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Associated Risk and Rectification during TBM Tunnelling

Satya Prakash[1]
Vinay Kumar Pandey[2,*]

[1]*Gujarat Metro Rail Corporation Limited, Ahmedabad, India*
[2]*Geosystems Infrastructures, Mumbai, India*

**E-mail:vinay78pandey@gmail.com*

ABSTRACT

Tunnellingusing Tunnel Boring Machine (TBM) has recently become the mainstream approach for the construction of long tunnels by the international tunnel engineering community. Modern tunnel industry prefers the TBM tunnelling due to economical, no or less over-excavation, environment friendly, better working performance, safer construction and time saving methods. TBM tunnelling, on the other hand, has also experienced problem/risk in the areas where the geology along the tunnel has large variation, or when it encounters a fault or shear zone, a fracture zone or high-pressure water ingress. In such areas the construction speed may greatly reduce and even causes jamming of TBM.

In this paper, the risks involved during the TBM tunnelling with different ground conditions, pre and post risk assessment and rectifications with Indian case studies covering TBM risks and rectification have been discussed. It has also been attempted to suggest the preventive methods tominimize the risks during TBM tunnelling.

Keywords:TBM tunnelling; Ground sinking; Water seepage; Lining segment cracks; TBM Jamming; Grouting

1. INTRODUCTION

For surface space limitations in metro cities, tunnel is the best option worldwide for the development of modern transport system, utilities and other infrastructures. There are various tunnelling methods but for longer tunnels,tunnellingusing tunnel boring machine (TBM) is considered safe, economical, time saving, small over-excavation, better working environment, safer construction and produceless disturbance to the rock mass and the environment. TBM is a machine, which has revolutionized the tunnelling industry by making tunnelling a safer, more economical for longer than 2.5km and opening the possibility of creating tunnels where it was not feasible in the past (Spencer et al., 2009). TBM method has recently become the mainstream approach for the construction of long tunnels in the international tunnel engineering community.

All the time people have risks in their life. Most of people think that risks are bad events which will destroy the project or cause a bad effect, but that's not true at all. Risk may be a threat or an opportunity so it may bring good events in addition to bad events. TBM tunnelling also involves the risks depending up on geological, hydrological and mechanical factors. Type of TBM to be deputed at site would be finalized based on the subsurface geological, geotechnical & hydrological interpretation and project techno-commercial feasibility. Apart from well-defined geotechnical investigations, one cannot rule out the chances of risk, which may be encountered as geological surprises such as unexpected change in rock class, shear zone, clay gouge, high water pressure or water table, tunnel sinking, formation of cavity, tunnel alignment deflection, cracks/damage of lining segment and others. If the geological variability along the tunnel is large or encounters a fault or shear zone, a fracture zone or high-pressure water ingress; the construction speed may greatly reduce and even cause jamming of TBM. Based on the risk observed during TBM tunnelling worldwide, professionals have proposed the rectification measures.

In this paper, the risks involved during the TBM tunnelling with different ground conditions and pre and post risk rectification measures have been discussed along with the preventive methods to minimize the risks. To highlight the approach, some Indian TBM tunnelling case studies have also been presented.

2. RISKS DURING TBM TUNNELLING

Site geology and hydrology of tunnel are main factors for any risk during TBM tunnelling. One of the great difficulties in urban tunnel construction is the impact of underground structures on adjacent structures. Most of the problems are encountered due to lack of knowledge of the poor ground conditions/risk zoneswhich were not observed during preliminary drilling and investigations. This results in delayed response and lack of technology to tackle the risk. Common problem includes the frequency of cutter replacement due to increased wear or damage of the cutter, jamming or excavation of the cutter head, rapid influx of groundwater, collapse of the membrane surface or difficulty in maintaining the membrane pressure and ground subsidence. It is a reality that a considerable amount of money and time are spent solving these problems and repairing the equipment (Gharahbagh et al., 2011). For efficient construction on special ground, it is essential to understand the clear definition of the special ground, the problems that may appear on the ground and countermeasures.

2.1 Geology and Geotechnical Factors

Before starting of tunnelling, geological and geotechnical investigations need to be carried out along the tunnel alignment and the probable risk zone for TBM tunnelling shall be identified. Geological and geotechnical parameters help to finalize the TBM selection, tunnel design, construction period and cost estimation. Geology plays a very important role in tunnelling. Any adverse and unforeseen geological condition may influence the safety of tunnels, loss of life, construction time and costs.

Selection of the alignment, cross section, and construction methods is influenced by the geological and geotechnical conditions, as well as the site constraints. Good knowledge of the expected geological conditions is essential for smooth tunnelling. Tunnel alignment is sometimes changed based on the results of the geotechnical investigations to minimize construction cost or to reduce risks. The underground water regime can further influence the ground “properties” and potentially deteriorate the conditions under which the tunnel is going to be constructed. Unexpected and significant ground features, like faults, constitute a major risk during construction.

Geological and geotechnical investigations become very crucial under the varying geological conditions especially in the Himalayan region, where large size long tunnels are under progress. Tunnelling in the Himalaya is very challenging due to sudden variation in rock quality, presence of shear and fault zones, water seepage or high water ingress and high overburden thickness (sometimes 1200 m or more).

Today, many classification systems that can be used for tunnel design have been developed and supplemented, which provide important information for predicting the behaviour of the ground. The classification systems can be divided into two categories, i.e., soft ground and hard rock. Tunnel construction in the soft ground is targeted to soil or rock of sedimentary layers that exhibits soil-like behaviour. The types of soil, grain size & plasticity and mechanical properties (strength, strain coefficient, permeability coefficient, etc.) are utilized as factors for evaluating the ground condition, and these factors have been comprehensively synthesized to date.

Geophysical exploration data can be very useful in providing grounds for extrapolation to areas that could not be obtained by drilling surveys, provided that the data obtained from the drilling survey adequately supports geophysical exploration data. In addition, geophysical exploration data could provide information about potential hazardous areas, the location of the ground where additional drilling investigations are needed.

It is difficult to obtain sufficient geological and geotechnical information across the tunnel alignment. To investigate the probable risk area during the construction stage, one can plan additional advanced drilling/probe hole and geophysical exploration methods during tunnelling. The most widely used techniques are ground penetration radar (GPR), tunnel seismic profiling (TSP), electrical resistivity detection, and bore tunnelling electrical ahead monitoring (BEAM). Data collected during excavations are continuously updated and analyzed. It isbeing used to interpret and predict interior ground conditions (Lee et al., 2016). Probe hole during the tunnelling is common method to forecast the poor ground condition, water ingress, changing ground condition or rock strength and presence of harmful gases. During TBM tunnelling in Mumbai, where rock is basalt and volcanic breccia with varying rock class between very hard to very poor with sudden water seepage, probe hole from tunnel face at expected risk zone gave time for risk reduction and taking precautionary measures such as change in TBM torque, rotation speed, grouting or drainage hole for water divergence. If unexpectedly, rock mass strength increases from very poor to very strong (such as rock strength 25 MPa to 90 MPa) for long stretch, TBM cutter disk is changed to minimize the wear and tear and keep good rate of advance.

2.2 Risks Related to Different Ground Conditions

Table 1 summarizes the general concept of ground conditions and the problems that may occur while passing through this ground.

Table 1 - Risks related to TBM tunnelling with different ground conditions (Jeong et al., 2018)

S. No.	Ground Condition	General Ground Description	Risks/Problems Encountered
1	Mixed ground condition	Mixed of soft and hard strata	High cutter wear/damage; Low cutting efficiency; Ground loss
2	Cobble andboulder ground	Cobble and boulder in cohesion less sand and gravel	Improper cutter rotation and stalling, uneven and excessive cutter wear; Water inrush; Much lower than expected advanced rate; Screw conveyor damage
3	Fault/shear zone, weak ground conditionor highly weathered rocks of all types	Weak ground condition, crossing the fault or shear zone or highly weathered rock	Instability of excavated face/roof; Excessive over break; Cutter head jammed/damage; Large water inflow
4	Clay soil	Either exposed in full face or mixed face with sandy or silty soil	Cutter head clogging; Adhesion problem
5	Squeezing ground	Time dependent large deformation occurred around the tunnel associated with creep caused by exceeding a limiting shear stress	Shield blockage/jamming problem; Cracks in lining segments
6	Swelling ground	Advances into the tunnel mainly account of swelling or expansion of ground. The capacity of swell to be limited to those rock that contain minerals with high swelling capacity	Cutter Jammed; Affect the production cycle due to sticky property of muck; Cracks in lining segments
7	High in-situ stress	In area of high in-situ stress rock burst, spalling and collapse of tunnel	Instability of tunnel face; rock burst; unstable large block of rock causing abnormal cutter head damage
8	High water pressure	Common in under-sea /river /large water bodies/ deep buried tunnel	Water/soil ejected through screw conveyor; High water inflow
9	Karstic cavity	Mostly filled with clay and water	Breaking of groundwater under high pressure; Subsidence at urban areas; Destruction of tunnel lining; Degradation of grout curtains
10	Gassy ground	Ground containing different gases (noxious, flammable or explosive)	Threatening personnel health; Harmful to the equipment's used

3. RECTIFICATION OF TBM TUNNELLING RISKS

On the basis of previous work by various researchers, Table 2 has been prepared which shows the TBM tunnelling risk types and their pre and post mitigation measures/rectifications. Subsequently, Indian case studies highlighting the risks and their mitigation measures during TBM tunnelling have been discussed.

Table 2–Risks in TBM tunnelling and their mitigation measures

S. No.	**RisksType**	**Pre-mitigation or rectifications measures**	**Post-mitigation or rectifications measures**
1	Ground sinking	Identify the risk prone area and carry out ground strengthening work before TBM tunnelling	a) Ground to be filled with impervious materials, b) Grouting to be done from inside the tunnel, c) Cracks to be filled with grouts.
2	Water ingress	Identify the expected water body pocket	a) TBM to be moved in closed mode, b) Grout to be injected ahead of face, c) Mucking to be done at pro-active basis, d) Chamber is constantly filled with 60-70% spoil. Support and balance tunnel face with compressed air to minimize water ingress, e) More primary and secondary grouting required to avoid the seepage from segment joints, f) Bypass/divert the water through probe hole.
3	Jamming of TBM	Identify the (i) low strength rock mass in tunnel sections where the chances of large deformations would occur, (ii) cave-in section accompanied by water inundation (iii) Use of fore-poles, spiles, pipe roof etc. and/or ground improvement by roof grouting and/orfull face grouting.	a) In case of the cutter head jamming, the typical remedial measures were comprised of the pulling the TBM back to a short distance and cleaning up the debris. This was followed by refilling the cavities with shotcrete or cement mortar from the feed-in cabin on the cutter head. b) Jammed releasing methods- Bypass tunnel, Top heading tunnel.
	Cracks in lining segments	(i) Identify the loose/sheared/faulted zone with water (ii) Segments to be joined and grout without any mechanical issue and proper monitoring of water seepage/ cracks developed	a) Ground improvement to be required b) Grouting between the cracks or water seepage

On the basis of Table 2, it is observed that ground sinking, high water ingress and poor ground conditions are the most common reasons for the risk associated with TBM tunnelling. For rectification measures ground improvement, grouting, dewatering, bypass tunnel (for jamming of TBM) and filling of sink hole by impervious materials are main rectifications measures to be applied in different ways for prevention from risks. The site geological monitoring and probe hole in expected risk zone might provide information about the surprises and risks ahead; accordinglytunnelling technique shall be prepared. Best TBM tunnelling depends on geology, expected risk and their prevention by close monitoring with emergency response team.

Indian TBM tunnelling cases where different risks have been faced and successfully rectified are discussed risk vise in the following paragraphs.

3.1 Indian TBM Tunnelling Cases

3.1.1Ground sinking

Ground sinking is most probable risk that happens during the TBM tunnelling in weak ground condition or sudden loss of pore pressure of soil due to high water discharge in tunnel. Building collapse, cracks in existing structures, collapse/sinking of road or ground have the direct impact on public. Rectification measures, in general,include filling of collapse ground with impervious materials, grouting from inside the tunnel to consolidate the filled material and grouting the cracks in existing structures.

A) Kolkata metro rail

The tunnelling work for under-construction 16.60-km East West Metro Railway project - a part of which constitutes India's first under-river train line had encountered an unpredicted aquifer resulting in water and silt gushing in to the TBM (about 14 m below the ground level) and triggering serious subsidence on several roads in central Kolkata's Bowbazar area close to the city's bustling office and business hub Esplanade and Dalhousie. Aquifers, according to Kolkata Metro Rail Corporation Limited sources, are bodies of permeable rock, sand or silt which can contain or transmit groundwater. The seeping water mixed with the soil led to the settling of ground surface, which in turn resulted in the partial collapse and cracks in the buildings. At least 10 buildings developed cracks on August 31, 2019; the number increased to 20 the next day and climbed up to 52 till September 3, 2019, prompting authorities to shift more than 400 dwellers to hotels or guest houses in the vicinity. Two buildings collapsed completely.

B) Chennai metro rail

On April 09, 2017, a sink-hole has been suddenly appeared on Anna Salai road, Chennai. An MTC bus and a car were devoured when the road suddenly caved-in creating a with 0-5 meters wide, 0-10 meters long and 0-2 meter deep hole.Sink hole as per the representative of Chennai Metro Rail Limited (CMRL) was due to existing loose soil pockets along the tunnelalignment where the tunnel boring machine (TBM) was operating. Chennai coast has many sedimentary deposits, which comprise of soft materials prone to settle easily and hence increased chances of ground settlement. CMRL has adopted a strict instrumentation scheme for monitoring of ground settlement/deflection induced by the on-going tunnelling work.

3.1.2Wateringress

In case of high water ingress during tunnelling, TBM needs to be operated in fully close mode maintaining air pressure of 2-2.5 bar constantly to reduce the water ingress.The chamber was constantly filled with 60-70% spoil to support and balance the tunnel face with compressed air to minimize the water ingress. The excess water was diverted through probe holes.

Polymerwas injected in chamber to consolidate the spoil into clay paste type consistency. To reduce the spillage of muck at ring erection area, instead of discharging spoil on belt conveyor; anMS pipe was installed at discharge gate with air compressor connection and the outlet of this pipe was directly done in muck skip.

A) Mumbai underground metro

Various locations in Mumbai Underground Metro have observed the high water ingress problem. During TBM operation at Marol Naka underneath the Andheri- Kurla road and crossing the Mumbai Metro-1 flyover where area comprises of Volcanic Breccia & Basalt rock. Basalt is good strength rock, but Breccia is moderately to low strength rock. As TBM reached underneath the road, minor water seepage started but no drop down in water table was observed. As TBM was moved further, intensity of water increased and during the ring erection maximum water pressure reached up to 4.5 bar and as chamber were opened for mucking, muck floated in tunnel. Cleaning the muckat high face pressure was critical issue and civil contractor suffered a lot. The methodology adopted in Kolkata metro was repeated here to combat with the high water ingress.

Another location of Mumbai underground metro faced the large amount of water inflow observed in both down and up line tunnels as alignment approaches close to the sea. The maximum water discharge was recorded as 800-1200 l/min. Due to high water pressure, grout behind the segment washed out over the front shield, which might have resulted in partial damage to the tunnel walls. Initially, tunnelling team did huge amount of grouting to control water but all in vain because high water pressure washed out the grout material every time. After several efforts, it was decided to continue the tunnel drive for another 10 m so that fresh rock will come and may be water can deviate from the face to the sides of tunnel. After 10 m of drive and ring built PU grout has been done at about 03 rings before the last ring and it will work as bulk head for grout. Similarly, a PU grout bund has been madebefore 50 rings behind. Also the decision to change the grout mix design by reducing the gel time without compromising the viscosity of grout and increasing the quantity of cement has been taken. After the systematic grouting have been done through the grout socket in the segment which resulted in controlling the water ingress effectively inside the tunnel.

B) Parbati hydroelectric project Stage II

In Parbati hydroelectric project Stage II, district Kullu in Himachal Pradesh, 9.05 km out of 31.5km headrace tunnel (HRT) was planned to excavate by TBM. The project is being constructed by National Hydroelectric Power Corporation Ltd (NHPC). The HRT passes through very close to Main Central Thrust (MCT), the rocks along HRT have undergone intense compression and thus are folded, faulted, foliated and jointed which is the typical characteristics of the Himalayan rocks.

The TBM section of HRT mostly comprises of granites/gneissose granites followed by quartzites. Bands of biotite schist, talc chlorite schist or metabasics were expected along the entire length of the TBM drive. The granites are hard and massive exhibiting well-developed foliations in some areas (Madan and Kumar, 2004). Total overburden along the TBM section varies from 100m at Hurla Nala (near Adit 2) to 1300m.

The initial reach of the TBM comprised of gneiss with schist bands and minor quartz lenses which were supported by rock bolts and wire mesh. The rock formation then changed to schistose gneiss with bands of chlorite schist, sometimes weak and highly jointed. Due to highly jointed rock, a 6.0 m x 2.5 m rock blocks were detached from crown portion at chainage (Ch.) 748m. The rock bolter could not access the cavity and pre-grouting was not possible because of tight joints. To tackle this problem, the ring beam had to be installed and the rock was supported with channels and girders. The cavity was back filled with concrete. The treatment work took about three weeks (Goel, 2014).

The failure on several gripper cylinders in the end of year 2004 caused approximately 8 weeks of down time. The unfavorable rock conditions like rock bursts and large over break were encountered in gneisses and quartzites. This has resulted into immediate requirement of rock support using steel ribs, fore poling, steel channel lagging and back filling with shotcrete. As the work progressed, the rock conditions got even worse, as several mica schist bands were encountered. These resulted in numerous over breaks requiring closely spaced (0.4 m c/c) steel ribs, lagging, fore poling and shotcrete immediate behind the cutter head. Significant convergence of tunnel walls was observed as well, requiring additional rock support behind the grippers. These measures further decreased the TBM progress (Sengupta et al., 2008).

In May 2007, routine probe drilling ahead of TBM tunnel in sheared and faulted quartzite having 900m overburden punctured a water bearing horizon which resulted in inflows of water of over 120 l/s containing about 40% sand and silt debris. The inflow was sudden and occurred at a high pressure which could not be contained. Eventually, over 7500m^3 of sand and silt debris buried the TBM. The project supposed to be commissioned in 2007 delayed for about 10 years (Goel, 2014).

3.1.3Jamming of TBM

Lee et al. (2019) and Shen et al. (2005) have discussed in details rectification measures for jamming of TBM during tunnelling due to fractured or poor ground condition. Mainly three types of failure modes for the stalled TBMs were identified, namely: (1) the cutter head jam, (2) the shield body jam, and (3) the burial of entire TBM.

In the case of the cutter head jamming, the typical remedial measures comprised pulling the TBM back to a short distance and cleaning the debris. This was followed by refilling the cavities with shotcrete or cement mortar from the feed-in cabin on the cutter head. If the jamming occurred between the telescopic shield and the cutter head, the remedial measures included excavating a bypass tunnel, relief excavation of the telescopic shield, and pilot geological exploration. If jamming occurred at the rear shield, relief excavation at the rear shield and extension of the over-mining backwards and drilling relief holes was required. Worst of all, if severe cave-ins were accompanied by water inundation and debris flow and this resulted in the breakdown of the TBM, excavating bypass tunnels from the side wall of the main tunnel behind the stalled machine was necessary in order to rescue the buried TBM.

The Himalaya presents significant tunnelling challenges, especially for TBMs, due to the difficult geology, weak zones, in-situ stresses and groundwater. Hydro projects that have experienced difficulties with TBM applications in the past include Dul-Hasti and Parbati-II projects, where gripper shields were deployed.

A) Dul-Hastihydroelectric project

The project is a run-of-the-river scheme, constructed on river Chandra, a tributary of river Chenab in Kishtwar district in Jammu & Kashmir, having capacity of 390 MW built by National Hydroelectric Power Corporation Ltd (NHPC). The main components of the Dul-Hasti power project are a 65m high and 186m long concrete gravity dam across river Chenab, a 10.6km long head race tunnel, a restricted orifice type, 18.25m diameter and 90m high surge shaft, one 6.7m diameter and 311.4 m long pressure shaft, an underground power house and a 7.46m diameter and 307m long tail race tunnel. Due to non-availability of a feasible site for an intermediate adit, it was decided to bore 6.75km upstream portion of 10.6km long tunnel using TBM with the finished diameter of 7.7m and remaining portion of the tunnel using drill and blasting method with the finished size of 7.46m horse-shoe shape. The construction was started in the year 1994-95 and completed in year 2007.

The project lies within lesser Himalayan zone and is characterized by a unique plateau like feature with Schists and Gneisses on the western side and Quartzites and Phyllites on the eastern side. Kishtwar regional fault divides the plateau into two lithological units. The power house and part of downstream HRT lie within Schists and Gneisses formation whereas the dam complex and upstream HRT rest in Quartzites and Phyllites sequence. The tunnel has number of small and major faults and shear zones having crushed gouge material. The interesting geomorphic feature of the project is fossil valley area. The detailed investigation carried out by NHPC has revealed that the fossil valley is filled up with lacustrine deposits comprising of sand, silt, clay and pebbles (Sengupta et al., 2008). Poor rock mass was expected during tunnelling, but the rock mass and ground water conditions encountered during construction were much more severe than expected. Variation in rock characteristics, existence of cavities, shear zones with crushed material and charged with high water pressure resulted in very less progress.

The TBM excavation faced many problems resulting in time and cost overrun. The major problems encountered were as follows (Goel, 2014):

- TBM had the facility of drilling advance probe holes of 50m length over crown portion of the tunnel. However, blow out at three closely spaced locations at invert sprang a surprise. The blowouts carried slushy discharge of 700l/s in the beginning and further increased to 1100l/s. This was later stabilized to 50-70l/s. The water also carried and deposited about 2500m^3 to 3000m^3 of muck comprising of sand, silt and pebbles. The blowout caused extensive damages with four motors and loco buried in the muck. The presence of full faced TBM left little scope for further investigations. No attempt had been made to choke the crater as this would have resulted in building up pressure. The crater was filled with boulders and graded material with wire mesh to prevent movement of material while the water had been allowed to free flow. Pumping arrangement was made to pump undesired quantity of water. This led to loss of around 4 months (Sengupta et al., 2008).
- Presence of pebbles and cobbles increased the consumption of cutters in six folds during excavation as compared to the consumption in ideal rock mass (1 cutter/m). Later, the consumption of cutter was brought down to 2 folds by NHPC- JSA JV.

- Due to poor geology, high water ingress and mechanical damage, the TBM tunnelling was abandoned after excavation of 2.86km long tunnel stretch and remaining tunnellingwas done using conventional methods. The experience of TBM in this project in Himalayan geology was not at all encouraging. The project is now commissioned and the commercial production started in April 2007.

B) Kishanganga hydroelectric project

The 330 MW Kishanganga hydroelectric project located on river Kishanganga, a tributary of Jhelum river, in Gurez valley to Bonar nallah near Bandipora in J&K State, India. About 14.75km out of 23.65km long head race tunnel was proposed to be constructed by TBM and the remaining 8.9km long tunnel is constructed by conventional drill and blast method. This is one of the longest HRT in India with maximum overburden of 1400m above tunnel. The HRT passes through andesite, phylliticquartzite, meta-siltstone and meta sandstone rock types through rock cover ranging from 400m to 1400m. Tunnelling in high rock cover zone is a real challenge due to squeezing and other geological problems. The rock formations have four to five joint sets along with the foliation plane. The rock masses along the tunnel also traversed by folds, shear zone and faults making the media more problematic. Together with the ground water the tunnelling was very difficult.

After launch of TBMin April 2011, the first 1.5km of the drive proved to be difficult. There were difficult ground conditions, unforeseen in the geotechnical baseline report, and the heading encountered Class-V rock mass (RMR<20). The crew had to struggle with unstable ground jamming the shield and blocking the cutter-head. A bypass tunnel was excavated manually over top of the TBM on three occasions - once in a shear zone where the overburden was 650m (Tunnel Talk, 2014).

Having been prepared for dealing with the geological surprises, the deployed TBM had the double shield fitted with top hatches near the rear of the machine to allow hand-dig towards the cutter-head. Other measures to mitigate geological challenges included ground consolidation with self-drilling bolts and foam and resin grout injections to fill cavities. Squeezing conditions and difficult fault zones were encountered during TBM tunnelling, which were successfully tackled. Extensive consolidation grouting is carried out in the difficult/worse geological sections. It is understood that TBM experienced crew was experienced enough to handle the adverse ground conditions associated with long reaches through weak zones in mountainous regions under high overburden in this HRT (Goel, 2014).

C) Tapovan-Vishnugad hydropower project

In TapovanVishnugad hydropower project (520 MW), Uttarakhand, India constructed by National Thermal Power Corporation Ltd. (NTPC),about 8.6km out of 12.1km long HRT wasplanned to be excavated by TBM. The project area consists of high grade metamorphic rocks belonging to Joshimath and Tapovan formations of the Central Himalayan Crystalline series. The rocks are mainly quartzites, gneisses, augengneisses and mica-schists. Three to four joint sets are present. Since the tunnel site has the main central thrust (MCT) in the vicinity and Himalaya is a tectonically active region, number of small or big shear zones and faults are also expected along the tunnel alignment. Presence of ground water in the tunnel and geothermal springs were also expected. In presence of water, mica schists and gneisses may be altered to clay. Hence clays were also expected during tunnelling. Overburden above the HRT reaches to 1100m. Therefore, there were chances of encountering various adverse conditions leading to squeezing, roof falls, chimney formations, water-in-rush, rock burst, spilling, etc. in the tunnel.

The tunnelling underway in Himalaya under complex and varying geological setup along with instances of rock wedge movements and high volume water inflows. In December 2009, at TM 3016m (RD 9317m), as the TBM entered into faulty, heterogeneous ground, a major wedge, moved out of the rock mass formation onto the front of the TBM. The wedge caused denting of up to 150mm and immediately stopped the TBM. Subsequent attempts to free the machine manually with very high thrust forces failed. By the following day, massive surge of slushy groundwater started to enter the tunnel under considerable pressure at the tail skin area and commenced further backwards into the annulus of the completed but not yet grouted segmental lining, washing out the pea gravel and filling fault breccia material into the gap. The high build-up of water pressure then caused the failure of two roof segments, allowing a massive inrush of water, about 700-800l/s, as well rock (fault breccia) material into the TBM area. The water ingress steadied to around 100-120l/s. The problem was addressed by excavation of about 180m of bypass tunnel (BPT) to reach on top of the dent and repair the damaged TBM shield from outside and divert water from the TBM to BPT through a D-shaped 2m x 2m drift (Saxena, 2013). A systematic diagram (Figure 1)shows action to improve the poor rock tunnelling ahead (by drill and grout) and retrieving of TBM face after jamming of cutter head.

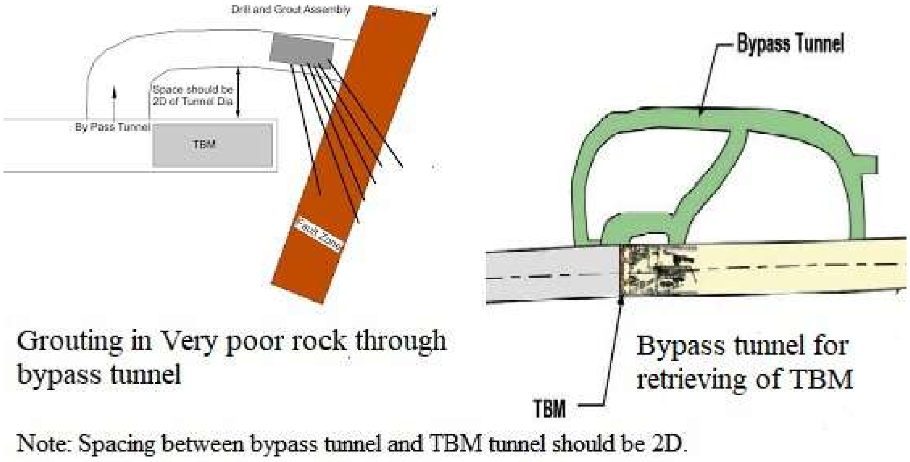

Figure 1 - Bypass tunnel for retrieving of TBM and grouting in poor rock

The second and third trapping events happened in February and October 2012 at Ch 5840 & 5859m respectively in 20m wide fault zone at a depth of about 700m. This fault zone lies at a very acute angle to the tunnel axis so that the TBM had to drive through this zone for at least 35m.

When the second event occurred, the face and surrounding conditions were initially dry and due to over excavation and collapse a cavity of large volume had developed around the cutter head and front shield of the machine in the soil-like stiff clay-rich fault gouge and breccia.

As in the first trapping event, water inflow (1-2l/s) started some 20h later. The situation then greatly deteriorated as the water rapidly eroded the water sensitive fault gouge and breccia causing further cavity development, ground creep and ground in-flow through the cutter head and shield openings trapping the TBM (Millen, 2014).

3.1.4Cracks in lining segments

Development of cracks in lining segmentsis a common risk occurring in tunnels. Yubing et al. (2017) have studied in detail the probable causes of segment damage and found that after being precast in the factory, the reinforced concrete lining segments will be influenced by various factors before the installation within the shield machine. Mishandling or transport without proper safety may lead to the damage and cracking of shield tunnel lining. The statistical data, as depicted in Figure 2, showed that there are mainly six reasons that will give rise to the damage and cracking in lining segment before the construction and completion of the tunnel. It is clearly shown that the top three causes, i.e. the assembly of lining ring (38.2%), the attitude deviation between shield machine and assembled tunnel linings (21.6%), and the non-uniform jacking forces (18.5%), all arise during segment installation and tunnelling process.

Some segments cracked or deviated after the installation in tunnel. A possible excessive deviation of adjacent segments of a support ring or adjacent rings from their proper position can cause problems to the segmental lining performance in terms of (a) water tightness and (b) structural integrity.

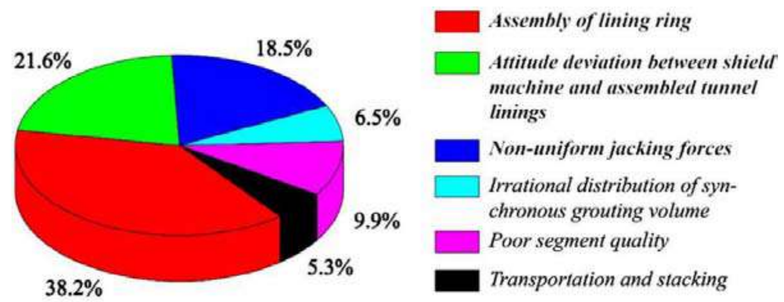

Figure 2 - Causes of segment damage and cracking (Yubing et al., 2017).

Concerning water tightness of a specific connection between adjacent segments or rings, this is generally depending on:

- The deviation (step) of the adjacent rings as regards the horizontal offset of the gaskets,
- The deviation (lip) of the adjacent segments of the same ring as regards the horizontal offset of the gaskets,
- The gap in relation to the proper (completely closed) position of the gaskets,
- The applied water pressure and the type of the surrounding soil in terms of permeability, and
- The existence of cracks in the vicinity of the gaskets that may allow water ingress, detouring the gasket, even in cases when the gasket itself is sufficiently waterproof.

Water tightness problems of specific joints and corresponding water seepage can be aggravated due to any of these factors. Increased segment steps and/or lips can cause water ingress, even with very low gap values. On the other hand, increased or even excessive values of steps/lips and/or gaps may not be recognized as water tightness problems, if the water table lies below the position of these deviations. Cases of cracking due to eccentricity (existing steps/lips) or any other reason during TBM advance can cause water tightness problems, even in cases when the applied water pressure is low and the segment gaps (joint width) are minor or even absent.

Concerning structural integrity, this has to be evaluated in terms of the additional loading posed on the segmental lining due to the offset of adjacent segments or rings. This possible offset causes eccentricity (creation of increased stresses in the concrete, due to the smaller contact surface between adjacent segments) which may become critical during tunnel construction, when large horizontal loads are applied on the segmental lining due to the TBM thrust forces. During tunnel operation, possible horizontal loads on the segmental lining are not significant compared to the thrust forces.

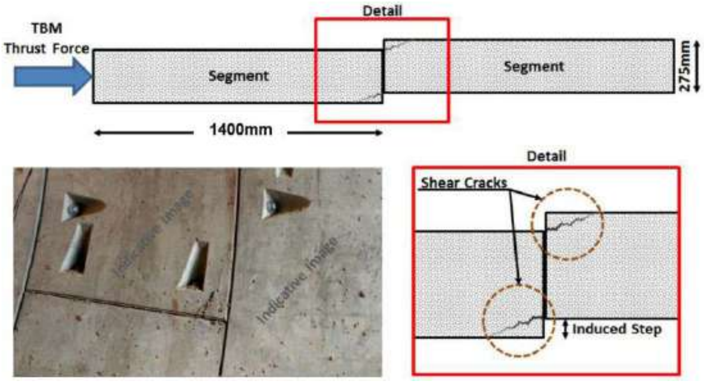

Figure3 -Sketch of spiling initiation mechanism due to segment step and excessive thrust forces

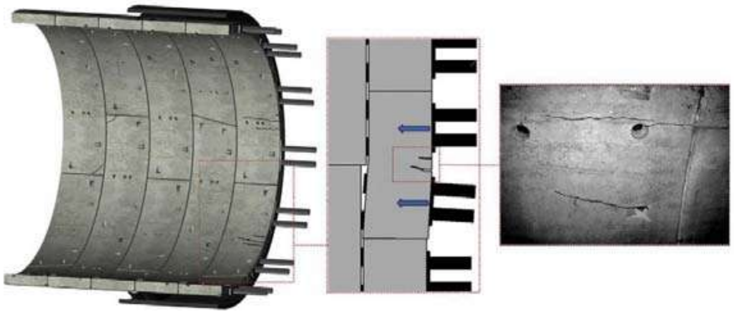

Figure4 -Damages observed due to contact imperfections (Cavalaro et al., 2012)

For repair of the segment from cracks it would be necessary to apply the remedial measures based on causes of damage in segment, which follow the following steps:

I. Distinction between micro cracks and damage cracks need to be made for already installed segment.
II. Micro cracks (in general smaller than 0.2mm) with in the groove need no repairs since filled with glue.

III. Damage cracks within the groove may be penetrated with epoxy resin of low viscosity/ or with other favourable approved material for total crack sealing.
IV. Primary and secondary grouting of the annulus of a segmental ring may provide some short term relief to leaks but will not provide a long term seal against water penetration because the grout will crack.
V. Annulus grouting pressure also impose loads on the lining leading to opening of minor cracks. Care is to be taken during grouting to reduce the possibility of damage to the ring by these loads.
VI. Gaps between the segment and precedent ring / contact deficiencies need to be minimised to avoid unequal thrusting reaction acting on the segments.
VII. Position of the jacks & segments need to be checked and the bolts location to be avoided.

3.1.5 TBMalignment deflection

During the excavation / advance phase the position of the TBM shall be continuously checked against the designed tunnel axis (DTA) to prevent undesirable movements of the machine and sudden changes in direction. The driving performance of the TBM is affected by the properties of the medium to be excavated. In soft material, the reaction of a machine weighing several hundred tons is quite different from a hard rock environment. In narrow radii, the required course corrections are more drastic, and therefore are more difficult, than on straight runs. The irregular locally excessive thrust on specific pads is due to steering actions for correcting the TBM alignment or excessive boring speed.

The purpose of the navigation system is to enable the TBM to negotiate accurately along the desired alignment ensuring also enough clearance between the extrados of the newly built ring and the intrados of the tails to reduce the risk of damaging the ring. The position of the TBM shall be determined on basis of the position in the global coordinate system (X, Y, and Z) of two known points:

(i)laser theodolite; (ii) backside prism.

TBM’s three-axis orientations in the underground space are crucial to machine steering control. The TBM positioning solution combines four functions: (i) TBM tracking automation through surveying-computing integration; (ii) wireless data communication enabled by wireless sensor networks; (iii) “virtual laser target board” program for TBM guidance; and (iv) real-time visualization of tunnel construction in a 3D environment.

For significant variation of thrust, forces must be applied for the streering reasons, i.e. in order to correct the TBM alignment. In such cases, the distribution of the applied thrust force on the pads is highly uneven, as few pads are taking increased loads to correct the alignment of the machine.

In the event of out-of-tolerance deviations from the DTA, the signals system reveals the event to the TBM operator and all users in the visualization screen. The direction of the TBM can be managed during the advance in two manners:

- Differential control of the thrust rams pressures on the six sets of rams;
- Control of the front (active) articulation ram extensions to steer the cutter head.

The system then can guide the TBM back to the DTA tangentially acting as a basis for the ring erection module (figure 5). This calculates in advance the segmental rings required following the correction curve, taking also into account parameters such as tail clearance, TBM position and allowed segment position combinations.

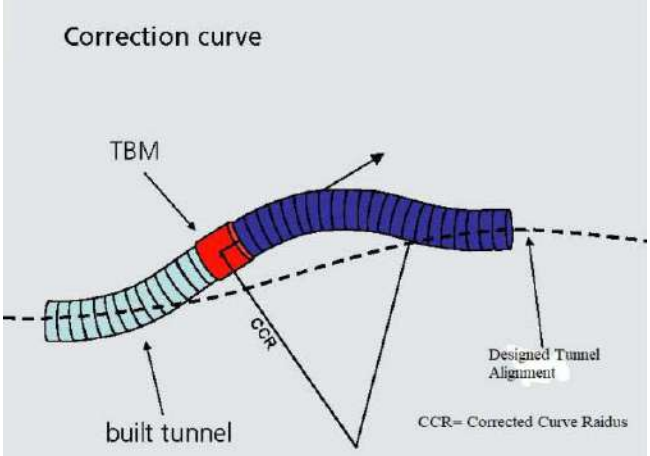

Figure 5 - Correction curve is implemented to guide the TBM back to the DTA

A) Mumbai underground metro

During the TBM tunnelling in Mumbai underground metro line-3 at one section, it was observed that TBM had tendency of going outside the tolerance limit i.e. 100 mm both side in horizontal and vertical planes. Then tunnelling team had adopted the following rectification measures:

- The articulation angle was increased from 1.20° to 1.40° as TBM was designed to work in thisradius and TBM was brought back gradually with in tolerance limit.
- The key selection was done carefully so that TBM shield should be oriented in the designed alignment.
- The propulsion rams (thrust jack) acting on leading edge of the last ring was monitored.
- Advancing process was strictly monitored to avoid axis deviation caused by advancing and ground subsidence.

4. CONCLUSIONS

Now TBM tunnelling is not new and there are various case studies for different type of risk with rectification methodology based on site geology and other limitations. But,it is suggested to adopt ‘prevention is better than cure’ approach and following the tunnelling process step wise.

Risks related to TBM have taken place due to poor ground condition, high water seepage, ground sinking, collapse of ground and existing ground structures, squeezing and swelling ground, cracks in segment and jamming of TBM. All these risks have been controlled or minimized through proper ground study; identifying the risk prone areas; closed monitoring during tunnelling and quick response with proper rectification techniques when an indicative or problematic zone is encountered.

Grouting and long-term close monitoring is better rectification for most of the risks and driving of bypass tunnel and heading shaft is final rectification, if TBM gets jammed. The site geological monitoring and probe hole in expected risk zone might save the risk surprises and give us time to be ready for rectifying the tunnelling activities. Best TBM tunnelling method depends on geology, expected risk and their prevention by closed monitoring with emergency response team.

References

Cavalaro, S.H.P., Blom, C.B.M., Walraven,J.C. andAguado, A. (2012). Structural analysis of contact deficiencies in segmented lining, Tunnelling and Underground Space Technology, 26(6), pp.734-749.

Gharahbagh, E.A., Rostami, J. and Palomino, A. M., (2011). New soil abrasion testing method for softground tunnelling applications, Tunnelling and Underground Space Technology, 26, pp.604-613.

Goel, R. K. (2014). Tunnel boring machines in the Himalayan tunnels,Indorock2014: 5th Indian Rock Conference 12-14 November 2014, pp.54-67.

Jeong, H., Zhang, N., Jeon, S., Jeon, H., Fun, I. and Seokwon, A. (2018). Review of technical issues for shield TBM tunneling in difficult grounds- Technical considerations for the construction of shield TBM on special ground,Tunnel and Underground Space, February, pp.1-24.

Lee, C.H., Chiu, Y.C. and Wang, T.T. (2019). Countermeasure of jammed TBM in rock tunnel excavation: Feedback from two cases studies, Tunnels and Underground Cities: Engineering and innovation meet archaeology, architecture and art – Peila, Viggiani& Celestino (Eds) Taylor & Francis Group, London, pp.3911-3920, ISBN 978-1-138-38865-9.

Lee, K.H.., Seo, H.J., Park, J.J., Park, J.H. and Lee, I.M. (2016). A probabilistic assessment of ground condition prediction ahead of TBM tunnels combining each geophysical prediction method, J. Korean TunnUndergrSp Assoc 18(3), pp.257-272.

Madan, M.M. and Kumar A. (2004). Tunnel boring machine (TBM) for construction of Parbati project tunnel – Problem faced during commissioning and suggestions for future projects, Proc. Int Conf on Tunnelling Asia 2004, December, New Delhi, India, pp. 45-61.

Millen, Bernard (2014). TBM tunnelling in the Himalayas, Tapovan-Vishnugad Hydroelectric Power Plant, India, ESCI Seminar Series, March, Salzburg, Austria. Source: www.victoria.ac.nz/sgees/about/events/esci-seminar-series-tbm-tunnelling-in-the-himalayas,-tapovan-vishnugad-hydroelectric-power-plant,-india.

Saxena, P.K. (2013). Tunnelling in the Himalayas, Construction World, Downloaded on 17.9.2014, Source: www.constructionworld.in/News.aspx

Sengupta, S.K., Saxena, P.K. and Bakshi, S.S. (2008). Tunnel boring machine in India experience, prospects and challenges, Proc. World Tunnel Congress, Agra, India, pp.1544-1551.

Shen, T. Y., Lee, P. S. and Yu, C. (2005). Failure modes of TBM and remedial measures used in the Hsuehshan Tunnel, International Symposium on Design, Construction and Operation of Long Tunnels, Taipei, Taiwan, pp.373-381.

Spencer, M., Stolfa, A., Bentz, E., Cross, S., Blueckert, C., Forder, J., Wannick, H., Guggisberg, B. and Gallagher, R. (2009). Tunnel Boring Machines, IMIA Conference Istanbul.

Tunnel Talk (2014). New award follows Seli Kishanganga success, May, Downloaded on June 12, 2020.

Yang Yubing, Zhou Biao, XieXiongyao and Liu Chao (2017). Characteristics and causes of cracking and damage of shield tunnel segmented lining in construction stage - a case study in Shanghai soft soil, European Journal of Environmental and Civil Engineering, pp.1-15.