Construction of Mahadevtar Tunnel and Challenges Faced During its Stabilization

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Abstract

The Mahadevtar tunnel, constructed by China State Construction Engineering Corp. Ltd. as the main contractor for Package 1, is situated in a lithology comprising rock from the Upper Nawakot and Bhimphedi Group. These rock successions are separated by the Mahabharat Thrust. The excavation method employed is the New Austrian Tunnelling Method (NATM), resulting in two fully lined tubes. During design and construction, variations in rock composition were encountered. Similarly, the expected support types for detailed design and construction also exhibited some diversity. Challenges during construction included weathered and jointed rock masses, fault and shear zones, and groundwater inflow. Overbreak and collapses occurred due to weak rock and joint conditions. Addressing these issues involved installing additional ribs, rock bolts, grouting, and replacing sections in some parts of left and right tunnels.

Keywords: Mahabharat thrust, sequential excavation method, new Austrian tunnelling method, rock mass rating, kinematic analysis, shear zone, faults, joints, formation, deformation and muck.

Introduction

Mahadevtar tunnel is twin tunnel which is one of the tunnels situated in Kathmandu-Terai/ Madhesh Fast Track (Expressway) road project. It has two tubes extended from the Ch. 26+740.6 to Ch.30+230 (Left tube) and from Ch. 26+732 to Ch. 30+154 (Right tube). Tunnels are 3489.4m and 3422.0m long connecting from Mahadevtar inlet to the Dhedre outlet respectively. The elevation of access tunnel entrance is EL. 972.00 (Approx.) while for exit is EL. 980.00 (Approx.). Excavation section is (height*width=14.62m*10.05m). The average longitudinal slope along the tunnel is 4.65% negative slope towards outlet. 13 nos. of connecting tunnels are also present out of which 9 for pedestrian and 4 for vehicle crossing.The tunnel excavation is based on NATM method with adopting RMR system to calculate the rock quality.

Geology

The rock comprises of the Lesser Himalayan succession. The main geological setting within the tunnel is Nawakot and Kathmandu Complex. Mahabharat Thrust (after it is naming as MT) separates Nawakot Complex to Kathmandu Complex. The south (outlet) starts from Benighat slate and ends with Kalitar Formation in the north (inlet). Table 1 summarizes the geological setting.

The rock condition while in excavation phase is quite varying with respect to investigation and design report. The design report divided Benighat slate and Jhikhu Carbonate band into two parts where each part sub-divided into limestone (315m thick) and slate (1150m thick). During excavation, instead of limestone, various rocks (slate, quartzite and phyllite) were encountered. Likewise, instead of slate, there was exposure of phyllite. Similarly, during construction in Bhaisedobhan Marble, the

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Table 1: Geological setting of the Mahadevtar Tunnel

Rock Unit	Group	Formation	Thickness (m)	Lithological Description	Age
Kathmandu Complex	Bhimphedi Group	Kalitar Formation	1000	Schist and micaceous quartzite	Precambrian
		Bhaisedobhan Marble	800		
		Raduwa Formation	1000		
		Mahabharat Thrust			
Nawakot Complex	Upper Nawakot Group	Robang Formation	200-1000	Phyllite and quartzite	Paleozoic
		Benighat Slate	500-3000	Slate, dolomite, schist and quartzite	

main rock mass was phyllite interbedded with marble and dolomite where marble was present in thin veins. During construction, only 250m thick marble had been found out of expected 810m thick marble in design report. The presence of phyllite significantly impacted rock quality.

Method of Excavation

Most of the alignment for the KTFT tunnel- consisting of two "tubes" each containing one track-is being constructed using principal tunnelling technique. The project employs the Tunnel construction using **Sequential Excavation Method (SEM).**

SEM is a technique in which a tunnel is sequentially excavated in phases and supported in a controlled manner. This method is also known as the new Austrian tunnelling method (NATM). The principle behind SEM is the integration of the behaviour of rock mass under load and the continuous monitoring of underground construction, also referred to as the "Design as you Go" approach. This method does not depend on any specific technique for excavation and support, rather depending on observed site conditions and prevailing rock strength, optimized support is provided. The excavation can be carried out with common excavation methods and equipment, chosen according to the soil/rock conditions. This underground method of excavation divided the space to be excavated into segments, then excavates the segments sequentially, one portion at a time. SEM method permits a tunnel of any shape or size to be excavated. SEM involves the sequencing of the excavation as well as installation of supports. Shotcrete (a kind of concrete sprayed from high-powered hoses) may be used to line the tunnel or support the face, and grouting (the injection of a cementing or chemical agent into the rock) may be used to increase the rock's strength and reduce its permeability. The permanent support installed for this type of tunnel excavation is usually a cast-in-place concrete lining.

Ground Classification

Rock/ground classification and the corresponding support types are determined generally on the basis of the parameters prescribed in the Standard specification. These terms of ground classifications are also applicable to the tunnel profiles and the support patterns used thereto.

Physical properties of ground are described below to provide helpful guidelines for determining support patterns.

Type P-3

Rock classification: Relatively solid, fair discontinuity orientation and stable.

The partial rock falls along discontinuity which is easy to slide relatively occur rarely, and displacement induced by tunnel opening would remain in the range of roughly 15 to 20mm or may be less due to elastic deformation.

RMR classification is as- 61 to 80 for P-3-1 and 41 to 60 for P-3-2 support type.

Type P-4

Rock Classification: Relatively solid but poor discontinuity and unstable.

The displacement created by the tunnel opening will tend to remain the limit of elastic deformation. The displacement induced by the tunnel opening may verge on the elasto-plastic boundary of 30mm when intrinsic rock strength of rock is lower than the tangential and radial stresses.

RMR classification is 35-40 for P-4-1 and 21-35 for P-4-2 support type.

Type P-5

Rock classification: Weathered, not solid, very poor discontinuity and unstable.

Since the discontinuity orientation is very poor, even the rock strength may be sufficient to hold the elastic deformation, loosing may continue along the discontinuities. The stand-up time of the cut face is so short that face shotcrete and ring cuts may be necessary.

RMR classification is <20(>40m) for P-5-1, <20(<40m) for P-5-2 support type.

Type P-6

Portals are frequently located in a generally weak geologic zone, where erosion develops and complicated topography is created. Thus, tunnelling or construction of the portal is likely to cause landslides or slope failures.

This type applies from the portal to the distance at which the depth of cover exceeds 2 times the diameter of the tunnel at the spring line.

Rock Quality During Excavation

Project has adopted the RMR (Bieniawsky, 1989) to calculate the rock mass classification. To classify a rock mass, the RMR system incorporates the following six basic parameters-

- Uniaxial compressive strength of the intact rock
- Rock Quality Designation (RQD)
- Discontinuity spacing
- Condition of discontinuity surfaces
- Ground water condition
- Orientation of discontinuities relative to the engineering structure

The RMR value calculated during excavation till May 2024 of both left and right tunnels are as given in table 2.

The RMR value calculated in the Mahadevtar tunnel shows that the maximum percentage of rock belongs to P-4-2 (67.96%) in the exit left tunnel. The minimum percentage of the support class falls in the entrance right tunnel, which is P-5-1 (0.76%). Rock class P-3-2 has not been encountered in the exit tunnel yet. Similarly, the rock class P-5-2 was predicted in the detail design report, but during excavation, it has not been found in any tunnels. The percentage of rock class in design report is as given in Table 2.

If we compare these two tables, we can analyse contrast in rock class predicted during detail design and actual condition. In design report the maximum percentage of support class was P-5-1 (46.89%) in exit right tunnel, but the actual condition turned out to be 9.75%.

Table 2: Percentage of the rock support class based on RMR value during excavation

Support Class	Entrance		Exit	
	Percentage of support class		Percentage of support class	
	Left Tunnel	Right Tunnel	Left Tunnel	RightTunnel
P-6	1.77	3.83	2.40	3.16
P-5-2	–	–	–	–
P-5-1	4.94	0.76	10.89	9.74
P-4-2	21.71	23.27	67.96	74.82
P-4-1	55.67	51.57	18.74	12.26
P-3-2	14.70	20.55	–	–

Table 3: Percentage of the rock class support based on RMR value in final design report (Book 4 of 8)

Support Class	Entrance		Exit	
	Percentage of RMR		Percentage of RMR	
	Left Tunnel	Right Tunnel	Left Tunnel	RightTunnel
P-6	2.50	2.75	2.91	3.21
P-5-2	16.39	19.81	21.49	18.94
P-5-1	40.73	42.84	23.73	46.89
P-4-2	8.41	6.97	29.18	15.73
P-4-1	3.07	2.84	22.66	15.21
P-3-2	28.85	24.77	–	–

6. Problems in Mahadevtar Tunnel

During the excavation of the Mahadevtar tunnel, several challenges arose due to the presence of phyllite and slate. The rock mass in the exit tunnel was weathered and weaker compared to the entrance. Issues such as groundwater inflow, collapses, weak rock, faults, and shear bands disrupted the excavation process. Following are the problems faced during excavation:

6.1 Ground Water

The groundwater conditions in the exit tunnel were nearly dry, but there was noticeable water seepage into the entrance tunnel. Within the entrance tunnel, some significant water seepage were observed. Near the MT area in the exit left tunnel, water was also flowing in. Apart from this specific location, the tunnel was mostly dry, with occasional dripping. The primary reason for water seepage is the presence of water-bearing lithology in the entrance area. Notably, in the marble section, water seepage was particularly pronounced.

6.2 Weak rock Mass

The primary lithologies in the entrance tunnel included schist, marble, and phyllitic quartzite, while the exit tunnel contained slate, phyllite, and additional schist. Some bands of graphitic slate were also observed in exit tunnel. Schist became visible in the exit tunnel after passing through MT. A thin band of green quartzite and carbonate, likely from the Jhikhu carbonate band, was also encountered. The compressive strength of rock mass in exit tunnel was calculated 2 in the RMR in most of the cases. In schist of exit left tunnel, value of rock mass ranged from 35 to 60MPa measured with Schmidt hammer. As a result, the RMR was calculated as 4 for this rock type. In exit tunnel, MT was encountered from LK29+236.8 to LK29+216.5 (See figure 1). The overall thickness of MT was 20.3m. The MT was dark black, easily crushable by hand, and haphazardly jointed. Some quartz lenses and deformed material were also present. Ground water was shower in this area. The RMR values ranged from 17 to 22, with most cases falling between 17 and 19. In the right exit tunnel, we anticipate encountering it at chainage RK29+180, which has not yet been excavated.

Figure 1: MT is exposed on the left in phyllite of Robang Formation at right

6.3 Collapse/Over Break

Most of the over break occurred due to joint conditions in the entrance tunnel. Although the lithological conditions in the entrance tunnel were favourable, the joint pattern resulted in wedge and toppling failure, causing over break. In most of the tunnels, wedge failure is dominant with some toppling failure. Additionally, multiple shear bands contributed to the over break in the tunnel, particularly in the exit tunnel. In the exit tunnel, weak rock (mostly graphitic in nature, leading to low shear strength) and unfavourable joint sets were responsible for the over break. The lithology consisted of moderately weathered, moderately strong to weak, jointed graphitic slate. The Rock Mass Rating (RMR) values where over breaks occurred ranged from 17 to 32. This suggests that the combination of weak rock and unfavourable joint conditions played a significant role in these over break incidents.

6.4 Shear Zone/Fault

In the Mahadevtar tunnel, the main fault is MT. It has already been encountered in the exit left tunnel but has not yet been encountered in the right tunnel. It is expected to be encountered approximately 20 meters from the existing face. Numerous shear bands and zones have been found in both the entrance and exit of the Mahadevtar tunnel. Local displacements of the rock mass are frequently observed in the entrance tunnel. The thickness of these shear bands ranges from 2 cm to 50 cm. They are filled with crushed materials and intersect the tunnel alignment. While some shear bands are almost horizontal, most intersect the tunnel at an angle. Additionally, there have been instances of over breaks due to the intersection of multiple shear bands.

6.5 Joints

In the Mahadevtar tunnel, joints are present in three sets, some of which are randomly distributed. These joint sets play a vital role in causing collapse or over break. In the RMR calculation sheet, the adjustment factor is typically calculated from -5 to -10. In the exit tunnel, the foliation plane opposes the dip, while other joint sets contribute significantly to collapse occurrences. The primary modes of rock mass failure due to joints are wedge and toppling failures. Toppling occasionally occurs, mainly in the entrance tunnel. It was slab like nature. The presence of thick beds in the entrance leads to frequent failures. In the exit tunnel, the rock mass is thinly foliated, with mostly tight separations and moderately narrow to moderately wide spacing. Additionally, some random joints intersect the rock mass, contributing to over break.

In the table 4, a range of joints is provided. Most of the failures were due to wedge and toppling. After conducting a kinematic analysis, it is also evident that the occurrence of plane failure is non-existent. In most cases, the rock mass has experienced wedge and toppling failure (See figure 2).

Table 4: Trend of rock mass in Mahadevtar tunnel

Trend	Entrance	Exit	Remarks
Tunnel Axis	Portal- 190° Curve- 203° Straight- 229°	30°	In entrance 3 types of sections are present
Foliation/Bedding	335-360°/50-80°	345-020°/60-70°	
Joint	220-270°/35-85° 110-190°/20-80° 55-80°/20-85° 295-310°/45-75°	07-18°/40-60° 120-170°/35-65° 30-60°/40-70° 210-240°/20-65°	Wedge failure is dominant in both tunnels.

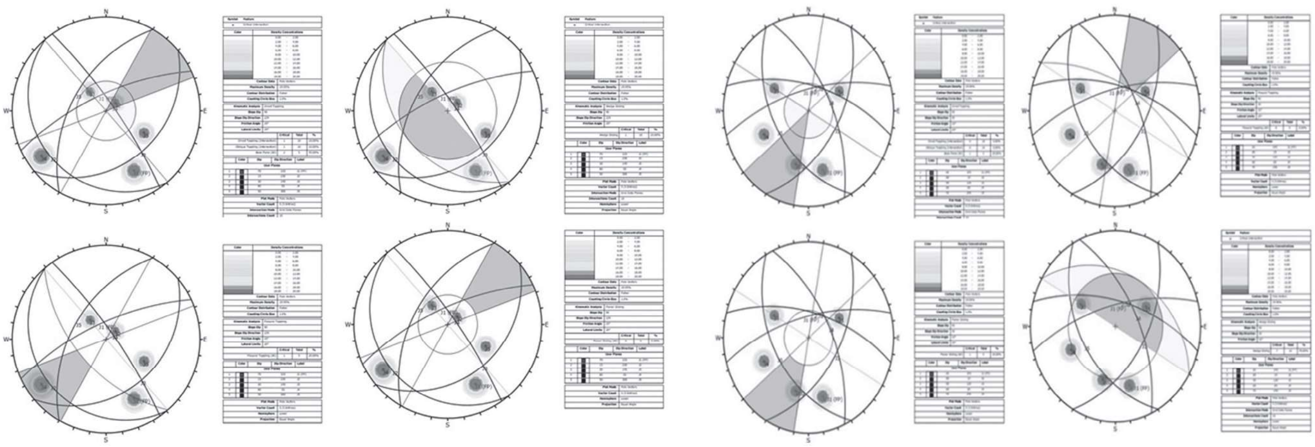

Figure 2: Kinematic analysis of entrance (left figure) and exit (right figure)

6.6 Deformation

Minor deformation has been observed in exit both right and left tunnel. Deformation in weak rock is common around the world. The lithology of the deformed area was light grey, thinly foliated, moderately weathered, moderately strong to weak phyllite. Almost all area was dry except some wet places observed during geological mapping. Some shear bands were observed which was up to 5cm thick. Shear bands were filled with crushed material and mostly in whitish grey. Some small over breaks were also occurred which was due to the presence of shear bands causing crown, plane, and wedge failures.

In deformed area, most of the RMR value of the left tunnel ranged from 26 to 31 which fell in P-4-2 class of rock as per design support. In right tunnel, range of the RMR value was 27 to 33 which came under P-4-2 rock class.

7. Excavation in Poor Rock Mass

Highly weathered rock mass was encountered in most of the portal section. After crossing 30 meters from the portal, the weathering of the rock mass decreased. Moderately to slightly weathered rock mass occurred throughout the excavated area. In some parts, fresh rock was also recorded, mostly in marble and quartzite. Yellow stain on joints was prominent in marble beds. The main reason for the deterioration of the rock mass was the shear zone and fault. Since groundwater inflow was observed in the marble area, water conditions occasionally created problems for excavation. The method of excavation in poor rock mass follows the following sequences, which are being adopted at the site.

7.1 Advance Forecast of Tunnel

The underground geological conditions are unpredictable and may lead to various anomalies, creating challenges during excavation. To better investigate the geological and hydrogeological conditions ahead of the tunnel excavation working face, we aim to enhance the accuracy of our geological exploration data. For this purpose, we utilize ground-penetrating radar (GPR) to forecast the alignment of the unexcavated tunnel. GPR effectively detects the surrounding rock geology, including cavities, karst formations, and water-rich areas behind the face (See figure 3). It provides information on rock conditions up to 30 meters from the tunnel face.

Figure 3: Conducting GPR survey in Mahadevtar tunnel

7.2 Filling with Muck

After the collapse, shotcrete is applied to the rock surface to strengthen the rock mass and protect it from further erosion. Subsequently, the face is sealed by filling it with muck transported from the disposal area. Filling the disposed muck up to the crown of the face prevents further collapse. This marks the initial stage of stabilizing the tunnel face

7.3 Roofing the Area

Generally, roofing is done using hollow pipes with a length of 4 meters and a diameter of 42 mm. These pipes are installed from the back chainage ribs to the face of the tunnel. They act as spilling rods, preventing rock mass spill and retaining broken rock pieces. Two layers of wire mesh are placed over the pipes. Once the collapsed area is fully roofed, shotcrete is applied to cover it. Vertical I-beam supports are also provided during roofing to prevent the pipes from falling. Additionally, large PVC pipes are installed from the roofing pipes to the crown of the tunnel, which will be used later for backfilling. Finally, after shotcrete application, the entire area is sealed.

7.4 Installation of Ribs

Installation of ribs should begin and continue up to the tunnel face. Ribs should only be installed in Unit A After rib installation, backfilling must continue, ensuring no voids are left in the crown or collapse area. Backfilling is done partially to prevent collapse due to the concrete load. Therefore, this area should be backfilled completely in sequence.

7.5 Installation of Rock Bolts

In collapse area the length of the rock bolt shall penetrate more than 2m inside the rock. The number of rock bolts shall be installed as per guidance of the engineer.

7.6 Installation of Fore Poles

After completing the installation of steel ribs and rock bolts, it is time to install fore poles. Fore poles are hollow, perforated pipes with a 42mm diameter and a length of 4m. These fore poles are installed after drilling around the periphery, from the crown to the spring lines, extending beyond the rock mass of the further excavation face. Drilling should start just above the last rib near the face or at a convenient location. After the installation of fore poles, all pipes are grouted to strengthen the ground inside the face, ensuring it can retain the rock mass and prevent further collapse.

7.7 Partial Excavation

After completing the treatment of collapsed area, it is time to proceed the face. Partial excavation of the face is advisable. If possible, it is better to excavate by breaker. Use of explosives is completly forbidden in such area. Excavating half of Unit A, the installation work of rib is started. Complete the rib installation by adding the other half of Unit A. It is necessary to install Unit A till the tunnel reach in safe condition. Fixing wire mesh and applying shotcrete must be completed in each installation of rib. Once Unit A is completely installed with full support, it is preferably installed ribs of Unit B. Installation of Unit B is taken place on one side only. It is recommended to excavate place for Unit B by breaker. Some 5 units or more of Unit B shall be installed in one side. After completing shotcrete and rock bolts in one side, Unit B in next side shall be started to excavate and ribs was installed. Parallel installations of Unit B on both sides are avoided.

Figure 4: At clock wise 1. Face sealing with muck, 2. Roofing in collapsed area, 3. Installation of ribs in Unit A and 4. Installation of ribs in Unit B

7.8 Full Excavation

After ensuring that there will be no problem in further excavation and that the collapsed area is fully supported and stable, the previously dumped muck must be removed. Before full excavation, a Ground Penetrating Radar (GPR) survey should be conducted. If any anomalies are detected, it is not advisable to excavate the full face. A breaker is recommended for full excavation; if that is not possible, then a smooth blast should be done. However, excavation should begin with single ribs until the collapse area becomes stable. The number of ribs can be gradually increased after some time.

7.9 Monitoring

Continuous monitoring is carried out till start of lining work. Different types of monitoring instruments such as MPBX, shotcrete-concrete pressure cell, strain gauge, load cell and piezometer are being installed from both sides for the continuous monitoring of the rock behavior.

8. Conclusion and Recommendation

The construction of the Mahadevtar Tunnel faced numerous challenges due to geological variations and weak rock conditions. The adoption of the NATM method and RMR system facilitated the identification and implementation of appropriate support measures. Continuous monitoring and adaptive strategies were crucial in addressing collapses, groundwater inflows, and weak rock masses. Future projects should consider enhanced geological investigations and adaptive excavation methods to mitigate similar challenges.

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