



International Journal of Innovative Research in Science Engineering and Technology (IJIRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)



Impact Factor: 8.699

Volume 14, Issue 5, May 2025

Risk Assessment and Mitigation in Deep Underground Metro Construction

Rakesh Salunke¹, Santosh Kinayekar², Siddesh Doke³, Akash Chauhan⁴, Ravindra Bomble⁵,
Suraj Khade⁶

Assistant Professor, Department of Civil Engineering, Alamuri Ratnamala Institute of Engineering and Technology,
Thane, Maharashtra, India^{1,2}

U.G. Student, Department of Civil Engineering, Alamuri Ratnamala Institute of Engineering and Technology, Thane,
Maharashtra, India^{3,4,5,6}

ABSTRACT: This study identifies the challenges associated with metro rail infrastructure projects. A comprehensive literature review highlights common risk factors, such as project delays and demand forecasting inaccuracies. The research fulfills the significant gap in the integrated assessment of construction methodologies, risk mitigation and megacities development impacts. Deep underground metro construction projects are inherently complex and fraught with a variety of risks due to challenging geotechnical conditions, high urban density and technological uncertainties. This paper presents a comprehensive framework for risk assessment and mitigation tailored to deep metro tunnel and station construction. Key risks identified include ground settlement, water ingress, utility disruptions, equipment failure and safety hazards. The study utilizes qualitative methods, quantitative methods, including risk matrices, fault tree analysis (FTA). Case studies from recent metro projects in densely populated cities provide insights into successful mitigation strategies such as real time monitoring systems, advanced ground improvement techniques and adaptive project management approaches. The findings underscore the importance of early-stage risk planning, stakeholder coordination and the integration of modern construction technologies to reduce uncertainties. The proposed framework serves as a practical guide for engineers, project managers and urban planners involved in large scale underground infrastructure development.

Mumbai is a financial capital of India, has experienced rapid population growth and urbanization. This study presents a detailed assessment of the planning, design and implementation strategies employed in deep underground metro construction. Mainly focusing on the use of Tunnel Boring Machines (TBM) and the New Austrian Tunneling Method (NATM). Comparative analysis with standard practices prescribed by the Indian Standard (IS) codes is also conducted. Risks associated with underground construction such as unpredictable hydro geological conditions, interference with existing utilities, settlement issues and environmental impacts. Fire safety, indoor air quality and aerodynamic comfort are also addressed, as they are paramount to passenger safety and operational reliability. This study contributes to civil engineering practice and education by offering a methodology for metro project feasibility that integrates technical, environmental and socio-economic dimensions. Furthermore, the report emphasizes the importance of interdisciplinary coordination, real-time project management and sustainable engineering practices. The role of metro infrastructure in enhancing urban connectivity, shaping travel behavior, promoting public health and boosting economic activity is explored.

KEYWORDS: Metro Construction, Tunnel Boring Machines (TBM), New Austrian Tunnelling Method (NATM) etc.

I. 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 enhance urban mobility. However, the planning and execution of underground metro projects, particularly in densely populated urban centers, involve substantial 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) and New Austrian Tunneling Method (NATM), highlights best practices for innovative solutions that enhance project safety, sustainability and efficiency. The ultimate objective is to contribute a structured approach to risk management that can be adopted across future underground metro projects in similar urban environments.

II. LITERATURE SURVEY

The development of underground metro systems in dense urban environments has been widely studied across global and regional contexts due to the complexity, scale and inherent risks of such projects. Various researchers have emphasized the need for comprehensive risk identification, assessment and mitigation strategies throughout the project life cycle.

Risks in underground metro construction are typically categorized into geotechnical, environmental, technical, financial, legal, and socio-political domains. According to Singh et al. (2015), the most frequent risks in Indian metro projects are construction delays, utility disruptions and land acquisition challenges. The selection of tunnelling methods such as Tunnel Boring Machine (TBM), New Austrian Tunneling Method (NATM) and Cut-and-Cover techniques greatly influences the risk profile of a metro project. Sharma and Goyal (2018) conducted a comparative analysis of TBM and NATM, concluding that TBM offers greater safety and speed in homogeneous soil conditions, whereas NATM is more adaptable to variable geology but requires continuous monitoring and flexible design adaptations. Studies on Delhi Metro, Hyderabad Metro and Bangalore Metro have revealed valuable insights into risk mitigation practices in Indian contexts. For example, the Delhi Metro project, documented by the Delhi Metro Rail Corporation (DMRC), is often cited as a benchmark for effective project management, risk control and stakeholder coordination. Risk mitigation practices included phased construction, robust project governance and integration of advanced monitoring systems. Manoj Supekar (May 2022), emphasized that metro tunnel construction is significantly constrained by prevailing geological conditions. The selection of a tunneling method must therefore be site-specific, taking into account subsurface variability. His paper reviews three principal tunneling techniques used in metro projects, detailing their operational principles, construction sequences, suitable geotechnical environments, advantages, limitations and recent advancements. The objective is to guide future subway station development and academic research. Poras S. Kawale (June 2022), detailed construction activities in Packages 5 and 6 of a Mumbai metro project, involving stations such as Dharavi, BKC and the Airport region. Executed by J Kumar Company and the China Railway Tunnel Group. This project highlighted the critical need for meticulous planning of TBM launching and retrieval shafts based on local topography and logistical constraints. The study underlines how initial TBM deployment planning plays a pivotal role in optimizing construction sequencing and minimizing surface disruptions.

III. METHODOLOGY

Metro Tunnel Construction Methods are:

- Cut and Cover Method: The tunnel is constructed by excavating a trench, building the tunnel structure inside it and then covering it up. This method is adopted in shallow tunnels, especially in areas where disruption is acceptable.

Steps to be followed:

- Divert utilities and traffic.
- Excavate trench.
- Construct tunnel base, walls and roof.
- Backfill and restore surface.

- Tunnel Boring Machine (TBM) Method: Uses a massive machine that bores through soil or rock while simultaneously installing tunnel lining. This method is adopted in deep tunnels at urban areas with minimal surface disruption. Types of TBMs are Earth Pressure Balance (EPB), Slurry Shield TBM and Hard Rock TBM. This method is safer in urban zones but have High initial cost, require long setup time and expensive machinery.

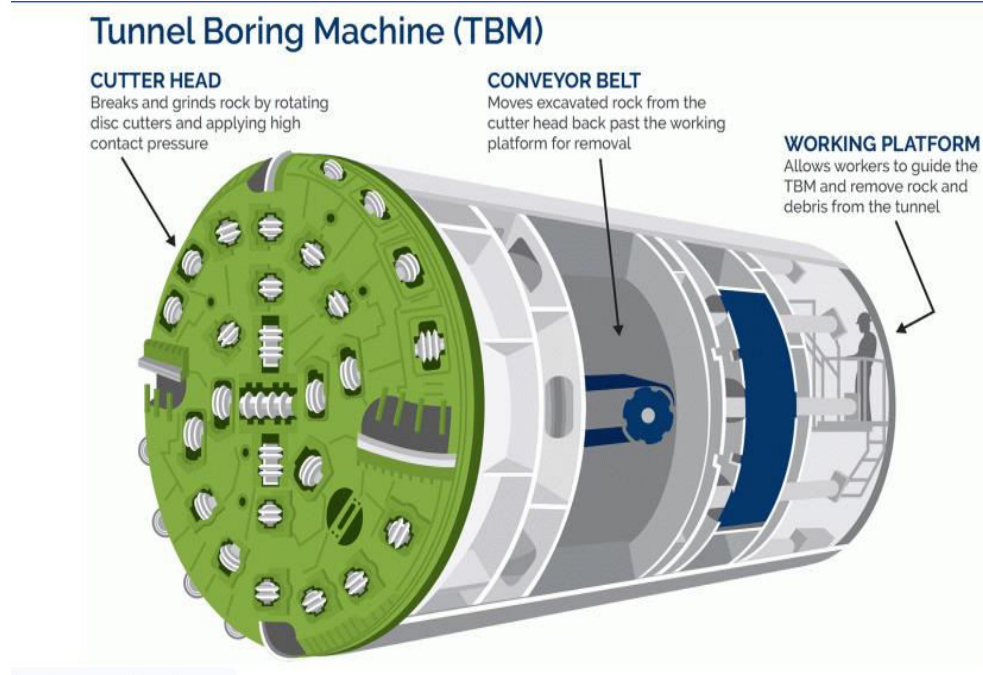


Fig. 1 Tunnel Boring Machine (TBM)

- New Austrian Tunnelling Method (NATM): this method relies on the surrounding rock/soil for stabilization. Excavation is done in small sections and sprayed concrete (shotcrete) is used immediately after excavation. This method is adopted in mixed ground conditions or variable geology. It requires constant monitoring for execution of work.
- Drill and Blast Method: This method is carried out by drilling holes in rock, filling them with explosives, blasting and removing the debris. This method is adopted in Hard rock conditions. It is flexible and relatively low-cost method and produces vibration and noise.
- Immersed Tube Tunnelling: This method is adopted for precast tunnel sections and underwater construction crossings the rivers. This method will be helpful for underwater projects. It requires dry dock fabrication, dredging and accurate placement.
- Sequential Excavation Method (SEM) / Mined Tunnelling: In this method the Tunnels are excavated in stages, often using road headers or controlled blasting, with temporary and permanent support installed progressively. This method is adopted for Urban environments, where space and vibration control are critical.

Risk Assessment and Mitigation in Deep Underground Metro Construction is structured into systematic stages to ensure a comprehensive analysis of risk factors, their impacts and the effectiveness of mitigation strategies.

- Data Collection includes Primary Data and Secondary Data
- Technical specifications and performance logs of tunnelling equipment (TBM parameters, support systems).
- Risk Assessment Framework.
- Identified risks were classified in Work Breakdown Structure (WBS) and Risk Breakdown Structure (RBS).

- Risk Analysis Techniques (quantitative and qualitative methods were used).
- Monte Carlo Simulation: To model risk impact on cost and time variables.
- Failure Mode and Effects Analysis (FMEA): To evaluate the severity and likelihood of individual risk elements.
- Bowtie Analysis: For visualizing risk causes, preventive controls and mitigation barriers.
- Risk Mitigation Strategy Development: Using the assessed risk levels and simulation outputs, appropriate mitigation strategies were developed based on the principles.
- Reduction of risk probability via preventive engineering controls
- Transfer of financial risk via contract provisions
- Retention of acceptable risks with contingency planning.
- The framework was validated using selected metro construction.
- For each case, actual project risks and outcomes were mapped against the predicted risk levels and mitigation actions from the proposed framework to test accuracy and robustness.

IV. EXPERIMENTAL RESULTS

This structured methodology enables a multi-dimensional understanding of risk in deep metro tunnel construction, blending expert judgment with data driven analysis. The approach ensures a holistic risk management strategy that is adaptable across different geotechnical environments and project typologies. The experimental phase of this study aimed to evaluate the identified risk factors, quantify their impact on underground metro construction projects and validate the effectiveness of proposed mitigation strategies.

Table 1. Risk Identification

Risk Category	Examples of Key Risks
Geotechnical	Unforeseen soil conditions, water ingress, boulders, rock hardness.
Technical	TBM breakdown, alignment errors, inadequate ventilation.
Financial	Cost overruns, delayed disbursement of funds, contract disputes.
Environmental	Groundwater contamination, noise/vibration, air pollution.
Socio-political	Land acquisition issues, public opposition, regulatory delays.

Table 2. Risk Categorization

Risk Factor	Probability	Impact	Risk Score	Priority Level
Unexpected Soil Conditions	5	4	20	Very High
TBM Mechanical Failure	4	5	20	Very High
Water Ingress	5	3	15	High
Delay in Land Acquisition	3	4	12	Medium
Stakeholder Disputes	2	3	6	Low

V. CONCLUSION

Deep underground metro construction projects represent a critical component of modern urban infrastructure, offering sustainable solutions to traffic congestion and urban mobility. However, these projects are fraught with complex and multidimensional risks that span geotechnical, technical, financial, environmental and socio-political domains. The successful execution of such projects requires a robust and systematic approach to risk assessment and mitigation. This study has demonstrated that geotechnical unpredictability, such as unforeseen soil conditions, groundwater ingress, and mixed strata tunnelling. These are remains the most significant source of risk, in addition to technical failures, including Tunnel Boring Machine (TBM) breakdowns. The inadequate alignment controls, were identified as high impact threats to time with cost performance.

Ultimately, the study concludes that the integration of proactive risk assessment with strategic mitigation planning not only enhances the reliability and safety of metro construction but also contributes significantly to budget adherence and timely completion. Indian cities are continuing to expand their metro networks by adopting a comprehensive and adaptive risk management framework. It is essential for ensuring the long term success of these transformative infrastructure projects.

REFERENCES

- [1] Li, X. Li, L. Chen, R. & Jim, C. Y. "Comprehensive Risk System Analysis and Factor Coupling in Underground Railway Space" ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, 2024.
- [2] Koothathongsumrit, N. & Chankham, W. "Risk Analysis of Underground Tunnel Construction with Tunnel Boring Machine by Using Fault Tree Analysis and Fuzzy Analytic Hierarchy Process" 2024.
- [3] He, K. Cui, T. Cheng, J. Huang, Y. Li, H. Chen, H. & Yang, "Safety Risk Assessment of Subway Shield Construction Under-Crossing a River Using CFA and FER" Frontiers in Public Health, 12, 1279642.
- [4] Zhang, Y. Liu, S. & Hou, S. (2024). "Dynamic Risk Early Warning System for Tunnel Construction Based on Two-Dimensional Cloud Model" 2024.
- [5] Rajgor, M. B., & Rawat, B. S. "Identification of Risk Elements in Safety, Health, and Environmental Management for Metro Infrastructure Projects" Journal of Propulsion Technology, 45(04), 2024.
- [6] Guo, Q., Amin, S., Wang, H., & Yan, H. "Coupling Characteristics of Construction Safety Risk and Complicated Factors of Metro Station: A Case Study of Ningbo" Journal of Propulsion Technology, 45(04), 2024.
- [7] Han, Y. Liu, X. & Zhang, L. "Mechanical Responses of Underground Carriageway Structures Due to Construction of Metro Tunnels Beneath the Existing Structure: A Case Study" Deep Underground Science and Engineering, 10(2), 2024.
- [8] Singh J. Singh P. Ravi V. Kumar S. Diwakar M. Al Mazroa A. & Gupta I. "Advancing Tunnel Construction Reliability with Automated Artificial Intelligence Under Geotechnical and Aleatoric Uncertainties. The Open Civil Engineering Journal, 18, 2024
- [9] Zhang, Y., & Yi, Z. "Application of RMP to Technical Risks in Metro Construction: Case Study of the GPE Project Tunnelling and Underground Space Technology" 147, 105716, 2024.
- [10] Huang, Z. Deng, X. Lei, C. Cheng, Y. Zhang, C. & Sun, Q. "Probabilistic Seismic Risk Assessment of Metro Tunnels in Soft Soils Sustainability" 16(18), 8218, 2024
- [11] Xia, Y. Xiong, Z. Dong, X. & Lu, H. "Risk Assessment and Decision-Making under Uncertainty in Tunnel and Underground Engineering" 2017.
- [12] Sihombing, M. Purba, H. H. & Purba, A. "Geotechnical Risk Assessments for Tunneling/Underground Projects" 2020.
- [13] Wang Z. Shafieezadeh A. Xiao X. Wang X. & Li Q. "Optimal Monitoring Location for Risk Tracking of Geotechnical Systems: Theory and Application to Tunnelling" 2022.
- [14] Klein S. & O'Carroll J. "Geotechnical Risk Assessments for Tunnelling/Underground Projects" 2017.
- [15] Ma, F. Ren F.; Yuen, K.F.; Guo, Y.; Zhao, C.; Guo, D. "The spatial coupling effect between urban public transport and commercial complexes: A network centrality perspective" 50, 101645, 2019.
- [16] Xu C. Liu X. Wang E. Wang S. "Prediction of tunnel boring machine operating parameters using various machine learning algorithms" 109, 103699, 2021.



INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA



INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

 9940 572 462  6381 907 438  ijirset@gmail.com



www.ijirset.com

Scan to save the contact details