Best Practices, Challenges, and Risk Management in Tunnelling

HOWDEN

Introduction

The rapid urbanization and exponential population growth in metropolitan cities have led to an increased demand for efficient and sustainable public transportation systems. Among the various modes of urban transit, metro rail systems have emerged as a reliable and eco-friendly solution to mitigate surface congestion, reduce vehicular emissions and enhancing urban mobility.

However, the planning and execution of underground metro projects, particularly in densely populated urban centres, involve highly technical, environmental and socio-economic challenges.

Deep underground metro construction is inherently complex due to a range of uncertainties associated with geological conditions, existing urban infrastructure and stakeholder coordination.

Projects of this nature often face significant risks including ground settlement, water ingress, tunneling-induced vibrations, delays due to public safety concerns. India’s megacities, such as Mumbai, have witnessed large-scale metro development initiatives aimed at transforming urban transit infrastructure.

This study aims to evaluate the risks associated with underground metro construction, focusing on their identification, assessment and mitigation strategies. The comparison of construction methodologies such as the Tunnel Boring Machine (TBM), Cut-and-Cover and New Austrian Tunnelling Method (NATM), has the best practices for innovative solutions that enhance project safety, sustainability and efficiency.

Risks in underground metro construction are typically categorized into:

- Geotechnical
- Environmental
- Technical (Design & Execution)
- Financial
- Legal
- Socio-Political Domains

This newsletter will provide insights over multiple areas of loss controls and risk management along with:

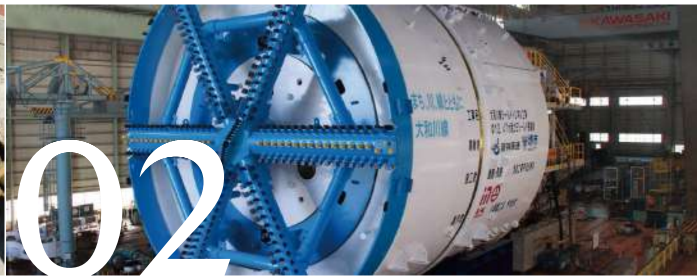
- Methodology of Tunnelling
- Hazards & Risks
- Loss Analysis
- Risk Engineering Management
- Case Study: SLBC Tunnel

Methodology of Tunnelling

There are multiple ways of construct a tunnel beneath the ground level, some of the major ones are as discussed follows:

Cut & Cover Method

This method is adopted in shallow tunnels, especially in areas where disruption is acceptable.

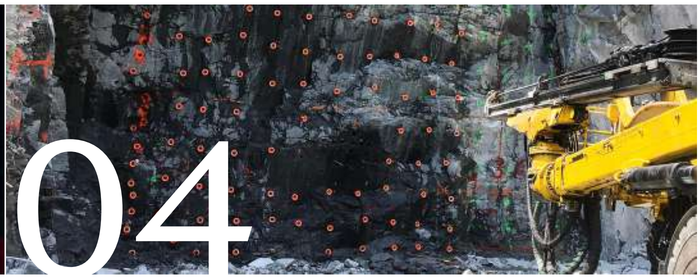


Tunnel Boring Method

This is adopted in deep tunnels at urban areas with minimal surface disruption.

New Austrian Tunnelling Method (NATM)

NATM relies on the inherent geological strength of the surrounding rock mass to support the tunnel & Project.



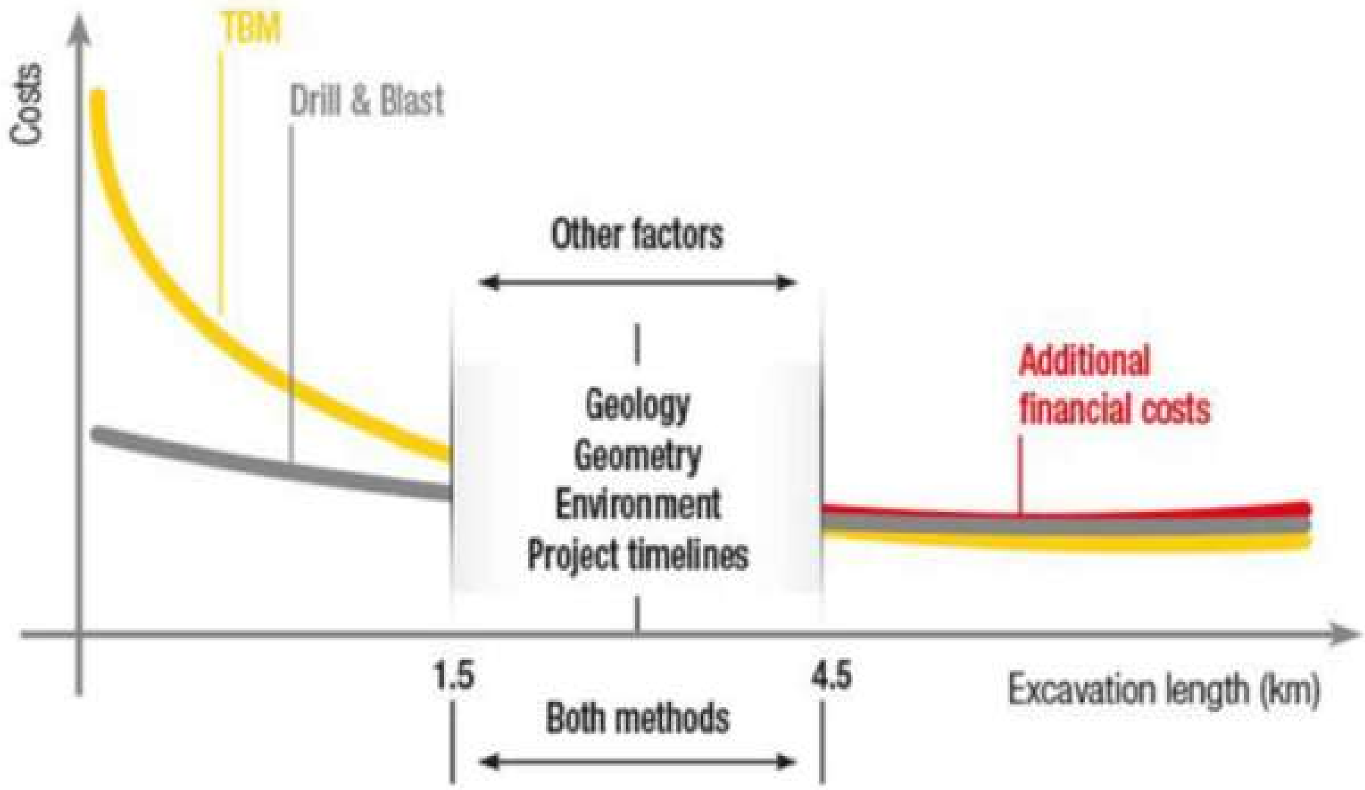
Drill and Blast Method (DBM)

Adopted in Hard rock conditions.it is flexible and relatively low-cost method and produces vibration and noise.

Immersed Tube Tunnelling

Adopted for precast tunnel sections and underwater construction crossings the rivers

Depending upon the multiple factors of projects such as length, depth of excavation and the cost related for the entire project appropriate calls can be made as per the following figure, there are areas where multiple tunnelling methods can also be adopted basis the requirement.



Tunnel hazards & risks

Identifying hazards and risks, along with determining the level of risk and how it is to be controlled, should be a continuous process that starts at the procurement, planning and design stages and is continued by the contractor and designer through the construction stage of the project into the operation and maintenance stage of the asset.Major hazard and their pertaining risks are mentioned as follows:

Geology	- Data deficiencies in ground investigation schemes - Weak ground zone and macro-geological features - Stratification and crown formation mechanics - Geotechnical baseline report (GBR)
Methodology	- Cutterhead clogging and torque spikes in rotary machines - Tail-skin seal failure - Sequential face uncoupling - Dynamic shockwave overpressure - Rock bursting and spalling - Retaining wall deflection - Strut and tie structural buckling
Approach	**Tunnel Face Stability and Support Measures Under Uncertainty** - Pipe umbrella systems - Limit analysis kinematic formats - Hydro mechanical coupling method **Proposed Instrumentation & Monitoring Coupled with "Realistic" Trigger Levels** - Kinematic-based deflection thresholds - Automated geotechnical instrumentation gantry **"Realistic" Estimation and Simulation of Overall Exerted Stresses on the Tunnelling Profile** - Automatic geo-technical instrumentation gantry - Long-Term longitudinal stress redistribution - Hyperstatic restraint segmental ring design
Project Execution	- Robust construction management plan (CMP) - Logistical supply-chain synchronicity - Emergency response and intervention protocols (ERIP) - Adherence to the approved design and method statements - Composition and qualification of the key project personnel and workforce

TBM Operations

Mechanical Challenges

- Moisture and Humidity Damage
- PLC Communication Failures
- Encoder Misalignment
- Overheating Drives

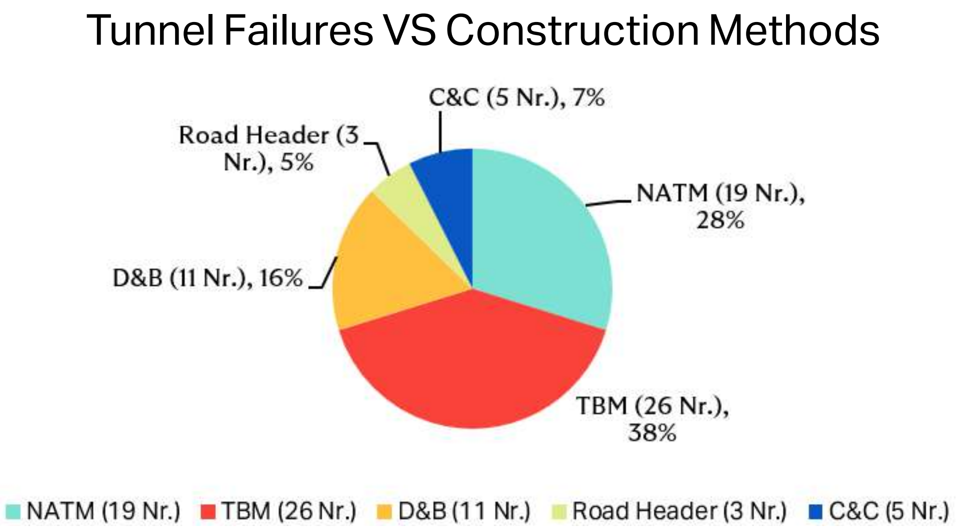
Ground Condition	General Description	Problem Encountered
Mixed Ground Condition	Mix of Hard and Soft Strata	High Cutter Wear Damage, Low Efficiency, Ground Loss
Cobble & Boulder Ground	Cobble & Boulder in Cohesion and Less Sand and Gravel	Improper Cutting Rotation & Stalling, Uneven Wear & Tear, Water Inrush, Conveyor Damaage
Weak Ground Conditioner, Fault Zone, Weathered Rocks of All Types	Weak ground condition, highly weathered rocks	Instability of excavated roof/ face, Over Break, Damaged Cutter Head, Water inflow
Clay Soil	Exposed in Full face or mixed face with sandy or silty soil	Cutter head Clogging, Adhesion Problems
Squeezing Ground	Time dependent large deformation occurred around the tunnel associated with creed caused by exceeding a limiting shear stress	Shield Blockage/Jamming Problems, Cracks in lining segments
Swelling Ground	Advances into 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, cracks in lining segments
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
High Water Pressure	Common in under-sea, river, large water bodies, deep dried tunnels	Water/Soil ejected through screw conveyor, Water inflow
Karstic Cavity	Filled with Clay and Water	Breaking of Ground Water under high pressure, Subsidence at urban areas, destruction of tunnel lining, degradation of grout curtains
Gassy Ground	Ground containing difference gases which are flammable or explosive in nature	Threatening personnel health, harmful to equipments used

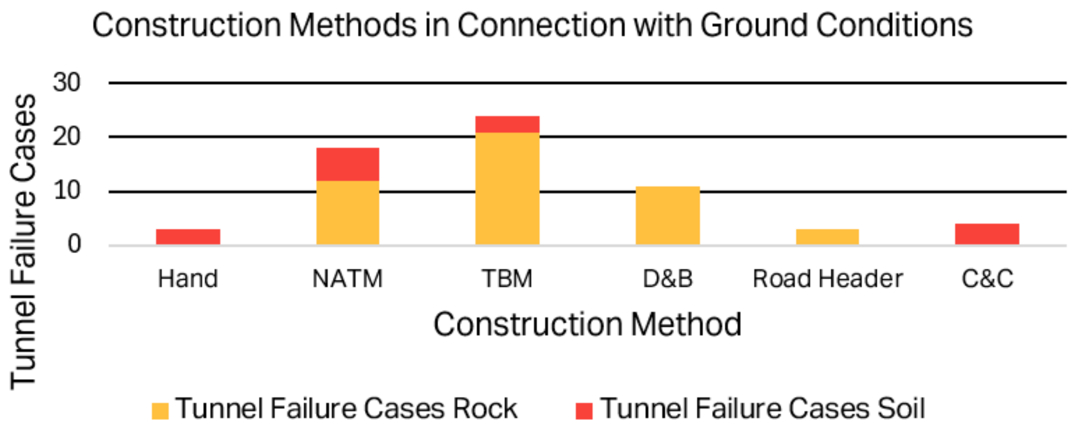
Tunnel losses analysis

Analysis of historical tunnel loss events shows that tunnel risk is not evenly distributed across failure modes, construction methods, or ground conditions. Instead, losses tend to cluster around a small number of recurring risk drivers that consistently generate the largest financial and schedule impacts. It is evident from the data that:

Conventional excavation methods show higher failure concentration

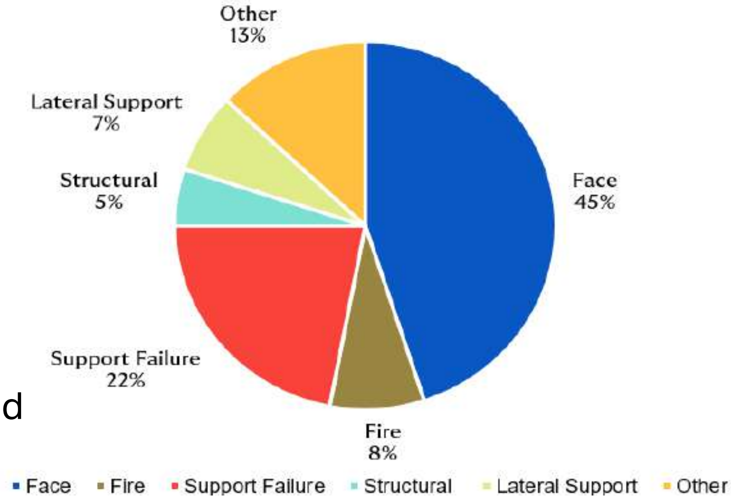
While Tunnel Boring Machines (TBMs) account for the largest individual share of recorded failures (approximately 38%), the study shows that when grouped broadly, conventional or non-mechanized tunnelling methods are associated with nearly two-thirds of failure cases. TBM losses seem to overrun the NATM related, perhaps due to the inclusion of higher values of the machinery (e.g. TBM and back-up system) used and the associated reinstatement costs. TBM tunnelling method is marginally outpacing NATM method but overall 'Conventional' tunnelling prevails by counting almost two thirds of examined cases.





General losses happen at the face side of the tunnel due to instability

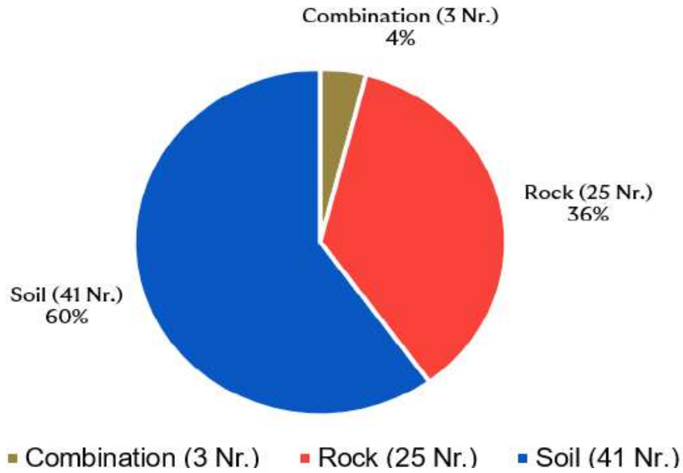
Among identified failure types, face instability accounts for nearly 45% of tunnel failures, making it the single most common loss trigger. Support failures contributed to 22% of cases and rest comes the other areas of failures including the lateral, support and structural failure.



Considering the sample size it was further evaluated that face failures happen largely in Soil type of ground conditions followed by rock type.

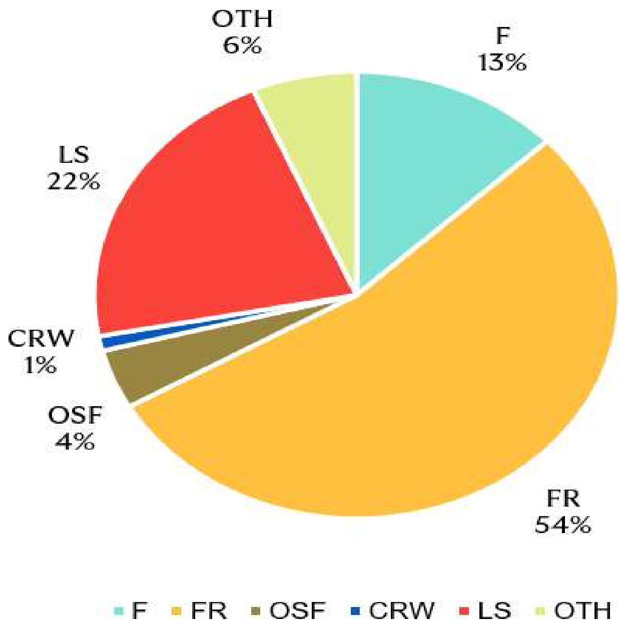
Ground conditions drive a majority of failures

Grid outages, UPS failures, generator breakdowns and electrical disturbances remain among the leading causes of downtime. As demand for power rises globally, maintaining reliable power infrastructure is becoming increasingly challenging.



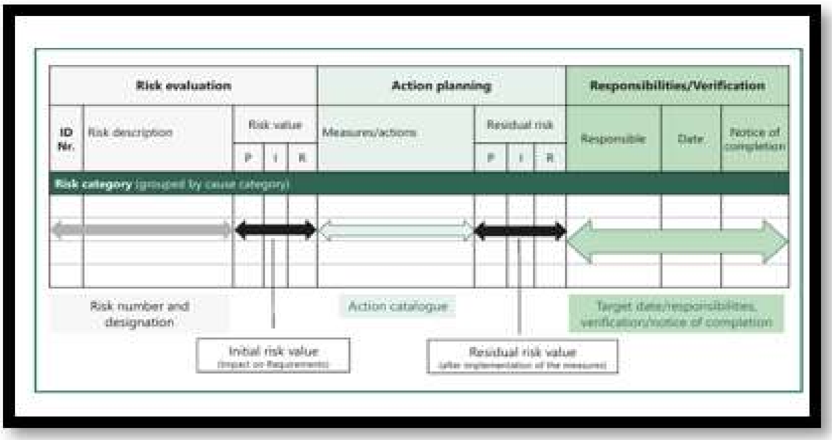
Fire Losses are the most significant cost drivers

Half of the cost is due to fires in the tunnels, especially during their operation. Very characteristic examples of fire events include the Eurotunnel fires (both in 1996 and 2008), the fire in the Montblanc tunnel and also the Tauern tunnel fire event in 1999 in Austria.



Risk engineering management

- Early and Continuous active involvement of experiences Risk Engineering Management Consultants
- Due Consideration of Project's Life Cycle, from Conceptual stages to Construction & Operational Phases
- Client's Role and Responsibilities of Utmost importance to ensure smooth execution of Project
- Risk Registers are significantly important to timely identify Project Risk Mitigation measures and Opportunities.



Example of a risk register

- Continuous risk engineering review of the tunnelling project through
    1. Benchmarking against the tunnelling Code of Practice
    2. Risk Engineering Site Surveys at regular intervals to confirm continuing compliance with the "Code"

Risk Survey Checklist

A robust risk assessment should evaluate the adequacy of ground improvement measures such as TAM or jet grouting, compatibility of TBM type with geological conditions, scope and reliability of instrumentation systems, and the presence of a well-defined TARP along with design assessment and review as per the accepted guidelines followed by a well defined Risk Register and required investigations before the initiation of the project.

Policy Conditions

Insurance and risk management frameworks should mandate the implementation of real-time monitoring systems and ground stabilization measures, particularly in sensitive zones. A review along with the project challenges and wordings from the policy needs to be assessed thoroughly to close the loop of an effective risk management measures.

- Sufficient Tunnel Works Limit included in the Insurance Policy meticulously deduced from a PML analysis
- Some of the Best Practices for such projects also include:
    1. Design should be made considering the extreme AOG events and should be based on the performance based construction specification.
    2. Develop Design Criteria for Vertical, Horizontal Clearances and sight distance along with Criteria for tunnel design life and future maintenance for structural, mechanical, electrical, and electronic systems and new tunnel rating.
    3. Develop an emergency response system plan with reference to NFPA 502 and NFPA 130
    4. Develop and share inspection practices among tunnel owners along with conducting a 3rd party design review and within the peer to review.
    5. Detect Surface Abnormalities well in time through Ground Penetrating Radar (GPR) method by evaluate the integrity of tunnel structures by detecting subsurface anomalies
    6. Implement use of LiDAR for inspection and mapping requirements, it is used to conduct detailed digital models that facilitate more structural analysis, including simulations of potential failure scenarios along with continuous monitoring
    7. Mitigation strategy depending upon the risk should be as follows:

Risk/Challenge	Mitigation Strategy
Ground settlement	Controlled TBM pressure, compensation grouting
Water ingress	Slurry TBM, waterproof lining, dewatering
Cutter wear	Predictive maintenance, optimized cutter selection
Mixed ground	Hybrid TBM, ground improvement
Alignment issues	Laser guidance, continuous survey

Case Study: Srisailam Left Bank Canal (SLBC)

A section of the under-construction Srisailam Left Bank Canal (SLBC) tunnel collapsed near Domalapenta in Telangana's Nagarkurnool district on 22nd February 2025, the collapse was almost 14km inside the tunnel which was happened just after 4 days of resuming work which was started after resuming project followed by a prolonged stoppage.

Around 50 workers were already inside the tunnel while 42 managed to escape and 8 were trapped near the Tunnel Boring machine, when a section of tunnel roof collapsed which led to inflow of water, mud, rocks and debris. After days of trying to evacuate the trapped workers with support of multiple government authorities including NDRF, SDRF, Army, Navy, GSI and NGRI experts the team was unable to reach them and authorities concluded that the 8 trapped workers have died, two bodies were recovered after weeks of recovery operations whereas 6 still remained buried. And the operations along with rescue operations were suspended considering the further risk of collapse.

Flow of events were as follows:

17th February 2025

Tunnel Work Resumed after long stoppage of work

22nd February 2025

At around 8:30 AM the tunnel collapsed, water and debris rushed into the tunnel collapsing TBM also and trapping 8 workers

22nd – 23rd February 2025

Rescue operations initiated, Heavy waterlogging, slush, and unstable conditions prevented rescuers from reaching the trapped workers. The zone was completely submerged and inaccessible

24th – 27th February 2025

Navy MARCOS, Singareni miners, rat-hole miners, GSI, and NGRI experts joined the operations, dewatering pumps were deployed to remove water, no communication was established during the entire scenario

28th February 2025

After nearly a week of search efforts and no signs of life, authorities concluded that all 8 trapped workers had died.

March and April

Rescue team reached the TBM and found in severely damaged condition, and the final section of tunnel completely blocked, GPR were used to search the sign of trapped people in the event. Team dismantled the TBM and removed debris and heavy cases of seepage and unstable ground conditions slowed the operations due to which only 2 bodies were beingn recovered.

Root Causes:

Basis the reports and information available in Open source domain, there has been no single root cause identified whereas possible contributing factors were evaluated which includes:

1. Heavy groundwater seepage from the overlying hill mass and aquifer zones. The tunnel was being excavated through a fractured rock formation with known water ingress issues.
2. Geological instability and fault/shear zones in the Nallamala hills. Experts suggested that weak geological formations may have given way, leading to roof failure.
3. Fresh cavities developing in the tunnel roof, which increased water inflow and weakened the tunnel support system. Project engineers stated that seepage suddenly intensified before the collapse.
4. The tunnel experienced multiple collapse events, not a single failure due to instability challenges and prolonged stoppage of project issues which affected the past monitoring and considering them in the future operations.

The collapse was likely not a single-point equipment failure or a simple human error. The evidence points to a combination of geological weaknesses, sudden high-volume water intrusion, and insufficient geotechnical risk management, which ultimately caused the tunnel roof to fail and resulted in the a huge disaster.

Key Lessons Learned:

The incident happened removed the masks of weakness in project monitoring and assessments, geotechnical investigations and readiness into evacuation plans. Consideirng the cases it was identified that

- Availability of only Geological studies are not enough for long tunnel projects
- Geological mapping and studies during the entire project excavation shall be carried out
  - Fault zones, shear zones, fractured rock, and aquifers must be identified before advancing the tunnel.
  - Independent reviews by agencies such as GSI, NGRI, or external experts should be mandatory before resuming work after long stoppages
- Water seepeage signs shall not be missed along with the project had history of water ingress. Significant increases in water inflow should trigger immediate work stoppage and reassessment.
- Robust monitoring has to be implemented at each point. Early-warning systems often prevent disasters by identifying deterioration before collapse.
- Desing of Emergency Escape and Access should be made mandatory along with procedures and evacuation plans, emergency responses procedures.
- Resuming the long stoppage of works shall be initiated through fresh risk assessment including the past history of events, ground conditions, tunnel support, hydrological survey and existing conditions
- Mandatory implement use of stop-work procedures .

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