



# Ground Characterization and TBM Performance Evaluation in Fractured Basaltic Terrain Near the Arabian Sea, India

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**Abstract** TBM tunneling in fractured rock masses in the vicinity of the sea is a major geological challenge, and such heterogeneous rock mass can lead to reduced productivity, a high risk of pressurized water inflow flooding the tunnel, and excessive ground movements leading to building damages in urban tunneling projects. A literature study was carried out to review the impact of difficult ground conditions on TBM tunneling. The presented work includes a case of the Mumbai Metro Line-3 UGC-01 project, a selected section where TBM alignment was passed mere 15 m off the coast of the Arabian Sea and this study is focused on ground characterization done to delineate the anomaly zones and further analyze the effect of difficult ground conditions on TBM operational and performance parameters in different weathering grades of basalt encountered near to sea section. Encountered ground conditions are divided into different zones based on the degree of fracturing in the rock mass, and further, all the TBM parameters are plotted to analyze the change in different zones. The paper also discusses the problems encountered during TBM excavation in each zone including high groundwater inflow and highly fractured rock mass. TBM operational and performance parameters which are analyzed include penetration per revolution, penetration speed, rate of penetration, weekly advance rates, cutter head rotation per minute, applied thrust force, and torque. The results highlight the effect of highly fractured rock masses, causing a significant reduction in TBM performance.

**Keywords** TBM performance · Ground characterization · Basaltic traps · Fractured ground · Geophysical

## Introduction

Shielded tunnel boring machines are widely used in urban areas for metro tunnel construction around the world as it offers fast, safe, and high-speed tunneling; however, complex geology can affect the TBM productivity significantly. Therefore, planning and execution of such urban tunnel projects call for adequate site investigations, detailed ground interpretation, accurate evaluation, and anomalies identification. Geophysical techniques and their correlation with borehole investigations can delineate the ground anomalies to a greater extent [1, 2] and can help predict difficult ground conditions during the early stages for successful completion and to avoid any time and cost overruns of the tunnel project.

Different researchers analyzed the effect of difficult ground conditions [3–6] including fractured, blocky rock mass, faulted zones, flowing ground, mixed face, and pressurized water inflow on TBM productivity [7–11]. Face collapse, water ingress, cavity formations are the major problems faced in the difficult ground as studied by many researchers [6, 12–14], and it leads to various issues including ingress of dragging a large amount of ground material causing settlements and can damage surface structures in an urban environment. Analysis of the TBM performance in such difficult ground becomes extremely important besides ground characterization to see the effect of changing ground conditions on machine and performance parameters. This paper includes a systematic study on ground characterization to delineate the anomaly zones

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before TBM arrival and to evaluate the machine and performance parameters in varied weathering grades of basalt encountered near to sea section.

The study area includes a selected section of twin tunnel stretch which was merely 15 m from the sea coast for a length of about 150–200 m. Pre-construction geotechnical investigations had inferred several anomalous zones including the varying degrees of fracturation in basaltic rocks near the sea, and therefore, it was essential to assess and reconfirm the identified ground anomalies. Detailed investigations through additional exploratory probe holes and geophysical methods, namely seismic refraction and electrical resistivity, were done to cross verify the anomalies predicted during the early stages, and later, the borehole data were correlated with geophysical data to delineate the fractured anomaly zone. During tunnel excavation, the strata encountered were highly fractured with high water ingress which lead to a reduction in TBM productivity significantly.

## Project Description and Geology of the Study Area

Mumbai Metro Line-3 is an under-construction project in Mumbai and once completed will be the first underground metro project in the city. The project is being executed in seven different packages and this study covers a section of UGC-01 which is near the Arabian Sea and the project is being executed by L&T STEC JV. The project scope involves the design and construction of four stations and an associated tunnel with 5.2 km of total tunnel length. Two crossovers shielded TBMs of 6.65 m cutter head diameter used for tunnel excavation with segmental lining and finished diameter of 5.8 m. This study covers a section of tunnel alignment between Cuffe parade and Vidhan Bhavan station which was nearest to sea from chainage 900 to 1080 M, and hereafter all details discussed refer to this section only (Fig. 1).

Geologically, Mumbai is part of Deccan volcanic traps that were formed by tremendous volcanic activity and developed a formation called Deccan traps covering 80% of the surface area of Maharashtra state. Deccan traps are the result of the deposition of subaerial lava flows of fissure eruptions [15] which covers around 5000 km<sup>2</sup> portions of the Indian Peninsula consisting of main lithologies, namely amygdaloidal to compact basalts, volcanic breccia, inter-trappean beds, and red boles [16].

The major geological formations which are commonly found in Mumbai city include basaltic terrain, volcanic breccia, intertrappean beds of shale with tuff bands, and red boles. Mumbai Island is originally known for seven separate islands connected by swamps. Later, reclamation was done at the end of the eighteenth century giving rise to a

landmass known as the Island of Bombay. A detailed figure indicating the merging of different islands with the timeline with the study location is shown in Fig. 2. The merging of different islands indicates a high risk of encountering backfilled or fractured material toward the seaside leading to high water inflows during the tunnel excavation.

Borehole investigations revealed geological conditions along the entire alignment are complex ranging from varying degrees of weathering grades of basalts and shale with tuff bands, and loss of water near to sea during permeability testing indicative of the high degree of fracturation and open joints within the rock mass. The main geological layers encountered in the tunnel section near to sea during geotechnical investigations are shown in Table 1.

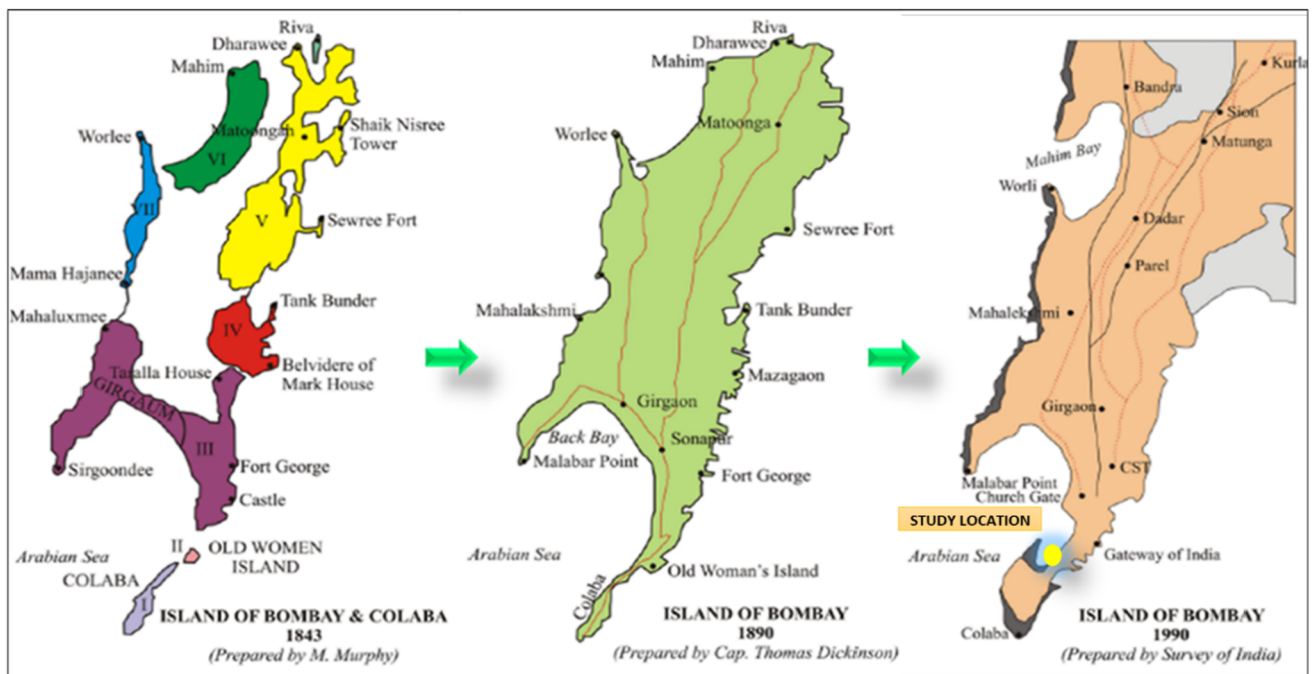
## Geotechnical Investigations

At the initial stage of the project, two boreholes (*BH* 01–02) were drilled as part of pre-construction investigations in the study area, and the borehole layout plan is shown in Fig. 3. The holes were around 30 m deep and 8 m below the tunnel invert. These boreholes revealed the overburden thickness ranging from 4 to 7 m with underlying basaltic traps of varying degrees of weathering and fracturation. *BH*-01 shows moderately to slightly weathered basalt, whereas *BH*-02 indicated highly weathered basaltic terrain (Fig. 4) with high permeability recorded during in situ testing.

Additional two probe holes, namely *PBH*-01 and 02 (Fig. 3), were drilled up to tunnel invert level, i.e., 21 m, to check the continuity of fractured strata toward the seacoast area. However, recovered competent basalt indicates high *RQD* and slightly weathered rock mass, and hence, continuity of fractured rock mass could not be established. One of the pre-construction stage boreholes *TBH* terminated at 10 m, and therefore, the correlation with this borehole could not be established at tunnel level. The developed geological profile is shown in Fig. 5.

Rock mass encountered during investigations were broadly categorized into three units having uniform characteristics, and a summary of geomechanical properties of these units is listed in Table 2. Groundwater table along the entire tunnel stretch is varying from 1 to 2 m below the road level, and variation in these levels is recorded due to tidal variations. Groundwater conditions during tunneling vary from ‘damp to wet’ in slightly weathered rock mass whereas ‘dripping’ to ‘continuous water inflow’ observed in the moderately weathered rock mass and ‘high’ to ‘very high’ water ingress recorded in highly to completely weathered rock mass. Shrestha et al. [18] investigated the effect of groundwater on faulted rock mass in TBM

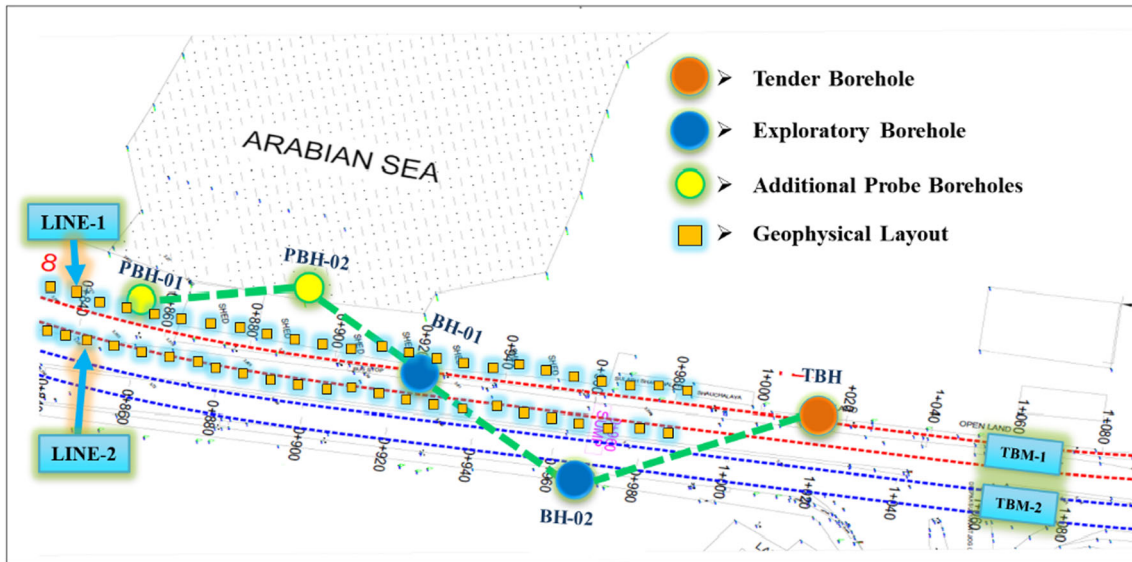
**Fig. 1** Tunnel alignment nearest to sea section



**Fig. 2** Merging of seven different islands of Mumbai and its reclamation [17]

**Table 1** Geological layers encountered during geotechnical investigations near the sea

Geological layers	Lithological description
WG—V and IV basalt	Weak to very weak completely to highly weathered gray to yellowish-brown highly fractured basalt with very closely spaced fractures
WG—III basalt	Moderately strong to strong, moderately weathered very dark gray basalt with moderately spaced subhorizontal to inclined iron-stained fractures
WG—II and I basalt	Very strong to strong slightly weathered to fresh gray fine-grained basalt/light gray basalt with widely spaced subhorizontal to subvertical fractures



**Fig. 3** Borehole investigations (left) and geophysical investigations layout (right)



**Fig. 4** Cores recovered during preconstruction borehole investigations (BH-01—left and BH-02 right)

tunneling and concluded that deformations may increase up to 30%.

Results of preconstruction boreholes and additional probe hole investigations revealed that the degree of fracturation is not continuous toward the sea (perpendicular to tunnel alignment); however, the continuity of fractured strata along the tunnel alignment is not established with the boreholes, and therefore, geophysical investigations were proposed along the alignment to delineate the anomaly zones.

### Geophysical Investigations

Geophysical methods, namely electrical resistivity tomography and seismic refraction tests, were proposed in the study area. It was a renowned fact important to point out again that borehole investigations provide point information and interpolated with an assumption that the ground was homogenous, and therefore, geophysical investigation

proposed as it provided continuous information along proposed lengths, and the results can be correlated with the borehole data. Two lines of 145 m each (one line nearest to sea and the other line above TBM-1 alignment) for resistivity tomography and seismic refraction survey were executed, and the layout for geophysical investigations is shown in Fig. 3.

The main objectives of carrying out geophysical investigation are:

- Precise determination of soil layer thickness and rock level.
- Deep weathering.
- Fractured and weak zones.
- Water-bearing formation.

The resistivity survey has revealed the presence of a low-resistivity layer in the entire section at tunnel depth in line 1 and indicates the presence of water-saturated layers as shown in Fig. 6 (left), whereas moving away from the

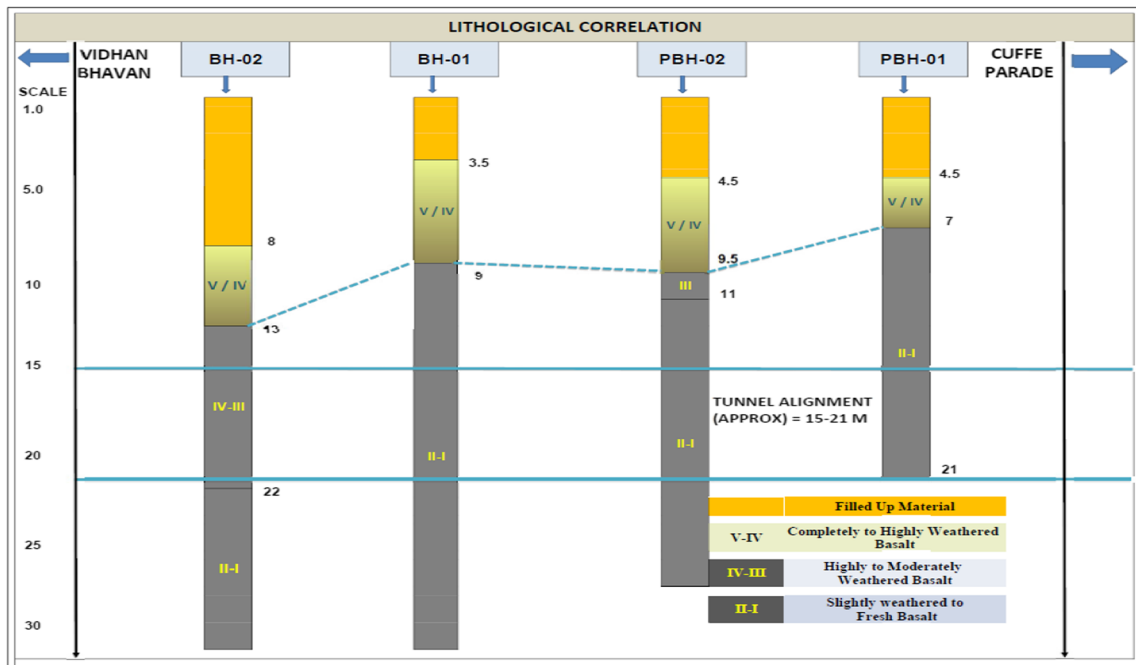


Fig. 5 Geological profile

Table 2 Summary of geomechanical properties of different geological layers

Parameter	TCR (%)	SCR (%)	RQD (%)	UCS (Mpa)	CAI	RMR
WG – V and IV basalt	10–70	0–60	0–30	< 25	0.8	0–40
WG – III basalt	60–100	50–90	40–70	< 50	1.4	41–60
WG – II and I basalt	80–100	70–100	70–100	> 60	1.6	61–80

TCR total core recovery, SCR solid core recovery, RQD rock quality designation, UCS uniaxial compressive strength of rock, CAI Cerchar abrasivity index, RMR rock mass rating

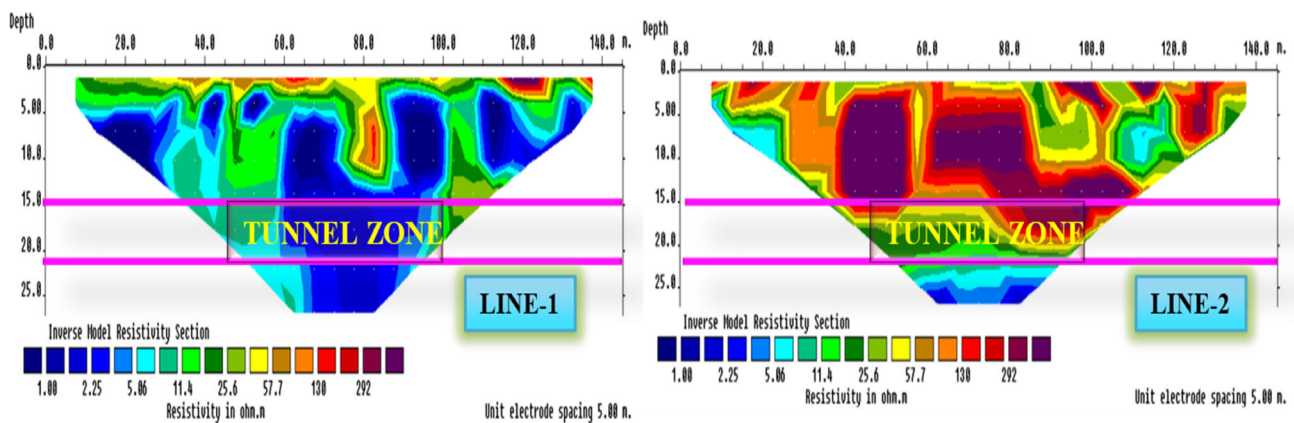


Fig. 6 Resistivity model 2D profile (line 1 and line 2) modified after Sindhwani et al. [19]

coast, the results indicate presence of high resistivity layer in line 2 as shown in Fig. 6 (right). The resistivity model 3D profile is shown in Fig. 7 indicating the low-resistivity

zones toward the seaside and high resistive zones on the other side.

Seismic refraction survey results revealed that the first and top layer of line-1 encountered compressional wave

velocity of about 280 m/s and represented topsoil, whereas the second layer encountered a velocity of about 1100 m/s and represented highly/moderately weathered rock strata up to the tunnel invert and, the third and final layer encountered an approx. the velocity of 2400 m/s reflects moderately weathered to slightly weathered rocky strata shown in Fig. 8 (left) and indicates a high-velocity layer (indicated as red) below tunnel invert level. The final layer of line-2 represented an approx. the velocity of 2700 m/s indicates the presence of competent rock mass as compared to line 1 and reflects slightly weathered to unweathered rock mass as shown in Fig. 8 (right).

Geotechnical and geophysical investigations results were correlated for better interpretation, and it is concluded from the developed subsurface model of this area that the fractured strata are not continuing toward the sea and across the tunnel alignment; however, fracturation is continuous along the tunnel alignment and the transition zone chainage from fractured to the unweathered zone is not delineated. Therefore, it is very likely to encounter a fractured zone and high-water ingress however the continuity of this fractured zone is not known and therefore to be closely monitored during an excavation along the TBM-1 tunnel alignment.

### Actual Ground Conditions and Effect of Difficult Ground on TBM Advance Rates

Two new Robbins' crossover single shield TBM were deployed in the project with a 6.65 m excavation diameter, and the cutter head of TBM is designed with a center screw and dual mode as hard rock and EPB mode capable of dealing with both soft and hard ground conditions and equipped with single- and double-disk cutters. The nominal disk cutter spacing is 90 mm, and the cutter head is driven by 8 motors with a maximum rotation speed of up to

8.75 rpm in hard rock mode. Key TBM specifications are presented in Table 3:

Actual ground conditions encountered near to sea from chainage 900 to 1080 M are divided broadly into three different zones based on the rock mass observed during face inspection and muck monitoring (Fig. 9) indicating different weathering grades of basalts encountered in each zone and had a significant difference in their effects on TBM operations. The description of different weathering grades of basalt encountered is included in Table 1.

Rock mass encountered during excavation includes different weathering grades starting from slightly to moderately to highly to completely weathered basalts. Face inspection and muck samples of each encountered zone are included in Fig. 10 (1–4). Slightly weathered grayish basalts in zone-1 indicate iron staining only along joints (Fig. 10-1), and minimal water seepage was observed from chainage 900 to 980 M. Zone-2 encountered as a transition from slightly to moderately weathered grayish to yellowish-brown basalts with a high degree of fracturation w.r.t zone 1. A low strength material and rock mass coloration changed up to 50% with moderate water ingress witnessed from chainage 980 to 1020 M (Fig. 10-2).

Zone-3 witnessed disintegrated and yellowish-brown colored rock mass (Fig. 10-3) indicating highly to completely weathered iron-stained basalt with very high volumetric joint count from chainage 1020 to 1065 M and caused a drastic reduction in advance rates of TBM due to recovered slush with huge water ingress from screw conveyor (Fig. 11). Beyond zone-3, rock mass changed to slightly weathered to fresh grayish basaltic rock mass (Fig. 10-4) having very low volumetric joint count and dry face.

TBM1 recorded an average and maximum of 45 m and 50 m per week advance in zone-1, respectively (Fig. 12), in slightly weathered to unweathered rock mass with compressive strength of > 60 Mpa, *RQD* in the range of

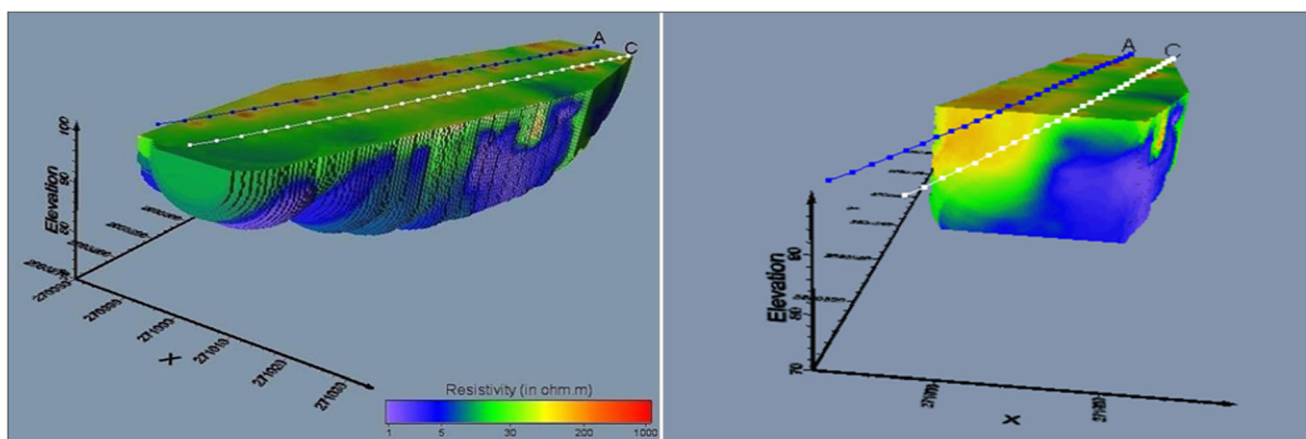
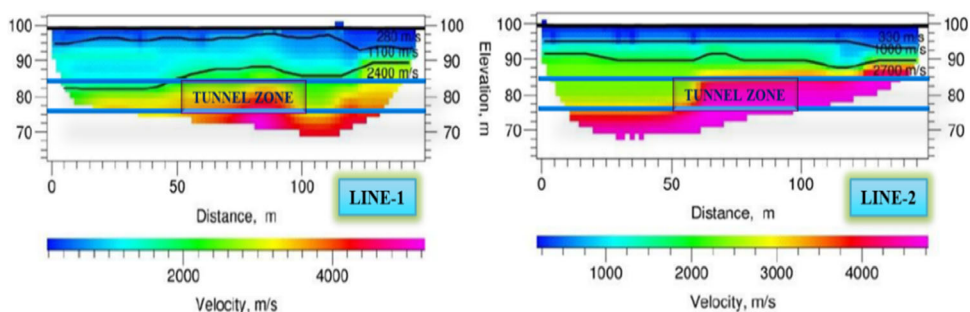


Fig. 7 Resistivity model—3D profile

**Fig. 8** Seismic velocity model (line 1 and line 2) modified after Sindhvani et al. [19]



**Table 3** TBM specifications

Parameter	Value
TBM Make	Robbins crossover
Machine diameter	6.65 m
Segment thickness	275 mm
Cutterhead power	1680 kW
cutter diameter	432 mm
Number of disk cutters	42
Cutterhead torque (hard rock mode)	2,316 kN-m at 0–6.9 rpm
Cutterhead torque (EPB rock mode)	9,356 kN-m at 0–1.71 rpm
Max. operating thrust	36,187 kN at 345 bar
Cutterhead speed	0–8.75 rpm

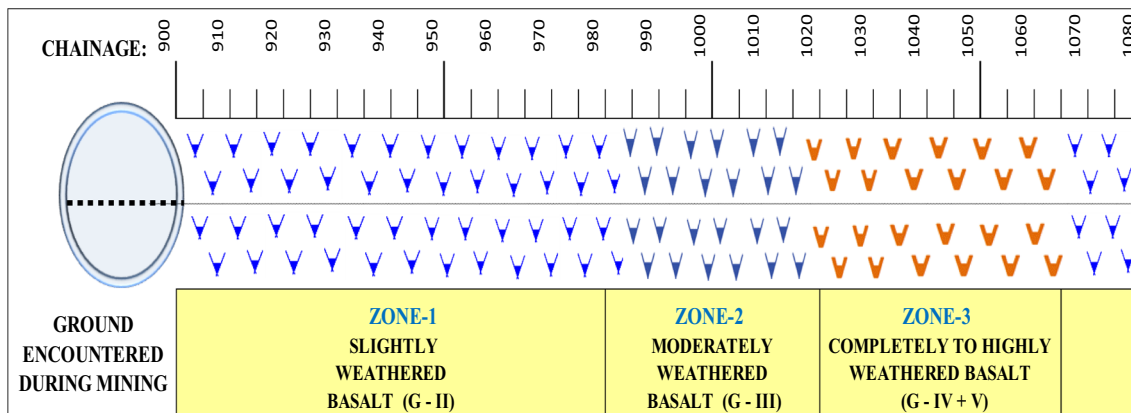
70–100%, and RMR of 61–80 range, whereas in zone-2, recorded 54 m per week advance with compressive strength of < 50 Mpa, *RQD* in range of 40–70% and RMR of 41–60 range. Zone-2 achieved marginally higher advance rates owing to medium compressive strength and a moderate degree of fracturing which favors the chipping process.

The advance rate in zone-3 shows a drastic reduction as recorded an average and maximum of 23 m and 26 m per week advance, respectively. As problems occurred majorly in zone-3 when the TBM encountered highly fractured rock

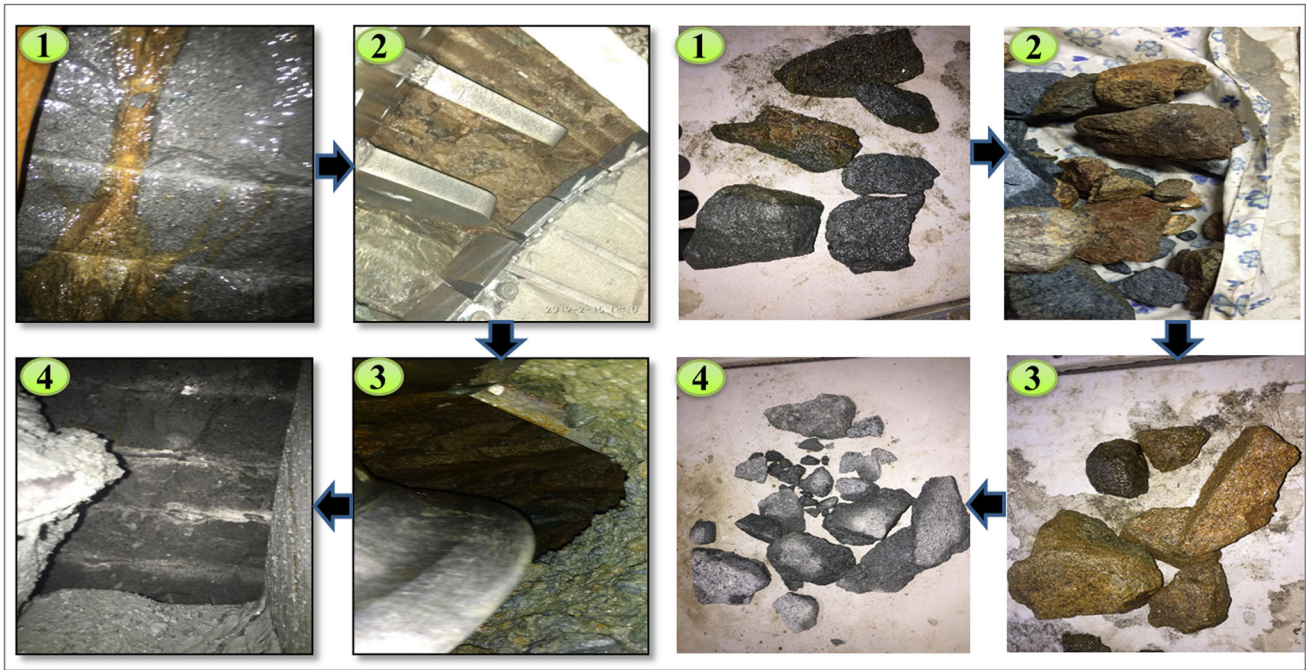
mass which led to high water inflows from screw conveyor along with fractured rock mass causing slush to overflowing onto a conveyor belt and further fall onto the segments below and thus causing the reduction in the overall advance rate of TBM1. Advance rates achieved in zone-3 are also the lowest advance rates owing to the highest degree of fracturing and near to sea leading to huge water ingress. Basalts with open joints in Deccan traps leading to water ingress was reported by other researchers [20, 21]. Beyond zone-3, TBM1 recorded an average of 45 m per week advance rate indicating the improved advance rates similar to zone-1.

**Analysis of TBM Operational and Performance Parameters in Changing Ground Conditions**

TBM operational and performance parameters have been evaluated for different weathering grades of basaltic rock mass and compared with the parameters recorded in zone-1 when the rock mass is slightly weathered to unweathered. Paltrinieri et al. [5] studied the effect of highly fractured and faulted ground on TBM performance and concluded a significant reduction in TBM performance in the faulted ground as compared to good ground conditions. Shirlaw et al. [22] discussed the impact of weathered rock mass on



**Fig. 9** Geological profile along tunnel alignment for the section near the sea



**Fig. 10** Encountered rock mass along tunnel alignment for the section near to sea

**Fig. 11** High water inflow on a conveyor belt from screw (left) and crushed rock mass (right)



tunneling and concluded that weathered rock mass leads to a higher permeability. Several researchers [23–26] considered  $P_{rev}$  (mm/rev), PR (mm/min), and PR (m/h) as the key performance indicators of TBM, and therefore, these parameters along with machine parameters, namely thrust force (kN), torque (kN-m), and rotation speed, RPM (rev/min), have been studied for different weathering grades of basaltic rock mass encountered from zones 1 to 3.

TBM operational and performance parameters in the three different zones are shown in Fig. 13, and each zone is separated from the other with a dotted line indicating a transition from one zone to another zone. Selected parameters were monitored by the TBM logging unit, and recorded files were analyzed later in spreadsheets.

### TBM Operational Parameters

Applied thrust force (kN) for zone-1 was in the range of 10,000–14,000 kN (Fig. 13a) due to the presence of slightly weathered to unweathered basaltic rock mass. In zone-2, the applied thrust force range is reduced to 8000–10,000 kN in the moderately weathered basaltic rock mass, and reduction is witnessed due to an increased degree of fracturation leading to ease of chipping process. In zone-3, the thrust force drastically increased up to 14,000–18,000 kN range in highly to completely weathered rock mass and the increase is observed due to the shield getting stuck in the highly fractured rock mass and collapsing strata on the face. Beyond zone-3, applied force reduced to 10,000–12,000 kN, thus indicating a stable and unweathered rock mass on the face similar to zone-1.



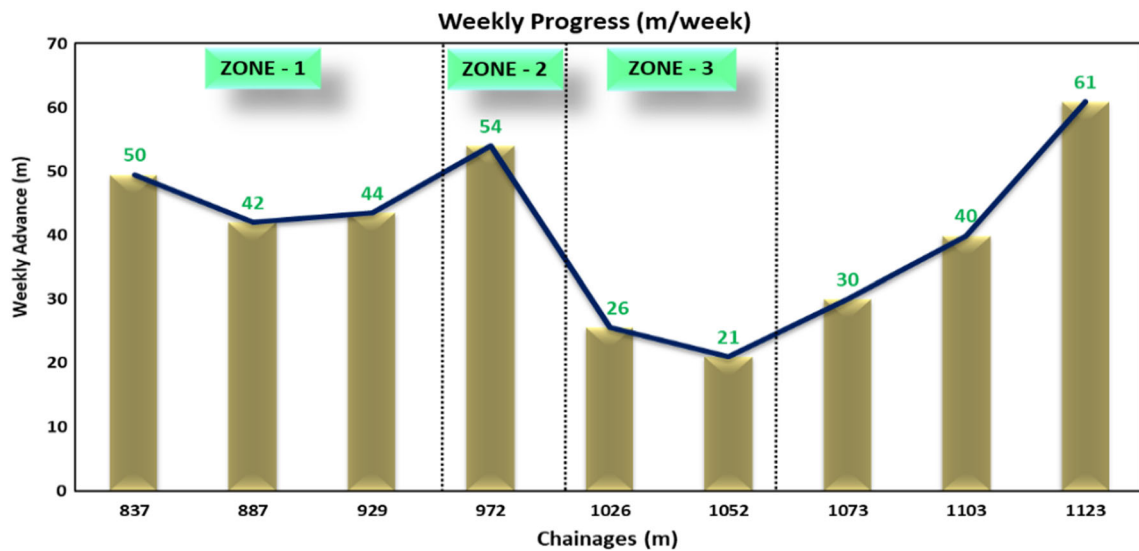


Fig. 12 Weekly advance rate of TBM1 for the section near the sea

Torque (kNm) recorded in zone-1 was in the range of 1500–3000 kN-m (Fig. 13b) and indicates smooth cutting of rock mass on face, whereas in zone-2, torque recorded was in a similar range and does not indicate any significant difference with zone-1 except that the lowest recorded torque values were reduced up to 1200 kN-m. In zone-3, the recorded torque values are highly scattered within a range of 1500–4500 kN-m and the upper range indicates a drastic increase in torque values as the cutters get more impact loading in undulated and highly fractured rock mass.

Cutterhead rotation speed, RPM (rev/min) for zone-1, was in the range of 2.0–3.2 rev/min (Fig. 13c) to achieve nominal penetration speed whereas seen an increased range of 3–4.5 rev/min in zone-2. In zone-3, a reduction in RPM has been observed in the range of 1.5–3.0 rev/min, and 50% of the recorded RPM values were below 2.0 rev/min in the highly fractured rock mass. Reduction in RPM is to limit the disturbance to the highly fractured rock mass and also efficiently control the removal of muck from screw to conveyor belt as this zone has caused huge water ingress with crushed rock mass material. A summary of the range of TBM operational parameters for three different zones is included in Table 4.

**TBM Performance Parameters**

Penetration per revolution,  $P_{rev}$  (mm/rev) was recorded in a broad range of 6–20 mm/rev with most of the values are within the range of 8–14 mm/rev in zone-1 (Fig. 13d), whereas in zone-2, initially, the  $P_{rev}$  recorded in the range of 8–16 mm/rev and progressively recorded increased penetration in range of 15–30 mm/rev in moderately

weathered basalt. High values of  $P_{rev}$  in zone-2 are mainly due to ease of boreability of rock mass with the decreased surface quality of joints and a significant reduction in compressive strength as compared to zone-1. In zone-3,  $P_{rev}$  was recorded in the range of 6–12 mm/rev in completely to highly weathered basalts.  $P_{rev}$  does not indicate any significant reduction in penetration mainly due to completely weathered and undulated rock mass with clay-filled joints which hinder the usual chipping process and instead create impact loading on cutters and cause more cutter wear in such cases. A similar effect is indicated in previous studies by Paltrinieri et al. [5] and Delisio et al. [27].

Penetration rate, PR (mm/min), is defined as the multiplication of penetration per revolution ( $P_{rev}$ ) and cutterhead rotation speed (RPM). PR was recorded in a range of 15–45 mm/min average rate in zone-1 (Fig. 13e), whereas zone-2 indicates an average PR range of 35–55 mm/min in moderately weathered basalts. A higher penetration rate is achieved in zone-2 mainly due to TBM operated at a high RPM range of 3.0–4.5 rev/min combined with high  $P_{rev}$ . In zone-3, PR indicates a reduction in penetration range of 10–20 mm/min due to reduced RPM for efficient control of muck removal and reduced  $P_{rev}$  in comparison with zone-2.

Rate of penetration, ROP (m/h), is defined as the total mined length divided by the total time taken for excavation of one ring (segment length varies from 1.2 to 1.5 m). In zone-1, ROP was recorded in the range of 1.5–2.2 m/h in slightly weathered basalts (Fig. 13f) whereas recorded increased ROP in the range of 2.0–2.8 m/h in zone-2 in moderately weathered basalts due to a combination of increased range of RPM and  $P_{rev}$ . Zone-3 indicates a drastic reduction in ROP ranging between 0.9 and 1.5 m/h

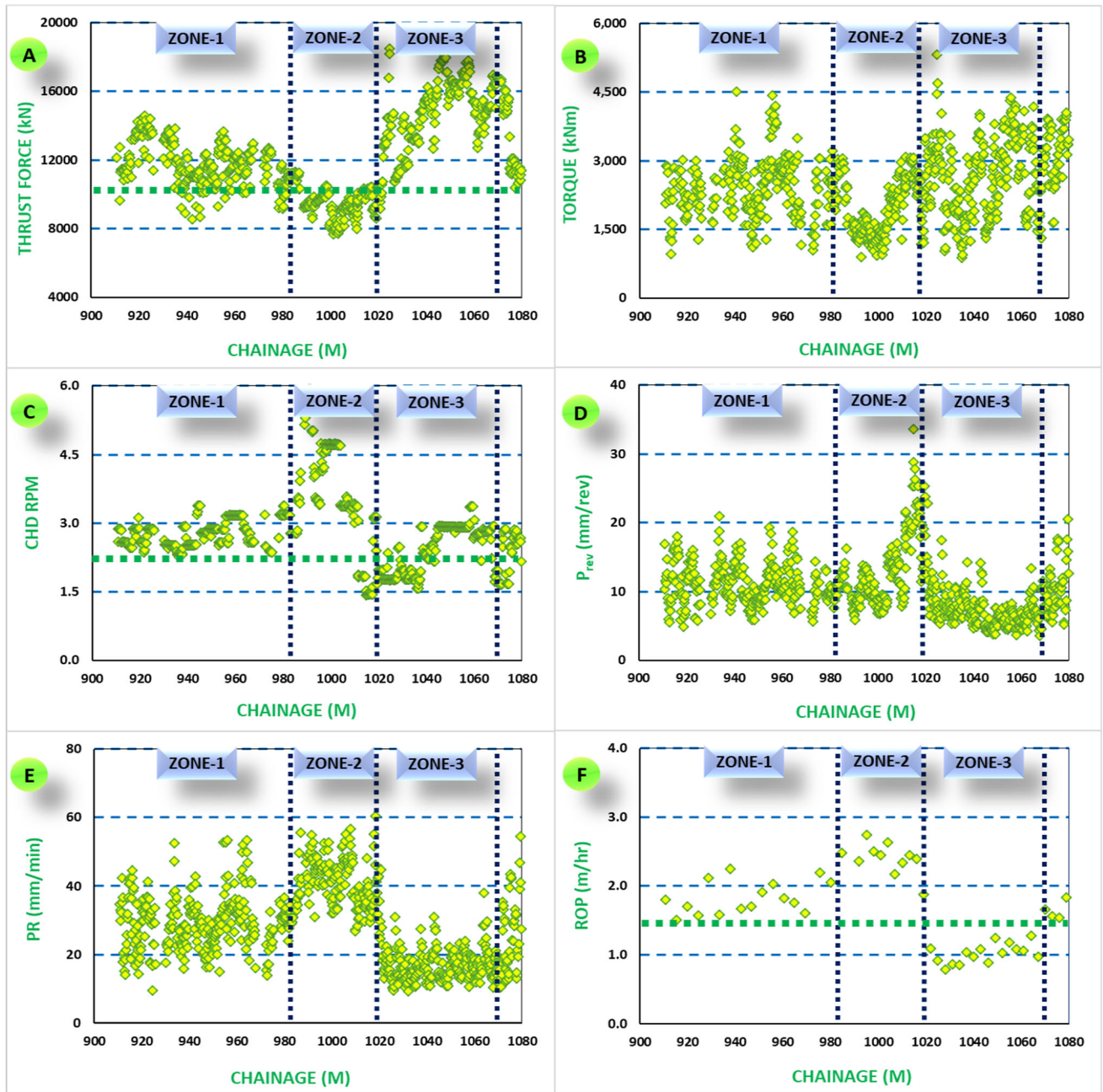


Fig. 13 TBM operational and performance parameters in the section near to sea

Table 4 Range of TBM operational parameters observed in different weathering grades of basalt

Parameter	Thrust force (kN)	Torque (kNm)	RPM (Rev/min)
G-I/II basalt	10,000–14,000	1500–3000	2.0–3.2
G-III basalt	8000–10,000	1500–3000	3.0–4.5
G-IV/V basalt	14,000–18,000	1500–4500	< 2.0

**Table 5** Range of TBM performance parameters observed in different weathering grades of basalt

Parameter	$P_{rev}$ (mm/rev)	PR (mm/min)	ROP (m/h)
G-I/II basalt	8–14	15–45	1.5–2.2
G-III basalt	15–30	35–55	2.0–2.8
G-IV/V basalt	6–12	10–20	0.9–1.5

mainly due to a combination of reduced RPM and decreased  $P_{rev}$  and TBM being operated slowly for efficient muck removal. A summary of the range of performance parameters is included in Table 5.

## Conclusions

Ground investigations along the tunnel alignment are crucial for the selection of TBM; however, zones of uncertainty cannot be eliminated, and such zones are known to be causing significant impact on TBM performance. This study aimed at ground characterization near the sea to delineate the anomalies to the greater extent and to analyze the effect of varied weathering grades of basaltic traps on TBM operational and performance parameters. The obtained results are discussed in detail below:

- Zone-1 proved to be good for tunneling with higher advance rates of up to 50 m/week consistently, whereas zone-2 led to high water ingress but managed well owing to high dewatering capacity and advance rates are in similar lines with zone-1. Zone-3 led to huge water ingress with slush and crushed rock mass which caused a reduction in advance rates of up to 25 m/week.
- Fractured rock mass of zone-3 led to a significant increase in applied thrust due to shield confinement caused by collapsing ground above the crown. For zone-2, a combination of high RPM and increased  $P_{rev}$  resulted in ease of boreability and chipping process, whereas in zone-1, there was a reduction in  $P_{rev}$  in comparison with zone-2 observed due to high compressive strength, unaltered joints, and low joint frequency.
- Ground conditions near to sea proved to be challenging, and the continuous presence of water significantly altered the joints and rock properties throughout millions of years of rock formation. Slightly to moderately weathered basaltic rock mass in zones 1 and 2 does not cause any reduction in TBM performance and advance rates, whereas highly to completely weathered and fractured basaltic rock mass of zone-3 caused a significant reduction in the TBM performance and advance rates.

Analysis carried out in this study will be useful for projects in similar lithostratigraphy or presence near to sea; however, there is a limitation as the case presented covers around 180 m length of tunnel alignment nearest to sea section where a significant change in operational and performance parameters is noticed.

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## Declarations

**Competing interests** The authors declare that there is no competing financial interests or personal relationship that could have appeared to influence the work presented in the paper.

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