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Successful Construction of Twin Railway Tunnel Using TBM in Lesser Himalayas

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ABSTRACT

The construction of a 14.58 km long twin Tunnel-8 of Rishikesh Karnprayag New Railway Project has been completed recently in Himalayas, by deploying two state-of-the-art single-shield TBMs, each having 9.11 m nominal bore diameter. The tunnel crosses Chandpur formations, comprising of high schistose and quartzite Phyllite, with anticipated squeezing of up to 450 mm, for which the TBMs and tunnelling operations were designed. Two new Herrenknecht TBMs, "*Shakti-1309A*" and "*Shiv-1310A*" were deployed, which commenced boring for 10.47 km in December 2022 and 10.29 km in March 2023, and finished TBM tunnelling in April 2025 and June 2025 respectively, delivering an average monthly progress of circa 370 m on both TBMs.

In this paper, the geological investigations, analysis of squeezing potential, risk mitigation mechanisms, TBM specifications and state-of-the-art technologies installed on TBM are highlighted including use of artificial intelligence and machine learning which made this venture a success and boosts confidence for taking up more TBM tunnelling in Himalayas in the future. Maximum part of the paper has been published as keynote in IndoRock 2025.

Keywords: Tunnelling; Himalayan Geology; TBM; Risk; Challenges

1. INTRODUCTION

Tunnel boring machine (TBM) method of tunnelling is a suitable alternative to drilling and blasting (D&B) method for long and deep tunnels, due to higher advance rates. TBM adoption in Himalayas has always been challenging due to high tunnel depth, water charged weak zones, folding and faulting formation structure, squeezing ground conditions of the Himalayan geology. Given these challenges, there are very few success stories of TBM tunnelling in Himalayas, and it becomes important to learn from all past projects before further TBM adoption for Himalayan tunneling.

In Rishikesh Karanprayag railway project, extensive ground investigations were carried out for selection and design of two 9.11 m nominal bore single shield hard rock TBMs for the project. The latest TBM technological advancements like enlargement of cutting diameter, convergence monitoring around shield area, hammer based seismic prediction, data analytics, artificial intelligence and machine learning were utilized to their fullest potential, resulting in average and peak monthly advance rates of circa 370 m and 710 m respectively. Both TBMs have successfully completed their journey of boring of 10.47 and 10.29 km respectively, each taking approximately 850 days.

2. PROJECT OVERVIEW

2.1 Rishikesh Karnprayag New Railway Line Project

Rail Vikas Nigam Limited (RVNL), *a Navratna CPSU under Ministry of Railways*, is constructing the 125.2 km long Rishikesh-Karnprayag Railway Project, which is aligned in a north-eastward direction through the challenging terrain and geology of the Garhwal Himalayas in Uttarakhand. The project alignment commences from the existing Virbhadra Railway Station (30°06'24'' N, 78°15'03'' E, 353.94 m AMSL) and culminates at newly designed Karnprayag Railway Station (30°17'07'' N, 79°13'54'' E, 908.20 m AMSL). The project entails an extraordinary 213.45 km of tunnelling, including 16 main tunnels, 13 escape tunnels, 7 adits, and numerous cross passages, traversing along the fragile and seismically active Himalayan belt, following the Ganga and Alaknanda River valleys, where the rugged topography and geological complexities demand some of the most advanced tunnelling and construction methodologies available today.

Figure 1 - Alignment of Tunnel-8 of Rishikesh Karanprayag Railway Project

2.2 Tunnel 8

Tunnel 8 is centrally located in this project and connects Devprayag Railway Station with Janasu Railway Station through a 14.58 km double line tunnel (Fig. 1). Tunnel 8 Portal 1 (30°07'41'' N, 78°36'8.8'' E, 486 m AMSL) and Tunnel 8 Portal 2 (30°13'47'' N, 78°41'36'' E, 546 m AMSL) house a part of the railway station at either ends due to space constraints, typical of the hill topography (Fig. 2).

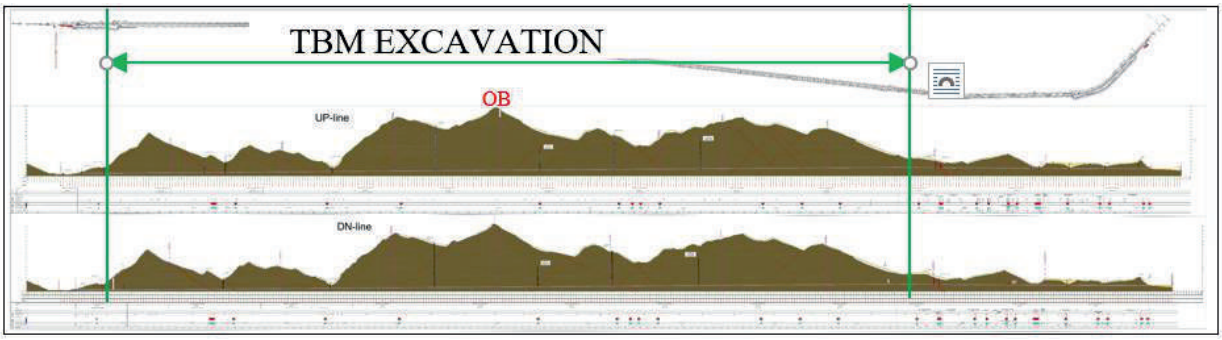

Figure 2 - Topography along Tunnel 8 showing stretch excavated by TBM (Highest OB is 855 m)

Tunnel 8 commences from both portals as a common tube for two tracks within the station area and subsequently separates into two separate tunnel tubes. Both TBMs were launched from Portal-1 side, into these separate tunnel tubes, namely Up line and Down line. The tunnel components and other alignment details for Tunnel 8 are presented in Table 1 and Table 2, respectively.

Table 1 - Components of tunnel 8 up-line and down-line

Sl. No.	Description	Start	End	Sl. No.	Description	Start	End
1	Single Tube having Double Track & platform	47+588 (Portal 1)	47+703	1	Single Tube having Double Track & platform	47+588 (Portal 1)	47+703
2	Single Tube having Double Track	47+703	48+068	2	Single Tube having Double Track	47+703	48+068
3	Diverging Tunnel Junction	48+068	48+124	3	Diverging Tunnel Junction	48+068	48+124
4	Up Line TBM Launch Tunnel	48+124	48+180	4	Down Line TBM Launch Tunnel	0+740	0+880
5	Up Line TBM Tunnel	48+180	58+649	5	Down Line TBM Tunnel	0+880	11+168
6	Up Line TBM Exit Cavern	58+649	58+722	6	Down Line TBM Exit Cavern	11+168	11+242
7	Up Line NATM Tunnel	58+722	61+216	7	Down Line NATM Tunnel	11+242	13+824
8	Diverging Tunnel Junction	61+216	61+242	8	Diverging Tunnel Junction	61+216	61+242
9	Single Tube having Double Track	61+242	61+810	9	Single Tube having Double Track	61+242	61+810
10	Single Tube having Double Track & platform	61+810	62+165 (Portal 2)	10	Single Tube having Double Track & platform	61+810	62+165 (Portal 2)

Table 2 - Vertical and horizontal geometry of tunnel 8 up-line and down-line

Trend	Gradient	Start (m)	End (m)	Length (m)
Up	1 in 650	484.46 (Portal-1)	486.33	512
Up	1 in 133	486.33	565.92 (B/through)	10628
Down	1 in 133	565.92	548.93	2283
Down	1 in 400	548.93	546.00 (Portal-2)	1154

Curve No.	Trend	Radius (m)	Start	End
C-17	Right hand	1275	50+949	51+034
C-18	Left hand	1000	59+578	59+648
C-19	Right hand	700	61+242	61+700

3. GEOLOGY AND GEOTECHNICAL INVESTIGATION

3.1 Regional and Local Geology

Tunnel 8 passes through the Lesser Himalayas of the Garhwal region of Uttarakhand. The Lesser Himalaya includes a thrust-bound sector delineated by two tectonic plates i.e. the Main Boundary Thrust (MBT) to the south and the North Almora thrust (NAT). The rock masses present in the area have undergone a complex history of burial and, following exhumation, have been subjected to huge stresses either in ductile or in brittle conditions. In fact, the tectonic style of the region is characterized by a folding and thrusting regime.

The seismo-genic sources nearest to the Project area is the NAT which trends NW-SE and is located circa 15 kms from Portal 2 of Tunnel 8. An earthquake of magnitude 6.5 is assigned to this thrust. The area is entirely belonging to low grade metamorphic rocks of Chandpur formation of Jaunsar Group, having a continuous sequence of light and dark grey phyllite with interbedded light grey and purple sandstone and siltstone and presence of quartzitic phyllite. The phyllites, because of NAT, are highly crushed and in places become a powdery mass. Near the NAT, these rocks are characterized by slickenside surfaces, water seepages, shearing and crushing effects, mylonitization, preferential weathering and erosion, schistose surfaces etc.

3.2 Geological Mapping and Geotechnical Investigation

Engineering Geological mapping was performed at multiple stages of the project, starting from the alignment planning stage to the design and construction stage. This started as a desk study in 2014 by reviewing existing geological maps, reports, aerial photographs, satellite imagery, and other relevant literature about the area. The information gathered was further reinforced by geological field survey in 2016, aiming to map the rock outcrops, identify and map the distribution of different rock and soil units and perform structural mapping by measuring and documenting structural features like faults, folds, joints, and cleavage planes. The rock joints exhibit persistence ranging from 1–3 m to 3–10 m, with surface conditions varying from slightly rough to smooth, and the shear seams and gouge fillings contain fillings that range from soft (thinly bedded) to hard (thickly bedded), and apertures varying from open to wide (0.1 mm to 5 mm). Weathering along the discontinuities ranges from slight to moderate. The collected data from mapping at various stages further set out the plan for the required geotechnical investigations.

In 2018, further surface and subsurface geological and geotechnical investigations were carried out to investigate the soil and rock conditions and their index and mechanical properties. Whereas geophysical seismic surveys were done at the tunnel portal areas; 9 out of total 15 boreholes were drilled in the tunnel stretch to be excavated by TBM (Fig. 3). All boreholes were drilled upto tunnel invert and NX size core samples were further tested in laboratory for Dry density (IS 13030), Uniaxial compressive strength test (IS 9143), Modulus of elasticity and Poisson's ratio (IS 9221), Point load strength index (IS 8764), Specific gravity (IS 1122), Tri-axial compression test (IS 13047), Cherchar abrasivity index (ASTM D7625-10). A summary is presented in Table 3.

Table 3 - Summary of Laboratory tests for boreholes falling in TBM part of Tunnel 8

BH	Chainage	Depth (m)	Dry density (g/cc)	UCS (MPa)	Modulus of elasticity (GPa)	Poisson's Ratio	Point load strength (MPa)	Specific gravity	Cerchar abrasivity index	Schmidt hammer hardness (MPa)
BH-63	47+650	40	2.63-2.96	47-50	25-45	0.18-0.24	1.70-2.50	-	1.91-3.57	40.17-49.73
BH-64	48+051	95	2.62-2.75	37-58	30-60	0.15-0.26	1.00-400	2.65-2.82	2.29-4.06	30.66-45.84
BH-65	49+318	210	2.69-2.98	23-44	20-40	0.12-0.25	3.00-5.30	-	2.21-2.92	44.89-48.60
BH-66	49+600	145	2.52-2.81	40-45	20-35	-	-	2.72-2.85	1.49-3.50	28.84-41.21
BH-67	51+070	70	2.29-2.81	20-45	10-27	0.22-0.29	-	2.51-2.85	1.90-4.40	36.19-43.09
NBHT-1	52+460	600	2.57-2.76	49-58	35-55	0.15-0.22	5.00-14.0	2.71-2.78	1.92-2.74	-
BH-68	54+270	260	2.67-2.85	25-42	18-60	0.16-0.28	1.70-3.20	-	2.20-2.65	38.15-53.77
NBHT-2	54+860	477	2.62-2.68	33-54	48-57	0.12-0.25	5.15-11.2	2.67-2.72	1.75-2.38	-
BH-71	56+540	375	2.03-2.89	30-55	16-69	0.14-0.39	1.75-4.6	2.52-2.83	1.93-3.88	28.38-51.46

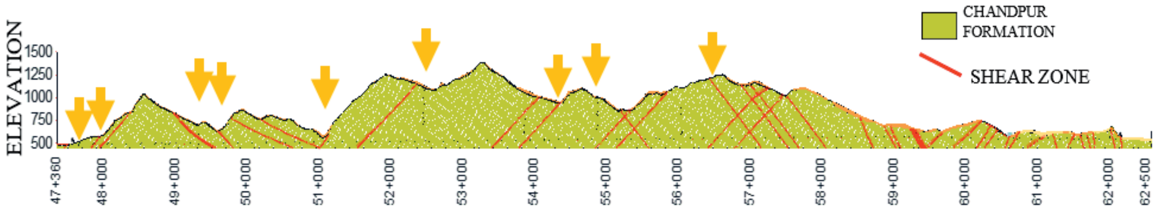

Figure 3 - Diagrammatic representation of Boreholes conducted for TBM stretch of Tunnel 8

In-situ tests like Permeability test result in Rock (IS 5529-1), Dilatometer test (IS 12955-1), Bore hole televiewer (BHTV) and Hydro-fracturing test (ISRM) were also conducted in few of these boreholes. A summary of Permeability testing is presented in Figure 3 & Table 4.

Table 4 - Summary of Permeability tests for boreholes falling in TBM part of Tunnel 8

Name	Chainage	Depth	Permeability 10^{-7}(m/s)	Water table depth (m)	Conductivity	Discontinuity condition
BH-63	47+650	40	-	20	-	-
BH-64	48+051	95	0.475-0.853	17	Very low	Very tight
BH-65	49+318	210	0.9412-1.322	3	Low- Very low	Tight-Very tight
BH-66	49+600	145	-	18	-	-
BH-67	51+070	70	0.301-0.89	7	Very low	Very tight
NBHT-1	52+460	600	0.23-1.84	85	Very low	Very tight
BH-68	54+270	260	0.233-0.997	86	Very low	Very tight
NBHT-2	54+860	477	0.941-1.840	109	Low	Tight
BH-71	56+540	375	-	52	-	-

Based on data available from ground investigations, rock units forming the geological profile were evaluated for anticipated rock mass rating (RMR_{89}) and GSI rating for further analysis. Based on combinations of in situ stresses, RMR, GSI, overburden, entire TBM tunnel length was divided into 12 distinct stretches (Table 5). Out of 10.47 km, anticipated rock mass assessment as per RMR_{89} classification was 74.51% - Class III (7801 m), 23.91% - Class IV (2503 m) and 1.58% - Class V (165 m).

3.3 Geotechnical Baseline Report

Based on field investigations and surveys, a geotechnical baseline report (*ASCE 2007*) was prepared with following aspects:

- Phyllite/quartzitic phyllite rock mass will be encountered with varying content of quartzite and weathering grade. Excavated muck must be analyzed regularly.

- Rock mass permeability is very low, and water ingress is expected from underground aquifers or through weak zones. Advance probing measures must be implemented during construction.
- Geological formations/rock types will not vary along the alignment due to the presence of a single geological formation i.e. Chandpur of the Jaunsar group.
- Rock strength mostly ranges 25-50 MPa (UCS) and upper limit being 60-65 MPa.
- Shear zones based on the geological mapping to be considered in addition to those encountered during borehole investigations. Advance probing measures must be implemented during construction.
- TBM stretch of Tunnel 8 is segregated into 12 critical stretches based on anticipated overburden range, RMR, UCS, water conditions, shear seams/ zones etc., as per mapping and test data (Table 5).
- Squeezing of rock mass around TBM shield is the primary risk to TBM tunnelling. Initial analysis of squeezing behavior is carried based on empirical and semi-empirical approaches (Table 6). TBM design must have a provision of convergence measurement in shield area.
- Other mitigation measures required in TBM design are long drainage holes, pre-grouting and spilling.
- The ground risks belong to the employer, whereas performance risks belong to contractor.

Table 5 - Ground parameters for 12 critical sections in TBM part of Tunnel 8

Sl. No.	Ch.	H m	ρ kN/m^3	E_{m} MPa	m_b	s	a	GSI	σ_c MPa	M_r	k_o	σ_v MPa	σ_h MPa	Average stress MPa
1	49310	198	27	11411	1.261	0.0048	0.505	52	55	600	0.73	5.346	3.920	4.395
2	49440	205	27	376	0.535	0.0003	0.526	28	15	350	0.27	5.535	1.469	2.825
3	51020	108	27	376	0.535	0.0003	0.526	28	15	350	0.28	2.916	0.808	1.510
4	51100	72	27	2564	0.851	0.0014	0.511	41	30	500	0.52	1.944	1.005	1.318
5	53250	855	27	11411	1.261	0.0048	0.505	52	55	600	0.42	23.085	9.772	14.210
6	53650	642	27	11411	1.261	0.0048	0.505	52	55	600	0.45	17.334	7.875	11.028
7	54725	538	27	2564	0.851	0.0014	0.511	41	30	500	0.30	14.526	4.377	7.760
8	55340	315	27	2564	0.851	0.0014	0.511	41	30	500	0.32	8.505	2.763	4.677
9	56105	563	27	5367	0.982	0.0022	0.508	45	40	600	0.35	15.201	5.386	8.657
10	56300	619	27	5367	0.982	0.0022	0.508	45	40	600	0.35	16.713	5.821	9.451
11	56680	706	27	11411	1.261	0.0048	0.505	52	55	600	0.44	19.062	8.445	11.984
12	57740	563	27	2564	0.851	0.0014	0.511	41	30	500	0.30	15.201	4.558	8.105

Note: Ch. - Chainage; ρ-density; σ_c - UCS; σ_v – vertical in-situ stress; σ_h – horizontal in-situ stress

Table 6 - Analysis of squeezing behaviour based on empirical and semi-empirical approaches

Chainage	Over-burden	Singh et al. (1992)	Verman (1993)	Goel et al. (1995)	Jethwa et al. (1984)	Aydan et al. (1993)	Hoek and Marinos (2000)	Max. radial deformation predicted (mm) H&M approach
49+310	198							64.40
49+440	205							451.20
51+020	108							451.20
51+100	72							157.10
53+250	855							64.34
53+650	642							64.34
54+725	538							157.10
55+340	315							157.10
56+105	563							113.55
56+300	619							113.55
56+680	706							64.34
57+740	563							157.10

Non-Sq. Mild Sq. Mod. Sq. Sq Severe Sq.

3.4 Detailed Analysis of Squeezing Potential during TBM Tunnelling

Squeezing of ground and jamming of TBM during tunnel excavation was one of the critical hazards addressed at Tunnel 8. Squeezing is a time dependent large deformation occurring around excavated tunnel associated with creep due to stress relaxation. The rate of creep or deformation depended upon geological conditions, in situ stress, groundwater flow, pore pressure and rock mass properties like strength and permeability. Squeezing ground may cause a series of difficulties such as sticking of the TBM cutter head or the shield, extensive convergences of the bored profile or destruction of the tunnel support. In very soft rock, clogging or sagging of the cutter head may also occur, and TBM bracing by the gripper plates may become impossible. These difficulties, alone or in combination with instabilities of the tunnel face and walls, may slow down or even obstruct TBM operation and, if occurring over frequent tunnel intervals or persisting over longer portions of a tunnel, may have a decisive effect on the feasibility of a TBM drive (Ramoni et al, 2006). Tunnel boring machine jamming in squeezing conditions occurs when the available thrust is not sufficient to maintain TBM advancement or to allow for TBM restart (Ramoni & Anagnostou, 2011; Zhao et al., 2012). Therefore, it was necessary to compute the distance from the tunnel face where the radial gap between the tunnel perimeter and the shield closes completely, and the ground becomes in contact with the shield (Fig. 4).

Therefore, to consider squeezing potential of ground and resulting hazard of TBM jamming, ground reaction curves were plotted based on estimated geo-mechanical properties using RocSupport software with Carranza-Torres (2004) approach to estimate the maximum deformation in the shield length of 9.85 m (Fig. 5).

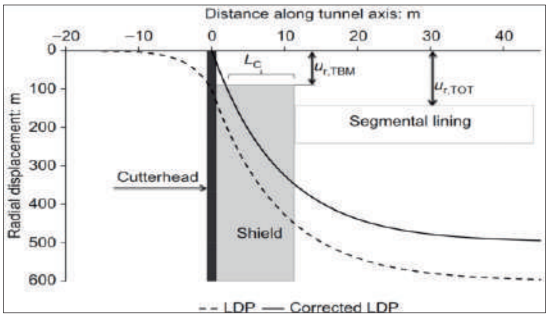

Figure 4 - Longitudinal displacement profile during TBM excavation

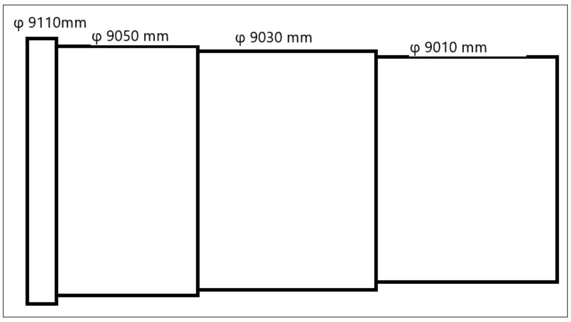

Figure 5 - Conicity of single shield TBM deployed at Tunnel 8

The LDP was calculated using the semi-analytical approach proposed by Vlachopoulos & Diedrichs (2009) and has been corrected in proportion with the pre-convergence of the ground. The stepping of the shields was ignored on conservative side and the shield was assumed as infinitely stiff. Following 4 cases were analyzed (Table 7):

I. Geo-mechanical properties of respective critical section, in-situ stress from Hydrofracturing tests validating with Sheorey's equation.
II. Geo-mechanical properties from Section 2 considered everywhere, In-situ stress from Hydrofracturing tests validating with Sheorey's equation.
III. Geo-mechanical properties from Section 2 considered everywhere, In-situ stress co-efficient as 1.0.
IV. Geo-mechanical properties from Section 2 considered everywhere, In-situ stress co-efficient as 2.0.

Table 7 - Analysis of squeezing potential for 12 critical sections

Section No.	1	2	3	4	5	6	7	8	9	10	11	12
Critical section chainage	49310	49440	51020	51100	52250	53650	54725	55340	56105	56300	56680	57740
(a) Geo-mechanical properties of the respective critical section, in-situ stress from Hydrofracturing tests validating with Sheorey's equation												
Max displacement (mm)	1.6	123.4	36.6	1.9	8.4	5.4	32.9	13.2	12.8	14.8	6.2	36.8
Tunnel convergence (%)	0.0%	2.7%	0.8%	0.0%	0.2%	0.1%	0.7%	0.3%	0.3%	0.3%	0.1%	0.8%
Plastic radius (m)	4.9	10.9	7.7	4.8	7.0	6.3	8.9	6.9	7.4	7.7	6.5	9.1
Remarks	1	4	2	1	1	1	2	1	1	1	1	2
(b) Geo-mechanical properties from Section 2 considered everywhere, In-situ stress from Hydrofracturing tests validating with Sheorey's equation												
Max displacement (mm)	2.8	123.4	36.6	18.8	26.6	15.8	1258	318.1	36.8	44.2	18.7	1431
Tunnel convergence (%)	0.1%	2.7%	0.8%	0.4%	0.6%	0.4%	27.6%	7%	0.8%	1%	0.4%	31.4%
Plastic radius (m)	5.7	10.9	7.7	6.6	9.0	7.8	24.5	14.9	9.1	9.6	8.2	25.8
Remarks	1	4	2	1	1	1	4	4	2	2	1	4
(c) Geo-mechanical properties from Section 2 considered everywhere, In-situ stress co-efficient as 1.0												
Max displacement (mm)	1.6	300.4	85.0	2.6	15.4	9.2	82.0	27.6	26.0	31.4	10.9	91.0
Tunnel convergence (%)	0.0%	6.6%	1.9%	0.1%	0.3%	0.2%	1.80%	0.6%	0.6%	0.7%	0.2%	2.0%
Plastic radius (m)	5.07	15.1	9.77	5.05	8.11	7.11	11.69	8.41	8.97	9.48	7.41	12.08
Remarks	1	4	3	1	1	1	3	1	1	2	1	3
(d) Geo-mechanical properties from Section 2 considered everywhere, In-situ stress co-efficient as 2.0												
Max displacement (mm)	2.1	596.6	134.2	3.6	23.7	13.7	140.2	42.6	40.8	49.7	16.3	151.7
Tunnel convergence (%)	0.1%	13.1%	3.0%	0.1%	0.5%	0.3%	3.1%	0.9%	0.9%	1.1%	0.4%	3.3%
Plastic Radius (m)	5.3	18.6	11.2	5.3	9.2	7.9	13.9	9.5	10.3	11.0	8.3	14.4
Remarks	1	4	4	1	1	1	4	2	2	2	1	4
LEGEND	1	No Overcut		2	50mm Overcut		3	100mm Overcut		4	FEM needed	

3.5 Geotechnical and other risks and their mitigation

Some of the key challenges facing underground construction projects of such magnitude and the mitigation measures which were adopted on the project to overcome these are shown in Table 8.

Table 8 - Key challenges and mitigation measures adopted

Sl. No.	Key challenges	Mitigation measures
1.	Availability of sufficient and reliable Geotechnical and Geological Data	Foot survey was conducted over the alignment for developing 3D geological model. 9 Nos. Boreholes were totalled 2275 m, deepest being 650 m. More details can be found in Section 2.
2.	Sharing of Geological and other construction risks	A Risk register was made part of tender document, which covered all foreseeable risk events with severity and likelihood of occurrence, mitigation measures and procedures and sharing of residual risks in terms of time and cost. A geotechnical baseline report was prepared, serving as baseline for expected ground properties with their distribution along the tunnel.
3.	Classification of rock mass for time and cost considerations	Rock mass for drill and blast tunnel was classified based on NATM principles of ground and system behaviours. For TBM tunnelling, classification was based on pre-grouting classes i.e., Type-1: No pre-grouting required, Type-2: Pre-grouting required along 50% or less circumference, Type-3: Pre-grouting required along more than 50% circumference.
4.	Reasonable project timelines	Time simulation of various construction events and their inter-relations was conducted considering enlarged Tunnel cross sections on either tunnel ends; design, manufacturing, transportation and assembling of TBM and segment factory, Manufacture of precast segments etc. Focus was also laid on all finishing activities scheduled after breakthrough of the Tunnel.
5.	Regulation of completion period based on actuals	Bidding forms were included at tender stage for contractor's commitment of performance rates in various ground types for NATM and TBM. This functioned as baseline for regulating time during construction, based on actual geological distribution of ground types encountered.
6.	Communication between parties	Weekly review meetings were conducted by all parties, generating recorded action points for subsequent follow ups. Detailed design support was active during construction period to modify the design and drawings and expedite the construction.
7.	Settlement of disputes	Dispute settlement mechanisms were part of the Construction contract, detailing the procedures. These mechanisms were utilized successfully to resolve few of the disputes in a timely manner, which could not be resolved at site level.
8.	Timely availability of critical workforce, machinery, and materials	Requirements were clearly stated in the Contract with a workable margin of flexibility, provide the construction performance does not suffer.
9.	Maintaining practicality of construction sequences	All parties regularly discussed the upcoming challenges facing the project to review and devise optimised construction solutions suiting actual situations and often resulting in change of drawings and design in advance to reduce adverse impacts.

3.6 Risk Register

A risk register was prepared covering all foreseeable risk events with their possible impacts and consequences, mitigation measures, levels of residual risks and its allocation. Necessary references to contract conditions were indicated wherever required. The ground risks were owned by Employer. Risks were categorized into following categories:

- Risks during Preconstruction stages, TBM design and manufacturing stage.
- Risks during construction stages (Meteorological, health and safety and seismological)
- Risks during construction stages (Availability of raw materials)
- Risks during construction stages (Due to working in dumping areas)
- Risks during construction stages (Due to logistics)
- Risks during construction stages (Due to TBM operation and maintenance)
- Risks during construction stages (During excavation due to ground)
- Risks during construction stages (Due to segmental lining and support installation)

4. CLASSIFICATION OF ROCK MASS FOR TIME AND COST CONSIDERATION

During TBM boring, regular tunnel face assessment and geological face mapping came with its own difficulties and risks. Therefore, the performance baseline was set considering the time and efforts required to advance TBM in different types of ground (Table 9). Universal type segments were provided which were suitable for entire tunnel length and support performance with flexibility and ease with low inventory. The only variable envisaged was the need of pre-grouting efforts which is regulated based on the geological conditions. While the cost of the pre-grouting efforts was conditioned in the bill of quantities on basis of as per actual grout consumed, the time effect of these efforts was provided in terms of advance rates anticipated in different types of grounds.

Table 9 - Ground type matrix tendered for the TBM excavation

Ground Type	Length wise % Expected	Probing and Pre-grouting Measures	Performance quoted by contractor	
			Daily (m)	Monthly (m)
Type 1	80	Probing (2 × 40 m) every 30 m	16	400
Type 2	15	Probing, drilling and grouting (50%)	12	300
Type 3	05	Probing, drilling and grouting (100%)	8	200

The payment for TBM excavation was kept uniform and left independent of the type of ground encountered. The Contractor was required to commit advance rates in each of these ground types, so that excavation time can be regulated based on required construction effort. During TBM excavation, there were very few instances of water ingress and only on one occasion water ingress was found substantial. Clogging of TBM discs was also observed at two locations. However, none of these events had any major impact on the TBM progress rates and hence not described in detail here.

5. TBM SPECIFICATIONS WITH LATEST STATE-OF-ART

Based on geological and geotechnical conditions established in the Geotechnical baseline report and adopted risk sharing mechanisms, the TBM specifications were provided in the tender. The Contractor was permitted to procure TBM, maintaining these specifications on a minimum basis (Table 10).

Table 10 - TBM specifications detailed in the tender

Item	Description
TBM Type, nominal bore diameter, shield conicity	2 Nos. - single shield rock TBM, nominal bore diameter 9110 mm with conicity of 10 mm/m
Compliances	Complying EN-16191, BS 6164, CAT-III checks and CE Certification.
Cutter head	10 bucket channels, 1 direction of mucking and 2 directions of rotation. 9 water spraying nozzles, 19-inch cutters (47 single and 8 double), retractable cutter head up to 600mm.
Electric main drive	Total installed power 4,200 kW (12 x 350 kW), Main bearing diameter 6,000 mm, Dual stage planetary gearboxes, Rotation speed stage I up to 2.51 rpm, Rotation speed stage II up to 6.30 rpm, Variable frequency drive (VFD), Torque box arrangement, Axial displacement with 9 cylinders 360/240-400, Sealing system (3 inner + 3 outer lip seals), Automatic lubrication system.
Drilling, probing and grouting	20 inclined and 6 horizontal channels of DN100 in the shield and cutterhead area, 2 Permanent hammer drills for inclined channels and one temporary for horizontal channels. Drilling capability 5-60 m (MWD and preventor valves) and limited core recovery from cutter head of up to 1 m length.
Segment backfilling	Primary: 6 component A pumps each 6.9 m^3/h, 6 component B pumps each 1.0 m^3/h, Total backfill capacity 41.4 m^3/h.
Wear protection	10mm Hardon 400 coating with hydraulic wear detection.
Cutters	19-inch cutters (47 single and 8 double discs @ 315 kN each)
Thrust	Nominal Thrust 1,08,619 kN and stand by thrust 1,29,308 kN
Torque	Maximum available torque for Stage-1 (13.81 kN-m), Stage-2 (27.95 kN-m) and breakout (31.11 kN-m)
Cutterhead enlargement	200mm enlargement of nominal bore diameter to 9310 mm for squeezing grounds.
Cutterhead offsetting	100 mm in vertical and horizontal directions. (Required to gradually enlarge cutterhead)
Conical shield design	Cutterhead dia. 9110 mm, dia. at tail end 9010 mm. (Conicity of 10 mm/m shield length)
Sheild extrados lubrication	2 x 12 lubrication ports to reduce skin friction with bentonite at points of contact between rock and shield.
Seismic exploration	Advance geophysical probing (Hammer or blast based) ahead of TBM.
MWD data logger for all hammer drills	For measurement of penetration rate, percussion pressure, rotation pressure and water ingress to characterize ground ahead of TBM.
Void measuring system	Measurement of rate of convergence of tunnel wall in shield area. 3 cylinders in shield roof section, measurement during ring building (Figs. 6 & 7).
Disc load monitoring	4 cutter discs were instrumented for graphical representation of variation of hardness of bored Tunnel face on continuous basis.
Other important provisions	TBM connected data management system for online data monitoring, Guidance system for TBM navigation, Ring sequencing for controlling

Item	Description
	segment installation, Ring convergence measurement system, Automatic tail skin clearance measurement system.

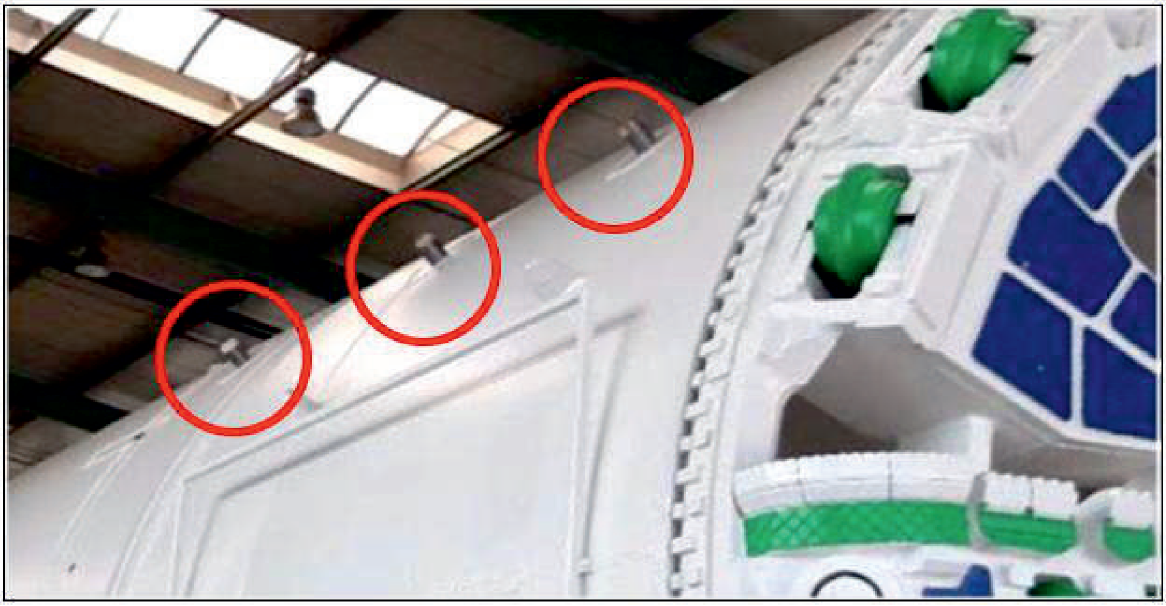

Figure 6 - Representative photo showing 3 cylinders of void measurement system (VMS) in TBM Shield

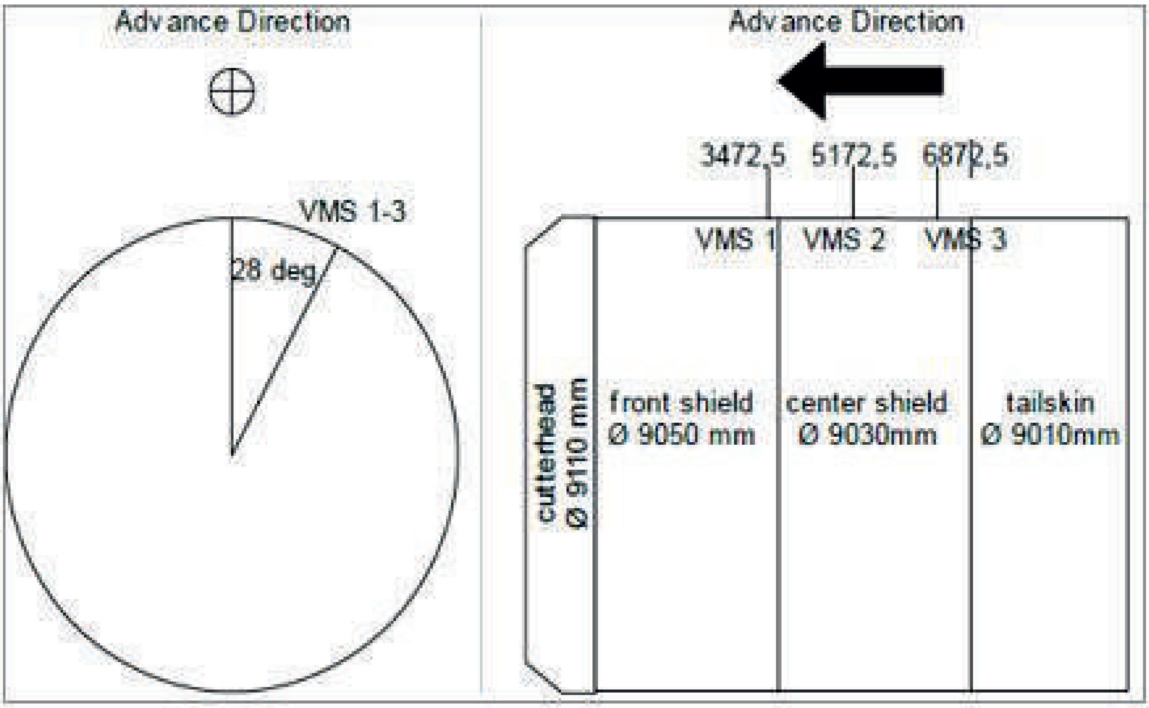

Figure 7 - VMS for TBM Shakti and Shiv

6. CONSTRUCTION OF TUNNEL 8 USING TBM

RVNL awarded the construction work of Tunnel 8 to M/s Larsen and Toubro (Contractor) on 14th January 2021. After multiple rounds of discussion with the TBM manufacturer`s, the contractor placed purchase order for two single-shield hard rock TBMs having 9.11 m nominal bore diameter with M/s Herrenknecht on 11th March 2021. The factory acceptance tests for S-1309A (TBM Shakti) and S-1310A (TBM Shiv) were successfully completed on 18th February 2022 and 27th April 2022 at M/s Herrenknecht factory in Schwanau, Germany. Both TBMs were successfully transported to India through sea to Mundra port and through road to the project site. TBMs Shakti and Shiv were assembled in a record time of 6-7 weeks and pushed to launch location on schedule for TBM boring inside individual tubes at locations indicated in SN 4 of Table 1. Both TBMs completed their TBM boring journey strictly on schedule (Table 11). The monthly and cumulative comparison between planned and actual performance is shown in Figure 8.

Table 11 - Timelines for tunnel boring of Shakti and Shiv

TBM	Boring commencement		Boring completion		Chainage		Distance (km)
	Planned	Actual	Planned	Actual	Start	End	
TBM Shakti (S-1309)	28th Dec. 2022	17th Dec. 2022	28th Apr. 2025	16th Apr. 2025	48+180	58+649	10.469
TBM Shiv (S-1310)	27th Feb. 2023	6th Mar. 2023	30th June 2025	30th June 2025	0+880	11+168	10.298

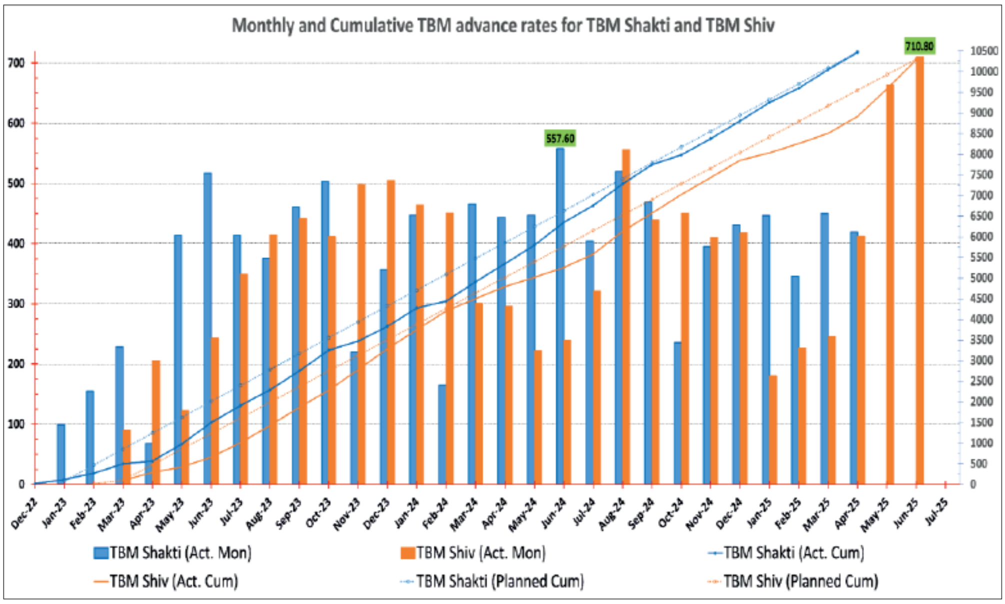

Figure 8 - Monthly and Cumulative advance rates for TBM Shakti (Blue) and TBM Shiv (Orange)

Table 12 - Monthly time percentage utilization of TBM Shakti and TBM Shiv

Categories	TBM Shakti Performance			TBM Shiv Performance		
	Average	Best	Worst	Average	Best	Worst
Advance	16.47%	21.86%	4.09%	15.48%	26.56%	8.06%
Lining	25.01%	35.21%	7.87%	20.66%	27.86%	9.10%
No Production	58.53%	42.93%	88.4%	63.86%	45.58%	82.84%
Applicable Month	Dec 22 to Apr 25	June 24	Apr 23	Mar 23 to June 25	June 25	Jan 25
Monthly Advance (m)		557	68		710	182

Applicable Chainage	48+180 to 58+649	53+981 to 54+539	48+679 to 48+747	0+880 to 11+168	10+457 to 11+167	8+726 to 8+908

Each TBM was equipped with 2250 sensors and all TBM data was accessible on real time basis from TBM manufacturer's online server. TBM utilization was critical to understand efficiency of TBM operations and were derived based on categorization shown in Table 12, after ignoring initial learning phase of 3 months from TBM deployment.

Furthermore, since the TBMs were running parallel in same direction, ground conditions of ahead TBM Shiv could be expected from the leading TBM Shakti, through analysis of captured TBM operational and derived parameters shown in Table 13.

Table 13 - TBM operational and derived parameters

Sl. No.	Operational parameters	Units	Sl. No.	Derived parameters	Units
1.	Total thrust force	kN	A	TBM Friction (Thrust force loss)	kN
2.	Main drive contact force	kN	B	Penetration rate normalized for Contact force	mm/Rev/Tn
3.	Backup gantry pulling force	kN	C	Penetration rate normalized for Torque	mm/Rev/Tn-m
4.	Main drive torque	Tn-m	D	Power (2π*RPM / Torque) (for each advance)	kW
5.	Rotation speed	RPM	E	Specific Energy (Energy required to cut 1 cum rock)	kWh/Cum
6.	Rate of penetration	mm/Rev	F	Boreability Index (Force required to generate penetration of 1mm / rev)	kN/mm/Rev
7.	Advance speed	mm/min			

The sensor data was captured every second of TBM operation, which could be aggregated over each TBM advance cycle, resulting in start, minimum, average, maximum and end data points. This data was downloaded regularly from TBM manufacturer's server for each advance for further analysis during advancements (Figs. 9 & 10).

Based on recorded data and examination of excavated muck, few prominent weak zones encountered with TBM Shakti are shown in Table 14. Each TBM advance is of fixed length of 1.7 m and the advance number indicates the number of advances done to reach a particular chainage. Inference of geological contrasts could be drawn easily based on this data, including TBM wise location, indicating the actual planar angle of the contrast zone with respect to both TBMs.

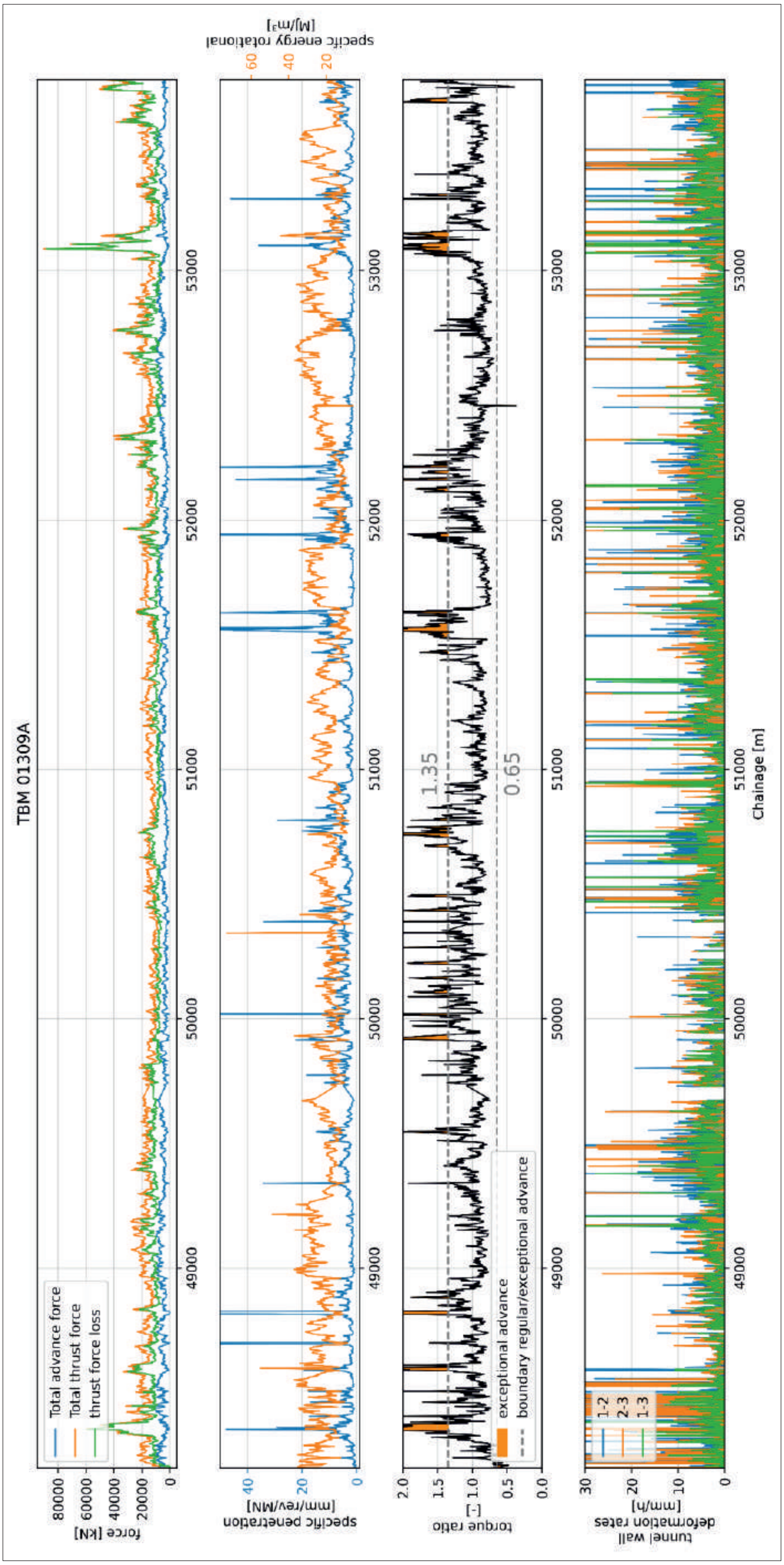

Figure 9 - Line-plot of TBM Shakti for few operational parameters

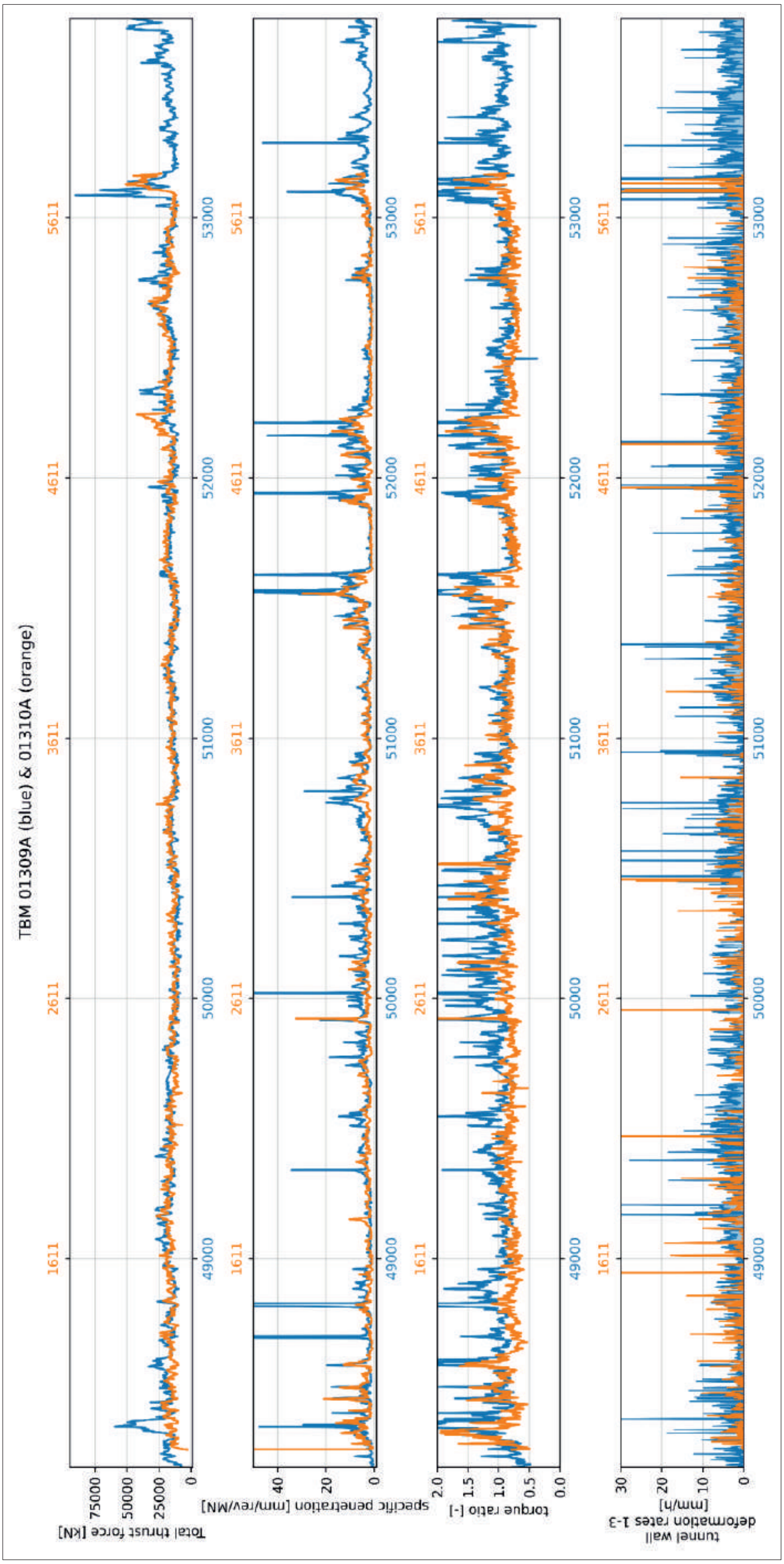

Figure 10 - Line-plot of TBM Shiv for TBM operational parameters

Table 14 - Mean operational parameters of TBM Shakti in encountered weak zones (SN 1 to 11) and comparison with a typical good zone (SN 12)

Sl. No.	TBM Shakti operational parameters (Mean Values)											
	From	To	Length (m)	Average over-burden (m)	Total thrust (KN)	Advance force (KN)	Friction force (KN)	Penetration rate (mm/Rev)	RPM	Torque (TN-m)	Advance speed (mm/min)	Advance number
1.	48+329	48+377	48	340	39812	2617	37200	17.00	1.83	3.48	30.65	95-123
2.	48+590	48+598	8	524	25554	1421	24132	13.31	2.67	2.81	35.63	248-253
3.	52+746	52+768	22	610	32311	4655	27655	13.49	3.83	2.62	45.67	2690-2703
4.	53+083	53+095	12	742	55178	1332	53845	17.91	2.35	2.49	41.38	2888-2895
5.	53+100	53+110	10	746	54590	1448	53142	23.42	1.51	2.88	34.11	2898-2904
6.	53+721	53+742	21	582	43146	3612	39533	12.86	3.38	1.94	40.51	3263-3275
7.	53+767	53+791	24	567	59323	3247	56075	15.30	2.89	2.65	39.24	3290-3304
8.	54+711	54+728	17	532	43331	5370	37961	14.64	3.98	2.37	52.86	3844-3854
9.	55+875	55+917	42	533	38580	2836	37544	22.02	2.89	2.72	60.47	4527-4552
10.	57+569	57+588	19	508	42566	4881	37685	28.64	2.21	4.34	58.18	5522-5533
11.	57+714	57+734	20	536	25814	4100	21714	29.82	2.21	4.25	65.54	5607-5619
12.	48+850	50+500	1650	268	15060	4558	10502	14.54	4.04	2.85	56.20	402-1371

7. USE OF ARTIFICIAL INTELLIGENCE (AI) AND MACHINE LEARNING (ML)

Use of AI and ML was globally done for the first time on TBM Shakti and TBM Shiv, to help predict potential risks while TBM tunnelling. Norwegian Geotechnical Institute (NGI) was engaged for this task. The scope of work included downloading data through python script from TBM data server every 3 h and its subsequent data analysis. For data analyses, few assumptions were made (i) Rockmass strength and behaviour is isotropic, (ii) Displacements are equally distributed around the tunnel periphery and (iii) Both parallel tunnels are treated as single tube tunnels without influencing each other (iv) Squeezing is influenced by four variables:

- Tunnel wall deformation rate
- Gross TBM advance speed (i.e., advance speed including standstills)
- Size of the shield gap at the position of the tail-skin
- The length of the shield that can be squeezed in

Given these variables, computation was done for the minimum required gross advance speed and / or required overcut to be able to "escape" a deforming tunnel wall and not get squeezed in given a fixed shield length. It was concluded that, given the fixed length of the TBM shield, if the tunnel wall deformation rate increases, either the gross TBM advance rate and / or the overcut must increase to avoid that the TBM getting stuck. Figure 11 (plot of deformation rates mm/hr vs gross advance rates mtr/h, the blue dots indicate condition of recent 5 advances, coloured based on total thrust applied for that advance) shows this analysis for TBM Shakti, considering a shield gap that results from a standard overcut of 94 mm (orange zone) and that from an overcut by cutterhead offset of 175 mm (Red zone). The deformation rates mostly ranged between 2-6 mm/hr; however, in weak zones, it occasionally peaked upto 10-15 mm/hr, where the contact between ground and TBM shield resulted in increase of total advance force. The motive was to maintain advance conditions above red and orange squeezing risk zones by maintaining required gross advance rates. No locations were encountered during TBM tunnelling, where tunnel deformations lead to TBM jamming.

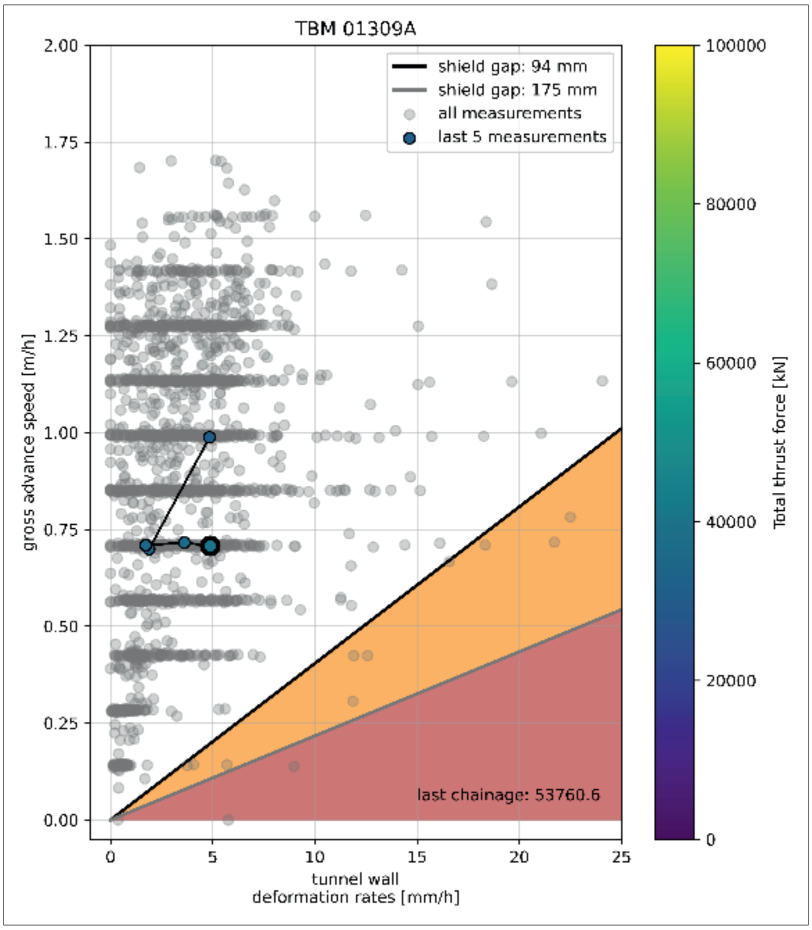

Figure 11 - Squeezing risk plot of TBM Shakti

NGI automated the data capture, data analysis and data sharing with project site, providing critical updates and raising cautions during TBM advance. This helped the project to replan their operations and maintenance cycles from time to time by controlling and reducing risk of TBM jamming and other hazards.

8. CONCLUSIONS

In this paper, at first, layout of Tunnel 8 of Rishikesh Karnprayag project was described along with geological and geotechnical properties. Secondly, adopted approach for computing squeezing potential of ground through empirical and analytical methods was explained in Section 3.4. A new approach towards defining TBM ground types based on excavation efforts rather than geological conditions was attempted on the project as described in Section 3.5. The TBM specification and latest state of art technologies adopted during TBM design were detailed in Section 5. Finally, the construction performance of both TBMs Shakti and Shiv and adoption of artificial intelligence and machine learning were detailed in Section 6 and Section 7.

The use of AI and ML was globally done for the first time on TBM Shakti and TBM Shiv, to help predict potential risks while TBM tunnelling. Main risk for TBM tunneling at Tunnel 8 was squeezing of ground and jamming of TBM. To predict jamming potential, real time analysis of convergence data was carried out to obtain rate of deformations and possibility of gap closure at tail shield end of TBM in relation to gross advance speed of TBM. Regular advance geophysical probing provided initial hints on the approaching poor grounds, where this study was done meticulously by watching short time trends of TBM operational parameters like total thrust, contact force, friction force, penetration rates and torque requirements. Depending on thickness of weak zone, real time decisions were taken frequently to strategize TBM advance with either bore enlargement, pre-grouting or to proceed with required advance speeds.

The successful completion of Tunnel 8 through TBM excavation showcases the importance of thorough geological and geotechnical investigations, understanding and analyzing the inherent ground risks and adopting latest and state of art technologies in TBM design along with emerging technologies like artificial intelligence and machine learning. The skill of deployed manpower and a good collaboration were equally important for a successful TBM excavation on Rishikesh Karnprayag railway project.

DISCLOSURES

The author declare no conflicts of interest related to this work.

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