Application of Tunnel Boring Machine for the Construction of Maroshi – Ruparel College Tunnel - Mumbai, India

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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. The tunnel is excavated through four shafts located at Maroshi, Vakola, Mahim and Ruparel College. The rock types encountered during the excavation of shafts and tunnel are fine compact basalts, porphyritic basalts, amygdaloidal basalts, pyroclastic rocks with layers of red boles and intertrappean beds consisting of different type of shales. The aim of the study / investigation is to evaluate the engineering behaviour of deccan volcanics particularly with respect to TBM performance and stability of the underground structures in various ground conditions encountered during excavation of the 5.83 km long Maroshi- Vakola stretch of the tunnel in Western Maharashtra. The Maroshi - Vakola tunnel passes under the Mumbai Airport and crosses both the runways with a cover of around 70 m. The tunneling work was carried out without disturbance to operations on the ground.

Introduction

With the advances in the tunneling technology, it has become possible to excavate tunnels with Tunnel Boring Machine (TBM) instead of adopting conventional drill and blast method under favorable ground conditions. The TBM technology is particularly advantageous for tunneling in congested metropolitan cities like Mumbai. Conventional drill and blast method pose problems of vibration and consequent damages to the properties and important structures on the surface. A review of tunneling methods show that the tunneling rates achieved by using the conventional method of excavation vary from 7.5 m to 81.5 m on a monthly average basis, depending upon the size of the tunnel, geology encountered etc. For the first time in India, a hard rock Tunnel Boring Machine was deployed for Bombay Water Supply Scheme earlier in 1984. The tunnel of 3.87 km length was driven with 3.5 m diameter gripper type TBM (Tribune no-ITA-AITES). The tunnel was reported successfully driven in 450 days with a best monthly advance of 376 m. After that construction of tunnel by TBM for expansion, rehabilitation and upgradation the distribution system of water supply in Mumbai is effective. The present project is a continuation to that successful efforts.

A tunnel between Maroshi and Ruparel College is being excavated by TBM to improve the water supply to Vakola, Mahim, Dadar and Malbar hill of Greater Mumbai. It is a 12.24 km long tunnel with a finished diameter of 3.0 m with a gradient of 1:600. A tunnel between Maroshi and Ruparel College is divided into three sections namely, Maroshi - Vakola (5.83 km long), Vakola - Mahim (4.55 km long) and Mahim - Ruparel College (1.86 km long). The tunnel is excavated through four shafts of 9 m dia. each at Maroshi (80 m deep), Vakola (63.5m deep), Mahim (60 m deep) and Ruparel College (60 m deep). The longest tunnel stretch between Maroshi-Vakola has been acomplished. The tunnel was excavated at an average El. -35.5 m (av.) below the mean sea level.

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An early warning on ground convergence is essential to avoid TBM from getting jammed by squeezing ground conditions and frequent damages due to rock fall by assessment of rock mass condition. The rock mass condition has been assessed by a precise judgment during forward probing and '3D' geological logging of tunnel. Based on rock mass classification, permanent rock supports for various shafts and tunnel sections as mentioned in Basic Engineering Design were recommended and installed accordingly. The tunnel boring was extremely challenging between the Maroshi and Vakola section due to heavy seepage and varying rock conditions. During monsoon, the seepage in the tunnel increased to about 25000 m^3 per day. Extensive grouting was carried out to control the same. Weak patches of rock necessitated widespread tunnel protection works to ensure safety.

Geology of the Project Area

Geologically the entire Mumbai area is occupied by the deccan basaltic flow rocks and the associated pyroclastic and the plutonic rocks of Upper Cretaceous to Palaeogene age classified as Sahyadri Group (Sethna, 1999). It is well known that Deccan volcanics cover a vast area of nearly 500,000 sq. km of the Indian Subcontinent and attain a thickness of 1.6 km above M.S.L. 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 differentiates with intertrappean beds, agglomerates and tuffs. The ultrabasic differentiates are of limited occurrence. Acid rocks include quartz trachyte. The agglomerate and tuff include reworked material as indicated by current bedding and graded bedding. The basalt flows of the area have been grouped into compound flows (i.e. pahoehoe type), simple flows and flows which do not fail in the above categories and hence termed as unclassified flows. The basaltic flows are typically of quartz and hypersthene normative with minor amount of olivine theolites. The lava pile of Mumbai is inturn intruded by columnar jointed medium grained doleritic dykes. The rock types encountered during the excavation of tunnel are fine compact basalts, porphyritic basalts, amygdaloidal basalts and pyroclastic rocks namely volcanic breccia, tuff and tuff breccia with layers of red boles. Intertrappean beds consisting of different type of shales were also observed during excavation. As per actual observations the whole sector was classified into the following three horizons, on the basis of the lithological characteristics.

Horizon-I : Tuff breccia / Tuff

Horizon-II : Amygdaloidal basalt / Compact basalt

Horizon-III : Intertrappean beds of shale

Geological Observations

a. Vertical Shafts and Assembly (DBM) Tunnels

For constructing the tunnels from Maroshi to vent hole and from Vakola to vent hole, vertical shafts were constructed at either ends. The inlet shafts of 80.0 m and 63.5 m depth from ground level having 9.0 m finished diameters have been constructed to lower down the TBMs in parts and then 5.4 m 'D' shaped assembly tunnels of 90.0 m and 60.0 m length were constructed to assemble the TBM for boring the tunnel. Both the vertical shafts and assembly tunnels were excavated by conventional drill and blast method. During this excavation, the ground vibrations were monitored to limit the peak particle velocity to the safe permissible limits. The details of excavated Maroshi and Vakola shafts are given in table 1.

b. Maroshi – Vakola Bored (TBM) Tunnel

A 5834 m long tunnel with an excavated diameter of 3.6 m with a designed gradient of 1:600 was excavated between the shafts at Maroshi to Vakola at a depth of 80 m (35.5 m RL) at Maroshi and 63.5 m (35.5 m RL) at Vakola. The alignment of the tunnel is N30°E

Table 1: Summary of Maroshi and Vakola Shafts

Description	Maroshi shaft			Vakola shaft		
Top of retaining wall	RL 46.5 m			RL 33.10 m		
Ground level	RL 45.19 m			RL 27.958 m		
Top of shaft	RL 38.7 m			RL 25.50 m		
Shaft invert	RL -35.5 m			RL -35.5 m		
Shaft excavation dia.	9.80 m			9.80 m		
Shaft finished dia.	9.0 m			9.0 m		
Method of construction	Drilling and Blasting (Controlled Blasting)			Drilling and Blasting (Controlled Blasting)		
Shape	Circular			Circular		
Date of starting	11-03-2008			11-04-2008		
Date of completion	28-05-2008 (51 Days)			08-06-2010 (47 Days)		
Depth of shaft	74.2 m (80 m from GL)			61 m (63.5 m from GL)		
Total No. of blasts	51			47		
Rock types	Type	Total thickness	Av. Pull	Type	Total thickness	Av. Pull
	Basalt	26.0 m	1.8 m per blast	Basalt	14.0 m	1.7 m
	Tuff breccia	38.5 m	1.4 m	Tuff Breccia	38.6 m	1.5 m
	Tuff	5.0 m	1.3 m	Tuff	-	---
	Contact of Basalt and Breccia	4.7 m	1.3 m	Contact of Basalt and Breccia	-	---
	Intertrappeans	--	---	Intertrappeans	8.4 m	1.95 m
	Drill length - 2.4 m per blast			Drill length - 2.4 m per blast		

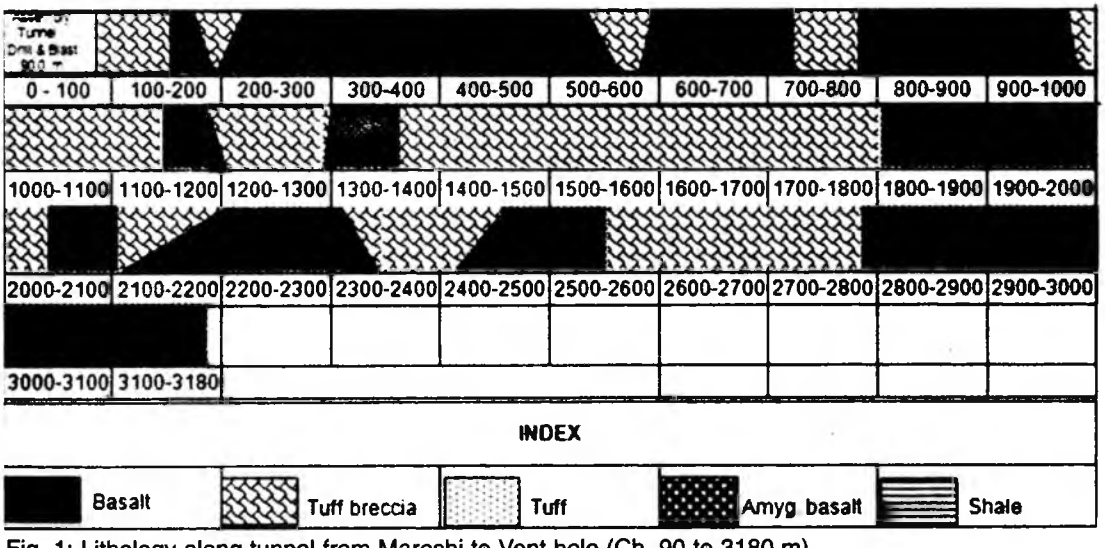

Fig. 1: Lithology along tunnel from Maroshi to Vent hole (Ch. 90 to 3180 m)

- S30°W. A vent hole was provided at Ch. 3176 m, where a change in the vertical alignment is noticed. The details of the excavated tunnels are given in table 2. Various rock types encountered during the tunneling from Maroshi to vent hole and Vakola to vent hole is given in fig 1 and fig 2.

Rock Mass Behaviour

Based on the engineering properties and RMR the tunneling media has been classified in to the following three categories / horizons to assess their bahaviour and the performance of TBM.

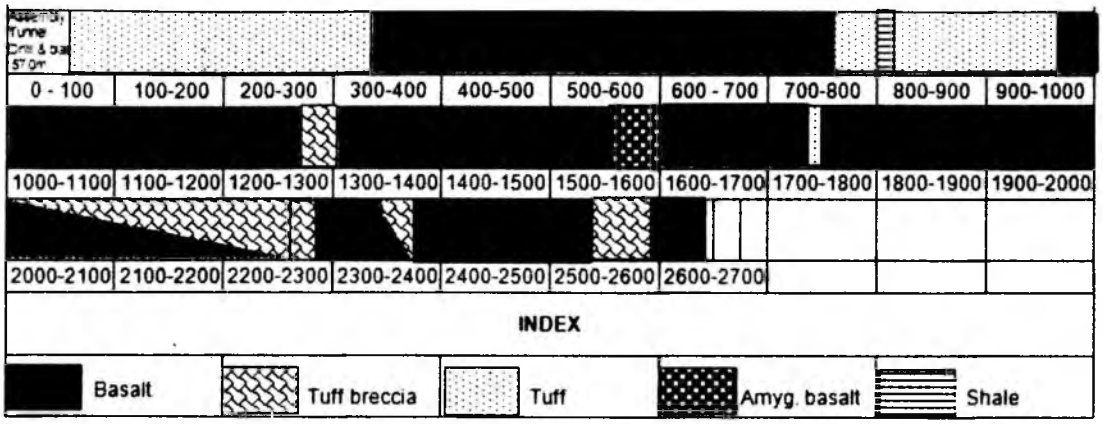

Fig. 2: Lithology along tunnel between Vakola and vent hole (Ch. 57 to 2645 m)

Table 2: Summary of Maroshi- Vent hole and Vakola –Vent hole tunnels

Description	Maroshi shaft to vent hole			Vakola shaft to vent hole		
unnel Boring Length	3086.34 m			2590.4 m		
oring Start Date	27 December 2008			07 November 2008		
oring Completion Date	26 September 2009			10 August 2009		
unnel boring Duration	9.1 months			9.2 months		
Monthly Average Tunnel Boring Progress	339.16 m/month			281.57 m/month		
Daily Average Tunnel Boring Progress	13.57 m/day			11.26 m/day		
Max. Boring Progress	29.5 m/day			39.9 m/day		
Max. Progress per month	542.6 m/month			474.4 m/month		
Rock Type	Type	Total Length	Av. PR	Type	Total Length	Av. PR
	Basalt	1612 m	2.41 m/hr	Basalt	1858 m	1.78 m/hr
	Amyg. Basalt	--	---	Amyg. Basalt	90 m	2.19 m/hr
	Tuff breccia	1165 m	3.07 m/hr	Tuff breccia	96 m	2.14 m/hr
	Tuff	--	--	Tuff	464 m	1.88 m/hr
	Contact of basalt and breccia	310 m	3.06 m/hr	Contact of basalt and breccia	90 m	0.90 m/yr
	Intertrappeans	--	----	Inter-trappeans	30 m	1.55 m/hr

Horizon-I: Tuff breccia /Tuff

A total of 1725 m (about 30% of the total length) of tunnel length (tuff breccia – 1261 m, tuff – 464 m) has been excavated in tuff breccias and tuff. Tuff breccia and tuff is generally less jointed or unjointed. Uniaxial compressive strength of the fresh tuff breccia is up to 56 MPa, while the UCS of weathered tuff breccia is up to 16 MPa. Based on RMR values, generally the rock conditions are fair to good except at or near to the flow contact where it shows poor to fair rock mass conditions. Generally, it was a suitable medium for tunneling by TBM due its impermeability, stability and high penetration rate. The rock mass properties, TBM performance and support details adopted in this horizon are given in table- 3 to 5.

Horizon-II: Amygdaloidal basalt / Compact basalt

The two main rock types encountered during the excavation of the tunnel were the compact or non vesicular basalt i.e. without any vesicles and amygdules (vesicles filled with secondary minerals) which give them a spotted appearance. The different diagnostic engineering properties between the compact

and amygdaloidal basalts lies in the degree of jointing and pattern. In this area occasionally basalts are transitional between these two types. The vesicular basalts have their engineering behavior similar to compact basalts.

About 60%, 3470 m length of the tunnel was excavated in compact basalt. The compact basalts shows a higher degree of jointing and never massive. Joints provide access to water, thus the compact basalt is likely to be water bearing. In addition, the fragmentation brought about by jointing make the compact basalt unstable during excavation especially if joints are closely spaced. They therefore, have proved troublesome in underground excavations. Rock fall was reported at tunnel crown and sides and rock bolting was recommended to support it. Even in a single basaltic flow layer there were some portions with close jointing and others was widely jointed or no joints at all. Due to its structural and textural variation the uniaxial compressive strength of the intact compact basalt varies from 65 MPa to 140 MPa and the rock mass falls under the Fair to Good rock category.

A total 90.0 m length of the tunnel was excavated in the amygdaloidal basalt. The amygdaloidal basalts were free of joints and are quite impervious when fresh. Due to the absence of divisional planes, the rock mass was stable in all kinds of cuts and excavations. Therefore considered to be a very suitable medium for tunneling, and all underground works can be expected to be trouble free.

Horizon-III: Inter-trappean beds of shale

These are the sedimentary beds found associated with the Deccan trap lava flows. They are made up of shales and volcanic detritus and are of lacustrine and fluviatile origin. The fine grained variety of shale has good compressive strength but is thinly bedded. Rock fall occurs due to its softening when in contact with water. Approximately 30 m of tunnel length was excavated in the shales, which is about 0.5% of total length. Due to its swelling beahviour the entire length was supported by steel ribs.

Support System

The Characteristics of joints in different rock types, various ground conditions encountered during tunneling and precautions for various ground conditions in Maroshi shaft and tunnel constructed by TBM between Maroshi and Vakola and various types of supports implemented (Fig. 3 to 8) during construction

Table 3: Summary of rock mass properties vis-a-vis TBM performance in Maroshi- Vakola tunnel stretch

Type	Varieties/Characteristic affect TBM performance and stability	RMR Class	UCS MPa	Rebound No.	Penetration Rate m/hr	
					Max.	Average
Basalt	• Compact and massive (strength) • Moderately Jointed (dry/seepage) • Very closely jointed (dry/seepage) • Fine grained/ Porphyritic	I to III	65 to 140	42 – 68	4.2	2.10
Amyg. Basalt	• Massive	I to II	52 to 85	--	--	2.19
Tuff breccia	• Breccia (dry/damp) • Tuff breccia (dry/damp)	II	23 to 56	18 – 42	5.5	2.60
Tuff	• Tuff (argillaceous/carbonaceous)	II	20 to 40	17 – 35	2.19	1.88
Contact of basalt & tuff breccia	• Filling material • Aperture • Wall strength • Weathering	II to IV	23 - 56 to 65 – 140	Not tested	4.8	3.06
Intertrappeans	Grey shale (dry/ wet) Carbonaceous shale (dry/wet)	II to IV	30 to 65	12 – 24	1.6	1.55

Table 4: Details of adopted support system in Maroshi to vent hole tunnel stretch

Chainage		Type of rock	Characteristics of joints	Condition of rock	Type of support required
From	To				
147.8	154.0	Highly jointed and weathered basalt (contact zone)	Closely spaced four set of joints, smooth joint surface coated with clay, cohesion between joints are very less	Contact zone of breccia and basalt. At crown three major joint planes are intersecting and forming wedge. Blocks are imperfectly interlocked	100 mm thick shotcrete with wire mesh and spot rock bolting of 3.0 m length
155.2	167.2	Highly weathered basalt and tuff breccia with intercalation of shale (contact zone)	Highly weathered wall rock surface, water was present in the joints, cohesion between rock mass is very poor due to filling of clay material	Chunks and flakes of rock mass begin to drop out of the arch or walls after the rock mass is excavated, rock mass absorb water, increase in volume and expand slowly into the tunnel due to presence of shale	Rib supports with 3.15 mm ms lagging plates as per site condition
287.0 324.0	288.0 325.0	Intact block of jointed basalt.	Smooth joint surface and imperfectly interlocked	Jointed rock mass	Spot rock bolting of length 1.5 m
329.5	335.6	Hard, jointed grey basalt	Prismatic and horizontal joints, smooth joint surface coated with calcite	Rock burst- a violent failure in hard (brittle) rock mass	100 mm thick shotcrete with wire mesh and steel ribs to supplement shotcrete
558.0	560.0	Contact plane of breccia and basalt	Filling of clay at contact plane, 50 to 100 mm separation	Rock mass weak at contact zone	Spot rock boiting of 1.5 m length
595.0	600.0	Hard, jointed grey basalt	Highly jointed, smooth and weathered joint surfaces	Raveling, chunks and flakes of rock mass begin to drop out after rock mass is exposed	100 mm thick shotcrete with wire mesh and spot rock bolting of 1.5 m length
725.5	730.6	Contact zone of breccia and porphyritic basalt	Highly weathered breccia was present. Rock mass between these zone was unstable	Huge chunk and flakes of rock mass may drop out from the crown	Segmental liner
730.6	740.9	Contact zone of breccia and porphyritic basalt	Weathered breccia, minor seepage was reported	It consist of almost chemically intact rock fragments which are entirely separated and imperfectly interlocked	Rib supports with 3.15 mm ms lagging plates as per site condition
2297	2303	Grey basalt	Jointed, joint surfaces are smooth planar and coated	Huge chunk and flakes of rock mass may drop out from the crown	Rib supports with 3.15 mm ms lagging plates as per site condition
2317.3 2330.5 2435.4	2323.4 2336.5 2448.4	Contact zone of breccia and basalt	Highly weathered breccia was present. Rock mass between these zone was unstable and disturbed	Cohesion between basalt and breccia is very feeble	
2542.8	2548.0	Grey basalt	Jointed, joint surfaces were smooth-planar and coated	Huge chunk and flakes of rock mass may drop out from the crown	
2659.8	2672.5	Tuff breccia	Improper interlocking	Feeble cohesion	
2731.0	2740.1	Grey basalt	Jointed, joint surfaces were smooth planar and coated	Huge chunk and flakes of rock mass may drop out from the crown	Steel Liner panel

Table 5: Details of support system adopted in Vakola to Vent hole tunnel stretch

Chainage		Type of rock	Characteristics of joints	Condition of rock	Type of support required
From	To				
762.0	770.0	Carbonaceous shale at crown	Layered, 50 to 100 mm thick wetted surface	Chunks and flakes of rock mass begin to drop out of the arch or walls after the rock mass is excavated, rock mass absorb water, increase in volume and expand slowly into the tunnel due to presence of shale	Rib supports with 3.15 mm mild steel (ms) lagging plates as per site condition
1,375.0	1,376.0	Closely jointed fractured basalt with traces of breccia	Joint surface is smooth and imperfectly interlocked	Jointed rock mass	Spot rock bolting of 1.5 m length
1,410.0	1,428.8	Closely jointed fractured basalt with traces of breccia	Highly jointed, joint surface is smooth and moderately weathered.	Chunks and flakes of rock mass begin to drop out of the arch or walls after the rock mass is excavated	Rib supports with 3.15 mm ms lagging plates as per site condition
1,428.8	1,433.8	Highly jointed and fractured basalt	Smooth joint surfaces, imperfectly interlocked, the block size is few cm to 30 cm	Huge chunk and flakes of rock mass drop out from the crown	Segmental liner
1,433.8	1,458.6	Closely jointed fractured basalt with traces of breccia	Highly jointed, smooth joint surface and moderately weathered.	Chunks and flakes of rock mass begin to drop out of the arch or walls after the rock mass is excavated	Rib supports with 3.15 mm ms lagging plates as per site condition
1,459.2	1,464.0	Closely jointed fractured basalt and breccia	Highly jointed, smooth joint surface and moderately weathered. Contact between breccia and basalt has low cohesion	Chunks and flakes of rock mass begin to drop out of the arch or walls after the rock mass is excavated	100 mm thick shotcrete with wire mesh and steel ribs to supplement shotcrete
1,464.0	1,469.0	Closely jointed fractured basalt and breccia	Highly jointed, smooth joint surface and moderately weathered. Contact between breccia and basalt has low cohesion	Chunks and flakes of rock mass begin to drop out of the arch or walls after the rock mass is excavated	Rib supports with 3.15 mm ms lagging plates as per site condition
1,484.0	1,486.0	Closely jointed fractured gray basalt	Hard compact grey basalt, At Right SPL jointed basalt is present, smooth joint surface and seepage through joints.	Highly Jointed rock mass	3 Rock bolt having length of 2m.
1,491.0	1,497.6	Closely jointed fractured gray basalt	Hard compact grey basalt, smooth and planar joint surface and seepage through joints	Highly Jointed rock mass. Block size 10 to 15cum	100 mm thick shotcrete with wire mesh

have been summarized in table 4&5. From Maroshi to vent hole, total 106.8 m, out of 3086.3 m, length of tunnel and in Vakola to vent hole 76.0 m, out of 2590.4 m, length of tunnel was supported by rock bolts, shotcrete, wire mesh, steel rib and steel liners. Based on the different classification systems like Rock Mass Rating (RMR) system (Bieniawaski, 1984, 1989), rock mechanics for underground mining (Brady and Brown, 1993), rock load in tunnels within various rock classes (Terzaghi, 1946) and guidelines for selections of steel sets for 6 m to 12 m tunnels in rock (Deere et. al. 1970), various types of supports were recommended and were followed for implementation by the project authorities. The support system was adopted as per actual ground conditions, availability of upport systems and the project strategy.

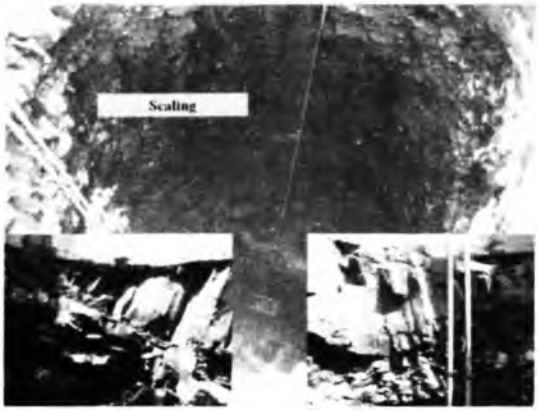

Fig.3: View of Maroshi shaft having 9.8 m diameter

Fig.4: Smooth tunnel surface in good rock mass

Fig.5: Rib support at lava flow contacts

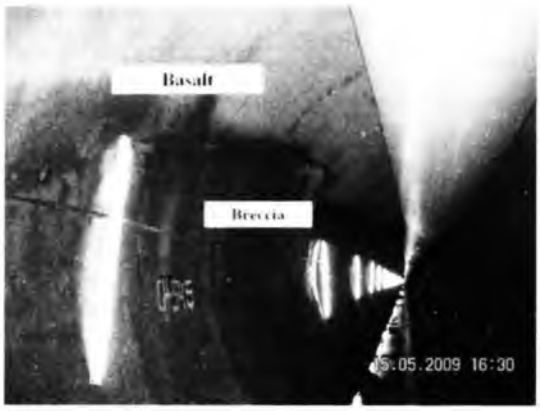

Fig.6 Steel liner panel support in jointed basalt

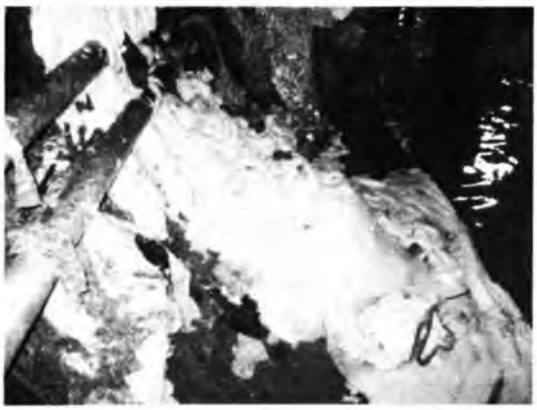

Fig. 7: Chemical grouting to control seepage

Fig.8: Flow contact of massive basalt and breccia

Conclusions

Based on the study, following important conclusions are drawn:

1. Tuff breccia is a sound medium for tunneling requiring few rock bolting incidences.

2. Compact basalt is also a sound medium for tunneling by TBM, but with many mutually intersected joint sets, resulting in block falls and heavy seepage. Precautions like closely spaced rock bolting, shotcrete and grouting are essential. Few locations needed chemical grouting.

3. Inter-trappean beds of shale posed problems with respect to driving side support for the TBM during advancing, as shale soften and slack when in contact with water.

4. Contact zones show break in the continuity of rock mass having different lithology or engineering properties. It provides path for water inflow. Rock mass in the vicinity of the contact zone is weathered and the interlocking joint surfaces are weak, which poses problems during boring and in ground stability.

5. This is one of the successfully completed part of this project, with an average penetration rate of 2.26 m/hr and a maximum monthly progress of 542.6 m, ensuring the safety. The case study promotes the use of TBM in other parts of Deccan Traps region, and for various up coming tunneling projects for hydropower, sewerage, water supply and transportation etc.

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References

Bieniawski, Z.T. (1984): Rock mechanics design in mining and tunneling. A.A. Balkema, Rotterdam, Netherlands, pp 55-92.

Bieniawski, Z.T. (1989): Engineering rock mass classification. John Willey & Sons, New York, 251p.

Brady, B.H.G. and Brown, E.T. (1993): Rock mechanics for underground mining, second edition, London: Champman & Hall, 571p.

Deere, D.U.; Peak, R.B.; Parker, H.; Monsees, J.E. and Schmidt, B. (1970): Design of tunnel support systems. High Res. Rec., No. 339, pp. 26-33.

Sethna, S.F. (1999): Geology of Mumbai and surrounding areas and its position in the Deccan Volcanic Stratigraphy, India. Jour. Geological Society of India, vol. 53, pp 359-365.

Subbarao, K.V. (1988): Deccan Flood Basalts (eds). Geological Society of India, Memoir 10, pp 1-393.

Terzaghi K. (1946): Rock defects and loads on tunnel supports. Rock Tunnelling with steel supports, ed. R.V. Proctor, and T. L. White, Commercial Sheering and Stamping Company. Yougstown, OH, pp 15 -99.