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Is geological uncertainty ahead of the face controllable?

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ABSTRACT: Today, tunnelling need not inherently be a risky activity in terms of geological conditions. Geophysical methods and their improvement in terms of accuracy and of an optimal integration into the tunnelling work flow have been continuously advanced. The quick provision of on-site information is out of question. Much more it comes to the question whether the information obtained from geophysical data is understandable in a broader sense and as a result helpful to control the geological uncertainty. Here, it is essential to obtain an image of the geological subsurface in a three-dimensional view. The prepared geological 3D model reveals the running of a potential hazard and enables spatial viewing from different perspectives. The new generation of the 3D tunnel seismic prediction system integrates the operational requirements as well as the demanded state-of-the-art data imaging procedure. The sophisticated concept is user-purpose oriented and leads the operator straight to the result in a 3D environment. A further step is done to control geological uncertainties ahead of the face in hard rock conditions.

1 Introduction

Tunnelling is still a risky undertaking where two major factors are related to. Firstly but not in general, there is a lack of knowledge, skills and experience. Involved parties of a tunnelling project may not be able to tackle risks issues during planning and construction since tunnel alignment, the assignment of rock mass quality and rock support requirements are major design tasks. Missing methods and technologies in the risk management process have a direct significant impact on the cost and time consumption of a tunnelling project.

Secondly, the geological complexity of each region is a challenge where weak rock mass quality, fracturing and weathering, groundwater ingress and for deep tunnels rock stress are major characteristics of the geology encountered during tunnelling.

However, whatever the nature of risk may be, one has to make very clear, that the basic principles of risk management have to be followed. Those people who create risks are responsible for controlling them. Just following prescriptive regulations might not be best practise in any case. Moreover, safe operations are achieved by implementing the right methods and achieving the goals to be set in advance. The overall goal is to reduce risks in such a way that they are always within acceptability.

The only way to achieve acceptability of risks is to control them. It is well known that risks could not be completely eliminated during the design phase and they have to be dealt with as a continuous process during construction. Continuous site investigations are indispensable because the greatest hazards during tunnelling are geological uncertainties which lie in wait ahead of the face. Numerous geo-methods are available today. One of the cutting-edge technologies with a proven record of success is the latest Amberg TSP-3D technology.

2 Predicting geological uncertainties ahead of the face

In general, rock mass is heterogeneous and it can be described by its rock quality, stress regime and groundwater behaviour. The rock quality is mainly related to rock mass strength, deformability, weathering and the presence of discontinuities. All these properties are somehow linked to each other as the rock strength may be influenced by discontinuities and foliation or schistocity, and their orientation. During the planning phase, the designation of rock quality is mostly based on surface observations and borehole data. They are not as reliable as observations in the tunnel during construction. Even in the tunnel, rock mass strength is difficult to estimate, because the strength and deformation of rock mass and an intact rock specimen differs. However, due to a certain scale effect there have been derived empirical formulae estimating the rock mass strength, such as Rock Mass Rating (RMR) (Bieniawaski, 1993), Geological Strength Index (GSI) (Hoek et al, 1998) and Q-value correlation (Barton, 2002).

Due to geological assessment constraints non-destructive geophysical site investigations while tunnelling have developed and improved significantly over recent times. In particular, when site investigations from the surface are limited given the topography, tunnel seismic imaging can detect lithological heterogeneities within distances up to hundreds of meters ahead of the face, many times more that of probe drilling alone. It is the most effective prediction method because of its large prediction range, high resolution and ease of application on a tunnel construction site.

Especially, tunnel excavations using tunnel boring machines (TBM) do not provide geological data of the tunnel face, and they often use continuous probe drilling from the tunnel face to overcome this drawback. Besides the only one-dimensional information given, probe drilling causes significant delays to excavation. A careful risk management has to address such constraints by adequate exploration and proper measures. Robust and reliable prediction methods have to be applied, which do not disrupt the tunnelling process and yield results quickly and at moderate costs. Varied TBM tunnelling projects have proven, that a three-phase based risk assessment to control geological uncertainties is an efficient approach.

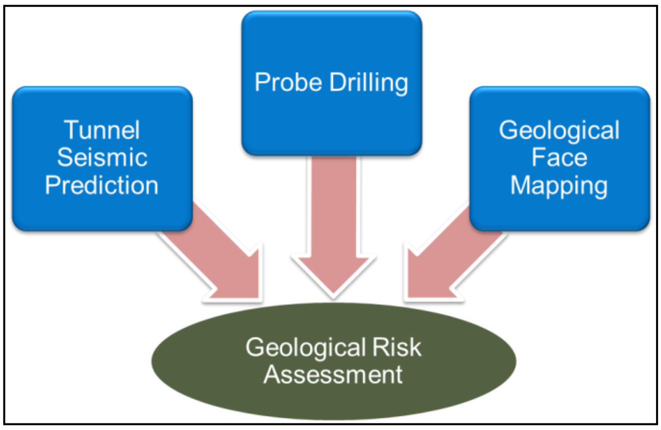

Figure 1. Three phases of geological risk assessment (Dickmann, 2012)

This approach uses the Tunnel Seismic Prediction (TSP) method to identify suspected fault zones identified from surface topography and geological mapping. Once the geological risk zone is identified, a probe drilling is carried out when the concerned zone is closer to the face. In addition, site geologists continually map the tunnel sidewalls to describe precisely the geological features encountered and to classify the rock mass for determination of the rock support (Dickmann, 2012)

Since many years, the TSP system has been successfully used in tunnelling projects worldwide. The system comprises seismic recording and receiver equipment specially designed for underground construction. The new generation of the TSP system comprises the wealth of outstanding experience and leads the user to the 3D vision of prediction results.

3 3D Tunnel seismic prediction ahead

The new TSP 303 system is an easy-to-operate system. The system setup and installation of the four sensitive triaxial sensors is simple and comparable with the setting of a rock bolt taking a total of 30 minutes.

Figure 2. Simple installation of receiver and recording units of the TSP 303.

The seismic acquisition geometry is restricted to source and receiver positions at or close to the tunnel. As a result reflection and scattering angles are small and the spatial resolution while imaging obstacles ahead is not optimum. Resolution is further decreased by seismic attenuation which is notably strong at the required high frequencies. Hence, careful data processing is very important in order to avoid inaccurate seismic predictions ahead of the tunnel, which may lead to misinterpretations. For example, discontinuities, which are structural or geological features that changes the homogeneity in the rock mass, may not being imaged to full scale, because only constricted portions of these zones could reflect waves towards the receiver due to the physical Snell’s law of reflection. The image will be enhanced by the use of more receivers such as two at both tunnel wall sides. Moreover, it could become quite meaningful to provide a second source line along the opposite tunnel wall side when the rock mass is very complex in terms of alternating strike angles or irregular obstacles such as cavities or Karst features. By all means, any increase of acquisition data quantity produces higher quality result images, in particular when it comes to 3D data processing.

The novel TSP 303 system integrates 3D data acquisition and processing software containing routines for optimal seismic imaging with respect to tunnelling requirements. It exploits the information in the seismic wave field by separate compression (P) and shear (S) wave analysis and the 3D-Velocity based Migration & Reflector Extraction technology (3D-VMR). The 3D-VMR technology provides an adequate and detailed 3D image of the ground leading to a more reliable interpretation compared to conventional 2D approaches.

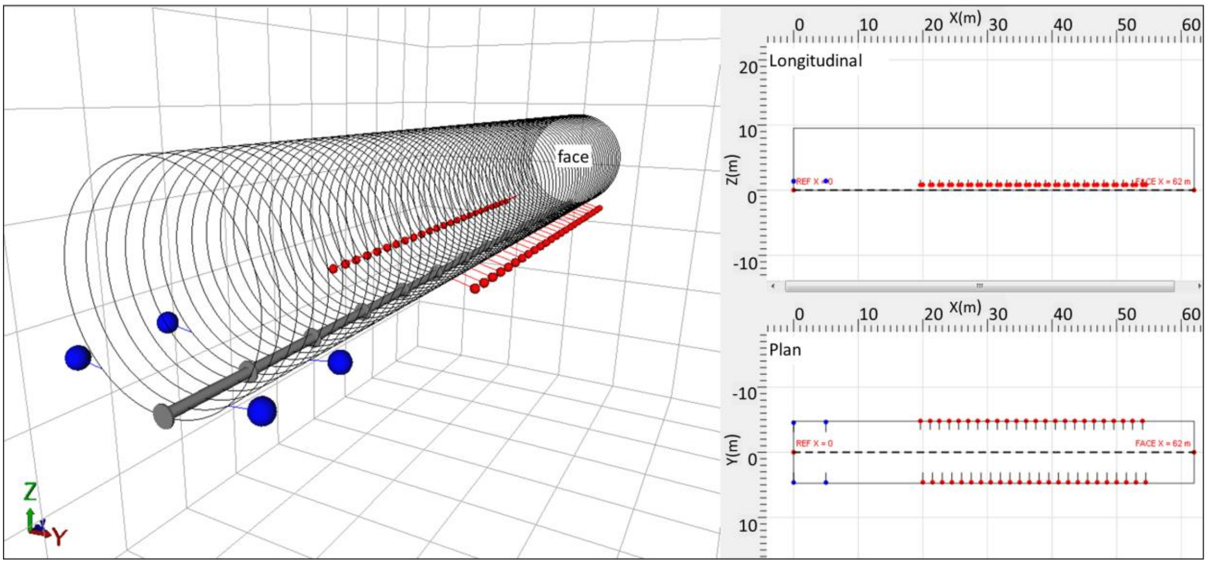

Figure 3. Example of a TSP receiver-source layout, blue dots: 4 receivers, red dots: 24 sources of small explosive charges per source line. Two source lines become meaningful - one each along left and right side wall – at complex rock mass geology.

4 Control of the geological uncertainties using the 3D-VMR technology

Advance knowledge of the spatial dimensions of geological fault zones, cavities, water bearing formations and changes in rock mechanical properties are key factors for a sound risk management, consistent operational safety and timely planning of construction countermeasures. It is well known what disasters may happen when a tunnel driving rushes into an unforeseen fault zone as figure 4 shows one.

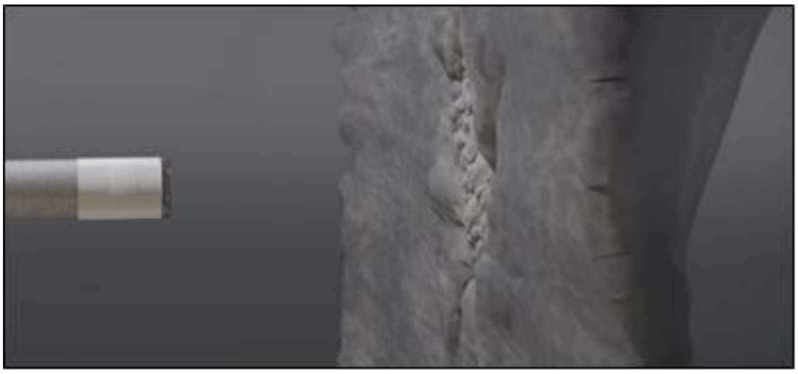

Figure 4. Possible worst case scenario: a TBM will likely rush into an unforeseen fault zone.

Seismic recordings are functions of time and measurement position and they should be converted to pure functions of space. The seismic migration is an inversion operation that rearranges the seismic refection data such that reflections and diffractions are mapped at their true locations.

The 3D-VMR technology investigates reflection seismic data in order to determine the wave velocity in the propagation medium. If the velocity model used in travel time computation closely resembles the true rock velocities, any migrated reflector element appears at the same location independent of illumination distance. For measurement geometries with small variation in the illumination angles, as in tunnel seismic exploration, it is a good approach to determine velocity via migrations with test velocities and a succeeding analysis of migration errors. The error information combined with the known used migration velocity yields a velocity model. This model forms the base for the next iteration until the final image computation yields the best fit model.

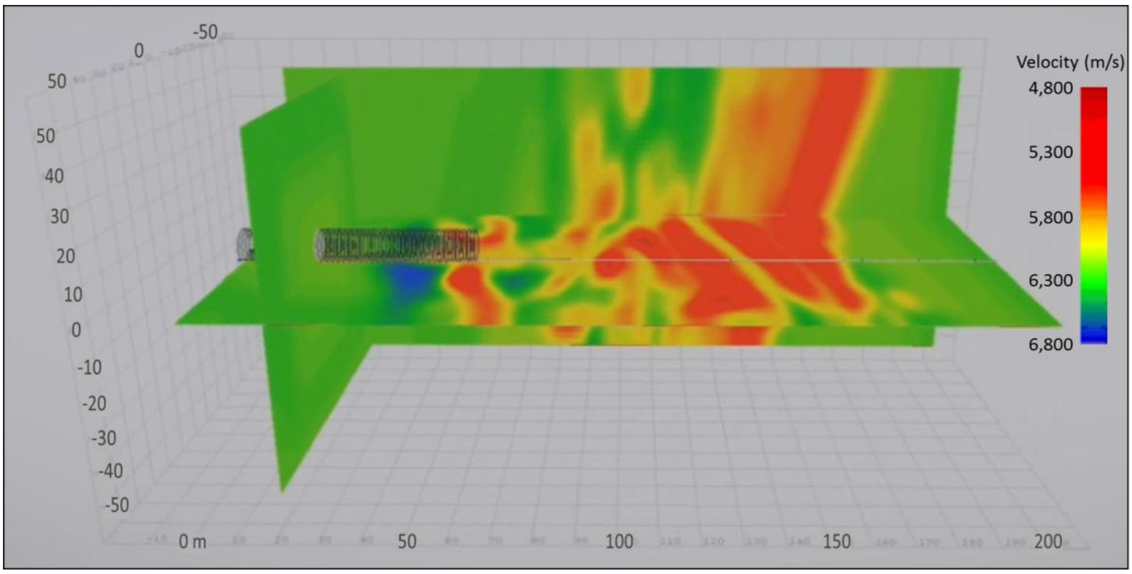

Figure 5. Perspective view of longitudinal, plan and cross section of a 3D velocity distribution (P-wave) 150 m ahead of the tunnel face.

Figure 5 shows a real case of rock mass consisting of intact Gneiss formation within the already excavated tunnel stretch. It illustrates the P-wave velocity distribution analysed by the VMR-technology, which is presented in planes of longitudinal, plan and cross views through the computed data cuboid of a size of 200 x 100 x 100 metres in tunnelling direction and in each vertical and horizontal direction, respectively. The tunnel alignment is centred in the cuboid. The same data is shown in Figure 6 in a full space view, where velocity values lower than 5,000 m/s have been extracted.

Around the tunnel, P-wave velocities of more than 6,300 m/s exist and represent an intact rock mass of high strength. Just in front of the tunnel face, a low velocity zone is indicated where highly jointed rock mass occurs. This zone retains a few metres and coarse jointing prevails on the subsequent section. About 70 metres ahead of the tunnel face a first fault zone becomes apparent almost cross-cut striking the prospective tunnel axis. This precursor is followed by another bigger fault intersecting the prospective tunnel from 80 to 92 metres ahead of the tunnel face. Further ahead intact Gneiss with coarse to moderate jointing returns and retains till the end of the forecast range.

Once the 3D-velocity distribution has been set, the next step of the 3D-VMR process is the 3D-reflector extraction. Here, the 3D-migration cuboid is being analysed and as a result reduced to this information, which reveals the most significant reflectors. A proper reflector image can now focus on zones within the rock mass, which are considered to be relevant for the further tunnelling.

Figure 7 demonstrates the result of the 3D-reflector extraction of the seismic data already shown in figures 5 and 6.

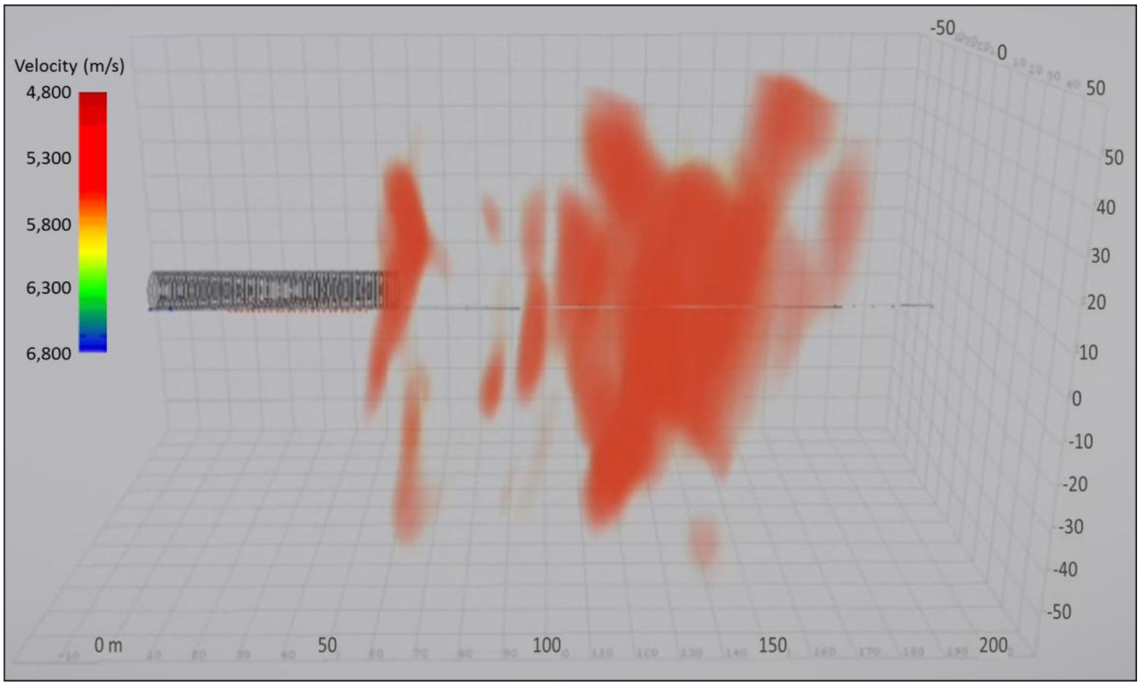

Figure 6. Full space perspective view of a 3D velocity distribution (P-wave)

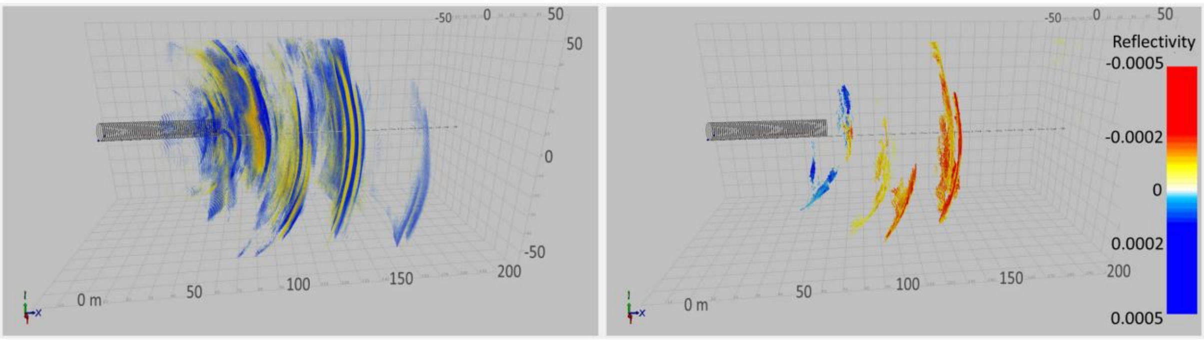

Figure 7. Left: Full 3D-migration image (P-wave); right: extraction of high reflectivity values of left image

In a further step, least-square-fit planes through the extracted relevant reflector elements are being computed (Figure 8). From these planes spatial locations are taken and the corresponding velocity information is picked from the velocity cuboids of the P- and S-waves. Combining the velocity model and the reflection image allows to interpret density variations. With this information further rock mechanical parameters of interest such as Young's modulus, Poisson's ratio, shear modulus etc. can be calculated using empirical relationships depending on the rock group or user-defined formulae for the density (Figure 9).

Bearing in mind that seismic measurements and their wave propagation phenomena are dynamic processes, the rock mechanical parameters obtained from them are of dynamic type. This circumstance consistently leads to misinterpretations when comparing dynamic Young's or shear modulus with data taken from laboratory tests. Van Heerden (1987) attributed the difference between static and dynamic moduli to the fact that rocks do not behave in a perfectly linear elastic, homogeneous and isotropic manner which is due to the presence of cracks. Cracks and non-linear response of the rocks affect the static measurements more than dynamic measurements leading to the differences in the static and dynamic moduli. Given the nature of the rock mass, it is not possible to obtain a general relation between the static and dynamic properties and hence empirical correlations have been developed. However, it is being generally noticed, that the difference between static and dynamic moduli decreases from rock types with low moduli (or low velocities) to rock types with high moduli (or high velocities) and from unconsolidated sediments to compact, non-fractured rock mass, respectively. In addition to this generally linear relation between static and dynamic moduli, a stress dependency had been observed and had led to a rather exponential relation (Van Heerden 1987). The VMR-technology of the TSP 303 system is making use of this exponential relation in order to guide the user in the comparison with dynamic and static moduli values.

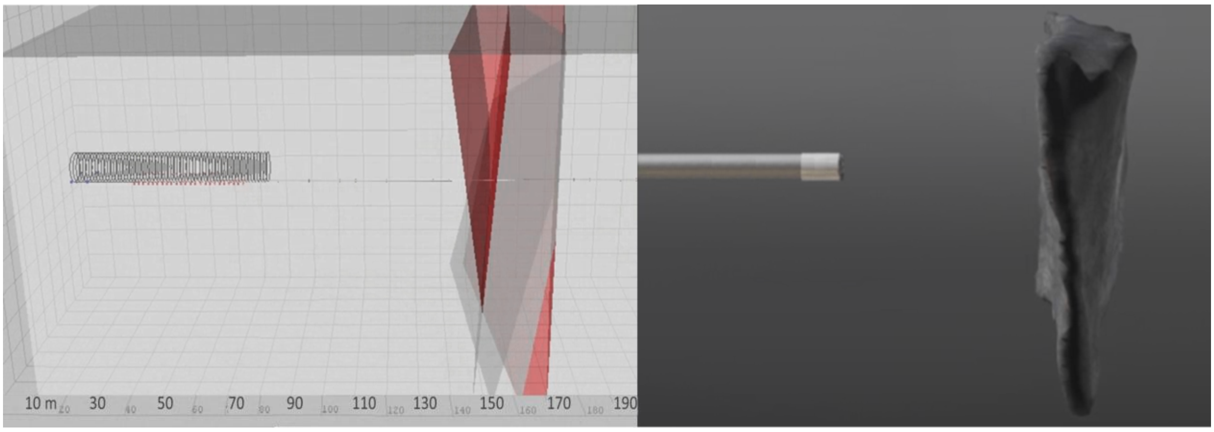

Figure 8. Left: Fitted reflector planes through the most significant reflector elements of the predicted fault zone; right: possible 3D-model of the predicted fault zone

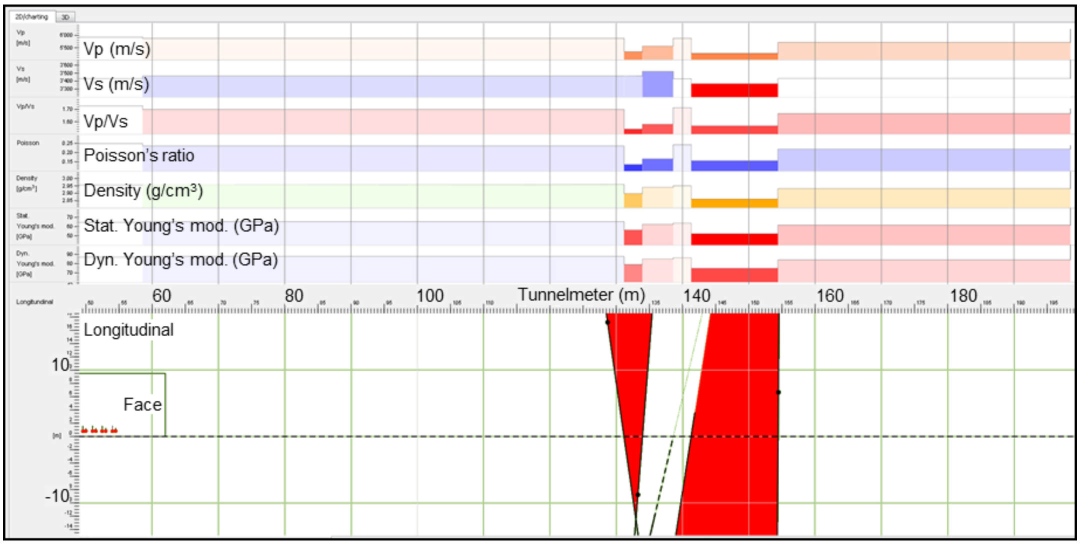

Figure 9. Rock mechanical properties (top) characterising the fault zone shown in the longitudinal section

The total processing and analysis time of the 3D tunnel seismic prediction system TSP 303 is about three hours on the construction site. Comprehensive reports can be given to the contractor within valuable time. Since the geological risk zone are identified, the contactor in agreement with the Engineer is able to decide, what measures are to be taken. Depending on the distance to the hazardous zone, he may decide to advance closer to the predicted zone. Once he has still got a safe range, he may carry out a shorter probe drilling to obtain evidence by the petrographical drilling profile. The confirmation may lead him to the decision of extensive roof bolting and/or pre-injection to treat the ground prior to excavation in order to stabilise the ground during excavation (Figure 10).

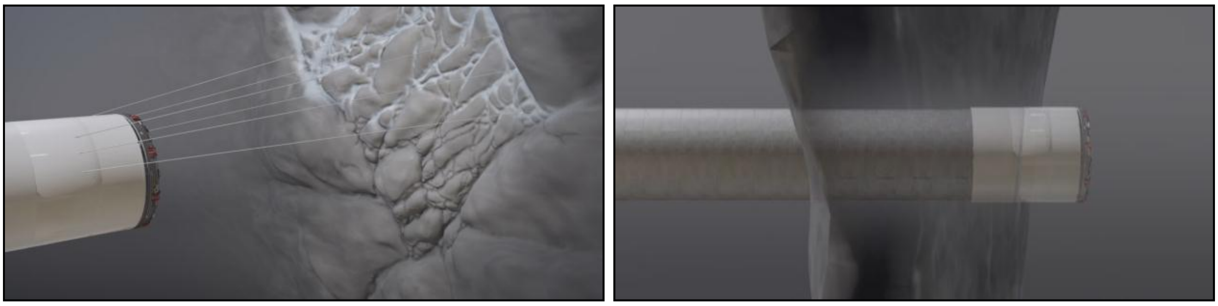

Figure 10. Left : pre-injection may become necessary to stabilise the ground prior to excavation; right: once the ground has been stabilised, advance can uninterrupted continue.

5 Conclusion

With the novel 3D tunnel seismic prediction system TSP 303 an important step is done in the geological 3D imaging that forms an essential integral part for the risk assessment during the tunnelling process. And yes, geological uncertainties ahead of the face in hard rock conditions become controllable.

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