Correlating rock support and ground treatment means with in-tunnel seismic data

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ABSTRACT: Tunnelling is a challenging task since it demands recurrent interaction and good understanding of the various disciplines of geotechnical engineering, geology and geophysics among others. Moreover, during tunnel excavation quantitative and qualitative data is continuously gathered by instruments and personnel from all these disciplines. Finding and understanding correlations between such datasets might provide useful information for the tunnelling work, hence, this task is not always straightforward and requires thorough analysis and validation of involved data. An interesting rock mass physical property is the seismic velocity, which is obtained during tunnel excavation easily and fast. Moreover, due to the physical relationship between seismic velocities and rock mass moduli, we investigate the correlation of geotechnical parameters derived from seismic data with common engineering practice for safe and efficient tunnel excavation. A real example shows how deviated parameters are in good correlation with rock classes in difficult sections during tunnel excavation.

KEYWORDS: Tunnelling, Geological forecast, Seismic exploration, Site investigation, Rock mechanical parameters

1. INTRODUCTION

In many projects, tunnelling operations face significant challenges due to the occurrence of uncertain or unknown geological structures, such as fault and shear zones, voids, and water inrush. These unforeseen events significantly delay the progress of underground work and negatively impact the schedule and project budget, but most importantly put personnel and machinery at risk. Geological uncertainties remain as a hazard even in projects with comprehensive geological and geotechnical investigations prior to the excavation phase.

However, when dealing with rock mass failures, it is important to understand how a weak rock mass surrounding deforms a tunnel as elastic deformation of the rock mass starts about two diameters ahead of the advancing face and reaches its maximum value at about two diameters behind the face as a reasonable approximation. At the face immediately upon excavation of the face about one third of the total radial closure of the tunnel has already occurred and the tunnel face deforms inwards (Hoek, 2012).

Therefore, systematic geologic prediction and site characterization during the excavation phase becomes a key aspect of project safety and a careful logistical approach to rock support operations. Traditionally, systematic exploratory drilling is performed from the tunnel face. Typical lengths of exploratory boreholes are in the range of 10 m and up to 150 m in highly critical zones. Certainly, soundings provide important lithologic information and, together with face mapping, allow characterization of the rock during tunnelling. However, these tools provide limited information on the spatial distribution of geologic structures in front of or around the tunnel face. In addition, large exploratory boreholes (>50 m) are expensive and require long execution times, resulting in undesirable downtime of tunnel production.

A good alternative or meaningful supplement to exploratory boreholes is the implementation of reflection seismic measurements during tunnel driving in order to obtain sufficient wide and three-dimensional rock mass characteristics.

2. THE IMPORTANCE OF SEISMIC DATA

Knowledge of the subsurface can be obtained through outcrop extrapolation, drilling, and geophysical measurements. Geophysical techniques during tunnelling help us understand the rock mass by creating images of the area ahead of the face. The most common and versatile method for imaging the subsurface is reflection seismics, which is usually applied today in three-dimensional volumes. 3-D seismic methods take a central position in the exploration and development of oil and gas fields since more than three decades. Algorithms for 3-D seismic data processing including 3-D migration and velocity analysis have now become an integral part of the seismic data processing systems in use today. The power of 3-D visualisation has given the industry the ability to create a geological model with the accuracy required to produce images in depth and with efficient effort. To make the best use of image volumes derived from 3-D depth migrations, seismic analysists now make extensive use of 3-D visualization in seismic interpretation. Using a volume-based interpretation strategy, they not only select interfaces as a contrast of acoustical impedance to describe the structural model of the subsurface, but they also use seismic attributes using wave signal recordings of all three spatial components to perform rock mechanics characterization of hazard images in the rock mass.

2.1 3D-Reflection seismics in tunnels

The use of three-component acquisition systems is particularly important for seismic applications directly in the subsurface. Here, sensors can be coupled directly to the bedrock in such a way that all three recording directions can be received in an equally good manner. This is principally important in order to record both body waves - compression and shear waves - so that rock mechanical characterization can be carried out from their velocity behaviour.

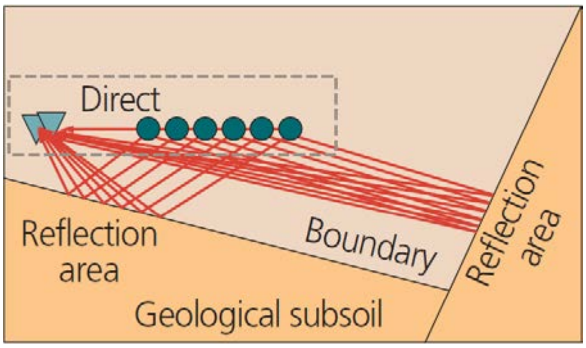

Figure 1 Principle of reflection seismics in an underground excavation. Sources of vibrations (dots) emit seismic waves; receivers (triangles) deployed in the excavation wall pick up body waves reflected at boundaries, such as an interface between two layers of different acoustic impedance (Dickmann, 2020).

Sources of vibrations generate body waves and transmit them from the tunnel wall into the rock mass, where they are then refracted or reflected at interfaces between rocks with different physical properties or rocks containing different fluids (Figure 1). The energy returning to the receivers along the tunnel wall is then recorded and processed to produce an image of the rock mass.

As seismic velocity is a very relevant parameter, a straight-forward algorithm needs to focus on its analysis and its behaviour on the surrounding rock. With some minor user interactions guided by data self-management and business intelligence, 3-D velocity models of the area ahead of the tunnelling face are obtained in short time using the TSP method during tunnelling (Dickmann and Krueger, 2013).

2.2 Correlation of rock classification with seismic data

The geotechnical classification of rock mass is mainly used to estimate the stability of the rock mass on site as a single geotechnical parameter such as the uniaxial compressive strength (UCS) cannot fully describe the rock mass behaviour. Hence, rock mass classification could play an important role for determining the necessary support and thus for the stability and safety of the tunnel. The importance of intact rock mass properties in determining rock mass stability is generally overshadowed by discontinuity properties, although in rocks with large discontinuity spacings or in weak and altered rocks, the influence of intact rock mass prevails (Bieniawski, 1989).

So, how do rock mass properties influence seismic velocities and is there a correlation of influencing factors on rock mass behaviour and thus rock mass classification with seismic velocities?

It is scientific evidence that different geological conditions such as jointing frequency, rock type and structure significantly influence seismic velocities such as the compressional wave velocity (Vp) according the early studies by Sjøgren et al. (1979) as compiled in Figure 2. Here, a Q-Scale had been added by Barton (1995) according to the near-surface, hard rock Vp–Q relationship in Equation (1) (Barton,1991).

$$Vp \approx 3.5 + \log_{10} Q \tag{1}$$

The empirical relationship in Equation (1) that is based on refraction seismic data can be assumed, if depths are shallower than 25 m and rocks are unweathered, non-porous and reasonably hard with a minimum UCS of 100 MPa.

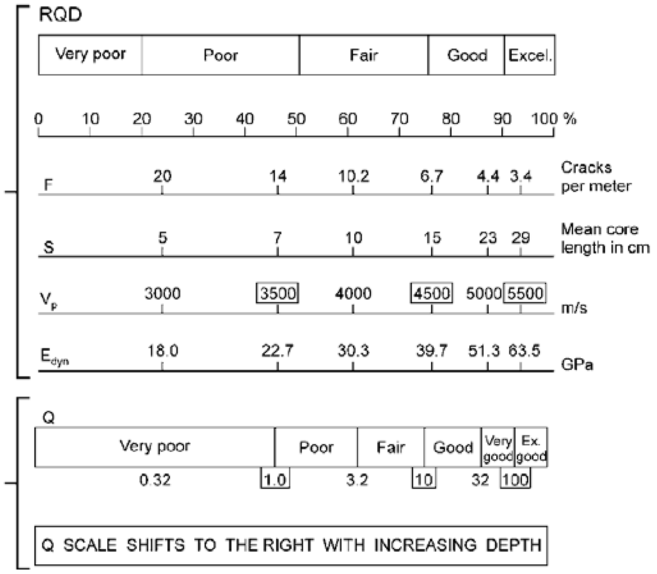

Figure 2 Mean values of physical and dynamic properties for hard, unweathered igneous and metamorphic rocks, based on shallow refraction seismics. Sjøgren et al., 1979. Q-Scale added by Barton, 1995.

If depth or stress effects come into play, then the Q scale must be shifted more and more to the right in relation to Vp with increasing depth, which also applies to the RQD and Fm^{-1} scales (Barton, 2006). However, as seismic velocities increase with depth, the first summand of Equation (1), that represents the compressional wave velocity in km/s at a Q-value of 1, must be replaced by higher values between 4.0 and 4.5, especially when reflection seismic measurements are performed directly at depth out of the tunnel.

Others found correlations between seismic properties and the rock quality designation (RQD) for moderately to well fractured rock in specific lithologies, which also led to the conclusion that there is no unique general correlation between RQD and Vp. El-Naqa (1996) stated that it is more useful to correlate the seismic velocity to a geomechanical classification system, e.g., the RMR or Q-System, as such a system considers several features that affect the geomechanical behaviour of the rock mass, such as the discontinuity characteristics and frequency. In any case, a calibration of seismic velocities for correlation with a rock mass classification should be performed for each tunnel project.

While in the 20th century correlations between compressional waves and rock behaviour were mainly the focus, in the last two decades more and more studies have been conducted to investigate shear waves as well. In hard rock, both body wave types are being influenced by rock mass properties in a similar way, but not in the same way. For instance, Giese et al. (2005) stated that there is a higher impact of the water saturation on the bulk modulus with respect to the shear modulus. Due to this, Vp reacts faster to changes in the water saturation. Thus, the shear wave velocity (Vs) is assumed to be a better indicator of changes in the lithology or the discontinuity density.

3. CORRELATION OF ROCK SUPPORT WITH SEISMIC DATA – CASE STUDY

In many tunnelling project worldwide preliminary geological and geophysical investigations applied from the earth's surface show that tunnel courses run through areas of complicated geology with possibly many thrust nappes and faults, with many different types of rock, and with a very high uncertainty about the ground conditions along the designed course of the tunnel.

This case study is from a real tunnelling project in Norway with a heading through geological formations of schist, mica schists and phyllite and anticipated fault lineaments of various strikes and dips.

Tunnel seismic prediction (TSP) measurements were carried out in this about 2 km long tunnel. They started immediately after the excavation began and were commissioned to analyse reflection seismic data out of the tunnel to forecast the geological conditions and to obtain maximum structural information with it. In addition, as is usually tendered and required in Norwegian tunnelling projects, the Measuring While Drilling (MWD) method as a function for logging and recording drill performance parameters during drilling of holes was compulsorily carried out in a tunnel. With it a further characterisation of the mechanical properties of the rock mass can be obtained as the parameter of rock hardness correlates with uniaxial compressive strength. The overall objective was to minimize geologic uncertainty, as the difficult ground situation along the section ahead consists mainly of gneiss alternating with phyllite, and a shear zone was expected nearby.

Figure 3 shows the entire comparison of results of one single TSP dataset forecasting a 150 m long tunnelling section ahead of the current tunnel face at station 2,009 m. Derived from the analysis of compression and shear wave velocities the rock mechanical parameters of dynamic Young's modulus and Bulk modulus along the forecasted tunnel axis characterise the rock mass to be excavated and zone it into five segments A-1 to A-5 (Figure 3a). The five zones are defined by changes in rock stiffness represented by the dynamic Young's modulus and by changes in rock compressibility represented by the inverse Bulk modulus and are designated by the green solid frames. Green dotted frames depict anomalies within the zones according to the Bulk modulus.

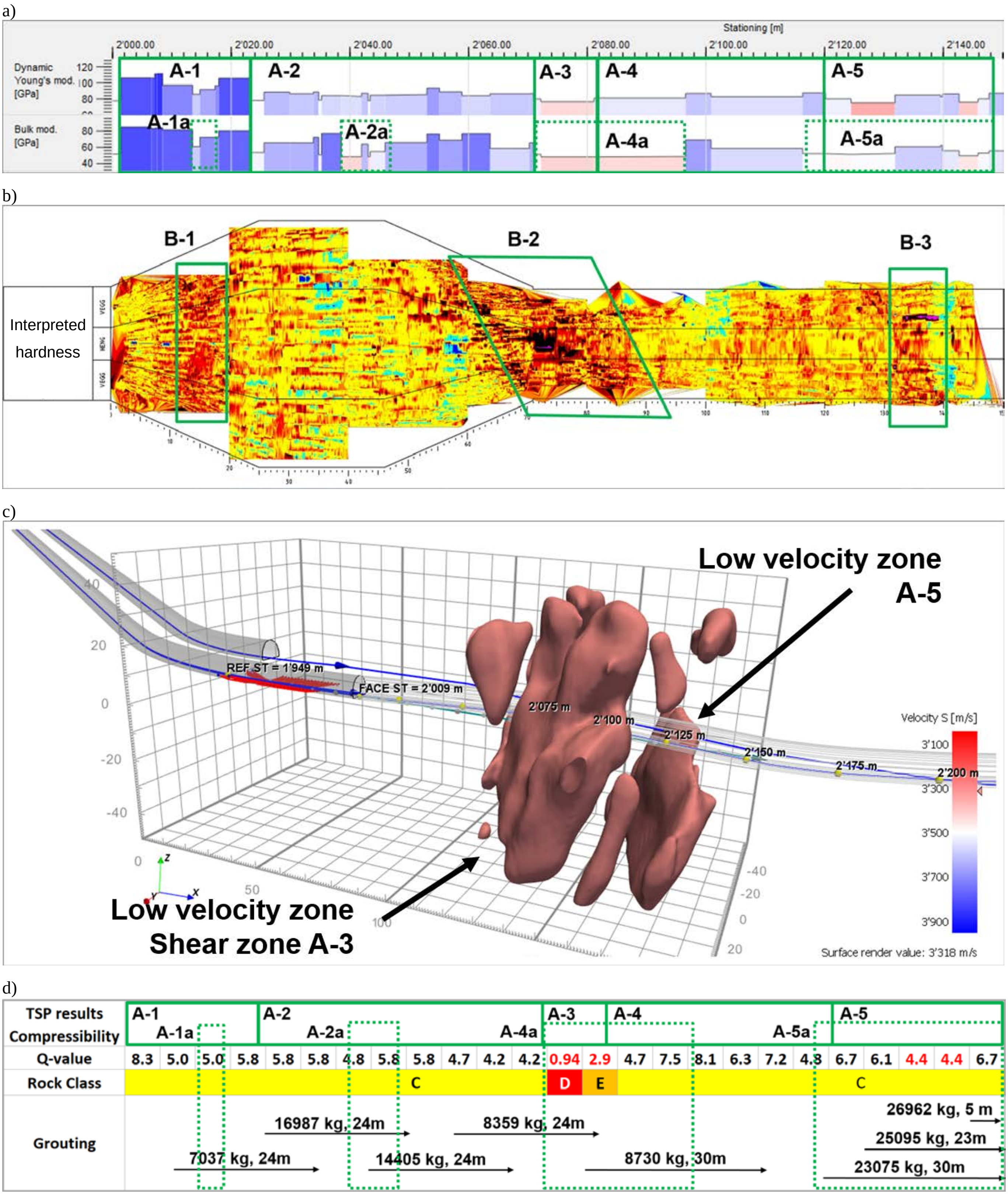

Figure 3 a) and c) present the results from one TSP campaign forecasting a 150 m long tunnelling section ahead of the current tunnel face at station 2,009 m. a) Parameter charts of dynamic Young's modulus and Bulk modulus derived from the analysed velocities of compression and shear waves illustrate increasing (blue) and decreasing (red) values, respectively. Green frames (solid and dotted) depict zones of various interest and behaviour.
b) shows the compilation of the interpreted hardness values of the MWD logging; each of about 10 metres of length from the respective working face along the shown 150 m section. The colour coding from mostly green over yellow to brown represents high to low hardness values as analysed from penetration rate logging during drilling. Green frames indicate areas of interest that are low hardness values.
c) shows the surface rendered volume plot of the shear wave velocity ahead of the working face below a threshold of 3,300 m/s. Arrows indicate the anomalies in zones A-3 and A-5.
d) shows a chart comparing different parameters as taken up from the encountered situation of ground conditions represented by the rock mass characterisation of the Q-value and its derived rock class and the grouting amounts applied in weak rock zones.

Table 1 Designated zones of different rock behavior as forecasted by one TSP campaign (RS: Rock Stiffness, RC: Rock Compressibility.)

Zone	Stationing	Description
A-1	2000 – 2024	High RS and low RC with local drop of RS at ST 2013-2018
A-2	2024 – 2071	Moderate RS with a 8 m wide centre zone of higher RC
A-3	2071 – 2082	Shear zone with lower RS and higher RC
A-4	2082 – 2120	Moderate RS with high to moderate RC (A-4a)
A-5	2120 – 2148	Alternating moderate to low RS with mainly higher RC

The five designated zones are described in Table 1. Figure 3c shows the complete tunnel situation at the time of the measurement. The reference point of which was at station 1949, where the two rear of the four seismic receivers had been installed in the tunnel wall on the right and left. From this point a 200 by 100 by 100 metre model had been built up to compute a velocity distribution of both compression and shear waves along a half metre grid in all 3 directions. The figure shows very clearly how the zones A-3 and A-5 can be mapped three-dimensionally by shear wave anomalies.

In comparison to the seismic data results in Figure 3a and c, Figure 3b shows the compilation of 15 interpreted rock hardness images obtained by the MWD logging of the many drillings from the 15 different working faces along the TSP forecasted section achieved after the entire section had been excavated. The colour coding from mostly green over yellow to brownish patches represents high to low relative hardness values as analysed from penetration rate logging during the many drilling at each working face. Here, three zones of relevance (B-1 to B-3) had been identified, which are designated by green solid frames. They show areas of reduced to very low hardness.

The results of relative rock hardness obtained by MWD measurements are in accordance with the TSP results as they find to some extent the same areas of softer rock (B1 & B3) and the shear zone (B2) near the tunnel with higher resolution but with a smaller spatial extent. The 3D-TSP shear wave velocity model in Figure 3c shows the spatial distribution of the shear zone in A-3 and forecasted further low velocity zones at A-3 and A-5 which are in line with the MWD zones at B-2 and B-3.

Figure 3d shows a chart comparing different parameters as mapped from the encountered ground conditions. They are combined into a Q-value as the rock mass characterisation. Here, the Q-values range from 0.94 to 8.3, which is almost no longer poor to reaching almost good. I accordance to this, rock classes have been designated as D (very poor) over E (poor) to C (fair to good). Despite the broad designation of class C along the forecasted 150 metre section, grouting measures indicate a further correlation parameter taking the grout amounts in weight per tunnel meter into account applied in weak rock zones, which correspond to the designated zones A-1a, A-2, A-3a and A-5a .

4. CONCLUSION

The amount of information available for a rock mass can be increased by geophysical techniques, which can provide an indirect assessment of its engineering properties. However, today geophysical measurements do not only provide valuable information about the ground condition during the preliminary studies, but also the more important during the excavation process, when the ground to be investigated is closer and safety becomes more relevant.

Seismic reflection data acquired in full space of the rock mass provide the most precise and valuable data and correlate to rock mechanical parameters and their characterising rating systems.

It has been demonstrated that the combined interpretation of rock properties for low velocity zones, of Young's and bulk modulus derived from seismic parameters complete the knowledge of the geological situation during the entire excavation in advance. Based on the better understanding of the geology and the underground conditions, accurate and suitable decisions were made in time before the final necessary amount of grouting and rock support had to be applied throughout predicted areas. This means a very significant added value for the contractor to minimise the geological uncertainties and to initiate timely measures for rock support.

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