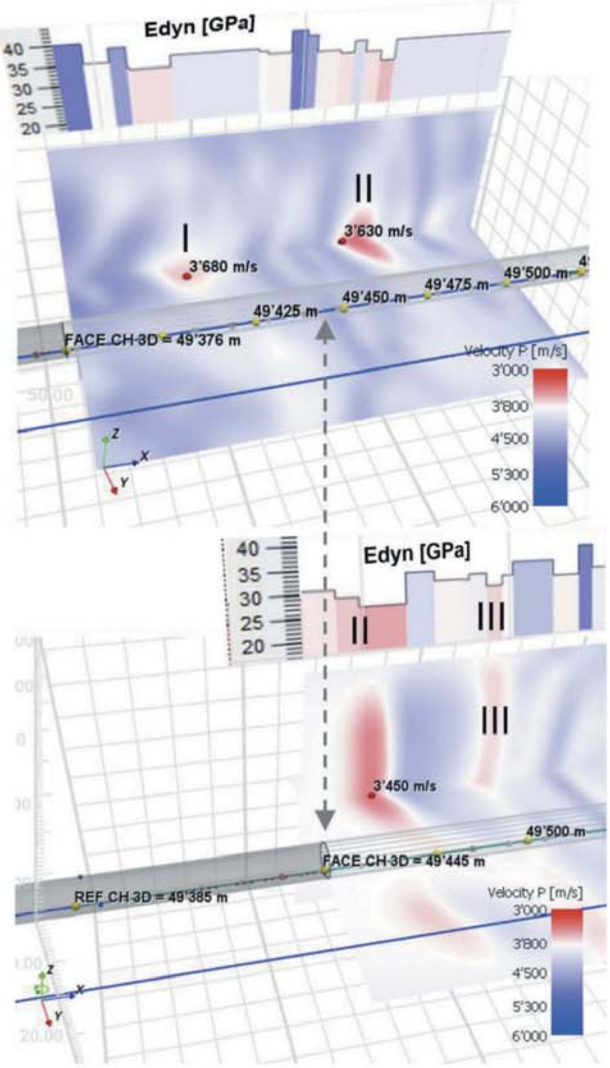

Figure 10. Longitudinal and horizontal 2D sections extracted from the 3D model of the Vp distribution. Top: campaign #7, bottom: campaign #8. On top of each figure, charts of Edyn variation in GPa are superimposed along the prediction range.

Campaign #8 was performed after 69 m excavation ahead of campaign #7, partially overlapping the prediction range of that campaign and shortly before the probable occurrence of the second anomaly. The result of campaign #8 not only confirmed the existence of a weak zone at the same location, but also enabled a more precise visualisation of the spatial distribution of the anomaly. According to the new result, the weakness zone reaches the tunnel section, and its influence area is two times larger at the tunnel level, 16 m instead of 8 m. The latter is based on the interception of the reflectors with the tunnel axis. Velocity and elastic values are slightly lower, Vp= 3,450 m/s and Edyn= 27 GPa.

Figure 11 shows the correlation between the TBM Contact Force (CF) and Edyn values obtained from Campaign #7 and #8 between chainages CH 49,440 and CH 49,500, approximately. According to the construction site personnel, CF has become an important parameter that allows conclusions to be drawn about the quality of the rock mass. Dropping

CF is an indicator of decreasing rock mass quality. For instance, CF < 4,000 KN is well correlated with poor rock mass. The lower the CF, the poorer the rock mass. In turn, increasing CF values are then associated with a rock mass of higher quality.

Along the selected chainages, the most significant CF drop is observed between CH 49,468 and CH 49,480, with CF values < 3,000 KN. This zone is in good agreement with the velocity anomaly (II) observed in the results of both TSP campaigns covering these chainages. Outside from this section, CF values > 4,000 KN dominate. Edyn values are in good agreement along most of the depicted section. However, in campaign #7 some opposite trend is observed between CH 49,452 and CH 49,464. Since this section lies in the far-field forecast of campaign #7 and is obviously embedded between two strong reflectors, one of which has a significant Edyn rise at around CH 49,446 and the largest drop from CH 49,466, sufficient resolution was not achieved to obtain reflectors that would better match this section. In fact, the influence of anomaly II can already distort the result for earlier chainages.

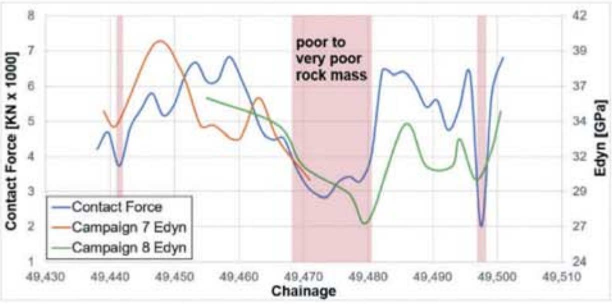

Figure 11. Diagram of TBM Contact Force versus Edyn as per Campaign #7 and #8 along selected chainages.

4 CONCLUSIONS

The new mechanised seismic source overcomes the current challenges posed by TBM tunnelling, namely the immediate identification of hazard zones and data acquisition without disrupting the production cycle and without downtime.

The percussion hammer is suitable for tunnelling with TBMs. It enables fast data acquisition during TBM stops for other activities.

In the present case study, critical areas such as shear/fault zones according to the GBR have not yet been encountered. However, areas with low to very low rock strength were encountered in these sections. These zones were correctly identified in various seismic campaigns and in some cases in exploratory boreholes and confirmed by the parameters logged by the TBM.

The information obtained from probe drills did not always match the TBM parameters, as was the case in some seismic campaigns, mainly due to the low to very low data quality.

Although much less energy is released into the ground with the impact hammer compared to explosives, sufficient spatial resolution is still achieved to identify geological structures that could be unfavourable for excavation. The penetration depth is naturally affected by this. However, this disadvantage is compensated for by uninterrupted data acquisition. This was demonstrated by the results of the two seismic measurements presented in this article. The first campaign made it possible to identify a possible weak zone in the far field about 90 metres before hitting it. In the subsequent campaign, which was carried out after about 70 metres of excavation, the weak zones were confirmed. The results of the second seismic campaign clarify the spatial extent and arrangement of this zone much better.

The TBM parameters, especially the contact force, corresponded well with the predicted zone of weakness.

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