How to turn geological uncertainty into manageable risk?

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ABSTRACT: Risk management became an integral part of most underground construction projects during the last decade. Still, there are parties, who may not plan for insubstantial unknown uncertainties of ground conditions because they are so unpredictable and out of scope of normal planning as they think. Finally, many of them end up as the most catastrophic events. Even known geological uncertainty is a risk that certainly exists without knowing how it will affect the work. Further, human biases form part of the way prior knowledge is being used to interpret data in a way it's anchored in one's mind or in a way that is just available. If no naive assessment of the uncertain situation is carelessly considered, risk becomes manageable if one know, detect and quantify the risk. A reasonable and cost-effective way to tread is the application of 3D-Tunnel Seismic Prediction on a regular base. Knowing what's ahead (in a case study) results in manageable risk.

1 INTRODUCTION

The very nature of tunnel projects implies that any potential tunnel owner will be facing considerable risks when developing such a project. Due to the inherent uncertainties, including ground and groundwater conditions, there might be significant cost overrun and delay risks as well as environmental risks. Also, as demonstrated by spectacular tunnel collapses and other disasters in the recent past, there is a potential for large scale accidents during tunneling work. Between 1994 and 2004, about 600 million US$ had been lost in 20 major projects where collapses had occurred. In 2006, tunneling projects became uninsurable due to a tremendous increase of loss ratio of 500%. It could give the impression that insurance had been the cheapest risk management tool. As a result, risk management became an integral part of most underground construction projects during the late 1990s. Since April 2003, international guidelines on tunneling risk management had been established showing how risk management may be utilized throughout the project's phases of design, tendering and contract negotiation and construction (Eskesen et al., 2004). Further, the insurance industry issued the joint code of practice for risk management of tunnel works in 2006 that is now being used worldwide and effective in risk sharing and encouraging best practice of risk management procedure in tunneling (Adeyemo, 2011). Eventually, this encouraging progress may lead to some tunnel builders' opinion that bearing the risk of loss and saving money by being uninsured might be a charming option.

Very well then; the overall term "risk management" is widespread and in everyone's lips in many fields of activity and expertise. Though, do we really sufficiently know about manageable risk?

In fact, manage risk stands for identify, assess, analyze, eliminate, mitigate and control risk, and it's a fallacy to believe that risk management could end before finishing the tunnel. In particular, it's the unknown uncertainty that comes as a geological hazard zone. There are still owners or contractors, who may not plan for these insubstantial events because they are so unpredictable and out of scope of normal planning as they think. Finally, many of them end up as the most catastrophic events.

2 RELEVANT UNCERTAINTIES

An owner's or contractor's ability to identify risk is limited by the certainty or uncertainty of risk. A simplified grouping of risk could be made like this: known certainties, known uncertainties, and unknown uncertainties. Actually, common understanding of risk is so closely associated to uncertainty that almost nobody would consider known certainties to be risks at all. If we know something is coming, we think of it simply as a circumstance to be addressed. Known uncertainties is a risk we know exists, but we do not know how it will affect us. The unknown uncertainties are unlikely to be addressed during project planning. However, even in the project planning they need to be addressed at least in order to budget for measures such as geophysical or more specifically seismic measurements necessary to identify the unknown uncertainties during the prospective construction phase. At the end of the day, there is always the one question: has the geology in the tunnel area been adequately explored and analyzed before and during tunneling?

2.1 *Constraints by measurement uncertainty*

In subsurface investigation, geophysicists typically measure, process and interpret the data and hand over the interpretation result to the geologist or geomodeller. She or he then integrates this result with other geologic data and compiles a geologic model. This conventional workflow fails to meet the challenges because it is not attuned to quantify uncertainty that is associated with every piece of geologic data due to resolution, sensitivity and noise.

In consequence, the workflow need to be changed where "measurement uncertainty" associated with seismic and geologic interpretation is quantified. With uncertainty collected at the early design and planning stages of an underground construction project, the interpretation becomes not a single geologic model but an ensemble of models that can be used to risk and improve decision making (Leahy and Skorstad, 2013).

The seismic image is impacted by the survey acquisition parameters of sources, receivers and geometry, the material response such as inelasticity, anisotropy and attenuation, environmental or electronic noise and signal processing procedures with their options of parameters. An interpretation should therefore be not merely a section of mapped seismic events, but also a description of the variability tolerated within the data. Quantifying the ambiguity in the prediction is the concept of measurement uncertainty (Leahy and Skorstad, 2013).

This measurement uncertainty is clearly different from the "conceptual uncertainty" in geologic interpretation, which derives from a range of concepts that geoscientists could apply to a single data set.

2.2 *Constraints by conceptual uncertainty*

Interpretations of seismic images are used to analyze subsurface geology and form the basis for many exploration and extraction decisions, but the uncertainty that arises from human bias in seismic data interpretation has not previously been quantified.

It follows that geoscientists use their prior knowledge to apply or generate a new concept to data in order to construct an interpretation and geological model. The initial geological model might be a fundamental source of uncertainty because it is dependent on the tectonic paradigm or concept used in its construction. Bond et al. (2007) argue that conceptual uncertainty can be more important than the uncertainty inherent in the positioning of boundaries or fault planes in a geological model (Figure 1). Human biases form part of the way prior knowledge is being used to interpret data. There are three relevant bias types in the context of geo-data interpretation, which are known from cognitive psychology. The Availability bias occurs taking the model or interpretation that is most dominant in one's mind. Anchoring bias is the failure to adjust from experts' beliefs, dominant approaches, or initial ideas. Interpreters expect to see a particular type of structure in a given setting such as a geographical location. Confirmation bias involves actively seeking out opinions and facts that support one's own beliefs or hypotheses.

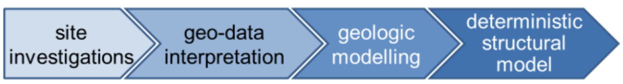

Figure 1. The conventional subsurface analysis workflow produces a single deterministic structural model of the ground.

Conceptual uncertainty is likely to be a major risk factor for disciplines in which decision making is based on prior knowledge and hence concepts of interpretation of data sets containing limited information.

2.3 *Implication to tunneling*

In tunneling, uncertainty could lead to fatalities and doesn't need to be accepted. Once a preliminary model or hypothesis has been generated, the real geological conditions in a tunnel project could be generally verified by collecting further data from pre-investigations from the surface or from geological mapping in the tunnel during the construction phase. Here, a continuous reconciliation of forecasted and observed data can be obtained resulting in a workflow where a geologically consistent structural model is updated. This process therefore becomes a constructive process rather than a simple mapping process that Leahy and Skorstad (2013) call a concept of model-driven interpretation (Figure 2).

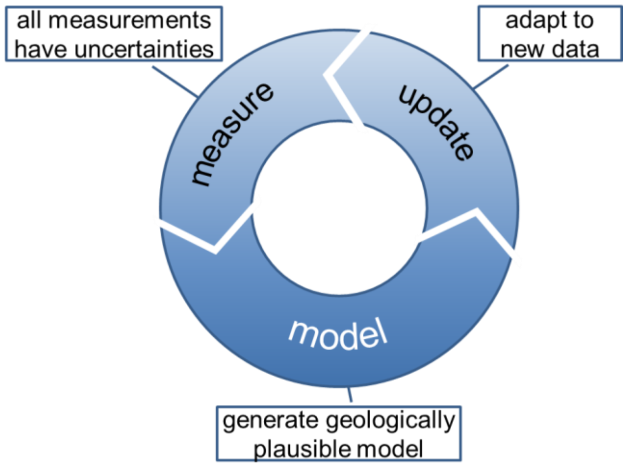

Figure 2. Model-driven interpretation workflow where measurement uncertainty allows for the generation of a geologically plausible model (after Leahy and Skorstad, 2013).

3 FROM GEOLOGICAL UNCERTAINTY TO MANAGEABLE RISK

The geotechnical risks that can affect projects result from a range of hazards associated with geological conditions, but also from hazards associated with the geo-engineering process. For example, active faults identified during pre-feasibility studies will pose one type of hazard, whereas a management decision to limit the extent of a site investigation to save money will pose another type of hazard. Although geological assessment constraints exist, hazards induced by saving money don't have to be taken into account unless a naive assessment of the situation is carelessly considered.

Non-destructive geophysical site investigations while tunneling 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 (Dickmann and Krueger, 2013).

The Tunnel Seismic Prediction (TSP) method detects changes in rock mass such as irregular bodies, discontinuities, fault and fracture zones ahead of the tunnel face (Dickmann and Sander, 1996). Employed as a predictive method during excavation process for both drill & blast and TBM headings, no access to the face is required to perform measurements, which are taken in tunneling production breaks of around 60 minutes. Acoustic signals are produced by a series of 24 shots of usually 50 to 100 grams of detonation cord aligned along one tunnel wall side and having an additional shot line along the opposite tunnel wall side in cases of more complex geology. Four sensor probes, consisting of highly sensitive tri-axial receivers, are contained in protection tubes whose tips are firmly cemented into boreholes of 45-50 mm in both side-walls. The 3-component receivers pick up the seismic signals which were being

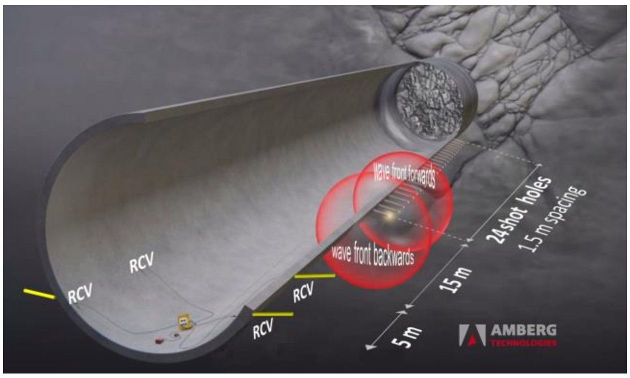

Figure 3.Measurement layout of the 3D Tunnel Seismic Prediction method consisting of usually 4 receivers (RCV) and 24 shot points.

reflected from any kind of discontinuity in the rock mass ahead. A highly sophisticated processing & evaluation software has been devised for ease of operation. The capability of the system to record the full wave field of compressional and shear waves in conjunction with the intelligent analysis software enables a determination of rock mechanical properties such as Poisson ratio and Young's Modulus within the prediction area. The final 2D- and 3D-summary results produced by the system software present as well detected events and boundary planes crossing the tunnel axis coordinates ahead of the face.

The owner and contractor can make know their risk, because they can detect and quantify the geological hazard. Unknown uncertainties should belong to the past and they become known uncertainties and in some cases even certainties. Once a geological risk zone is identified, the contactor in agreement with the Engineer is able to decide, what measures are to be taken.

With a regular tunnel seismic operation, you identify your geological risk detecting hazards and quantifying their impact to your tunneling job. By this means, the tunnel builder can understand the risk as chance or thread and even very economical. Depending on the heading length and type of the project, the investment in knowing the risk by a regular TSP operation is just between 0.7 % and 1.8 % of the time-related site costs such as labor costs, provision of installations and energy expenses. In other words, all investments in this technology are already paid after saving 3 to 7 days of downtime. How easily may happen one unforeseen incident of water ingress that would

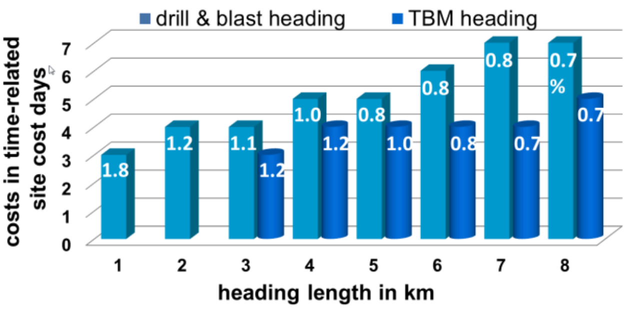

Figure 4. TSP expenses when applied on a regular base dependent on heading length and excavation method. Expenses are based on time-related site costs. Numbers in bars give TSP expenses in percentage of total heading days.

cause 3 days downtime at its best, not infrequently one month. Figure 4 illustrates the TSP expenses in time-related site costs. For TBM operation, a minimum heading length of 3 km is assumed. Here, a reduction of only three to five days of downtime pays off TSP operations on a regular base. In conclusion also from an economic point, does it really make sense to even think about limit site investigations to save money? The answer is clear with regard to ITA's guidelines for tunneling risk management: any implementation of measures to eliminate or mitigate risks where economically feasible or required according to the specific risk objectives or health and safety legislation is to be ensured (Eskesen et al., 2004).

By way of example, the next chapter illustrates how these operations contribute to measures economically mitigate risk.

4 CASE STUDY

The objective of this case study is a geological prediction of minimum 100 m ahead of the tunnel face and in addition, the verification of the results of an existing probe drill. Since geology is known from an extrapolation approach from a parallel tunnel, TSP was requested verify the appearance and characteristics of fault and fracture zones and their crossing to the planned tunnel axis.

4.1 *Site Location*

The geology encountered within the seismic layout between receiver reference location and face location at meter 57 is dominated by weathered volcanic breccia. The geomechanical classification is class III-IV according to RMR rock mass rating. The rock behavior at the tunnel face is seen as instable. With on-going excavation following rock behavior is assumed:
meter 60 to meter 75 - Fault zone or heavily fractured, Class IV, instable face,
meter 75 to meter 161 - Volcanic breccia, Class III, stable face,
meter 161 to meter 168 - Fracture zone, Class IV, short-term stable face,
from meter 168 onwards - Volcanic breccia, Class II-III, stable face.

4.2 *Probe drill result & geological forecast*

Figure 7a summarizes the geological forecast based on the 30 m probe drill result between tunnel face at meter 57 and end of drill at meter 87. The on-going geological forecast represents the extrapolation of the encountered geology of the parallel tunnel until meter 182. The already excavated tunnel and the first 3 m of the probe drill is placed in a weathered Volcanic breccia where the geomechanical rock conditions shows fair to poor rock mass quality (RMR classification III- IV). Between meter 60 and meter 75 a Fault zone with decreased and poor rock mass quality (RMR classification III- IV) is embedded. At meter 75 the rock mass improves significantly and a change to good quality (RMR classification III- II) was found, although with a fractured contact zone of 4 m length until meter 79. The remaining section of the probe drill to meter 87 revealed Volcanic Breccia. The further geological forecast, based on information of the parallel tunnel, doesn't indicate any other tunneling relevant or significant rock mass change, except a smaller 7 m long fracture zone included between meter 161 and meter 168.

The geo-hydrological conditions can't be considered critical. However, dripping water with low permeability of 1.25 l/s was present in the weathered volcanic breccia and fault zone between meter 45 and meter 75 and extends into the fractured contact zone up to meter 79.

The subsequent volcanic breccia doesn't show any presence of water and is considered to be dry to the area of the forecasted embedded fracture zone, where a low permeability might become possible again.

4.3 *3D investigation*

The measurement was carried out with the latest TSP 303 technology. This novel 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 (Dickmann and Krueger, 2013).

Figure 5 illustrates the SH-wave velocity distribution in a cropped display of a computed data cuboid of 200 x 50 x 50 metres in tunnelling direction and in each vertical and horizontal direction, respectively. The tunnel alignment is centred in the cuboid. The copping reduces the display to velocities smaller than 2,050 m/s. Around the tunnel, SH-wave velocities of more than 2050 m/s exist and represent rock mass of weathered volcanic breccia. Just few meters in front of the tunnel face, a low velocity zone up-dipping and left striking and an extension of approx. 20m is indicated where highly fractured rock mass occurs. Behind this zone, the velocity increases and returns to values of good rock mass conditions. About 100 meters ahead of the tunnel face the velocity drops down again and a second low velocity zone becomes visible, almost cross-cut striking the prospective tunnel axis from approx. meter 160 to 170. Further ahead, intact rock mass returns to good conditions and retains till the end of the forecast range at meter 200.

With the combined velocity information of both P- and S-waves, 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 7).

Figure 7b) shows five graphs, which describe the predicted curve progression of the P-wave velocity, S-wave velocity, Vp/Vs ratio, Poisson ratio, Density and Dyn. Young's Modulus along the tunnel axis. The graphs are also colour shaded below their respective chart line. Figure 7c) represents the longitudinal model view of the 3D-TSP result with reflectors and boundary shading according to Young's modulus values. A colour change takes place at a reflector element extension from its location and

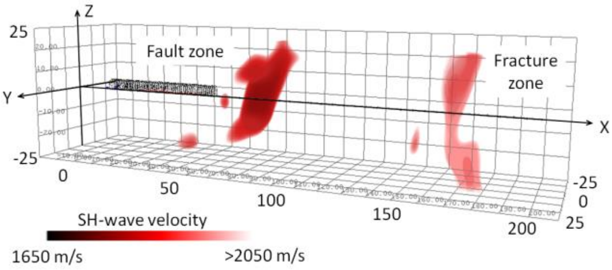

Figure 5. Full space perspective view of the cropped 3D velocity distribution (SH-wave) revealing fault and fracture zone.

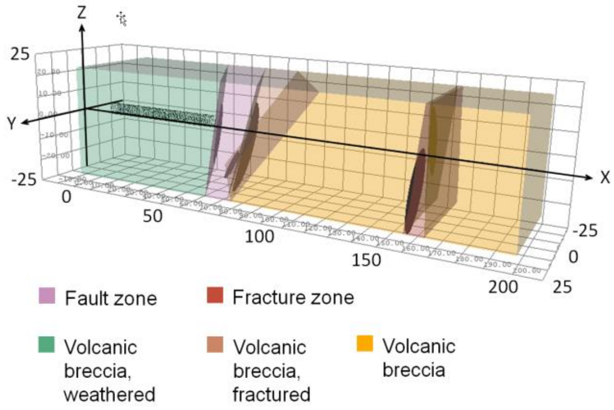

Figure 6. 3D-TSP geological model highlighting fault and fracture zones in their environment of volcanic breccia.

orientation in space and its intersection point with the tunnel axis.

The measured reference velocity of the direct P-wave in the area of the measurement layout was 3,540 m/s (S-wave 2,050 m/s, Vp/Vs 1.73), corresponding to the fair to poor rock mass of the weathered volcanic rock.

Beyond the tunnel face location at meter 60, the values of the mentioned parameters begin to decline. P-wave velocity (2,840 m/s) declines more than S-wave velocity (1,800 m/s) and both considerably show the fault zone extension until meter 75. Its relative low Vp/Vs ratio (1.60-1.58) represents a zone of mostly unconsolidated breccia in a higher stress regime where water presence does not influence the shear wave, significantly.

A contact zone between meter 75 and 90 indicates a strong fractured not weathered volcanic breccia. Within this transition zone, the situation (Dyn. Young’s Modulus) slowly changes to better and good condition until meter 90, according to the decreasing fracturing that was being found. This better rock mass condition persist for about 70 m.

About 100m ahead of the tunnel face, at meter 161, the P-wave velocity drops again slightly (from 3,760 m/s to 3,630 m/s), while the S-wave velocity drops stronger (from 2,150 m/s to 1,940 m/s) indicating a fracture zone forecasted for this area. This zone extends over about 5m where the higher increasing Vp/Vs ratio (from 1.75 to 1.87) also indicates possible water bearing.

As a last step of interpretation, the seismic geological model is presented in Figure 7d) as the plan view of the rock mass changes along the tunnel axis. The geological borders are the start and end point of interrelated reflectors within same rock mass characteristics derived from the rock properties.

Conclusively, it is shown that the seismic prognosis is in very good agreement with the geological findings of the probe drill and the further geological forecast. The result points out the fault zone and fracture zone as rock mass change critical for the tunnelling. In contrast to the probe drill, TSP found a widened fractured rock mass in the contact area between the fault zone and stable volcanic breccia. In addition, the result confirms the stable rock conditions after the excavation will have passed the fault zone and before entering the fracture zone.

5 CONCLUSION

It is well proved that a sound knowledge on measurement uncertainties and the consistent way of a model-driven interpretation won’t pose hazards caused by a wrong understanding of cost savings. Generating and updating geological plausible models with means of continuous cost effective 3D-Tunnel Seismic Prediction applications during tunneling is the right way to turn geological uncertainty into manageable risk.

REFERENCES

Adeymo, A. 2011. Risk Management of Tunnelling projects. *IRM Construction SIG Meeting*, 26th July 2011.

Bond, C.E. ; Gibb, A.D.; Shipton, Z.K. and Jones, S. 2007. What do you think this is? "Conceptual uncertainty” in geoscience interpretation. *GSA Today*, v.17, no.11, p.4-11.

Dickmann, T. and Krueger, D. 2013. Is geological uncertainty ahead of the face controllable? *World Tunnel Congress 2013 Geneva, Underground – the way to the future!* G. Anagnostou & H. Ehrbar (eds), CRC Press

Dickmann, T. and Sander, B.K. 1996. Drivage concurrent Tunnel Seismic Prediction (TSP). *Felsbau.* v. 14, no. 6, p.406-411

Eskesen, S.D.; Tengborg, P.; Kampmann, J. and Holst Veicherts, T. 2004. Guidelines for tunnelling risk management: International Tunnelling Association, Working Group No. 2. *Tunnelling and Underground Space Technology*, 19, p.217–237

Leahy, G.M. and Skorstad, A. 2013. Uncertainty in subsurface interpretation: a new workflow. *First Break*, v.31, no.9, p.87-93.

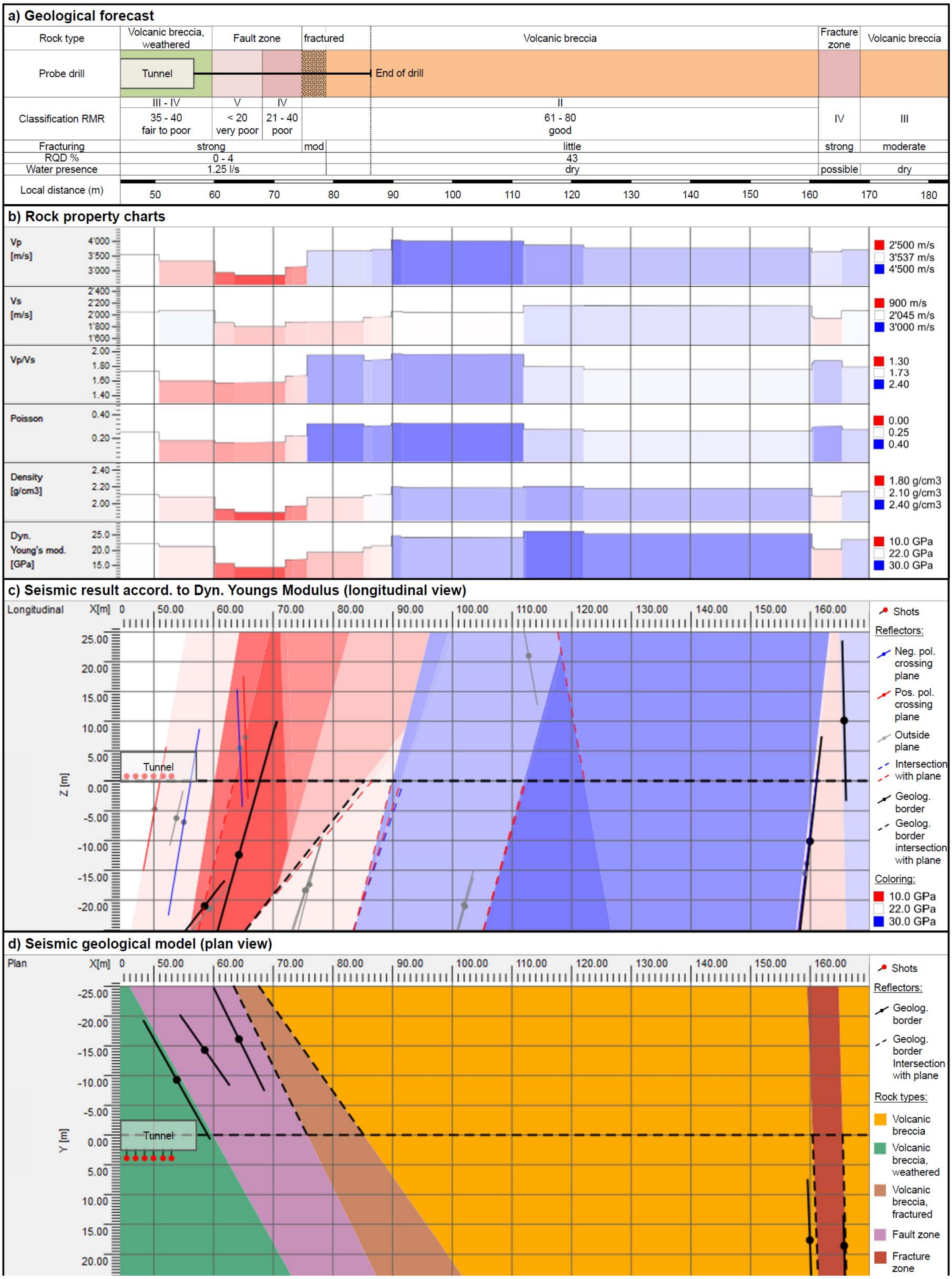

Figure 7. a) Geological forecast with 30 m long probe drilling from tunnel face b) Rock property charts derived from TSP measurements c) TSP result with reflectors and boundary shading according to Young's modulus values in longitudinal view d) Seismic geological model in plan view.