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Performance characteristics of tunnel boring machine in basalt and pyroclastic rocks of Deccan traps – A case study

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ABSTRACT

A 12.24 km long tunnel between Maroshi and Ruparel College is being excavated by tunnel boring machine (TBM) to improve the water supply system of Greater Mumbai, India. In this paper, attempt has been made to establish the relationship between various litho-units of Deccan traps, stability of tunnel and TBM performances during the construction of 5.83 km long tunnel between Maroshi and Vakola. The Maroshi–Vakola tunnel passes under the Mumbai Airport and crosses both runways with an overburden cover of around 70 m. The tunneling work was carried out without disturbance to the ground. The rock types encountered during excavation are fine compacted basalt, porphyritic basalt, amygdaloidal basalt, pyroclastic rocks with layers of red boles and intertrappean beds consisting of various types of shales. Relations between rock mass properties, physico-mechanical properties, TBM specifications and the corresponding TBM performance were established. A number of support systems installed in the tunnel during excavation were also discussed. The aim of this paper is to establish, with appropriate accuracy, the nature of subsurface rock mass condition and to study how it will react to or behave during underground excavation by TBM. The experiences gained from this project will increase the ability to cope with unexpected ground conditions during tunneling using TBM.

1. Introduction

The Brihanmumbai Municipal Corporation (BMC) has decided to change all surface water pipelines and to create subsurface systems by constructing tunnels to avoid problems of leakage, unconventional loss and also to protect water from contamination. The water supply systems through surface pipelines in Mumbai are age-old, built for more than 70 years. These supply systems leak frequently and need repeated maintenance. All these pipes are highly pressurized and badly encroached by the population, which makes maintenance difficult. In Maroshi and Vakola sections, these pipes pass below the runways of Mumbai Airport and in case of strong burst it will affect the ground below the runways. The decision for the construction of tunnels was made because tunnels have advantages of low maintenance and less security accident. With the development of tunneling technology, it is possible to excavate tunnels with tunnel boring machine (TBM) under favorable ground conditions instead of adopting conventional methods like drill-and-blast method. For the Mumbai water supply scheme, a hard rock TBM was deployed earlier in 1984 and a tunnel of 3.87 km was driven with 3.5 m diameter gripper type TBM (Tribune no-ITA-AITES). The tunnel was reported successfully excavated in 450 days with a best monthly advance of 376 m. Construction of the tunnels has improved substantially the distribution of water supply system in Mumbai, which is an effective manner. Prior to these projects, worldwide experiences in driving tunnel through basalts and pyroclastics rocks with full-face were limited. The present scheme is a continuation to those successful efforts.

To improve the water supply to Vakola, Mahim, Dadar and Malbar Hill of Greater Mumbai, a 12.24 km long tunnel between Maroshi and Ruparel College is being excavated by TBM. The tunnel is divided into three sections, i.e. Maroshi–Vakola (5.834 km long), Vakola–Mahim (4.549 km long) and Mahim–Ruparel College (1.859 km long) (Fig. 1). The longest tunnel between Maroshi and Vakola has been completed. A vent hole of 30 cm diameter at Chainage 3230 m at Maroshi–Vakola section was drilled for releasing pressure. For constructing tunnels from Maroshi to the vent hole and from Vakola to the vent hole, vertical shafts were constructed at either end. The inlet shafts of 82.0 m and 68.0 m in depth

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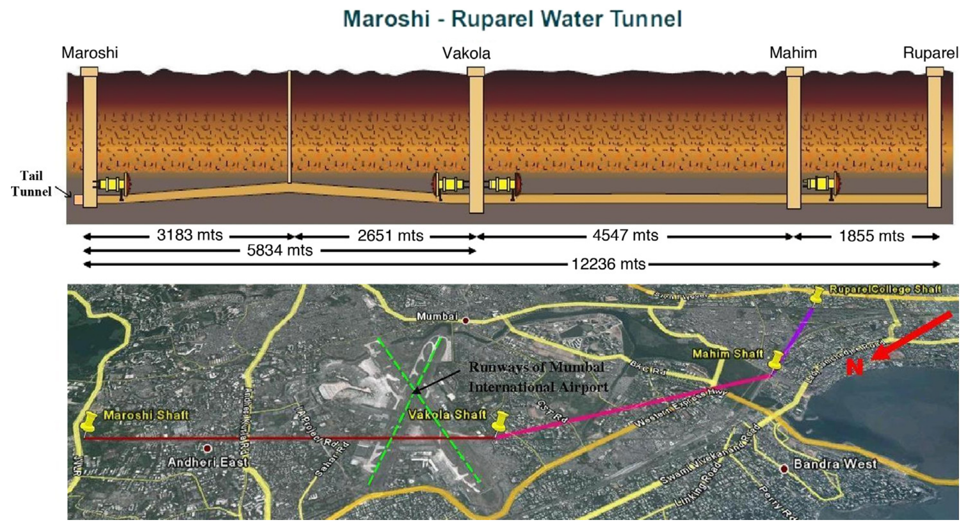

Fig. 1. Longitudinal section and plan of tunnel from Maroshi to Ruparel College.

from ground level, 9.0 m in diameter, were constructed at Maroshi and Vakola respectively to lower the TBMs parts. 5.4 m D-shaped assembly tunnels of 90.0 m and 60.0 m length were constructed for assembly of TBMs. On the opposite side along the tunnel axis, two 50 m long tail tunnels were also excavated to facilitate muck car movement while unloading. Vertical shafts, assembly tunnels and tail tunnels were excavated by conventional drill-and-blast method.

The invert level of tunnels at Maroshi and Vakola shafts is −35.50 m below the mean sea level (m.s.l.) while at the vent hole it is −30.63 m below m.s.l. The excavated diameter of a tunnel was 3.6 m with a designed gradient of 1:600 and its alignment is N30° E – S30° W (Table 1). The tunnel boring was extremely challenging between Maroshi and Vakola section due to heavy water seepage, varying rock strata condition and presence of various weak zones. In this paper, an attempt has been made to establish the relationship between various litho-units, stability of tunnel and TBM performance during the construction of these tunnels. Relationships between rock mass properties, TBM specifications and the corresponding TBM performances have also been established. The rock mass conditions were assessed by precise judgment using forward probing and "3D" geological logging of tunnel walls. Studies indicate that in Deccan traps, variations in rock types, flow contacts, rock strength, and volumetric joint amount with presence of weak zones have predominantly affected the penetration rate and stability of tunnels (Jain et al., 2011).

The rock mass has the characteristics of both the intact rock and the discontinuities, therefore the existing discontinuity conditions certainly affect the rock breakage process. It has been well recognized that joints or fractures have an important effect on the TBM performance (Howarth, 1981; Bruland, 1998; Cheema, 1999; Gong and Zhao, 2009). The discontinuities can facilitate rock breakage, because cracks induced by TBM cutters easily develop with the existing discontinuities. On the basis of a large number of case studies, Bruland (1998) concluded that with the decrease of joint spacing, the TBM penetration increases distinctly.

The influence of joint orientation on TBM penetration rate was widely observed in the tunneling projects (Gong and Zhao, 2009). Aeberli and Wanner (1978) observed that the advance rate of TBM increases with the increase of the angle between TBM axis and the planes of schistosity in a homogeneous schistose phyllite. Similar phenomena were also observed by Thuro and Plinninger (2003) in phyllite and phyllitecarbonate-schist interbedding. Bruland (1998) summarized the effects of joint orientation of different classes and made similar observation. The penetration rate increases with increasing angle between tunnel axis and joint plane as the angle is less than 60°, and then decreases with increasing angle. However, the maximum penetration rate was recorded when the angle was equal to 60°. Bruland (1998) also noted that with the increase of joint spacing, the effect of joint orientation on TBM penetration decreases. Each joint set may have different effects on the TBM penetration rate. The higher the joint density or frequency is, the larger the effect of the joint set on the TBM penetration rate is (Gong and Zhao, 2009).

2. Geology of the study area

Geologically, the entire Mumbai area is occupied by the Deccan basaltic flow and the associated pyroclastic and plutonic rocks of Upper Cretaceous to Palaeogene age classified as Sahyadri Group (Sethna, 1999). Deccan basalt of Mumbai Island is considered to be the youngest basalt of Eocene age (Subbarao, 1988). Overall, the geology around Mumbai indicates presence of ultrabasic, basic and acid differentions with intertrappean beds, agglomerates and tuffs. The ultrabasic differentiates are of limited occurrence. Acid rocks include quartz trachyte. The agglomerate and tuff include reworked materials as indicated by the current bedding as well as graded bedding. The lava pile of Mumbai is intruded by columnar jointed, medium grained doleritic dykes. The rock types encountered during tunneling are fine compacted basalt, porphyritic basalt, amygdaloidal basalt and pyroclastic rocks, namely tuff and tuff breccia with layers of red boles and intertrappean beds consisting of different types of shales. The thickness, presence and structural characteristic of fine compacted basalt, porphyritic basalt, and amygdaloidal basalt vary in different flows, depending on properties of magma, cooling history and geological conditions at the time of formation, which make these rock types suitable or unsuitable for engineering structures. Vesicles and amygdales increase toward the top of a flow unit which in turn merges into the bole at some places. The red bole is overlain by the massive strata of the next younger flow unit. Vesicular basalt with empty gas cavities and amygdaloidal basalt with gas cavities filled with secondary minerals like zeolites, carbonate minerals and secondary silica, i.e. agate, etc., do not have a regular pattern of jointing and are massive, while compacted basalt with no gas cavities is usually jointed.

Table 1
Salient features of Maroshi–vent hole and Vakola–vent hole tunnels.

Tunnels	Tunnel boring length (m)	Shape	Excavated diameter (bore section) (m)	Finished diameter (m)	Excavation quantity (m^3/m)	Volume (total excavation) (m^3)	Lining (reinforced cement concrete, RCC)-grade and thickness	Concrete quantity (m^3/m)
Maroshi–vent hole	3086.34	Circular	3.6	3.0	10.18	31,419	Total lined: M-20 and 300 mm	3.11
Vakola–vent hole	2590.4	Circular	3.6	3.0	10.18	26,370	Total lined: M-20 and 300 mm	3.11

Tunnels	Boring start date	Boring completion date	Tunnel boring duration (month)	Monthly average tunnel boring progress (m)	Maximum progress per month (m/month)	Daily average tunnel boring progress (m/d)	Maximum boring progress in one day (m/d)
Maroshi–vent hole	27 Dec. 2008	26 Sep. 2009	9	339.16	542.6	13.57	29.5
Vakola–vent hole	7 Nov. 2008	10 Aug. 2009	9	281.57	474.4	11.26	39.9

The lava flows show various types of structures such as joints, fractures, vesicles, veins, breccias clasts, mafic-dykes and amygdule with different shapes like circular, elliptical and irregular boundary. Due to the emplacement of the traps upon the eroded surfaces of the earlier rock strata, minor undulations in the flow were also observed. The general flows contact dip varies between 30° and 45° in N020°–N040° and N200°–N220° directions. Some flow contacts were open, filled with weathered, altered or soft materials while some were tight and commonly coalescent. Open flow contacts provide passage for water and weathered materials. Weathered or soft materials are generally deposited during the time internal between two flows. The angle between the tunnel axis and the flow contact was 80° and penetration rate was less at flow contact. The advance rate was low in case of open flow contact zones while it was high in tight flow contact zones.

The sequences of flows are different in different chainages of tunnel indicating they do not have regular structure like ideal sedimentary rocks. In sedimentary rocks, beds having plane surfaces tops and bottoms, constant dip, uniform thickness and wide lateral extent, such a disparity in sequences could validly be interpreted as a fault. It has now been well established that Deccan trap basalt flows do not have such regular structure, and have limited the lateral extent and stretch out over short distances. There is variation in thicknesses, i.e. flows usually have different thickness in different parts. Its tops and bottoms are not regular plane surfaces with constant dip but irregular surfaces. As a result, it is almost invariable that flow sequence in boreholes, which were drilled during the investigation does not normally match. This disparity however does not indicate faulting as it would be in case of beds with regular structural behavior. Hence, the possibility of the occurrence of a fault between boreholes need not be apprehended merely because flow sequence in boreholes does not match, as this disparity is the outcome of the structural irregularity of the basalt flows.

Traps show two or more sets of vertical joints. Horizontal joints are parallel to the top or bottom surfaces. Two sets of columnar joints were observed in thicker flows. Fractures were identified and they were generally parallel to the prominent joint directions. Conchoidal fracturing of rock mass was a common feature. Generally, amygdaloidal basalt and tuff breccia were massive while in porphyritic basalt the spacing of joint sets was more than 2 m and in fine grained jointed compacted basalt it varied from 10 cm to 30 cm. Generally, TBM penetration rate was greater in fine compacted basalt than that in the porphyritic basalt. Veins are extension fracture that was filled with mineral deposits of quartz, calcite and zeolites of different dimensions. They were generally sheet like or tabular or regular in shape. Veins have major influences on cavability and fragmentation and may be weaker or stronger than the wall rock. In the tunnels, generally, calcite and zeolite veins were mapped. About 32 cm to 3.5 m thick mafic dykes were mapped in the Vakola shaft area. The dyke exhibits prominent columnar joints, which were formed due to differential volume changes in cooling and contracting magma. No curviplanar (fold) structure was observed during the geological "3D" logging of the tunnel wall.

The mineralogical content of basaltic rocks was analyzed for each rock type. Major mineral composition of fine grained basalt and porphyritic basalt constitutes plagioclase (40–45%), pyroxene (15–20%), glass (10–15%), iron oxide (8–10%), and secondary calcite (7–10%), and groundmass was composed of plagioclase, pyroxene and glass. The mineral contents of the amygdaloidal basalt and tuff breccia are plagioclase (35%), devitrified glass (30%), pyroxene (20%), and oxide phase (15%), and groundmass was composed of glass, chlorite, calcite and zeolite. Cutter abrasion in basalts and breccia was less due to less quartz and low silica percentage. Basalt generally has a composition of SiO_2 (45–55%), total alkalis (2–6%), TiO_2 (0.5–2%), FeO (5–14%) and Al_2O_3 (14% or more). The content of CaO is commonly about 10% and that of MgO is usually in the range of 5–12%.

3. TBM specifications

WIRTH TB-II-320H and TB-II-360H TBMs were used for the excavation of Maroshi–vent hole and Vakola–vent hole tunnel sections respectively. These are refurbished full face hard rock TBMs and refurbishment was carried out under supervision of equipment manufacturer. TBMs were previously used in earlier projects with similar bore diameter. TB-II-320H TBM has done 4.5 km boring at previous project and was idle at workshop for 3 years. TB-II-360H TBM has done 7.5 km boring at earlier project and was also lying at workshop for 3 years before used at this project site. TBMs specifications collected from the documents provided by the manufacturer are given in Table 2. The operating parameters including thrust force, torque and rotation per minute (RPM) of the machine are important for understanding the effect of geological conditions on the machine performance and for penetration rate measurement.

4. Physico-mechanical properties of rocks

The rock strength is directly related to the performance of TBM. Uniaxial compressive strength (UCS) and Brazilian tensile strength tests were performed in accordance with the procedure recommended by ISRM (Brown, 1981). These are the parameters to evaluate the rock mass boreability. Laboratory rock strength test results of core samples are given in Table 3.

Table 2
Principal specifications of TBMs employed in Maroshi–Vakola sections.

Tunnel sections	TBM model	Type	Input supply (kV)	Cutter head diameter (m)	Cutter numbers	Cutter disk diameter (mm)	Cutter spacing (mm)	No. of buckets
Maroshi–vent hole	WIRTH TB-II-320H	Hard rock, open type	11	3.6	31 (center cutters-6; face cutters-17; pregauge cutters-5; gauge cutters-3)	432	62	5
Vakola–vent hole	WIRTH TB-II-360H	Hard rock, open type	6.6	3.6	31 (center cutters-6; face cutters-17; pregauge cutters-5; gauge cutters-3)	432	62	5

Tunnel sections	No. of scrapers	Cutter head speed (rpm)	Cutter head torque (maximum) (bar)	Cutter head thrust (maximum) (bar)	Stroke (mm)	Muck handling capacity (m/h)	Estimated weight (t)
Maroshi–vent hole	2 × 5 sets = 10 scraper plates	0–14	225	220	1100	5	107
Vakola–vent hole	3 × 5 sets = 15 scraper plates	0–12	185	220	1100	5	107

Table 3
Laboratory rock strength results of core samples.

Rock type	RQD (%)	UCS (MPa)		Point load test (Is50, MPa)		Brazilian tensile strength (MPa)		Brittleness index	
		Range	Average	Range	Average	Range	Average	Range	Average
Fine compact basalt	30–90	33.35–115.90	78.20	–	–	2.57–13.31	9.46	8.26–15.12	8.26
Porphyritic basalt	90–100	115.87–143.33	130.60	–	–	8.76–15.26	13.28	8.31–15.78	9.83
Amygdaloidal basalt	95–100	54.10–65.70	59.80	–	–	–	–	–	–
Tuff breccia	95–100	26.43–50.20	34.46	1.33–3.44	2.38	1.5–3.2	2.35	4.60–11.5	14.48
Tuff	95–100	15.68–24.28	18.40	0.5–1.25	0.87	1.6–3.8	2.7	4.12–15.17	6.8
Flow contact zone	40–60	12.40–31.87	14.60	–	–	–	–	–	–
Intertrappeans (shale)	45–75	28.30–34.35	31.32	–	–	4.90–6.10	5.50	4.63–7.10	5.70

UCS is one of the most important rock strength parameters for rock mass condition evaluation and is commonly used to assess rock mass boreability. It has been proved that when the rolling cutter indents the rock, the stress exerted must be higher than the rock strength. The rock strength affects the rock behavior under compression. During the excavation of tunnels, the penetration rate is distributed in a large range from about 2 mm/rev to more than 12 mm/rev due to the effect of UCS. A loading rate of 200 N/s was adopted. Some models for predicting penetration rate show that the penetration rate is directly associated with rock UCS (Graham, 1976; Farmer and Glossop, 1980; Rostami and Ozdemir, 1993; O'Rourke et al., 1994). The penetration rate decreases as the UCS increases, for example, the penetration rate is about 6.3 m/h at 25 MPa of the rock UCS, and 1.9 m/h at 105 MPa of UCS. Generally, the penetration rate and UCS show a linear relationship.

Brittleness index is another parameter to understand the performance of TBM. The rock brittleness index is defined as the ratio of rock compressive strength to tensile strength. The effect of rock brittleness index on TBM penetration process was studied by Gong and Zhao (2007). The result shows that with increasing rock brittleness index, the cutter indentation process gets easier. Cutter indentation means the rolling cutter intrudes into the rock, and then generates small and large fragments as well as internal cracks. Generally, the penetration rate increases with increasing rock brittleness index but there is not a linear relation due to the effects of other rock mass parameters like jointing pattern in the rock mass.

5. Assessment of rock mass

A detailed engineering geological investigation was carried out in the tunnels to acquire the geological and/or geotechnical details, i.e. rock description, rock discontinuity orientation and description, groundwater condition, etc., for rock mass quality assessment. Various rock types encountered during tunneling are illustrated in Figs. 2 and 3. Some researchers have correlated TBM performance to rock mass classification systems using RSR (rock structure rating), RMR (rock mass rating), Q-system and IMS (integrated mass system) (Innaurato et al., 1991; McFeat-Smith and Broomfield, 1997; Sundaram et al., 1998; Sapigni et al., 2002; Hamidi et al., 2010). In this project, the rock mass was characterized using RMR classifications (Bieniawski, 1989). RMR values were calculated after geological mapping and measurements of discontinuity data. Rock mass classification for different litho-units of tunnel sections are given in Figs. 4 and 5. In the Maroshi–vent hole section, 1160 m length fell in good rock mass category, while 1098.5 m, 453 m and 375 m lengths fell in fair, very good and poor rock mass categories respectively. In the Vakola–vent hole section, 1510.5 m length was of good rock mass category, while 998 m, 60 m and 22 m lengths were of fair, very good and poor rock mass categories respectively. Generally, the rock conditions were fair to good except at or near the flow contacts where poor to fair rock mass conditions were observed. For medium quality rock masses (RMR of 40–75), the maximum TBM performances (penetration rate and advance rate) were achieved while lower penetration was for poor and very good rock masses.

Based on petrographic, textural and structural characteristics, their engineering properties and RMR, the tunneling rock media were classified into three main categories, i.e. basalts (amygdaloidal basalt/compacted basalt/porphyritic basalt), pyroclastics (tuff/tuff breccia) and intertrappeans (shaly material), to assess their behaviors and the performances of TBM. The different diagnostic engineering properties of amygdaloidal, compacted and porphyritic basalts lie in the degree and pattern of jointing. In this area, commonly basalts were transitional between these three types. About 62.25%, i.e. 3534 m length, of the tunnel was excavated in basalts (compacted basalt-3341 m, porphyritic basalt-193 m).

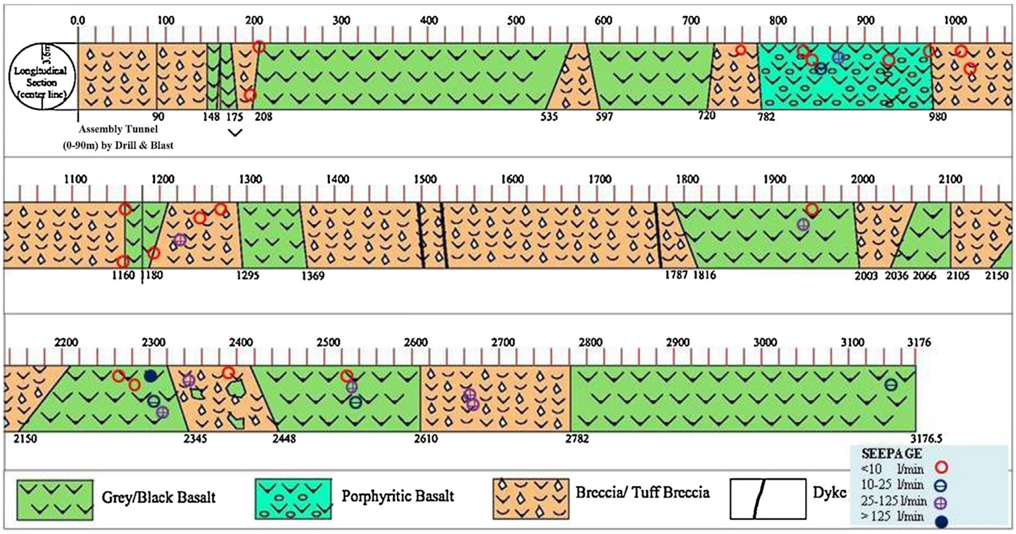

Fig. 2. Lithological mapping along tunnel from Maroshi to vent hole (Ch. 90–3180 m).

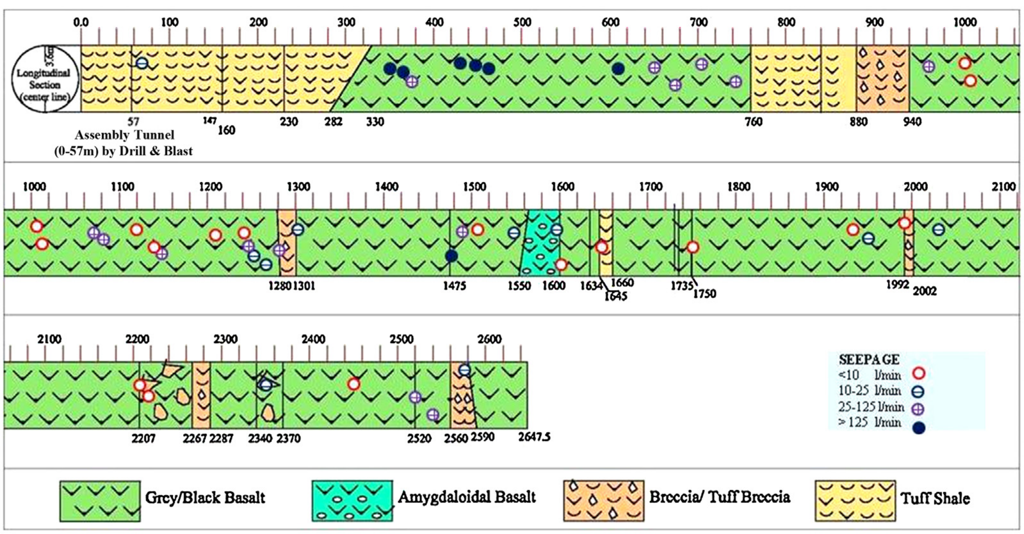

Fig. 3. Lithological mapping along tunnel from Vakola to vent hole (Ch. 57–2645 m).

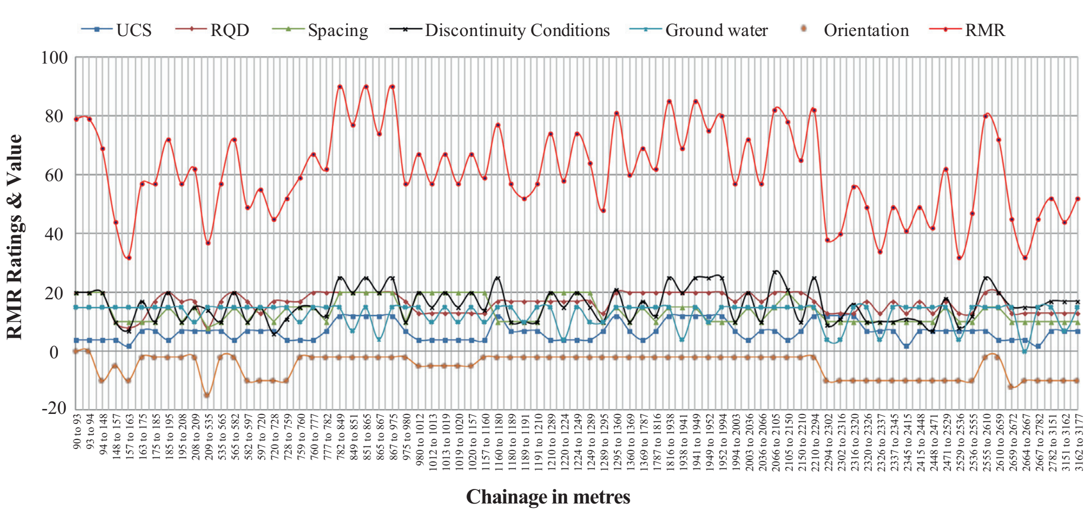

Fig. 4. RMR rating at different chainages along Marosh–vent hole tunnel.

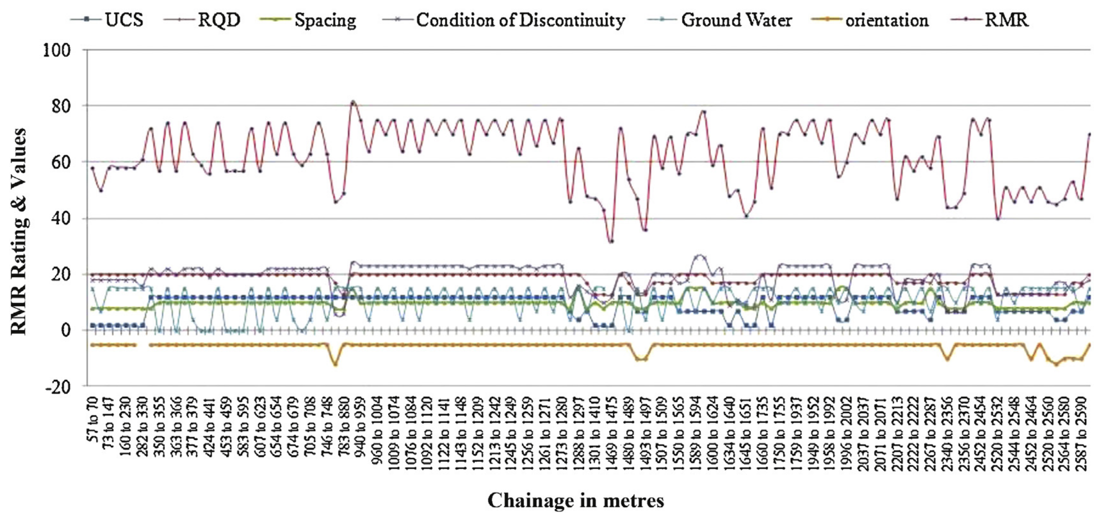

Fig. 5. RMR rating at different chainages along Vakola–vent hole tunnel.

The fine compacted basalt showed a higher degree of jointing. Joints provided access to water, thus, the compacted basalt is water bearing. In addition, the fragmentation brought by jointing made the compacted basalt unstable during excavation especially when joints were closely spaced. Rock falls were reported at tunnels crown and sides, and rock bolts were implemented to prevent them. Porphyritic basalt was widely jointed and provided stable ground condition for TBM tunneling. Even in a single basaltic flow, there were some portions with close jointing and others were widely jointed. Due to its structural and textural variation, the UCS of the intact basalt varied from 33.35 MPa to 143.33 MPa and the rock mass fell in fair to good rock mass categories.

A total of 35.0 m, i.e. less than 1% of the tunnel length, was excavated in the amygdaloidal basalt. Amygdaloidal basalt was free of joints and quite impervious when fresh. Due to the absence of divisional planes, the rock mass was stable in all kinds of cuts and excavations. Therefore, the amygdaloidal basalt was considered to be a very suitable medium for tunneling, and all underground works in it can be expected to be trouble free. The UCS of the intact amygdaloidal basalt varied from 54.10 MPa to 65.70 MPa and the rock mass fell in good to very good rock mass categories.

A total of 1617 m of tunnel length (about 28.48% of the total length) (tuff breccia-1257 m, tuff-360 m) was excavated in tuff breccias and tuff. Tuff breccia and tuff were generally less jointed or unjointed. UCS of the fresh tuff breccia was up to 50.20 MPa, while the UCS of tuff was up to 24.28 MPa. Tuff breccia was a suitable medium for the tunneling by TBM due to its impermeability, stability and high penetration rate, but excavation in tuff with TBM was not very much favorable because it led to cutter jam problem and affected the production cycle due to sticky property of muck, thus taking longer discharge time at every transfer point of mucking system.

There were sedimentary beds known as intertrappean beds associated with the Deccan trap lava flows. They were predominantly made up of argillaceous and carbonaceous shales. The fine grained variety of shale had good compressive strength, i.e. up to 34.35 MPa, but it was thinly bedded. Rock fall occurred due to its softening when contacting water. Approximately 90 m of tunnel length was excavated in the intertrappean shales, which was about 2% of total length. Due to its swelling behavior, the entire length was supported by steel ribs. The percentage distribution of different rock types mapped in tunnel sections is given in Table 4.

6. TBM performances

Prediction of TBM performances requires estimation of both penetration rate and advance rate. Penetration rate is defined as excavating the distance divided by the operating time during a continuous excavation phase, while advance rate is the actual excavating and supporting distance divided by the total time and it also includes downtime for TBM maintenance, machine breakdown and tunnel failure (Alber, 1996). The performance of TBM depends on the intact rock and rock mass properties as well as on the TBM specifications and TBM operation parameters. TBMs utilization achieved in these tunnels varied according to the proportion of different litho-units, capacity of muck disposal system, delays for support installation, management of water inflows and a variety of electrical/mechanical backup and service delays. Boring time cycle details from Maroshi to vent hole and Vakola to vent hole with respect to international norms are given in Fig. 6 (Robbins, 1990). TBMs deployed at those two sections were of different input capacities and because of this, in similar geological conditions the performance characteristics were different for both stretches as given in Table 5. Because these were the refurbished TBMs, the average advance rate for both tunnels was 1.86 m/h and 1.34 m/h, respectively, and was low due to breakdown and contractors downtime. Penetration rate was higher in case of tuff breccia because of its medium strength (Brown, 1981) and fell in good rock mass category, which was considered as a suitable medium for tunneling. Penetration rate was low in case of porphyritic basalt because of its very high strength and fell in very good rock mass category. In those chainages, where breccia was mapped, seepage and unstable ground condition were also insignificant. The large number of flow contacts encountered were unfavorable for TBM operations, resulting in a low advance rate. In the mixed face ground (flow contacts), TBMs could not operate efficiently due to cutter head vibration and working face instability. Graphical view of penetration rate in various litho-units of Maroshi–vent hole and Vakola–vent hole sections are given in Figs. 7 and 8, respectively.

Cutter abrasion is of obviously economic importance. Overall average cutter consumption for the Maroshi–Vakola tunnel section was 54.58 m per cutter change or 556 m^3 per cutter change. The average cutter consumption for Maroshi–vent hole stretch was 73.48 m/cutter change or 748 m^3 per cutter change, and 41 m per cutter change or 425 m^3 per cutter change for Vakola–vent hole stretch. The highest cutter wear, i.e. 20 m per cutter change, was

Table 4
Percentage distribution of different rock types in the tunnel sections.

Rock types	Maroshi–vent hole section		Vakola-vent hole section	
	Total length (m)	Percentage of length (%)	Total length (m)	Percentage of length (%)
Fine compact basalt	1439.5	46.64	1901.5	73.40
Porphyritic basalt	193.0	6.25	–	–
Amygdaloidal basalt	–	–	35.0	1.35
Tuff breccia	1131.0	36.64	126.0	4.9
Tuff	–	–	360.0	13.9
Flow contact zone	323.0	10.47	78.0	3
Intertrappeans	–	–	90.0	3.47

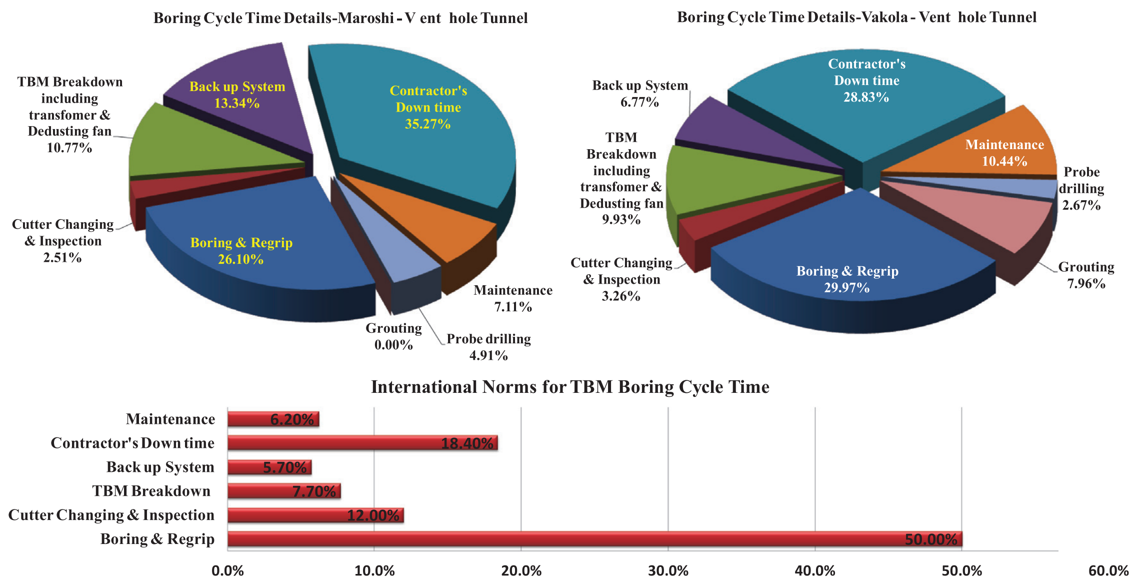

Fig. 6. Boring time cycle details with respect to international norms – Maroshi to vent hole and Vakola to vent hole.

Table 5
Summary of TBM performance characteristics for different litho-units of tunnel sections.

Tunnel sections	Rock types	UCS (MPa)	Turning movement (bar)			Thrust (bar)			Penetration rate (m/h)		
			Min.	Max.	Ave.	Min.	Max.	Ave.	Min.	Max.	Ave.
Maroshi–vent hole	Compacted basalt	33–116	85	130	115	90	139	113	1.49	3.66	2.31
	Porphyritic basalt	115–143	90	140	123	80	150	139	0.66	3.74	1.49
	Tuff breccia	26–50	91	125	108	65	100	80	1.38	4.11	3.11
	Flow contact zone	–	85	125	110	69	120	95	2.18	3.28	2.66
	Total length		85	130	109	65	139	96	1.38	4.11	2.66
Vakola–vent hole	Compacted basalt	33–116	74	142	110	53	115	90	1.61	2.55	2.0
	Amygdaloidal basalt	54–66	70	130	90	50	110	75	1.47	2.91	2.07
	Tuff breccia	26–50	55	115	78	40	106	60	1.71	2.88	2.3
	Tuff	16–24	62	63	61	35	56	45	1.79	1.89	1.8
	Flow contact zone	65–140	70	125	98	56	115	87	1.53	2.01	1.8
	Intertrappeans	30–65	30	70	53	35	61	48	2.36	2.85	2.6
	Total length		30	142	95	35	115	78	1.53	2.88	2.1

Table 6
Summary of cutter abrasion in Maroshi–vent hole and Vakola–vent hole sections.

Description	Number along Maroshi–vent hole		Number along Vakola–vent hole		Total number along Maroshi–Vakola
	Fitted	Changed	Fitted	Changed	
Center cutter	6	No change	6	4	16
General cutter	17	No change	17	15	49
Pregauge cutter	5	4	5	6	20
Gauge cutter	3	7	3	6	19
Total cutter	31 + 11 = 42		31 + 31 = 62		104
Length of boring/cutter	73.48 m/cutter		41 m/cutter		54.58 m/cutter
Excavation/cutter	748 m^3/cutter		425 m^3/cutter		556 m^3/cutter

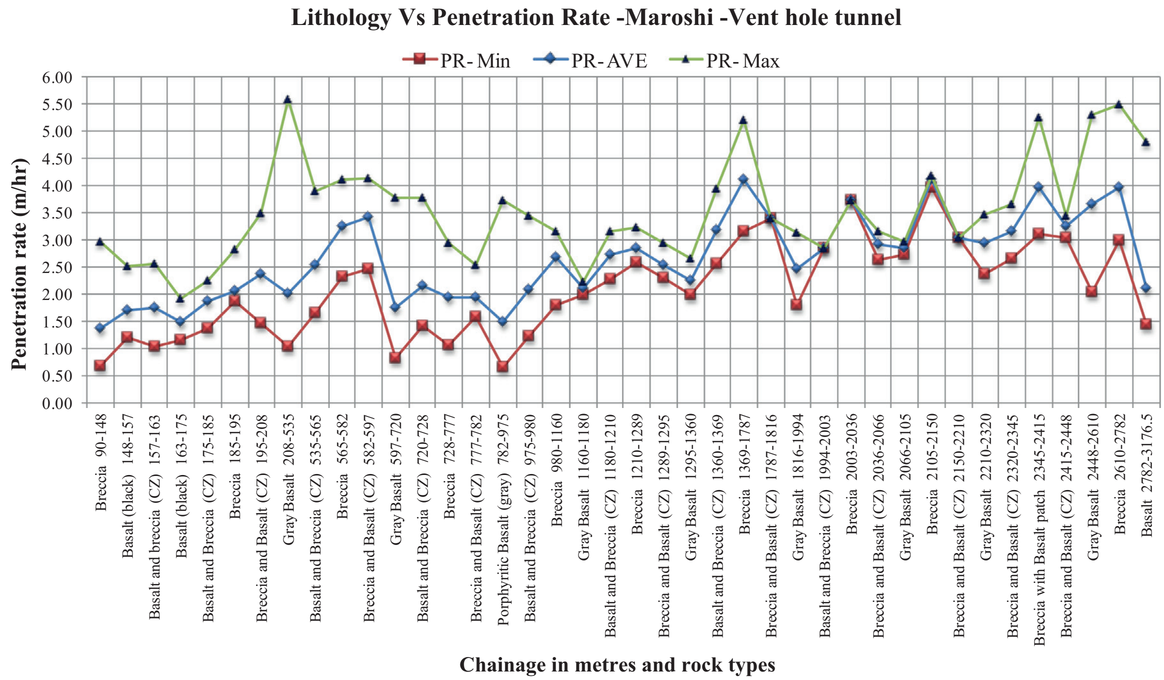

Fig. 7. Lithology vs. penetration rate along different chainages of Maroshi–vent hole tunnel.

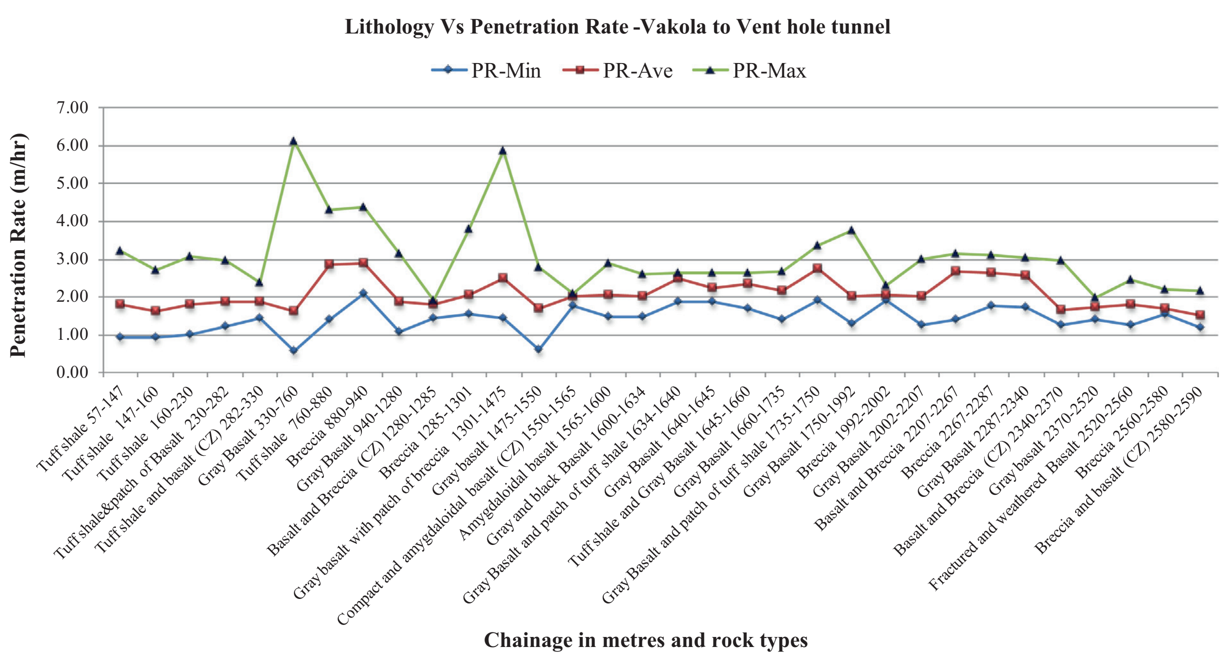

Fig. 8. Lithology vs. penetration rate along different chainages of Vakola–vent hole tunnel.

recorded from chainage 57 m to 330 m in Vakola–vent hole tunnel section. At this stretch, tuff with patches of carbonaceous shale and basalts was encountered and highest cutter wear was induced by blocking of cutters rotation due to sticky muck. Cutters abrasion in basalts and breccia was low due to less quartz and low silica percentage, compared to granitic and quartzitic rocks where very high cutter consumption was reported (Goel, 2008; Gong and Zhao, 2009). Basalts generally have a composition of 45–55% SiO_2. The position of the cutters on cutter head is shown in Fig. 9 and the profile created after cutting is illustrated in Fig. 10. Types of abrasion and corresponding details of cutters for TBMs used in Maroshi–vent hole and Vakola–vent hole tunnels are given in Table 6.

A gripper TBM (open TBM) can achieve higher advance rates than a shield TBM only, if a small amount of ground support is required (Farrokh et al., 2011). TBM performance can be improved by increasing the penetration rate and decreasing the time for ground support installation. Open-type machines can be equipped with support installation equipments like ring erectors, anchor drills and wire mesh erectors, etc., to enable the mechanically assisted installation of rock support measures behind cutter head. Penetration rate improvement is limited by the ground material

Fig. 9. Cutters position on cutter head of 3.6 m diameter.

Fig. 10. View of excavated tunnel face using TBM (Vakola–vent hole tunnel section).

and equipment capacity, such as the maximum permissible cutter loads and the installed torque and thrust. In WIRTH TB-II-360H TBM model, the maximum pressure of thrust cylinders was 220 bar, and cutter head RPM and rotation pressure were 12 and 185 bar respectively. In WIRTH TB-II-320H TBM model, the maximum pressure of thrust cylinders was 220 bar, and cutter head RPM and rotation pressure were 14 and 225 bar respectively. Especially in case of open-type TBM operation, machine utilization can be improved and thus TBM advance rate can be increased by reducing the time for ground support. The other components affecting the performance of the TBM are maintenance, utility installation, transportation, surveying, ventilation, etc., but their contribution to overall downtime is generally small (Martin, 1988). In this case, generally, ground support installation was carried out during TBM maintenance and other downtimes. Details of month-wise and overall progress/utilization of TBMs are shown in Tables 7 and 8. Average utilization coefficient (U = advance rate/penetration rate) for the Maroshi–Vakola tunnel was 76%, which was much higher

Table 7
Details of overall and month-wise TBM progress/utilization in Maroshi–vent hole tunnel.

Description	Month	Boring length (m)	Boring time (h)	Ave. resetting time (min)	Total resetting time (h)	Number of stroke	Avg. stroke length (m)	Avg. penetration rate (m/h)	Avg. advance rate (m/h)
Actual progress/utilization (from January to September in 2009)	January	116.5	75.08	6.57	22.67	207	0.56	1.55	1.19
	February	284.9	151.42	8.54	44.83	315	0.9	1.88	1.45
	March	355.6	207.42	8.71	53.58	369	0.96	1.71	1.36
	April	421.5	179.83	7.41	49	397	1.06	2.34	1.84
	May	491.9	145.33	5.68	44	465	1.06	3.38	2.6
	June	542.6	189.50	7.22	61.75	513	1.06	2.86	2.16
	July	410.5	126.67	6.31	40.083	381	1.08	3.24	2.46
	August	179.5	68.33	5.48	15.33	168	1.07	2.63	2.15
	September	281.8	155.17	5.45	24.25	267	1.06	1.82	1.57
Total		3084.8	1298.75	6.82	355.50	3082	0.98	2.38	1.86

Table 8
Details of overall and month-wise TBM progress/utilization in Vakola–vent hole tunnel.

Description	Time	Boring length (m)	Boring time (h)	Ave. resetting time (min)	Total resetting time (h)	Number of stroke	Avg. stroke length (m)	Avg. penetration rate (m/h)	Avg. advance rate (m/h)
Actual progress/utilization (from November 2008 to July 2009)	Nov. 2008	52.9	33.34	4.03	13.24	197	0.27	1.59	1.14
	Dec. 2008	261.6	159.58	5.90	41.92	426	0.61	1.64	1.30
	Jan. 2009	271.3	193.75	11.22	59.08	316	0.86	1.40	1.07
	Feb. 2009	474.4	228.17	10.10	77.58	461	1.03	2.08	1.55
	Mar. 2009	381.0	189.17	10.74	67.83	379	1.01	2.01	1.48
	Apr. 2009	352.1	174.75	10.00	62	372	0.95	2.01	1.49
	May 2009	412.8	199.00	10.06	70.75	422	0.98	2.07	1.53
	June 2009	257.7	138.67	12.61	55.92	266	0.97	1.86	1.32
	July 2009	113.7	69.67	13.17	26.33	120	0.95	1.63	1.18
Total		2577.5	1386.09	9.76	474.66	2959	0.85	1.81	1.34

because of less ground support requirements, i.e. 10.25% of tunnel length only and less cutter consumption (556 m^3 per cutter).

7. Support system

For the support, economic reinforcement system was selected in order to effectively cope with the stress change of the site rock included by excavation and to ensure the safety. The maximum overburden cover above the crown of the tunnel varied from 65 m to 80 m which was not very high. The reinforcement pattern used for each rock mass class was based on the reinforcement standard of Barton (2000) which was modified from Q-system standard for Norwegian Method of Tunneling (NMT) (Grimstad and Barton, 1993). RMR values were assessed and then converted to Q according to the correlation between RMR and Q given by Bieniawski (1989):

$$Q = e^{(RMR-44)/9} \quad (1)$$

Since TBM tunnels have a multiple of purposes, a range of safety requirements exists as in the case of drill-and-blast tunnels. The excavation support ratio (ESR) concept used in the Q-system for modifying the effective tunnel dimension, when selecting support, was used for support design in TBM tunnel. The ESR was applied to 1.5 according to the ESR values that Barton (2000) suggested for TBM support/liner selection. The equivalent dimension (D_e) was applied by dividing the span of the tunnel by the fore-mentioned ESR and it was 2.4 m.

The rock bolt length (L) can be estimated from the excavation width (B) and the ESR (Barton et al., 1974):

$$L = 2 + \frac{0.15B}{ESR} \quad (2)$$

By applying the above formula, the length of rock bolt was calculated to be 2.36 m. The value of Barton TBM Q-system chart proposed is 2.2–2.6 m. The proposed value of basic design was 2.0–2.5 m, accordingly rock bolt was applied according to the site conditions.

Tunnel support measures were applied at several specific locations from work platforms behind the cutter head. Tunnel support and rock reinforcement methods, such as rock bolts, shotcrete, wire mesh, steel rib and steel liner panel were used in TBM tunnels. The rocks met within the tunnels were generally self-supported. Rock bolt is the fastest ground support method in the open-type TBM tunnel. Rock bolts of 25 mm diameter, with corresponding yield strength of approximately 200 kN, and steel quality of 500 N/mm^2 was used.

The shotcrete of 50–100 mm thickness was applied considering what was proposed by Q-system. Shotcrete was normally applied in the backup area; however, under difficult conditions, 100 mm thick shotcrete with wire mesh was applied immediately behind cutter head. Steel rib with 3.15 mm MS lagging plates was also installed in the problematic areas. Steel liner panels were used in very poor rock masses where rock bearing capacity was very low.

The first support was installed at a distance ranging from 4 m to 6 m from the working face, i.e. immediately behind the cutter head shield while other supports were generally installed after passage of the main body of the TBM. From Maroshi to vent hole, total 399.88 m out of 3086.34 m length of tunnel and from Vakola to vent hole, total 180.40 m out of 2590.40 m length of tunnel were supported and various types of supports are summarized in Table 9. Finally, the tunnels were lined by M-20 grade 300 mm thick roller compacted concrete (RCC) lining, which was completed in 16 months. Perforated drainage pipes of 2 in. diameter, attached to wire mesh were provided.

Table 9
Summary of supported length of Maroshi–Vakola tunnel.

Support type	Rib support (m)	Steel liner panels (m)	Spot rock bolts (m)	Rock bolt with wire mesh (m)	50/100 mm thick shotcrete with wire mesh and spot rock bolting (m)	Total supporting length (m)
Maroshi–vent hole	84.33	14.10	95.00	91.90	114.55	399.88
Vakola–vent hole	66.00	5.00	10.00	0.0	99.40	180.40

Due to the vicinity of this project to the Arabian Sea and its creeks, Powai Lake and upsteam Mithi River, high ingress of both salt and sweet water from the jointed basalts and flow contacts was measured. The minimum seepage recorded was 3 L/min while the maximum was 250 L/min. During monsoon, the tunnel seepage had increased to about 25,000 m^3/d and in average it was 7850 m^3 per day. Heavy ingress of water during boring was one of the reasons for reduction in advance rate because fine particles generated by boring were separated from muck and deposited in the invert area of cutter head due to the heavy ingress of water. Manual cleaning of this was time-consuming. To tackle the seepage areas, prior to final RCC lining, chemical (solution) grouting and cement grouting were done. Chemical grouting was done through 2 m deep and 32 mm diameter holes while cement grouting was done through 4–20 m length and 32 mm diameter holes. For cement grouting, ingredients used were portland cement (140 kg), fly ash (15 kg), water (70 L), pre-hydrated diluted gum (8 L) and super plasticizer (naphthalene based) (1.40 L). Polyurethane grout was used for solution grouting because it was injectable into very fine aperture also. 20,190 kg chemical and 6527 cement bags were used for chemical and cement grouting. During the probing, when water quantity exceeded 25 L/min, pre-excavation cement grouting was carried out to prevent seepage which also improved the rock mass quality and stabilized ahead the working face thus increasing the advance rate. Post grouting was done through sleeve pipes, provided between the drainage pipes.

To arrest the heavy seepage by chemical or cement grouting, boring activity was stopped because arrangements made for carrying grouting did not allow the movement of locomotives which were used to transport the detritus (muck) into mine cars.

8. Discussion and conclusions

The Deccan traps of the study area consist of a number of flows separated from each other at some places by inert-trap ash beds and ancient buried soils (red bole) and behave as a multiaquifer system. The rock types encountered during excavation were fine compacted basalt, porphyritic basalt, amygdaloidal basalt, tuff breccia, tuff and intertrappeans shales. Amygdaloidal basalt, porphyritic basalt and tuff breccia which are impervious and generally massive. They were very suitable media for tunneling using TBM, whereas the compacted basalt at some places was proved troublesome because of its jointing nature. Amygdaloidal basalt, with gas cavities filled with secondary minerals was unjointed, impervious and TBM tunneling was trouble free. There was a wide variation in the pattern of jointing of compacted basalts. Some were closely jointed whereas others were broadly jointed and joints were generally tight. Over-break was recorded during TBM tunneling, especially when it was imperfectly interlocked. In the zone of compacted basalt, heavy seepage was recorded along many mutually intersected joint sets. Rock support system like closely spaced rock bolting, shotcrete with wire mesh and cement grouting was carried out in those locations. At few locations chemical grouting was also done. In fine to medium grained porphyritic basalt, joints were widely spaced and tight, and during TBM tunneling no over-break occurred. The average "penetration rate" in the fine-grained compacted basalt was 2.15 m/h which was more than those of the porphyritic basalt and amygdaloidal basalt, but the "advance rate" in porphyritic and amygdaloidal basalts was higher. Porphyritic and amygdaloidal basalts TBM tunnels were unsupported, that's why the "advance rate" was higher.

The suitability of excavation and stability in volcanic breccia and tuff depend on the nature of the matrix, in which the explosion fragments are embedded, and degree of consolidation. Volcanic breccia with lava matrix is usually suitable as it behaves like amygdaloidal basalt. Well cemented tuff breccia and tuff offer suitable media for TBM tunneling due to their impermeability, stability and high penetration rate. However, clay minerals available in the pyroclastics (tuff and tuff breccia) rocks make cutter jam problem as well as affect the production cycle due to sticky property of muck, taking longer discharge time at every transfer point of mucking system. At few chainages, softened and decomposed volcanic breccia was mapped, which was supported by shotcrete with wire mesh, spot rock bolting and rib.

Shales were unstable due to their inherent softness which was further aggravated by their closely spaced laminations. Shale itself was impervious, but along bedding planes water was present. Shale posed problems with respect to driving side support for the TBM during advancing, as shale softened and slacked when it was in contact with water. Whole stretch of the tunnel, where shale occurring was supported by steel rib.

Flow contact zones show break in the continuity of rock mass with different lithologies and/or engineering properties. Degree of suitability for tunneling at flow junctions depends on tightness, thickness and weathering state of filling materials. Tight and fused flow junctions were suitable for tunneling. Open flow junctions provide path for water inflow. Usually the rock mass in the vicinity of the contact zones was weathered and the interlocking of joints was weak, which posed problems on ground stability. It was very difficult for gripping of jacks and maintaining the alignment of TBM cutter heads in highly weathered and clay filled contacts zones. In the event of such type of soft ground when gripper pads, the tunnel invert level was difficult to maintain, with the result fluctuation in the tunnel invert, causing water ponds due to seepage of water in the tunnel. This fluctuation of tunnel invert also affected the main rail track and thus the train speed and train derailment also. Because of water ponds formation due to uneven tunnel invert when the locomotives passed through the water ponds, motors of locomotives mounted under the chassis of locomotive fell frequently which also contributed at large to low productivity in tunnel progress. Highly weathered and soft material filled flow contacts were supported by steel liner panels and steel rib whereas tight to slightly open, unweathered contact zones were supported by rock bolt and shotcrete with wire mesh.

An average penetration rate of 2.10 m/h and a maximum monthly progress of 542.6 m, ensuring tunneling safety, were achieved. The study provided better understanding of using TBM in other parts of Deccan traps region, and of various upcoming tunneling projects for hydropower, sewerage, water supply, irrigation and transportation, etc. Suitable geological and geotechnical conditions exist in Deccan traps for the underground construction, and for this reason underground space should be regarded as an important natural resource to be utilized wisely to reduce the population pressure on surface.

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References

Aeberli U, Wanner WJ. On the influence of discontinuities at the application of tunneling machines. In: Proceedings of the 3rd international congress IAEG; 1978. p. 7–14.

Alber M. Prediction of penetration, utilization for hard rock TBMs. In: Proceeding of the ISRM international conference of Eurock'96. Rotterdam: A.A. Balkema; 1996. p. 721–5.

Barton N. TBM tunneling in jointed and faulted rock. Rotterdam: A.A. Balkema; 2000.

Barton N, Lien R, Lunde J. Engineering classification of rock masses for the design of tunnel support. Rock Mechanics 1974;6(4):189–236.

Bieniawski ZT. Engineering rock mass classification. New York: John Willey & Sons; 1989.

Brown ET. Rock characterization testing and monitoring: ISRM suggested methods. Oxford and New York: Pergamon Press; 1981.

Bruland A. Hard rock tunnel boring. PhD Thesis. Trondheim: Norwegian University of Science and Technology; 1998.

Cheema S. Development of a rock mass boreability index for the performance of tunnel boring machines. PhD Thesis. Golden, USA: Colorado School of Mines; 1999.

Farmer IW, Glossop NH. Mechanics of disc cutter penetration. Tunnels and Tunnelling 1980;12(6):22–5.

Farrokh E, Rostami J, Laughton C. Analysis of unit supporting time and support installation time for open TBMs. Rock Mechanics and Rock Engineering 2011;44(4):431–45.

Goel RK. Evaluation of TBM performance in a Himalayan tunnel. In: Proceedings of world tunnel congress 2008—underground facilities for better environment and safety; 2008. p. 1522–32.

Gong QM, Zhao J. Influence of rock brittleness on TBM penetration rate in Singapore granite. Tunnelling and Underground Space Technology 2007;22(3):317–24.

Gong QM, Zhao J. Development of a rock mass characteristics model for TBM penetration rate prediction. International Journal of Rock Mechanics and Mining Sciences 2009;46(1):8–18.

Graham PC. Rock exploration for machine manufacturers. In: Bieniawski ZT, editor. Exploration for rock engineering. Johannesburg: A.A. Balkema; 1976. p. 173–80.

Grimstad E, Barton N. Updating of the Q-system for NMT. In: Proceedings of the international symposium on sprayed concrete—modern use of wet mix sprayed concrete for underground support. Oslo: Norwegian Concrete Association; 1993. p. 46–66.

Hamidi JK, Shahriar K, Rezai B, Rostami J. Performance prediction of hard rock TBM using Rock Mass Rating (RMR) system. Tunnelling and Underground Space Technology 2010;25(4):333–45.

Howarth DF. The effect of jointed and fissured rock on the performance of tunnel boring machines. In: Proceedings of ISRM international symposium on weak rock; 1981. p. 1069–74.

Innaurato N, Mancini R, Rondena E, Zaninetti A. Forcasting and effective TBM performances in a rapid excavation of a tunnel in Italy. In: Wittke W, editor. Proceedings of the 7th international congress on rock mechanics; 1991. p. 1009–14.

Jain P, Naithani AK, Singh TN. Application of tunnel boring machine for the construction of Maroshi–Ruparel College Tunnel–Mumbai, India. Journal of Engineering Geology 2011;37(1–4):151–9.

Martin D. TBM tunnelling in poor and very poor rock conditions. Tunnels and Tunnelling 1988;20(3):22–7.

McFeat-Smith I, Broomfield J. Mechanised tunneling for Asia: realising the benefits, avoiding the pitfalls, workshop manual. IMS Tunnel Consultancy Ltd; 1997.

O'Rourke JE, Spring JE, Coudray SV. Geotechnical parameters and tunnel boring machine performance at Goodwill Tunnel, California. In: Nelson PP, Laubach SE, editors. Proceedings of the 1st North American rock mechanics symposium. Rotterdam: A.A. Balkema; 1994.

Robbins RJ. Tunnel mechanics in hard rock. In: Civil engineering for underground rail transport. London: Butterworth; 1990. p. 365–8.

Rostami J, Ozdemir L. A new model for performance prediction of hard rock TBMs. In: Rapid excavation and tunneling conference proceedings; 1993. p. 793–809.

Sapigni M, Berti M, Bethaz E, Busillo A, Cardone G. TBM performance estimation using rock mass classifications. International Journal of Rock Mechanics and Mining Sciences 2002;39(6):771–88.

Sethna SF. Geology of Mumbai and surrounding areas and its position in the Deccan Volcanic Stratigraphy, India. Journal of the Geological Society of India 1999;53:359–65.

Subbarao KV. Deccan flood basalts. Bangalore: Geological Society of India; 1988.

Sundaram NM, Komoo I, Rafek AG. The influence of rock mass properties in the assessment of TBM performance. In: Proceedings of the 8th international IAEG congress. Rotterdam: A.A. Balkema; 1998. p. 3353–9.

Thuro K, Plinninger RJ. Hard rock tunnel boring, cutting, drilling and blasting: rock parameters for excavatability. In: ISRM 2003 – technology roadmap for rock mechanics. Johannesburg: South African Institute of Mining and Metallurgy; 2003. p. 1–7.