© Volume 2, Issue 9, ***September*** 2026 | JATIR
ISSN: 3139-8464 (p)

Cost Estimation and Cost Control Techniques for Underground Tunnels

Ashvin Dhruva Gajbhiye
Student Researcher, Master of Technology, Department of Civil Engineering, with Specialization in Construction Technology and Management Chhatrapati Shivaji Maharaj University, Panvel Navi Mumbai, India

Abstract—**Underground railway tunnels constructed using the New Austrian Tunnelling Method (NATM) in India are highly susceptible to cost overruns due to adverse geological conditions, productivity loss, and uncertainties in resource planning. This study develops a comprehensive bottom-up cost estimation and cost control framework for an 820 m long NATM railway tunnel (Tunnel T1) excavated by the drill-and-blast method. The proposed methodology integrates detailed geotechnical investigations, rock mass classification (RMR and Q-System), excavation cycle analysis, muck haul lead calculations, equipment productivity, manpower deployment, and resource-based costing to generate realistic project estimates. Cost sensitivity analysis demonstrates that variations in rock class distribution, support requirements, and haul distance significantly influence the total construction cost. The results identify underground excavation and final reinforced concrete lining as the major cost contributors, together accounting for the largest proportion of project expenditure. An Earned Value Management (EVM)-based monitoring system, supported by dynamic risk registers and periodic cost reviews, is proposed to improve cost control during construction. The study also establishes a practical framework for quantifying the financial impact of adverse geology, additional temporary works, and productivity reduction in EPC tunnel projects. The developed model provides a replicable and field-oriented tool for cost engineers, project managers, and contractors involved in NATM railway tunnel construction in India.**

Index Terms—**New Austrian Tunnelling Method (NATM), Bottom-Up Cost Estimation, Cost Control, Railway Tunnel, Rock Mass Rating (RMR), Q-System, Earned Value Management (EVM), Drill-and-Blast Tunnelling.**

I. INTRODUCTION

Underground railway tunnels are a critical component of modern transportation infrastructure, particularly in densely populated and environmentally sensitive regions where surface alignment is impractical. In India, the rapid development of high-speed rail, metro, and highway projects has led

ISSN: 3139-8464 (p)

to a significant increase in the construction of tunnels using the New Austrian Tunnelling Method (NATM). NATM is widely adopted because of its flexibility in adapting excavation and support systems according to actual ground conditions, making it particularly suitable for heterogeneous rock formations encountered in the Western Ghats and other complex geological terrains.

Despite its engineering advantages, NATM tunnel construction is highly vulnerable to cost escalation arising from adverse geological conditions, changes in support classes, groundwater ingress, overbreak, reduced excavation productivity, and additional temporary works. Conventional estimation practices often rely on historical unit rates or parametric models, which inadequately represent the actual resource consumption and productivity variations experienced during construction. Consequently, many underground infrastructure projects suffer from significant budget overruns and schedule delays.

II. PROBLEM STATEMENT

Accurate cost estimation and effective cost control remain major challenges in Indian NATM tunnel projects. Existing estimation models generally emphasize preliminary budgeting and do not sufficiently integrate detailed geotechnical investigations, rock mass classification, excavation cycle time, muck haul logistics, equipment productivity, and resource-based costing. Furthermore, there is limited research on quantifying the financial impact of adverse geological conditions, productivity loss, additional support measures, and contractual claims within Engineering, Procurement and Construction (EPC) tunnel projects. The absence of an integrated bottom-up framework reduces the reliability of project estimates and weakens cost control during execution.

III. RESEARCH OBJECTIVES

The primary objective of this study is to develop a practical and comprehensive bottom-up cost estimation and cost control framework for an 820 m long NATM railway tunnel (Tunnel T1) constructed using the drill-and-blast technique. The specific objectives are:

- To develop a resource-based bottom-up cost estimation model for NATM tunnel construction.
- To evaluate the influence of geological conditions (RMR and Q-System) on excavation productivity and support requirements.
- To analyze the effect of muck haul lead distance, equipment utilization, and manpower deployment on project cost.
- To identify the major cost drivers through activity-wise cost analysis and sensitivity assessment.
- To establish a cost control framework incorporating Earned Value Management (EVM), productivity monitoring, and dynamic risk registers.
- To provide a replicable methodology for improving cost estimation and cost control in future Indian railway tunnel projects.

This research aims to bridge the gap between theoretical cost estimation models and practical field implementation by integrating geotechnical, operational, and financial parameters into a unified decision-support framework for NATM tunnel construction.

IV. LITERATURE REVIEW

Previous studies on tunnel construction cost estimation have focused on statistical, parametric, artificial intelligence, risk-based, and engineering-based approaches. Researchers such as Membah and Asa, Rostami et al., Petroutsatou et al., and Sayadi et al. demonstrated the importance of geological conditions, excavation methods, equipment productivity, and haul distance in determining tunnel construction costs. Other studies by Flyvbjerg et al., Einstein, and Muir Wood highlighted the significant influence of uncertainty, geological risk, inadequate investigation, and project management on cost overruns. Engineering references such as Chapman et al., Lunardi, and ITA publications further established the relationship between ground conditions, support systems, construction methodology, safety, and project performance.

However, most existing studies concentrate on overall or planning-stage cost estimation and provide limited treatment of activity-wise productivity losses, rock-class-specific cycle times, additional support requirements, increased resource consumption, and changing geological conditions during actual construction. There is also limited integration of RMR/Q-System classification, geological mapping, muck haul distance, equipment utilization, and real-time cost control into a single bottom-up framework.

Therefore, the present study develops a project-specific bottom-up cost estimation and cost-control framework for the 820 m Tunnel T1, integrating geological conditions, RMR-based excavation and support, cycle-time analysis, resource requirements, productivity, and cost-control techniques such as EVM and risk registers.

V. RESEARCH GAP

The comprehensive review of existing literature reveals several important gaps that remain insufficiently addressed in tunnel cost engineering:

- Most studies emphasize planning-stage cost estimation, with limited focus on continuous cost monitoring and real-time decision-making during construction.
- Existing models inadequately integrate detailed geotechnical investigations, site survey data, and rock mass classification (RMR/Q-System) into bottom-up cost estimation.
- Limited research combines geological mapping, instrumentation monitoring, and excavation productivity within a dynamic cost forecasting framework.
- Very few studies explicitly evaluate muck haul lead distance and its influence on dumper fleet sizing, equipment utilization, and operating costs.
- Activity-wise cycle time analysis for heading and benching under different RMR classes remains insufficiently investigated.
- Practical frameworks integrating site survey, geology, lead distance, productivity, and resource-based costing for Indian NATM railway tunnels are largely unavailable.
- The linkage between cost estimation and cost control using Earned Value Management (EVM), dynamic risk registers, and productivity monitoring is relatively weak in existing literature.

The present research addresses these gaps by developing a comprehensive bottom-up cost estimation and cost control framework for an 820 m NATM railway tunnel (Tunnel T1). The proposed methodology integrates geological investigations, RMR and Q-System classification, excavation cycle analysis, muck haul logistics, equipment productivity, manpower planning, resource-based costing, Earned Value Management, and dynamic risk assessment to provide a practical decision-support tool for underground railway tunnel projects in India

VI. METHODOLOGY

1) Research Method

This study adopts a quantitative case study approach using an 820 m long NATM railway tunnel (Tunnel T1) constructed by the drill-and-blast method. Primary project data were collected from construction records, geological mapping, daily progress reports, equipment logs, and resource deployment records.

2) NATM and Rock Mass Classification

The tunnel was excavated using the New Austrian Tunnelling Method (NATM), where excavation and support systems were modified according to actual ground conditions. Rock quality was classified using both the Rock Mass Rating (RMR) and Q-System, which determined the excavation sequence, primary support class, and lining requirements

3) Bottom-Up Cost Estimation

A bottom-up costing model was developed by estimating the quantities and unit costs of individual construction activities, including:

- Survey and geological investigations
- Excavation (Heading, Benching & Invert)
- Primary support (shotcrete, rock bolts, ribs)
- Waterproofing and drainage
- Final concrete lining
- Contact grouting
- Muck transportation
- Plant, equipment, manpower, and indirect costs

4) Cycle Time Analysis

Excavation productivity was evaluated through detailed cycle-time analysis comprising drilling, charging, blasting, ventilation, scaling, mucking, support installation, and surveying. The influence of different rock classes on advance rate and resource consumption was incorporated into the cost model.

VII. RESULTS AND DISCUSSION

5) Cost Analysis

The activity-wise cost analysis indicates that final reinforced concrete lining and underground excavation with primary support constitute the largest share of total project expenditure. Increased support requirements in poor rock significantly raised material consumption, labour hours, and equipment operating costs.

6) Sensitivity Analysis

Sensitivity analysis demonstrates that project cost is highly influenced by:

- Rock class distribution (RMR/Q-System)
- Muck haul lead distance
- Excavation advance rate
- Support class modifications
- Equipment productivity and utilization

Among these parameters, geological variability produced the greatest impact on total project cost.

7) Productivity Assessment

The analysis shows that excavation productivity decreases considerably in poor geological conditions due to additional scaling, probe drilling, geological mapping, support installation, and safety measures. Reduced advance rates resulted in increased manpower, equipment standby, and indirect costs, highlighting the importance of geology-based productivity planning.

VIII. COST CONTROL FRAMEWORK

A practical cost control framework was developed by integrating project planning, productivity monitoring, and financial performance measurement.

1. Earned Value Management (EVM)

EVM was adopted to evaluate project performance using Planned Value (PV), Earned Value (EV), and Actual Cost (AC). Schedule Performance Index (SPI) and Cost Performance Index (CPI) were used to identify deviations from planned progress and expenditure.

2. Dynamic Risk Register

A geology-focused risk register was developed to monitor risks related to poor rock, groundwater, overbreak, equipment breakdown, and support modifications. Each risk was assigned probability, impact, mitigation measures, and responsible personnel for continuous monitoring.

ISSN: 3139-8464 (p)

3. Monthly Cost Review

Monthly reviews compared planned and actual quantities, productivity, resource utilization, equipment hours, and expenditure. The review process enabled early identification of cost deviations and supported timely corrective actions during tunnel execution.

IX. CONCLUSIONS

This study developed a comprehensive bottom-up cost estimation and cost control framework specifically for NATM railway tunnels constructed in variable geological conditions. The proposed methodology successfully integrates geological investigations, RMR/Q-System classification, excavation cycle analysis, muck haul logistics, manpower, equipment productivity, and activity-wise resource costing into a single practical model.

The results demonstrate that adverse geological conditions significantly reduce excavation productivity and increase support requirements, temporary works, and overall construction cost. The integration of Earned Value Management, dynamic risk registers, and monthly cost reviews provides an effective decision-support system for controlling project expenditure during execution. The developed framework offers practical value to contractors, consultants, and project owners undertaking future NATM railway tunnel projects in India.

ACKNOWLEDGMENT

I would like to express my sincere and heartfelt gratitude to my esteemed guide, Dr. R. P. Singh Kushwah, Professor & Dean of Chhatrapati Shivaji Maharaj University, Panvel Navi Mumbai, India, for his invaluable guidance, continuous support, encouragement, and constructive suggestions throughout the course of this research work. His expertise, patience, and thoughtful guidance have been instrumental in shaping this dissertation and enabling me to complete the research successfully.

REFERENCES

[1] Membah, J., & Asa, E. (2015). Estimating cost for transportation tunnel projects: A systematic literature review. International Journal of Construction Management, 15(3), 196–218.

[2] Rostami, J., Sepehrmanesh, M., Alavi Gharahbagh, E., & Mojtabai, N. (2013). Planning level tunnel cost estimation based on statistical analysis of historical data. Tunnelling and Underground Space Technology, 33, 22–33.

[3] Petroutsatou, K., Georgopoulos, E., Lambropoulos, S., & Pantouvakis, J.-P. (2012). Early cost estimating of road tunnel construction using neural networks. Journal of Construction Engineering and Management, 138(6).

[4] Petroutsatou, K., & Lambropoulos, S. (2010). Road tunnels construction cost estimation: A structural equation model development and comparison. Operational Research, 10(2), 163–173.

ISSN: 3139-8464 (p)

[5] Petroutsatou, K., Maravas, A., & Saramourtsis, A. (2021). A life cycle model for estimating road tunnel cost. Tunnelling and Underground Space Technology, 111, 103858.

[6] Sayadi, A. R., Lashgari, A., & Paraszczak, J. (2012). Hard-rock LHD cost estimation using single and multiple regressions based on principal component analysis. Tunnelling and Underground Space Technology, 27(1), 133–141.

[7] Gale, W. M., Kaiser, P. K., & Morgenstern, N. R. (1986). Computer estimation of tunnel costs. Tunnels & Tunnelling International, 18(3), 49–52.

[8] Einstein, H. H. (2004). Decision aids for tunneling: Update. Transportation Research Record, 1892, 21–29.

[9] Flyvbjerg, B., Skamris Holm, M. K., & Buhl, S. L. (2002). Underestimating costs in public works projects: Error or lie? Journal of the American Planning Association, 68(3), 279–295.

[10] Flyvbjerg, B., Skamris Holm, M. K., & Buhl, S. L. (2004). What causes cost overrun in transport infrastructure projects? Transport Reviews, 24(1), 3–18.

[11] Chapman, D., Metje, N., & Stark, A. (2010). Introduction to Tunnel Construction. CRC Press / Taylor & Francis. ISBN 978-0-415-46910-3.

[12] Muir Wood, A. M. (1992). Tunnelling: Management by Design. E & FN Spon / Chapman & Hall. ISBN 978-0-419-17630-4.

[13] Lunardi, P. (2008). Design and Construction of Tunnels: Analysis of Controlled Deformation in Rocks and Soils (ADECO-RS). Springer. ISBN 978-3-540-73874-6.

[14] European Commission. (2014). Guide to Cost-Benefit Analysis of Investment Projects: Economic Appraisal Tool for Cohesion Policy 2014–2020. Directorate-General for Regional and Urban Policy, Brussels.

[15] International Tunnelling and Underground Space Association (ITA). (2009). ITA Working Group Reports. International Tunnelling and Underground Space Association, Lausanne, Switzerland.