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Construction Challenges Encountered During Shield TBM Tunneling in Sunkoshi Marin Diversion Multipurpose Project, Sindhuli, Nepal

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Abstract

In Nepal, Tunnel Boring Machines (TBMs) are now used for excavating tunnels in inter-basin water transfer projects. TBM excavation requires a significant upfront investment and detailed planning. A crucial step before starting TBM tunneling is a thorough geotechnical investigation. However, challenging steep terrain can make it hard to gather accurate ground information. Apart from geological factors, experience, skills, and informed decision-making during tunnel construction phases are essential. For critical sections, relying on on-site investigation methods during construction is advisable. This underscores the importance of comprehensive investigations both before and during construction for effective and cost-efficient TBM projects. Experience with a specific TBM type, the double shield type, reveals a potential issue: there's a risk of TBM getting stuck due to squeezing of rock mass and cutterhead tilting when the orientation of TBM aligns almost parallel to the bedding/foliation strike. Data on rock mass and TBM parameters were collected through fieldwork. Additionally, a study was conducted to understand methods used to release a stuck TBM at chainages 2+156 m and 4+669 m.

Keywords

TBM,Squeezing, Shield, Cutterhead,By-pass

1. Introduction

In Himalayan region, tunneling is quite challenging tasks because of tectonic setting which is relatively recent (about 70 million years), as a result the rock mass in this region are heavily folded, fractured, faulted, sheared and deeply weathered. Tunneling through numerous zones of weakness, fractures and faults is thus a matter of reality [1].

The conventional method of tunneling Drill and Blast is common in our context in which section to be excavated is drilled either manually or by mechanized means and filled with explosives which is detonated and rock material is blown out of the face. Due to environmental reason, geological and topographical condition it is not always reliable to use drill and blast tunneling. Recently, new and advanced mechanized tunneling method TBM was introduced in Nepal with first project 12.2km long Bheri-Babai Diversion Multipurpose Project (BBDMP), successfully excavated by Double Shield TBM in only 17 months[2]. The TBM was selected for the first time in Nepal due to its longer length and unavailability of intermediate adit tunnel location [3]. Also, due to same reason Double Shield TBM was selected for the Sunkoshi Marin Diversion Multipurpose Project (SMDMP). The general working principal includes excavation equivalent to effective stroke, re-gripping and new excavation [4].

The SMDMP is an inter-basin project to transfer water from Sunkoshi River to Marin Khola, a tributary of the Bagmati River via 13.3 km long tunnel. The project has two purposes, to divert water for irrigation and to generate electricity. The design flow of this project is 63 m^3/sec and it has power station to generate electricity of 31.07 MW [5]. The headrace tunnel passes through Siwaliks, Main Boundary Thrust (MBT), Lesser Himalaya, Mahabharat thrust (MT), and higher Himalayan rocks. This article includes details of construction challenges faced during Shield TBM tunneling in regards to TBM jamming because of squeezing and cutterhead tilting. Also, it incorporates detail analysis of release plan adapted to free TBM from stuck position.

2. Brief on Project

Sunkoshi Marin Diversion Multipurpose Project is located in Sindhuli district at a distance of 115 km southeast of Kathmandu as shown in Figure 1; it is a second project in which TBM has been selected to construct the tunnel in Nepal. The Project is named as multipurpose project because it has two purposes, i) to divert water from Sunkoshi river (surplus basin) to Marin River which is one of the tributary of Bagmati River and ii) to generate electricity of 31.07 MW . The 13.3km long headrace tunnel of diameter 5.5m will divert 67 cumecs to Marin River for the irrigation of 122,000 ha of agricultural land of Bara, Rautahat, Sarlahi, Mahottari, and Dhanusha district. The location of overall project components enclose within the boundary range of Latitudes 27°20'38"N and 27°15'30"N and Longitudes 85°59'03"E and 85°52'29"E. Seismically, the entire project area falls under seismic hazard zone with Seismic Zoning Factor (Z) of 0.4 (NBC 105:2020). Recognizing its importance to the development of Nepal mainly from irrigation perspective, the Government of Nepal has considered it as a Project of National Pride.

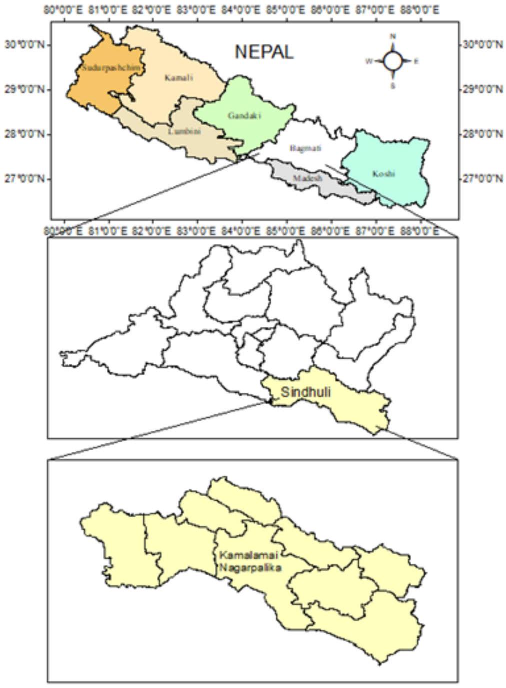

Figure 1: Location of Study Area

2.1 Geology of the area

The project area consists of rocks of the Siwalik Group, Lesser Himalaya and Higher Himalaya. The Siwalik Group consists of sedimentary rocks of the fluvial origin and the Lesser Himalayan and Higher Himalayan rock consists of metamorphic and igneous origin. The Headrace Tunnel (HRT) alignment is crossed by Main Boundary Thrust (MBT) and Mahabharat Thrust (MT) at one and two locations respectively. Around first 4km tunnel length encounters Siwaliks rocks and the remaining length generally consist of syncline structure and its syncline core is higher Himalayan Gneiss and Granite.

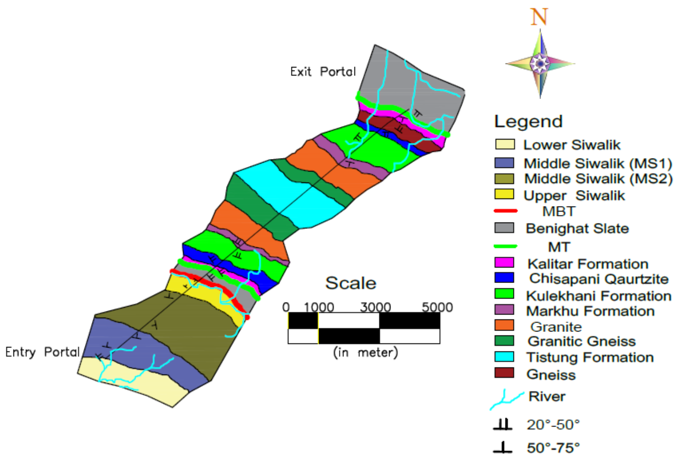

Figure 2: Geological Map of SMDMP [6]

2.2 Mapped Rock Mass Qaulity

The rock mass classification with RMR system along the headrace tunnel (HRT) was carried out along its excavated 7836 m length of tunnel from the manhole which is located at the bottom left side of cutterhead. The different parameter

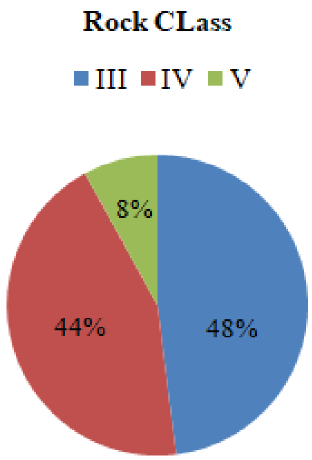

Figure 3: Actual Rock Mass Quality Percentage Along 7886 m Excavated Headrace Tunnel

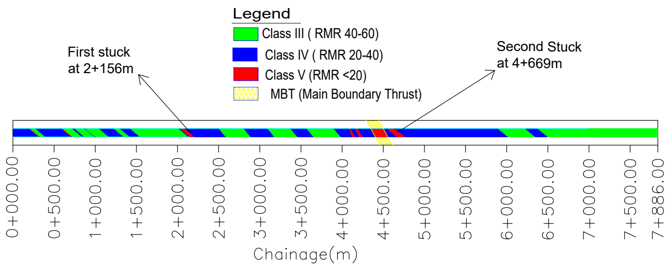

Figure 4: Mapped Rock Mass Quality Along HRT of SMDMP

like Uniaxial Compressive Strength (UCS) of intact rock, Rock Quality Designation (RQD), spacing of discontinuities, condition of discontinuities, groundwater condition, and orientation of discontinuities are rated for the classification of rock mass. All the parameters are added to get final value of RMR except last parameter mentioned i.e. orientation of discontinuities.

Figure 4 and Figure 5 shows that various rock mass class present along the headrace tunnel which mainly varies from class III to V. The first stuck of TBM occurred at chainage 2+156 m due to tilting of cutterhead. The second stuck of TBM occurred at chainage 4+669 m due to squeezing of rock mass in forward and telescopic shield.[5]

Rock mass classification using RMR system was adopted to evaluate the rock mass quality. The different parameters of RMR were taken from face mapping data at respective critical chainage along headrace tunnel alignment up to the excavated section i.e. except for chainage 10+444 m and 13+100 m. The RMR for these two chainage is adopted based on rock mass condition suggested by Geotechnical Baseline Report of SMDMP. The critical sections along tunnel is selected based on various facts shown in Table 1 and the corresponding rock mass classification based on RMR system as shown in Table 2.

Table 1: Chainage of Critical Section and Description

HRT Chainage [m]	Description
0+170	Jhor Khola
2+156	TBM stuck chainage due to tilting of cutter head
3+383	Dhaman Khola-Upper Siwalik
4+669	TBM stuck chainage due to squeezing-Benighat(SL)
7+800	Maximum overburden along HRT-Granite
10+444	Tyan-Tyan Khola-Markhu (NL)
13+100	Thrust zone-Benighat(NL)

Table 2: Rock Mass Classification at Critical Section Along HRT

HRT Chainage	Rock Type / Rock Condition	RMR Value
0+170	Highly weathered Sandstone inter-bedded with Mudstone and Siltstone along with water dripping in upper-left portion of face	42
2+156	Highly jointed, crushed Sandstone with soft infilling (clay)	37
3+883	Conglomerate with dominant clast of Quartzite along with Sandstone and Mudstone.	42
4+669	Weak Phyllite with quartz Vein	16
7+800	Slightly weathered, medium to high strength Granite.	50
10+444	Medium banded Schist intercalated with Laminated Quartzite	35
13+100	Micaceous Schist with Quartz veins intercalated with Quartzite and Dolomite	22

3. Evaluation on TBM Jamming due to Squeezing

The deformation on unsupported rock mass is computed and if this deformation value is less than the void between TBM and rock mass, TBM can advance easily. If the deformation is more than the void between TBM and rock mass, there will be contact between rock mass and the shield, then the thrust capacity of the machine comes into play. The double shield TBM used in SMDMP has thrust capacity of 47,124KN and it is provided by the combination of 17 jacks. Also, the average void between cutterhead and shield is 60mm and difference between maximum excavation diameter and shield diameter is 130mm. The different approaches are used to evaluate squeezing at critical sections which are explained below.

3.1 Hoek and Marinos Approach (2000)

It is a semi-analytical method which can predict the squeezing potential along with its magnitude measurement. It is formulated assuming circular tunnel with hydrostatic stress

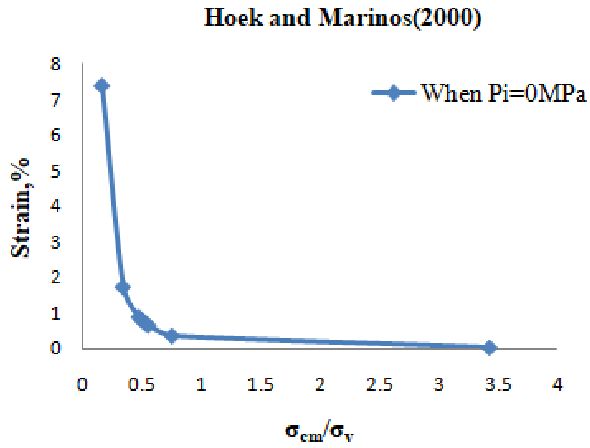

Figure 5: Ratio of rock mass strength to vertical stress vs. strain percentage

field where support pressure will act uniformly around tunnel's periphery.

Table 3: Squeezing prediction by Hoek and Marinos (2000) approach

Chainage	σ_{cm}	σ_{cm}/σ_v	Strain (ϵ%)	Deformation (mm) $P_i = 0$ MPa
0+170	4.12	3.431	0.02	1
2+156	7.23	0.504	0.79	50
3+100	5.69	0.440	1.03	66
3+883	2.54	0.500	0.8	51
4+669	1.56	0.165	7.38	472
10+444	11.87	0.756	0.35	22
13+100	1.01	0.341	1.72	110

At chainage 4+669m the significant deformation of magnitude 472mm is estimated which is very severe squeezing problem according to the categorization of Hoek and Marinos approach(2000). The deformation is more than void between cutterhead and shield even when maximum overcutting is done i.e. 130 mm. Similarly, at chainage 13+100m squeezing of magnitude 110mm is estimated, the deformations is more than the average void between cutterhead and shield i.e. 60mm but by over-cutting the rock mass at this chainage, the contact between rock mass and the shield can be prevented so that TBM jamming risk can be reduced.

3.2 Convergence Confinement Method

The interaction between Ground reaction Curve (GRC), Longitudinal Deformation Curve (LDP), and Support Characteristics Curve (SCC) can be computed by using the Convergence Confinement Method (CCM) ([7]). GRC represents relationship between decreasing internal pressure p_i and increasing radial deformation of the tunnel wall u_r. LDP is the graphical representation of radial displacement u_r that occurs along the excavated unsupported length of tunnel. At around 8R distance behind the face there will be maximum convergence $u_r max$ and at around R distance ahead of tunnel one-third of maximum deformation. SCC describe the relationship between increasing support pressure p_s and increasing radial displacement u_r of the support.

$$P_s = K_s \cdot u_r \tag{1}$$

where K_s denotes the elastic stiffness of the support. The closed ring support type, pre-cast concrete lining (M50) is designed throughout the headrace tunnel. Support Characteristics Curve (SCC) is constructed considering concrete lining. The various parameter of concrete lining are Unconfined Compressive Strength of 50 MPa, thickness 300mm, Poisson's ratio 0.2, and Young's modulus of elasticity 29275 MPa.

The input parameters used for plotting CCM are radius of tunnel 6.54m, unit weight of rock 0.027 MN/m^3, far field stress 9.45 MPa, UCS of intact rock 34 MPa, Hoek and Brown Parameter m_i 7, Poisson's ratio 0.33, dilation angle 0°, and the face effect is taken as 13 m (length of shield).

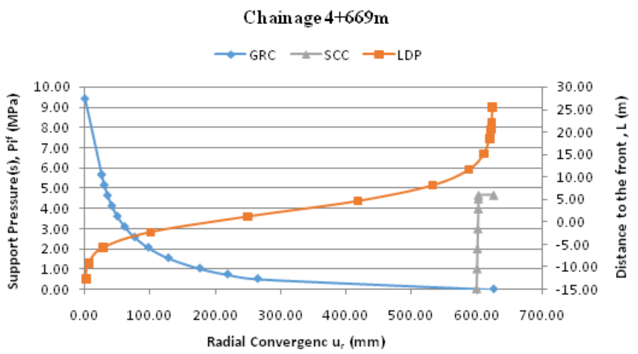

Figure 6: Schematic representation of GRC,LDP and SCC at Chainage 4+669 m

Table 4: Data output from plotting GRC, LDP, and SCC Curves at 4+669m

Parameter	Value
HRT Chainage	4+669
Picr [MPa]	5.67
$ur_{\max}$ [mm], when $P_i = 0$ MPa	625
ur at face [mm]	192
ur at 13m behind face [mm]	599
$Ps_{\max}$ [MPa]	4.67

Figure 6 illustrates that the deformation goes on increasing further behind the tunnel face and reaches its maximum value when the face effect becomes zero, when no internal support pressure is installed. The deformation at 13m (length of shield) behind the face of tunnel is almost similar to the maximum deformation $u_r max$. Table 4 shows that the deformation at face is 192 mm which is more than the void space available between shied and rock mass even when excavation with maximum overcutting is done. It shows there is possibility of TBM shield getting stuck due to squeezing.

3.3 Numerical Analysis

Two dimensional valley model was prepared using RS2 software, to determine principal stresses that exist before the excavation of the tunnel. The bottom is fixed vertically (Y direction). The left and right sides are fixed horizontally (X direction). The top is free to move in bot X and Y directions. All four corners are constrained in both X and Y directions. Gravity-based field stress is applied, considering actual ground condition. In this way, the model was set up.

Table 5: Input parameters for valley model

Description	Symbol	Unit	Value
Tectonic stress	σ_{tec}	MPa	5
Trend of tectonic stress	θ_t	degree	N 10°E
HRT trend	θ_c	degree	N 50°E
Angle between tectonic stress and HRT trend	α_t	degree	40°
Locked in horizontal stress (In plane)		MPa	2.934
Locked in horizontal stress (Out of plane)		MPa	2.066
Stress ratio (In plane)			0.760
Stress ratio (Out plane)			0.668

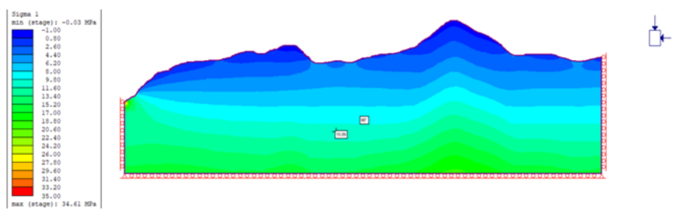

Figure 7: Valley model for HRT at chainage 4+669m

Table 6: Output parameters from valley model

Chainage (m)	σ_1 (MPa)	σ_3 (MPa)	σ_z (MPa)	Angle
4+669	10.59	8.65	9.84	98°

3.3.1 Model Setup

For the analysis of critical tunnel section 4+669m, the 2D box model of the tunnel having width more than five times its excavation was constructed with boundary restrained in both directions. The in-situ stress values are taken from the output of valley model as shown in Table 6. The disturbance factor (D) has been taken as zero since it was TBM tunnel. The rock mass parameters value used for the analysis is shown in Table 7.

Table 7: The rock mass parameters value set for analysis

Parameter	Value
Overburden (m)	350
Density (MN/m^3)	0.027
Ei (MPa)	19270
σ_{ci} (MPa)	34
m_i	7
GSI	11
σ_1 (MPa)	10.95
σ_3 (MPa)	8.65
σ_z (MPa)	9.84
θ (CCW)	98°

Elastic Analysis

The strength of the material around the tunnel's edges, before adding support is not strong enough. The strength factor value is less than one around the tunnel periphery as shown by the Figure 8. This means we have to investigate the possibility of material failure using plastic analysis. So, further plastic analysis is carried out.

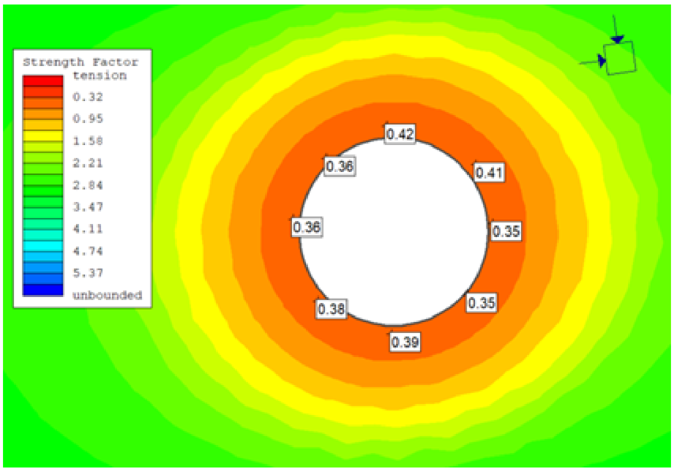

Figure 8: Strength factor before installation of support

Plastic Analysis

The maximum closure u_{max} of the tunnel is 350mm which occurs on right periphery of the tunnel and this is about 5.45% of the tunnel diameter. The plastic zone radius (R_{pl}) is 12.4m measured from center of tunnel to the far yielded point which is located 177.2° clockwise from horizontal direction as shown Figure 9. The unsupported section (X) lies almost 13m behind the tunnel face i.e. close to tail shield. The ratio of distance from tunnel face to tunnel radius (X/R) is 4.06m and the ratio of plastic zone radius to tunnel radius (R_{pl}/R) is 3.875m. By using Vlachopoulus and Diederichs method, the above values are plotted to get a ratio of closure to maximum closure equal to 0.82 as shown in Figure 10. Therefore, the closure equals 287 mm which means 82% of total deformation will already take place before the application of support.

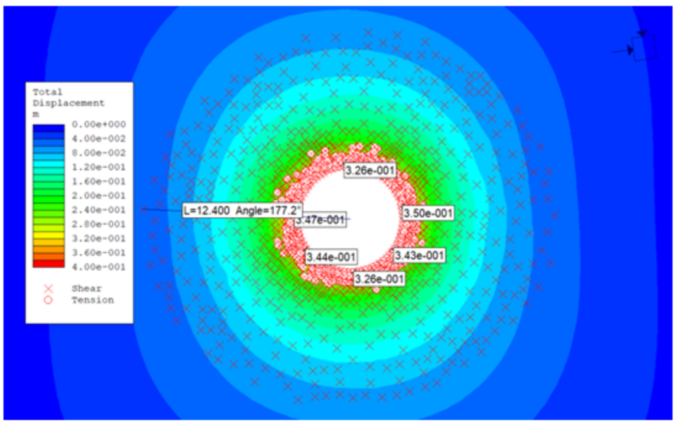

Figure 9: Total displacement and radius of plastic zone

Before the application of support, deformation of 287 mm takes place which is far more than the void space between the shield and cutterhead even when maximum overcutting is done. It implies that there is possibility of TBM getting stuck due to squeezing of weak Phyllite at this section. Also, the machine got stuck due to extreme squeezing of rock mass in forward and telescopic shield.

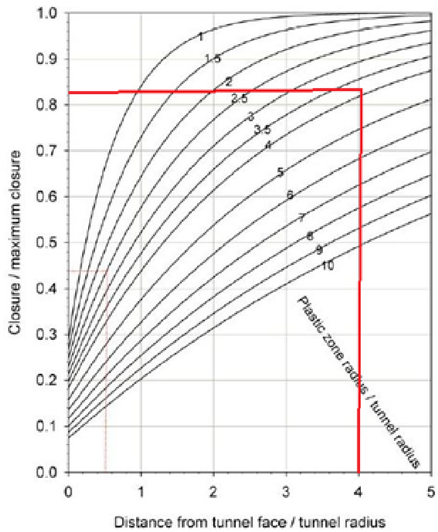

Figure 10: Improved LDP (Vlachopoulus and Diederichs, 2009)

3.4 TBM stuck at Chainage 4+669m

On 31st March 2023-night shift, the TBM encountered weak geology containing low-strength Phyllite with Quartz veins at face, which is different from the information predicted prior to the excavation indicating that the stretch of the tunnel alignment from 4+181 to 4+985m is made up of fresh to moderately weathered, thin to medium bedded, dolomite intercalated with thinly foliated slate with quartz veins. The different countermeasure was taken but advance of TBM was not possible. The torque of the cutterhead increased drastically, forward and telescopic shield got squeezed and TBM stopped to advance further at chainage 4+669 m.

3.4.1 Geological Condition at TBM Stuck Location

The TBM got stuck in Benighat Slate (Bg) geological section located between the MBT and MT fault zone. The phyllite with maximum quartz veins was observed in the full cross-section in almost powder form (80%) with poor self-stability and water free condition. This indicates there was possibility of extreme deformation, collapse, cutterhead jamming and squeezing of the shield. The geology encountered by different shields at stuck position is represented by Figure 11.

Cutterhead, Forward Shield and Telescopic Shield

The observed rock formation primarily composed of Phyllite (100%), which exhibits remarkably low strength. Within this Phyllite, there are maximum Quartz veins present and no underground water presence. The overall classification of this rock mass falls into category V and the rock mass is exceedingly unstable.

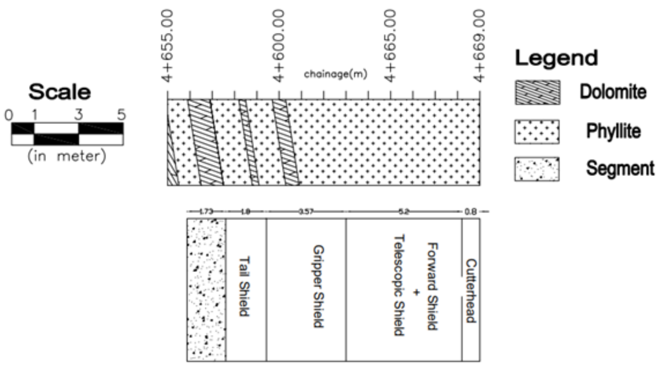

Figure 11: The position of TBM at stuck with respect to rock type it encountered

Gripper Shield and Tail Shield

The observed rock type is composed of phyllite (90%) and dolomite (10%). Within Phyllite, there are quartz veins present and it is characterized by its lower strength. Dolomite with medium to low strength range 5 to 15 MPa with moderate weathering was observed. Overall, the rock formation demonstrates varying degree of weathering and strength marked by different lithology, predominantly Phyllite, followed by Dolomite.

3.4.2 Stepwise action adopted on site

The stepwise countermeasures adopted to tackle the situation are as follows:

- In order to prevent the Tunnel Boring Machine (TBM) from getting stuck, continuous excavation was preferred at site without any pause. This decision is made because the phyllite is quite weak and can squeeze the TBM if it stops. The choice turned out to be good one, as the part of TBM called gripper shield could extent up to 10-12mm, and the pressure on it kept increasing, going beyond 300 bars afterwards.
- The torque and thrust has increased to the level that the TBM cannot go further rotating and advancing. So, it is decided to clean the cutterhead bucket, cutter teeth and chute. However, restarting the cutterhead proved unsuccessful as the torque had already reached its maximum capacity.
- Polyurethane (PU) injection is done at the upper part of the cutterhead and at front shield to consolidate the ground and prevent further collapse. After injecting PU two times, the cutterhead torque reduced to normal level (around 400KNm) but main thrust reached maximum capacity. So, TBM restart failed both in double-shield and single –shield mode.
- Then, high pressure pump is used to inject the hydraulic oil into ground near the forward shield. This is done to lessen the friction force. However, TBM could not proceed further again.
- The torque on the cutterhead is back to normal which indicated that the polyurethane had managed to prevent more collapsing. Additionally, the gripper shield and tail shield could retract the cylinder without any issues. This led to the conclusion that the shield and telescopic shield were being squeezed by the extremely weak geology. As a result, the TBM got stuck at the point marked as 4+669.332m along the tunnel.
- Finally, considering the situation that the gripper shield's pressure has risen to approximately 300 bars and continues to increase daily, coupled with detection of seepage at the tunnel face. It was decided to tackle the situation with the construction of bypass tunnel. The aim of this approach is to diminish the friction encountered by the shield to release the TBM from stuck condition as early as possible.

3.4.3 Causes of TBM Stuck

- As discussed above, the pulverized Phyllite rock was observed which is totally different from what has been anticipated prior to excavation.
- The weak Phyllite rock mass kept collapsing from the tunnel face and crown, and the TBM couldn't continue advancing because the torque on the cutterhead had reached its maximum limit. Despite trying various corrective actions, the main thrust on the TBM reached its highest point, even though the torque on the cutterhead returned back to its normal state. As a result, the TBM stayed in the same spot for more than four days. The weak Phyllite kept deforming continuously, and ultimately, the telescopic and forward shields got squeezed.
- The TBM became immobilized within the geological segment known as Benighat Slate (Bg), located between the Main Boundary Thrust (MBT) and the Mahabharat Thrust (MT). This particular geological zone, referred to as Bg section, lies within the critical region affected by thrust zone, which makes it a crucial area for tunneling. In author's opinion, a systematic program for drilling probing holes should have been prearranged prior to the excavation at this type of critical sections.

3.4.4 Construction of bypass tunnel to release TBM

The construction of bypass tunnel was done from both sides of the tail shield. These excavations targeted the area where the forward shield and telescopic shield was stuck. The aim was to reduce the frictional force between the shield and the surrounding rock, thus facilitating the release of the TBM. The geometry of bypass tunnel is shown in Figure 12.

The position between 2:30 to 5:00 and 9:30 to 7:00 was selected to initiate the excavation of inlet for the bypass to the right and left side of the tail shield respectively as shown in Figure 12. This inlet was constructed with a cross-sectional dimension of 2 meters in depth and 1.5 meters in width. Once the excavation of the inlet section was finalized, proceeded with the excavation of a parallel transition section adjacent to the shield which acts as the connecting zone between the inlet and the release segment. The length measures 3.87m, and the width of the bypass tunnel remains consistent i.e. 2 meters. The height of this section gradually shifts from 2 meters to 3.6

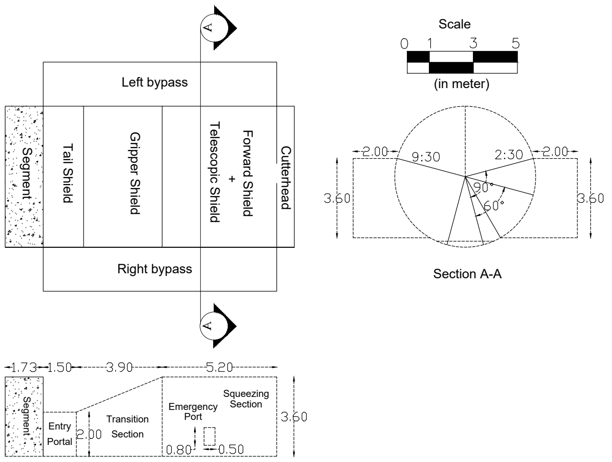

Figure 12: Plan and Cross-section for Right and Left Bypass tunnel

meters, creating a gradual height transition. After the transition section has been successfully excavated, further excavation was carried out in the direction aligned with the shield, moving towards the TBM stuck section. The dimension of excavation in this segment is length 5.2 meters, width 2.0 meters and an excavation height of 3.6 meters.

Figure 13: Inlet portal and transition section in view [5]

It took around 24 days to release TBM from stuck position. So, monthly advance achieved was only 166 m since TBM remained ideal for more than three weeks in the month of April, 2023.

4. TBM Stuck due to Cutterhead tilting

Figure 14 shows that the trend of tunnel alignment is perpendicular to bedding/foliation plane for majority of the case which is favorable condition for tunneling but for few cases the trend of tunnel length axis is parallel to it and this is unfavorable condition for tunneling. The chances of cutterhead encountering different rock types in face increases when length axis of tunnel becomes parallel to strike of bedding/foliation. If the observed rock types have significantly different hardness and strength, it becomes difficult to maintain the alignment of the tunnel which ultimately enhances the probability of cutterhead tilting. The unfavorable condition lies in Middle Siwalik MS2A between chainage 1+995m to 3+214m. At chainage 2+156m, the TBM got stuck due to cutterhead tilting on 5th of January, 2023. The left top side of the face consists of weak Mudstone and the remaining area was highly jointed Sandstone and considerable groundwater was in-gressed in the left frontal side of the cutter head. The shield of TBM was tilted towards right side and it came in contact with surrounding rock. It is due to the fact that in left side cutter disc kept revolving but no advancement occurred due to slippery face because of continuous ingress of water from left-top side.

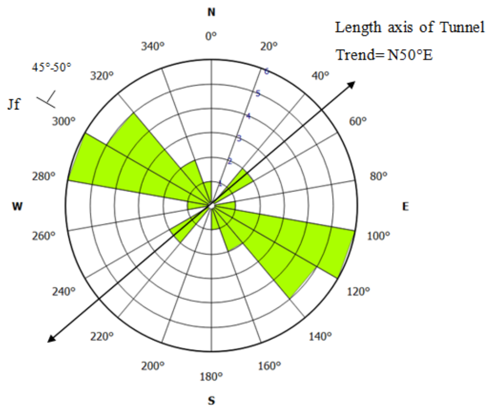

Figure 14: Joint Rosette of HRT of SMDMP considering bedding/foliation plane

Figure 15: Bypass cavity excavation undergoing on right side at chainahe 2+153m [5]

Bypass cavity was constructed on right side from telescopic shield to free the contact between shield and surrounding rock with jack hammer as shown in Figure 15. Also, Polyurethane (PU) injection was done on the left frontal side to reduce the water ingress and to strengthen the rock mass. It took around nine days to release TBM from stuck position.

5. Conclusion

The experience of TBM tunneling have shown that underground engineering is always affiliated with uncertainties and risk even though excavation was done with sophisticated mechanized machine. In SMDMP, double shield TBM got stuck at chainage 2+156m and at chainage 4+669m during the excavation of 8 km tunnel, but the reason behind the stuck was different. At chainage 2+156m, TBM got suck due to cutterhead tilting and therfore right side shield came in contact with surrounding rock. At chainage 4+669m , TBM got stuck due to squeezing that occured in forward and telescopic shield. The machine became ideal for 33 days in total considering both stuck. Following are the major conclusion drawn from this paper.

- In TBM tunneling, relation between strike of tunnel axis and bedding/foliation plane plays an important role from excavation point of view as the chances of cutterhead tilting increases when tunnel axis becomes parallel to strike of bedding/foliation plane and when cutterhead encounters face having significantly varying rock in term of hardness and strength.
- In weak and deformable rock masses, squeezing is one of the critical stability challenges which causes shield TBM to get stuck even when it does excavation with maximum overcutting.
- It is always better to perform site investigation during construction, while approaching critical sections to understand the nature of ground so that preventive measures can be adopted prior if needed. Horizontal Seismic Profiling (HSP) and Probe Hole Drilling was possible to perform in SMDMP during routine maintenance period of cutter disc.

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