

Long Range Underground Prediction of Ground Behaviour/Hazards at Tunnel T13 in USBRL Project using TSP

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Abstract

Estimates of uncertainties and its associated risk during the construction process are essential information for decision making in any stage of a tunnel project. Dealing with adverse ground condition at any depth can be problematic, which will lead to a significant delay and cost upsurge if it is not adequately predicted. The amount of information available for the ground can be increased by specialised geophysical technique, which provide indirect assessment of engineering properties. The aim of such type of geophysical investigation is to model the expected behaviour of the ground and thus to predict the scenarios indicating potential variations in the quality of the rock mass during underground excavation. Tunnel Seismic Prediction (TSP) as an advanced geophysical method for estimating ground condition ahead and around of unexcavated areas in tunnelling quantifies mechanical ground parameters based on body waves velocities (compression and shear wave velocities). Seismic velocities are sensitive to rock mass quality, porosity, stress state, and water condition. The method is widely accepted because of its long prediction range and high resolution. TSP 303 is used in tunnel T13 of Udhampur Srinagar Baramulla Rail Link (USBRL) Project in J & K, India and achieved a remarkably high prediction accuracy of 90 per cent. The prediction of ground condition at T13 helped to prevent potential failure/collapses to occur. In this article the use of seismic properties of ground to assess the geomechanical behaviour ahead of the face of the tunnel is illustrated.

Keywords: GCD, I-System, SRH, tunnelling, TSP

1. Introduction

Geophysical investigations in underground engineering imply a series of geophysical methods. The tunnelling industry has already identified the potential of these non-destructive methods that valuably contribute to the assessment of the ground condition and to the provision of an interpretative prediction guideline for advancement. Due to long range prediction and high resolution, seismic methods are classified as optimized methods in which they are usually preferred for the assessment of the ground condition/s.

Many tunnels are located in areas with relatively weak access along the alignment and excavated/bored under extremely high overburden. These two factors often result in limited geological information. It would be reasonable to state that the deeper the tunnel, the greater the level of uncertainties due to less accurate geotechnical data available.

The normal approach to assess the geomechanical condition is to obtain the geological section along the tunnel by observation, borehole drilling, and surface geophysical

survey. However, factors like overburden, thickness, and topography may limit the potential of these methods to obtain the precise and sufficient information. In excavation through inaccessible mountain even an extensive geotechnical baseline report can miss the critical ground surprises. This can create a big challenge for both drill and blast and TBM drive in terms of their performance and safety.

The safe operation can be achieved by implementing the right method. The overall goal should be minimising the risk in such a way that it always is within acceptability (Dickmann, 2013, Dickman and Krueger, 2014, Dickmann et al, 2018). The only way to achieve the acceptability of risk is to control them. Knowing in advance where the significant geological boundaries intersect the tunnel axis can help to prevent hazards such as large failures, collapses, and extreme ground conditions.

2. Overview of Tunnel Seismic Prediction

The TSP is based on the evaluation of elastic body waves, which are being excited by detonation charges providing the best signal to noise ratio and the least restrictive conditions for recording and processing (Figure 1).

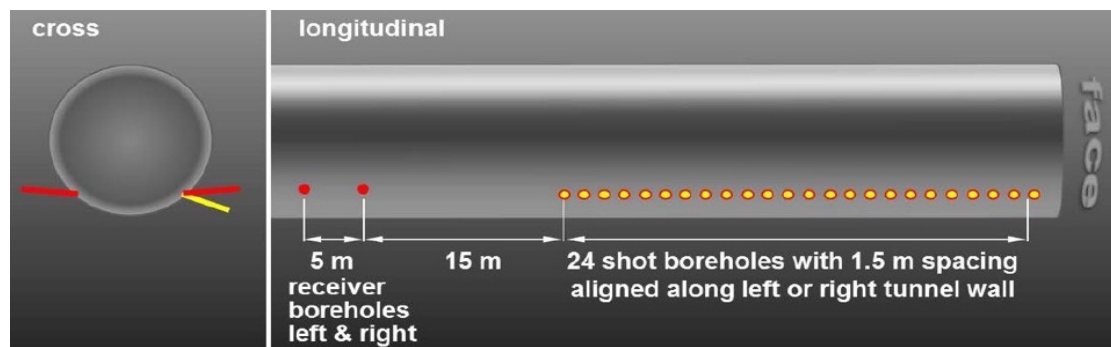


Figure 1. Measurement layout of the 3D Tunnel Seismic Prediction technique (TSP 303) consisting of usually 4 receivers (RCV) and 24 shot points

The body waves travel as compression or shear waves through the ground and are being reflected at interfaces with different mechanical properties like density or elasticity. Thus, by separation of the different wave types using three-component-sensors it is possible to derive information about the mechanical properties of the ground such as dynamic modulus of elasticity. Even in rather complex geomechanical hard rock condition, prediction ranges of 100 - 150 m can be achieved.

Acoustic signals are produced by a series of 24 shots, containing 25 to 100 grams of explosives. 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 (Figure 1). The 3-component receivers pick up the seismic signals, which have been reflected from any kind of discontinuity in the ground ahead.

A highly sophisticated processing and 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 ground mechanical properties such as Poisson Ratio and Young's Modulus within the prediction area.

3. Specific Aspect of Tunnel Seismic Operation

The necessary operations to perform a tunnel seismic measurement in a typical TSP setup can be integrated into the construction operations without any interference with the excavation work. Boreholes for receivers can be prepared using ordinary drilling systems. Explosive charging can be conducted as simple as tamping of a single cartridge in a short hole.

Installation of seismic receivers as well as charging and shooting of holes may take place during maintenance intervals or short excavation breaks of about one hour. This operation time can be further reduced by splitting the campaign into two parts that can be carried out on consecutive days.

For advancing of a long and deep tunnel, the decision had been usually made for the use of a TBM. There is even a tendency to specify a shielded machine when in fact an open machine may do the job. Here, the use of precast segments will constitute a crucial point because it shall limit seismic surveys since the ground is not accessible at all. In order to avoid large-scale drilling measures through the precast segments, it would be 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 1.5 meters fit perfectly to the regular spacing of the seismic layout (Figure 2). 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 ground strengths like weathered mudstone. The settlements become less with increasing ground strength.

Damage-free blasts can be performed if the blowouts 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 drive with segmental lining where any damage to lining elements due to the required explosive charges can be excluded.



Figure 2. Installation of TSP sensor into 2 m deep inside the side wall - NATM (left) and TBM (right)

4. Case Study

Himalayan mountain range is arc-shaped, convex southwards with syntaxial bends at the western and eastern ends (Figure 3). The syntaxial western bend is parallel to a continental scale deep fault known as the Chaman Fault. The Himalayan Mountain range is subdivided into four principal tectonic zones, from south to north these are: Sub-Himalaya, Lesser Himalaya, Higher Himalayan Crystalline, and Tethyan Himalaya. Himalayas are known to be very seismically active and the number of earthquakes has been recorded in historical times. Tunnel T13 project is located in the state of J&K and alignment passes through highly undulating and steep hill slopes of the younger Himalayas.

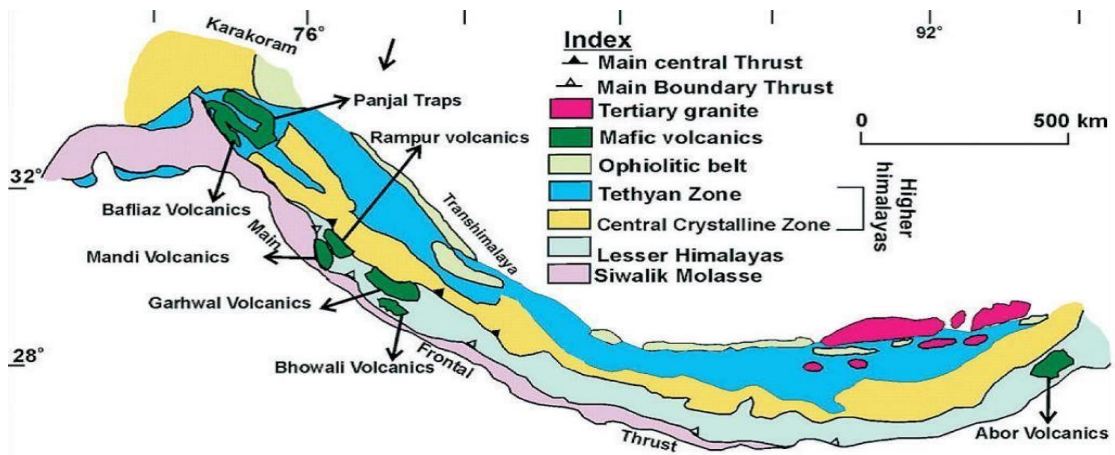


Figure 3. Outline geological map of the Himalayan Mountain Belt (Ahmed, 1988)

Table 1. Chronological order of Geological formation of the USBRL project area.

Group/Formation	Age	Lithology
Quaternary Deposits	Sub-recent to recent (Pleistocene to Holocene)	Terrace deposits, scree/ debris, slope wash, river borne material and alluvial soil.
Murree formation	Eocene to Miocene	Purple to reddish coloured sandstone, siltstone and claystone.
Sabathu Formation	Paleocene to Eocene	Variegated shale of Khaki, olive green and pale/yellow colour interlayer with calcareous sandstone, shale and nummulitic limestone
Jangalgali Formation	Cretaceous-Eocene	Chert/Quartz breccia, ferruginous sandstone/shale/ and pisolitic/non pisolitic bauxite
Sirban Group	Khairikot Formation	Quartzite, dark grey slate and variegated shale with stromatolitic limestone/dolomite bands.
	—————Meso-Proterozoic	
	Trikuta Formation	Dark grey to light grey dolomite, stromatolitic dolomite, slate, quartzite and subordinate limestone

The area falls in Seismic zone V of the standard seismic zoning map of India. Present alignment passes through terrain of rugged morphology occupied by round or sub round crested ridges and hills. The project alignment for Tunnel T13 passes through the Lower Murree formation of Upper Eocene age. It comprises of purple, brown to greyish alternate bands of medium to fine grained sandstone, siltstone, and claystone. Rock mass is highly fractured, sheared, and jointed in nature with the presence of numerous bands of pseudo-conglomerate. These rocks are much prone to weathering and erosion. On account of high tectonic activities in Himalayas, the rocks along the alignment are folded, over-thrusted and faulted at many places, resulting into highly jointed and crushed rocks. In this regard, Figure 3 is representing the anticipated L-Profile of the project T13 including three main geological zones and project line.

Government of India planned a 326 km railway line to provide an alternative and a reliable transportation system to state of Jammu & Kashmir (J&K) with the Indian Railway network from Jammu to Baramulla. The project has been declared as a Project of National Importance. Jammu-Udhampur-Katra-Quazigund-Baramulla Railway line is the largest project in the construction of a mountain railway since independence of India (Figure 4). Udhampur-Srinagar-Baramulla Rail Link (USBRL) is a mega project for construction of main part of above-mentioned railway line. It passes through young Himalayas with tectonised zones including major thrust faults.



Figure 4. USBRL Project Layout

The USBRL is in various stages of progress in the balance length from Katra to Banihal. The client for the project is Northern Railway (NR) as one of the 16 and of course largest route kilometres railway zone of Indian Railway (IR).

Tunnel T13 is located in the state of J&K and alignment passes through highly undulating and steep hills of younger Himalaya and through the Murree formation of upper Eocene age. It includes twin tunnels comprising of Main Tunnel (MT) and Escape Tunnel (ET) together with 24 Cross Passages (CPs) as part of USBRL Project.

The T13 has been assigned to Konkan Railway Corporation Limited (KRCL), which is a Union Government Company headquartered in Mumbai. Conduction of TSP is

awarded to AMBERG Engineering headquartered in Switzerland with an Indian branch in Gurgaon.

This paper focuses on the TSP measurement on tunnel T13P1 ET between CH62898 to CH63076 as shown in Figure 5.

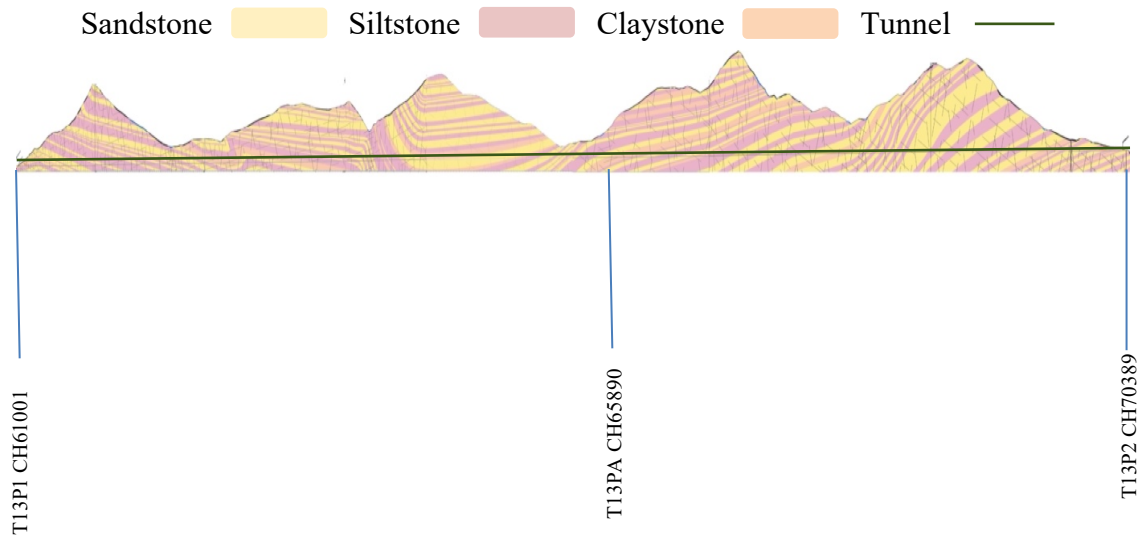


Figure 5. Location of TSP campaign & Geological L-Profile of Tunnel T13

Table 2 presents an overview of Tunnel T13's features.

Table 2. Salient features of T13 Tunnel	
Type	Twin (MT & ET)
Total Length (MT)	9.37 km
NATM Portion	9.37 km
Total Excavated Length	3.67 km
Water Inflow	Dripping in most of the length
Lithology	Sandstone, Siltstone & Claystone
Geo-structure	Techtonised - Moderately to Highly Jointed

Geotechnical/geomechanical observations of measurements is summarised as follows:

- Surrounding ground's main material: Siltstone
- Overburden ≈ 150 m
- No of JS: 3+
- RQD < 55
- UCS of Intact Rock ≈ 70 MPa
- UCS of Rock Mass < 7 MPa
- (I)-05 – (I)-06 (as per I-System; Bineshian (2019a, 2019b, 2020a))
- Water condition: Dripping (GCD = 6 – 15; Bineshian (2020b))
- Infilling of the discontinuities: Gouge comprising silt and clay
- Orientation of discontinuities: Unfavourable

- V_p : 4000 – 5600 m/sec (Primary Wave Velocity); Figure 5
- V_p : 2200 – 3100 m/sec (Primary Wave Velocity)
- ERZ: VH with MSK IX-X (Earthquake Risk Zone)
- SS: FRS (Fibre Reinforced Shotcrete), SysRB (Systematic Rock Bolting), and SRH (Stress Release Holes; Bineshian (2020c))
- Mechanical behaviour of surrounding ground: Minor – mild squeezing
- Excavation Technique (ET): Full face

Figure 6 shows the 2D rock property chart and plan view of dynamic young's modulus along seismic axis. Red colour at chart of Dynamic Young's Modulus generally indicates reduced rock stiffness whereas blue colour indicates enhanced rock stiffness.

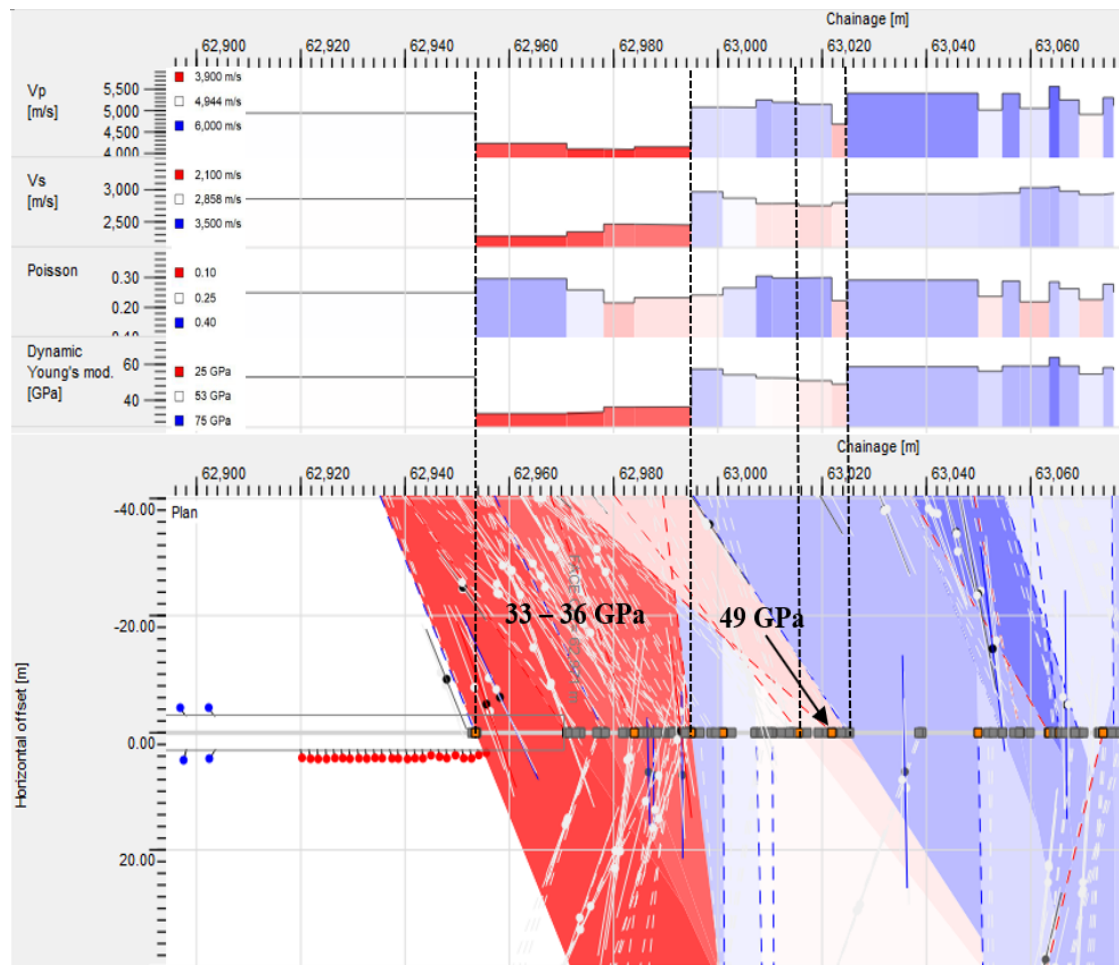


Figure 6. Ground property chart and plan view of dynamic young's mod along seismic axis

The estimated reference value of dynamic Young's Modulus (E_{dyn}) is 53 GPa and it varies between 33 GPa to 64 GPa along the tunnel axis. Directly ahead of tunnel face, E_{dyn} decrease abruptly below the reference value. In addition to this, the distribution of P –wave velocity is shown on Figure 7.

In some section ahead of face, P-wave velocity is below the reference value i.e., 4,433 m/s, which allows inferring that at some of these sections decrease in rock stiffness might be expected.

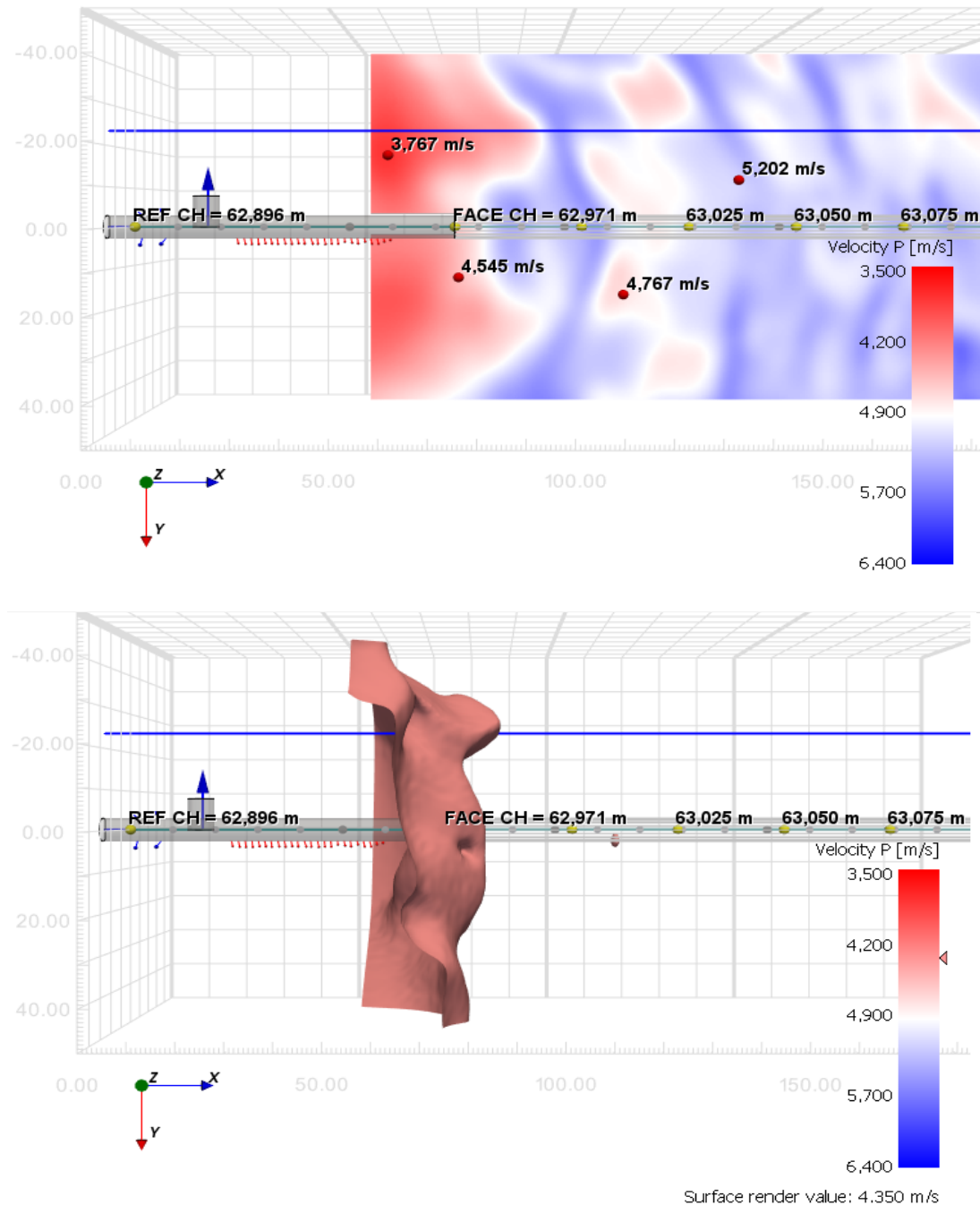


Figure 7. Top view of 3D P wave velocity model along MT as well as ET axis (top) and surface rendering of 3D-P wave velocity lower than 4,350 m/s (bottom)

In addition to predict the behaviour of rock mass, it is also possible to explore the possibility of water bearing zones on the basis of variation in poisson ratio which is being calculated from primary & shear wave velocity. Figure 8 shows the distribution of rendered Poisson's ratio of $\sigma \geq 0.29$ within the prediction range around & ahead of the tunnel axis.

Depending on the seismic response at a given site, Poisson's ratio greater than equal to 0.29 are assumed as good indicators of these possible water bearing zone.

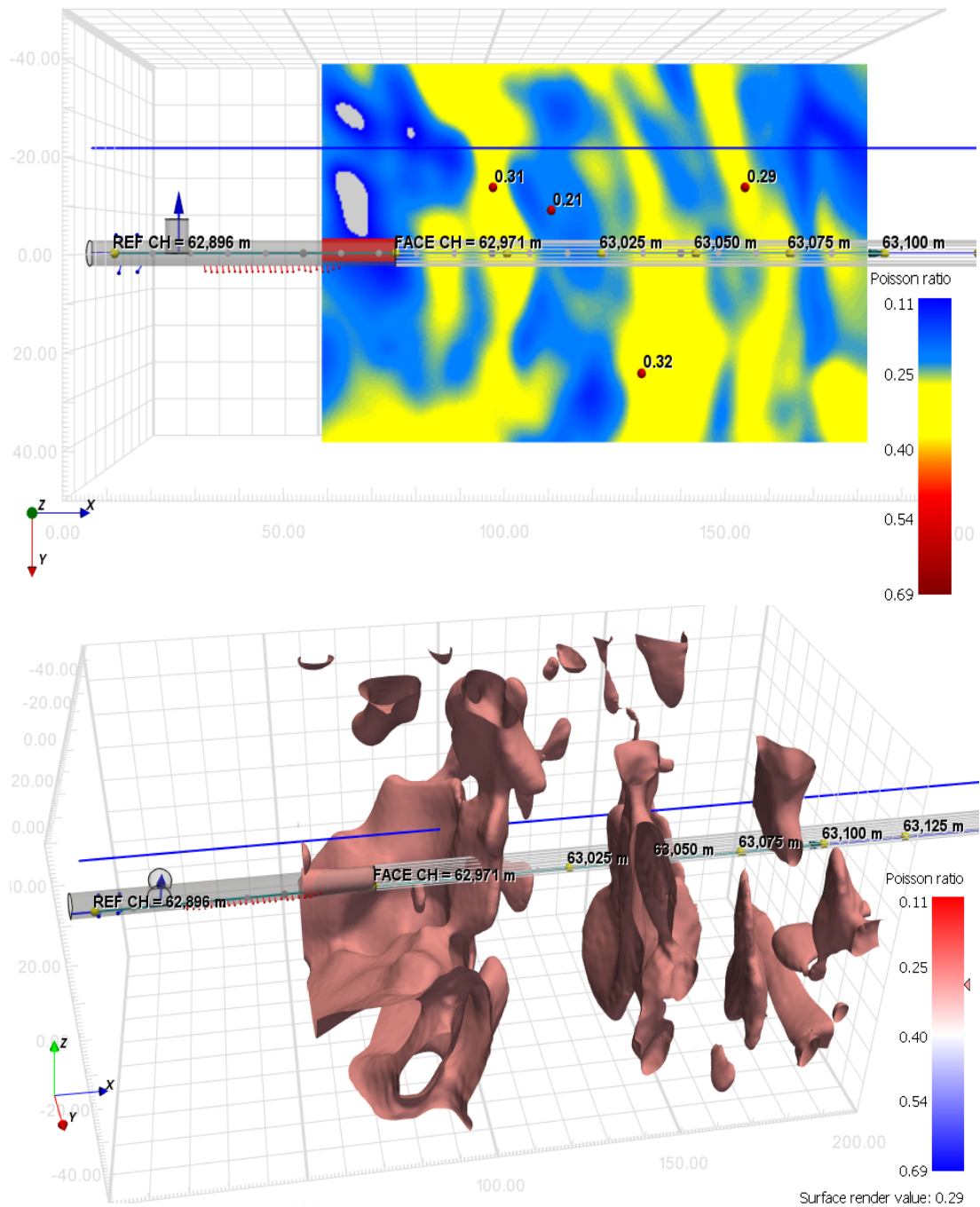


Figure 8. Distribution of poisson ratio along MT as well as ET axis (top) and 3D view with surface rendering value of 0.29 (bottom)

TSP has been conducted at CH 62954 and a length of 122 m ahead was predicted. TSP has predicted the ground using I-System (Bineshian, 2019a, 2019b, 2020a) as weak to fair rock mass (including (I)-05 to (I)-08 as per I-System's classification) ahead of above-said chainage.

TSP results were compared with actual gathered data from site during excavation and a 90 per cent matching is obtained. Appendix 1 presents TSP results and Appendix 2 provides a comparison conducted by Client and Contractor's Engineers/Geologists. As can be seen mismatching is only 10 per cent of the length, which is not also deviated

from the quality predicted; however, it has given more conservative info compared to the actual data obtained.

On the basis of comparison of TSP prediction with actual ground condition encountered, calibration of seismic parameters for a given site can be initiated. A valid calibration will certainly increase the accuracy while doing data analysis in further measurements. So, it is always necessary to conduct the TSP measurements on a regular interval which enable Client/contractor to tackle any further ground surprises.

TSP procedure consumed only 0.12 per cent of drive in such challenging condition in tunnel. Hindrance caused by TSP procedure is almost nothing (≈ 1 hr 35 mins for 122 m length of tunnel) while the prediction is tuned to have 90 per cent matching with actual condition encountered.

Tunnelling in the initial stretch was an exceptionally challenging due to weak surrounding ground and water bearing zone; however, due to having high accuracy prediction no failure or collapse happened and therefore based on the prediction provided, prevention techniques are applied to prevent occurrence of any type of gravity or lateral failure or even caving. It is strongly recommended to tune the TSP results by conduction of GCD (Bineshian, 2020b), EC (Exploratory Coring), or BH (Blind Hole Probing) for a safe drive in tunnel.

5. Conclusions

As per the stated comparison, TSP prognosis has close correlation with actual ground condition encountered including ground class and water condition. The prediction of the ground condition at T13 helped the client and contractor to prevent potential failure and collapses to occur in the tunnel with an accuracy of at least 90 percent.

Geophysical methods are an essential part of modern tunnelling, which enables continuous risk assessment and management during construction. They are meaningful and necessary tools in modern tunnelling and it is well noted that the tunnelling community continuously overcomes its scepticism and doubts about the potential of these methods. When exactly realising the optimal use of them, tunnelling will become more predictable in both costs and risks.

TSP can be the right way to turn the geomechanical risk/s and hazard/s into manageable condition/s. This advance technology can give a project the required support in overcoming the risk associated with geomechanical uncertainties.

The TSP operation does not make any disturbance to tunnelling work if operated systematically. As it is presented in this paper, it only took 0.12 per cent of progress time for the length of prediction. To increase the accuracy, such type of geophysical techniques should be used in a regular manner.

Globally, TSP is a well-established geophysical technique for ground prediction in NATM or conventional methods of tunnelling comprising of mechanized or drill and blast excavation technique/s including full face boring systems or partial sequential digging/excavation techniques.

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Appendix 1. TSP Results for T13P1 ET

Table 3. Detailed results of TSP for T13P1 ET including measured physical and predicted mechanical properties

CH (m)	V _P (m/s)	V _S (m/s)	v	E (GPa)	TSP Interpretation
62898 – 62954	4,944	2,858	0.25	53	Reference rock stiffness (Siltstone, (I)-06 and water bearing)
62954 – 62971	4,234	2,279	0.30	33	Decrease in rock stiffness (I)-08 – (I)-09 and possible water bearing zone
62971 – 62978	4,105	2,343	0.26	33	Decrease in rock stiffness (I)-08 - (I)-09 and possible water bearing zone
62978 – 62984	4,092	2,465	0.22	36	Decrease in rock stiffness (I)-08 - (I)-09 and possible water bearing zone
62984 – 62995	4,152	2,452	0.23	36	Decrease in rock stiffness (I)-08 - (I)-09 and possible water bearing zone
62995 – 63001	5,081	2,968	0.24	57	Almost similar to reference, (I)-06
63001 – 63007	5,075	2,868	0.27	54	Almost similar to reference, (I)-06
63007 – 63010	5,249	2,783	0.30	52	Similar stiffness to reference, (I)-06 – (I)-07 and possible water bearing zone
63010 – 63015	5,195	2,786	0.30	52	Similar stiffness to reference, (I)-06 – (I)-07 and possible water bearing zone
63015 – 63022	5,148	2,752	0.30	51	Similar stiffness to reference, (I)-06 – (I)-07 and possible water bearing zone
63022 – 63025	4,682	2,797	0.22	49	Decrease in rock stiffness, (I)-06 - (I)-07
63025 – 63050	5,406	2,934	0.29	59	Increase in rock stiffness, (I)-05 - (I)-06
63050 – 63055	5,014	2,945	0.24	56	Increase in rock stiffness, (I)-05 - (I)-06
63055 – 63058	5,401	2,947	0.29	59	Further increase in rock stiffness, (I)-05 - (I)-06
63058 – 63064	5,053	3,032	0.22	59	Increase in rock stiffness, (I)-05 - (I)-06
63064 – 63066	5,564	3,050	0.29	64	Increase in rock stiffness, (I)-05 - (I)-06 and possible water bearing zone
63066 – 63069	5,249	2,978	0.26	59	Increase in rock stiffness, (I)-05 - (I)-06
63069 – 63074	4,912	2,923	0.23	55	Slight decrease in rock stiffness, (I)-05 - (I)-06
63074 – 63076	5,303	2,943	0.28	58	Increase in rock stiffness, (I)-05 - (I)-06 [End of Prediction]

(I)-Class I-System's Classification (Bineshian, 2019a, 2019b, 2020a)

CH	Tunnel Chainage
V _P	Body Wave – Primary Wave Velocity
V _S	Body Wave – Shear Wave Velocity
v	Poisson's Ratio
E	Dynamic Young's Modulus

Appendix 2. Comparison of TSP vs Actual Condition for T13P1 ET

Table 4. Geomechanical comparison for TSP's resulted prediction and observed condition during excavation at T5 Tunnel

CH (m)	TSP Interpretation	Actual Condition/s		Matching Comparison
		(I)-Class	Water Condition	
62898 – 62954	(I)-06 + Water (Reference)	(I)-08	Dripping	100%
62954 – 62971	(I)-08 – (I)-09 + Water	(I)-08	Dripping	100%
62971 – 62978	(I)-08 - (I)-09 + Water	(I)-08	Showering	100%
62978 – 62984	(I)-08 - (I)-09 + Water	(I)-08	Showering	100%
62984 – 62995	(I)-08 - (I)-09 + Water	(I)-08	Showering	100%
62995 – 63001	(I)-06 + Water	(I)-07	Dripping	(I)-06 predicted, (I)-07 observed
63001 – 63007	(I)-06 + Water	(I)-07	Dripping	(I)-06 predicted, (I)-07 observed
63007 – 63010	(I)-06 – (I)-07 + Water	(I)-07	Dripping	100%
63010 – 63015	(I)-06 – (I)-07 + Water	(I)-06 - (I) - 07	Dripping	100%
63015 – 63022	(I)-06 – (I)-07 + Water	(I)-06 - (I) - 07	Dripping	100%
63022 – 63025	(I)-06 - (I)-07	(I)-06	Damp	100%
63025 – 63050	(I)-05 - (I)-06	(I)-06	Damp	100%
63050 – 63055	(I)-05 - (I)-06	(I)-06	Dripping	100%
63055 – 63058	(I)-05 - (I)-06	(I)-06	Dripping	100%
63058 – 63064	(I)-05 - (I)-06	(I)-06	Dripping	100%
63064 – 63066	(I)-05 - (I)-06 and possible water bearing zone	(I)-06	Dripping	100%
63066 – 63069	(I)-05 - (I)-06	(I)-06	Dripping	100%
63069 – 63074	(I)-05 - (I)-06	(I)-06	Dripping	100%
63074 – 63076	(I)-05 - (I)-06 [End of Prediction]	(I)-06	Flowing	100%
(I)-Class	I-System's Classification (Bineshian, 2019a, 2019b, 2020a)			