

# Geotechnical Challenges and Innovative Solutions in the Construction of the Underground Metro

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## ABSTRACT

The construction of urban underground metro systems poses significant geotechnical challenges, particularly in densely populated areas with complex subsurface conditions. This research investigates the geotechnical issues encountered during underground metro line construction and evaluates the innovative solutions implemented to mitigate these challenges. The primary objectives were to identify the critical geotechnical risks, assess the efficacy of the adopted techniques, and propose recommendations for future underground metro projects. A comprehensive case study approach was employed, involving extensive site investigations, and data collection from project reports. The findings revealed significant challenges related to groundwater management, soil heterogeneity, and nearby structures, necessitating advanced construction methods such as ground improvement techniques, dewatering systems, and soil-structure interaction analyses. The study concluded that a thorough understanding of site-specific geotechnical conditions and the judicious application of specialized techniques is crucial for successfully executing underground metro projects in urban environments. The insights derived from this research contribute to the body of knowledge in geotechnical engineering and provide valuable guidance for future urban infrastructure developments.

**Keywords:** Underground metro, challenges, and solutions.

## INTRODUCTION

The advent of urban underground metro networks has emerged as a transformative solution to address the transportation needs of densely populated cities. These intricate subterranean systems alleviate surface congestion and contribute to sustainable mobility by reducing air pollution and carbon emissions. Beyond their functional role, underground metros serve as catalysts for economic growth, enabling seamless connectivity between commercial hubs and residential areas. Furthermore, these resilient systems offer uninterrupted mobility during extreme weather conditions and enhance urban planning by optimizing land resource utilization. As cities evolve, underground metro networks have become integral to sustainable urban development, striking a delicate balance between efficient transportation, environmental stewardship, and economic progress.

The construction of underground metro lines is an engineering marvel that demands meticulous attention to geotechnical factors. These subterranean transportation systems traverse complex subsurface environments, encountering challenges from varying soil conditions, groundwater levels, and existing structures. Geotechnical considerations ensure these underground infrastructures' stability, safety, and longevity. Comprehensive site investigations, thorough soil characterization, and advanced modeling techniques are crucial for accurately assessing the geotechnical risks and developing effective mitigation



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strategies. From groundwater management and soil improvement techniques to structural reinforcement and soil-structure interaction analyses, addressing geotechnical challenges is paramount in minimizing potential hazards, optimizing construction processes, and safeguarding the integrity of underground metro lines throughout their operational lifespan. The present study aims to identify the key challenges in urban metro construction, assess the effectiveness of the solution through case study analysis, and explore innovative techniques for mitigating common geotechnical issues.

## **LITERATURE REVIEW**

Islam and Shahin (2016) study dealt with the effects of various loading conditions and water table presence must be carefully considered for both cut and cover and NATM excavation methods. Research has shown that surface settlement tends to be larger for shallow foundations compared to pile foundations. Som (2017) reported that metro building through densely populated areas has led to resource constraints and prolonged construction timelines. The project has encountered particularly difficult conditions in congested urban zones. Dewanjee (2018) addressed the unique challenges of underground tunneling in Kolkata, due to the city's dense urban fabric and the need to preserve its heritage structures. The geological complexity of the Ganga-Brahmaputra deltaic region, characterized by juvenile alluvial deposits, further complicates the tunneling process. The study details how specialized ground improvement techniques and mitigation measures have been employed. Yadav et al. (2018) study dealt with the implementation of continuous monitoring, meticulous planning, and ground-strengthening techniques in urban tunneling projects to protect existing structures and infrastructure. The study highlights how advanced excavation methods are employed to handle challenging soil conditions, and specialized grouting techniques are used to safeguard surface buildings. It also emphasizes the importance of comprehensive instrumentation and monitoring systems for assessing and mitigating the impact of tunneling on the urban environment. Bastola et al. (2020) reported the unique challenges faced in the Kathmandu Valley's metro construction, which are attributed to its complex urban geology, including soft lacustrine deposits and river crossings. The study examines how engineers have addressed these issues through advanced design techniques, precise instrumentation, and the use of Earth Pressure Balance Tunnel Boring Machines for constructing twin 6-meter diameter tunnels.

## **CHALLENGES IN METRO CONSTRUCTION**

The construction of the urban underground metro system faced numerous significant obstacles during construction. Some of the typical obstacles in metro construction are discussed below.

### **Geotechnical Challenges:**

#### ***Cramped underground space with dense utility networks***

Urban underground spaces pose significant challenges for metro construction due to their congested nature. These areas are typically crowded with a complex network of existing utilities, including water pipes, sewage systems, electrical conduits, gas lines, and telecommunication cables. This dense infrastructure leaves minimal space for new metro tunnels, requiring meticulous planning and innovative engineering solutions. Engineers must navigate this underground network using detailed utility mapping and advanced surveying techniques. The limited space demands careful consideration of tunnel alignment and excavation methods to minimize disruption to existing services. Utility relocation or protection measures are often necessary, adding complexity and cost to the project. To address these challenges, project teams employ advanced technologies like Building Information Modelling (BIM) and 3D visualization tools while innovating tunneling techniques. Successful navigation of these cramped conditions requires a multidisciplinary approach, combining geotechnical engineering, utility management, and urban planning expertise. Figure 1 shows the typical utilities found in one of the metro projects in Delhi.



**Figure 1.** Typical utilities were found in one of the metro projects in Delhi [8]

### ***Variable subsurface conditions including soft sediments and fault zones***

The geological profile along urban metro routes often presents a complex and variable landscape, posing significant challenges for construction. These subsurface conditions can change dramatically over short distances, encompassing a range of materials from soft sediments to hard rock, and may include fault zones. Soft sediments, such as alluvial deposits or clay layers, can lead to settlement issues and require specialized tunneling techniques to maintain stability. Hard rock sections, while generally more stable, present their challenges in terms of excavation methods and equipment selection. Fault zones are particularly problematic, as they can introduce weak, fractured rock or create pathways for groundwater ingress. This geological diversity necessitates a flexible approach to construction, with methods and equipment often needing to be adopted as tunneling progresses. Engineers must carefully consider soil-structure interactions at every stage, employing advanced geotechnical modeling to predict behavior and design appropriate support systems. The variability in subsurface conditions also impacts the choice of tunnel lining systems and influences the overall structural design of the metro infrastructure. Comprehensive site investigation and continuous ground monitoring during construction are essential to manage the risks associated with these variable subsurface conditions effectively.

### ***Tunneling near existing structures in congested urban areas***

Tunneling in congested urban areas presents unique challenges due to the proximity of existing structures. The process of excavation and tunnel construction can induce ground movements, potentially leading to settlement or lateral displacement of nearby buildings. This risk is particularly acute in densely populated urban centers where structures may have varying ages, foundation types, and structural conditions. To mitigate these risks, engineers employ a range of sophisticated monitoring techniques and preventive measures. These typically include real-time settlement monitoring using precise leveling and tiltmeters, as well as the installation of inclinometers to detect lateral ground movements. Advanced numerical modeling is used to predict potential ground deformations and their impact on adjacent structures. Preventive measures may involve underpinning of nearby buildings, compensation grouting to offset ground loss, or the use of more controlled excavation techniques such as Earth Pressure Balance (EPB) tunnel boring machines. In some cases, temporary support systems are installed to protect particularly vulnerable structures. The success of urban tunneling projects often hinges on the careful implementation of these monitoring and protection strategies, coupled with a proactive approach to risk management and stakeholder communication. Figure 2 shows the Metro line construction at Bangalore where the tunnel alignment passes through the urban area.



**Figure 2.** Metro line construction at Bangalore where the tunnel alignment passes through the urban area.

### ***Determining the optimal tunnel alignment and depth***

Determining the optimal tunnel alignment and depth for an urban metro system is a complex process that requires careful consideration of multiple factors. This crucial decision impacts not only the construction phase but also the long-term stability and operational efficiency of the metro system. Engineers must balance geological conditions, which may include varying rock types, soil properties, and groundwater levels, with the presence of existing underground structures such as building foundations, utility networks, and other tunnels. Surface constraints, including historical buildings, environmentally sensitive areas, and urban planning considerations, further complicate the alignment selection. The depth of the tunnel influences construction methods, station design, and passenger accessibility, while also affecting the system's vulnerability to surface disturbances and seismic events. Advanced 3D modeling and Geographic Information Systems (GIS) are often employed to analyze various alignment options, considering factors such as construction cost, operational efficiency, and environmental impact. The optimization process typically involves iterative design reviews and stakeholder consultations to achieve a balance between technical feasibility, economic viability, and community acceptance. Ultimately, the selected alignment and depth must ensure project feasibility, minimize risks during construction, and provide a stable and efficient metro system for decades to come.

### **Construction Challenges:**

#### ***Limited access to equipment and material transport***

Urban metro construction projects face significant logistical challenges due to limited access to equipment and material transport. The dense urban fabric, characterized by narrow streets, congested traffic, and restricted access points, complicates the movement of heavy machinery and bulky construction materials to and from work sites. This constraint necessitates creative transportation solutions and meticulous scheduling to maintain project efficiency. Engineers often must devise alternative routes, utilizing a combination of smaller vehicles for material delivery and modular equipment that can be assembled onsite. In some cases, temporary access roads or dedicated construction corridors may be established to facilitate movement. Just-in-time delivery strategies are frequently employed to minimize on-site storage requirements and reduce traffic disruption. The use of underground conveyors or purpose-built shafts for vertical transport of materials can reduce surface congestion. Additionally, night-time operations for major deliveries and equipment transfers are often implemented to minimize the impact on daily urban activities.

These logistical challenges not only affect project timelines but also have significant implications for cost and environmental impact, requiring a delicate balance between construction needs and urban functionality.

### ***Restricted space for staging and site logistics***

Urban metro construction projects face significant challenges due to the scarcity of open space for staging and site planning. In densely built urban environments, the availability of areas for storing materials, setting up equipment, and managing construction activities is severely limited. This constraint necessitates highly efficient site management strategies and innovative solutions. Project managers often must optimize the use of every square meter of available space, implementing dynamic staging plans that evolve as construction progresses. The use of vertical storage systems and just-in-time delivery schedules helps to reduce stored materials on-site. Off-site storage facilities and prefabrication techniques are frequently employed to reduce the space required at the construction site. Modular construction methods, where components are manufactured off-site and assembled on location, can significantly reduce on-site storage and workspace requirements. Additionally, temporary structures such as multi-level platforms or decked areas over excavations may be used to create additional working space. The restricted space also influences equipment selection, favoring compact machinery and multi-purpose tools. These space constraints not only affect construction efficiency but also impact project timelines and costs, requiring careful planning and coordination to ensure smooth project execution in dense urban areas.

### ***Surface settlement risks in weak soils***

Managing surface settlement risks in weak soils is critical to urban metro construction. Excavation and tunneling activities can induce ground subsidence, particularly in areas characterized by weak or compressible soils such as soft clays or unconsolidated sediments. This settlement poses significant risks to surface structures, including buildings, roads, and utilities. To mitigate these risks, engineers employ a range of ground improvement techniques and monitoring strategies. Common approaches include soil grouting, jet grouting, and deep soil mixing to enhance soil strength and reduce compressibility. In some cases, ground-freezing techniques may be used for temporary soil stabilization. The choice of tunneling method, such as Earth Pressure Balance (EPB) machines, can also help minimize ground loss and associated settlement. Continuous monitoring is essential, typically involving a combination of surface leveling, inclinometers, and extensometers to detect ground movements in real time. Advanced numerical modeling is used to predict settlement patterns and inform preventive measures. Where necessary, compensation grouting may be employed to offset ground loss and control settlement. The successful management of surface settlement risks requires a proactive approach, combining geotechnical expertise with monitoring and rapid response procedures to ensure the integrity of surface structures throughout the construction process.

### ***Vibrations Near Sensitive Structures***

Controlling vibrations near sensitive structures is an important concern in urban metro construction, particularly when working in areas with hard rock or near historic buildings. Construction activities, such as drilling, blasting, and the operation of heavy machinery, can generate significant vibrations that may cause structural damage or affect the integrity of nearby structures. To mitigate this risk, engineers employ a range of vibration control measures and carefully select appropriate construction methods. Vibration monitoring systems are typically installed to provide real-time data on vibration levels, allowing for immediate adjustments to construction techniques if necessary. Low-vibration excavation methods, such as hydraulic splitting or chemical expansive agents, may be used instead of traditional blasting in sensitive areas. When mechanical excavation is required, equipment selection focuses on low-vibration alternatives, and operational parameters are optimized to minimize vibration transmission. Isolation techniques,

including trenches or wave barriers, can be implemented to reduce vibration propagation through the ground. Additionally, work schedules may be adjusted to limit vibration-intensive activities during sensitive periods. The successful control of construction-induced vibrations requires a comprehensive approach, combining predictive modeling, continuous monitoring, and adaptive management strategies to ensure the protection of surrounding structures throughout the project duration.

### ***Navigating complex urban obstacles during tunneling***

Urban tunneling for metro construction frequently encounters many complex obstacles beneath city streets, presenting significant challenges to project execution. These obstacles can include buried foundations of long-demolished buildings, unexpected archaeological remains of historical significance, or utilities that have accumulated over decades of urban development. Navigating these challenges requires a high degree of flexibility in tunneling techniques and the ability to rapidly adapt plans when unforeseen conditions are encountered. Comprehensive pre-construction surveys, including ground-penetrating radar and exploratory boreholes, are essential but may not reveal all subsurface complexities. As a result, tunnel boring machines (TBMs) are often equipped with ground-probing technology to detect obstacles ahead of the cutting face. When obstructions are encountered, teams must be prepared to implement alternative excavation methods, such as hand mining or specialized cutting tools. In some cases, temporary access shafts may need to be constructed to remove obstacles or implement localized ground treatment. The presence of archaeological finds can necessitate careful excavation and documentation procedures, potentially involving collaboration with heritage experts. Successfully navigating these urban obstacles demands not only technical expertise but also close coordination with city authorities, utility companies, and other stakeholders to minimize disruptions and ensure project continuity.

### **Seismic Considerations:**

#### ***Diverse geological profiles along the metro route***

The construction of urban metro systems often encounters diverse geological profiles along the route, presenting significant challenges for seismic design and engineering. As the metro alignment traverses different geological formations, it may encounter a range of conditions including soft alluvial deposits, weathered rock, competent bedrock, and fault zones. This geological diversity results in varying seismic responses along different sections of the metro system. Soft soil deposits, for instance, can amplify seismic waves and increase the risk of liquefaction, while bedrock sections may transmit seismic energy more directly. These variations necessitate a seismic design approach for each segment of the metro system. Engineers must conduct detailed site-specific seismic hazard analyses to understand the unique characteristics of each geological zone. This information is then used to develop customized design parameters, including ground motion predictions and soil-structure interaction models. The structural design of tunnels, stations, and other metro infrastructure must be adapted to account for these varying seismic conditions, potentially incorporating different levels of flexibility, reinforcement, or isolation systems in different sections. This segmented approach to seismic design ensures that each part of the metro system is appropriately engineered to withstand the specific seismic risks associated with its local geological context, enhancing the overall resilience of the urban metro network.

#### ***Need for site-specific seismic hazard analysis.***

Urban metro projects require a comprehensive site-specific seismic hazard analysis due to the inadequate basic seismic data for such complex infrastructure. This detailed analysis is important for accurate risk assessment and appropriate design, taking into account the unique geological and seismological characteristics of the urban environment. The process involves a thorough investigation of local fault systems, including their geometry, slip rates, and potential for generating earthquakes. Geotechnical studies

and site response analyses carefully evaluate soil amplification effects, which can significantly modify seismic wave propagation and intensity. Historical seismic activity in the region is meticulously reviewed to understand patterns of earthquake occurrence and potential maximum magnitudes. Advanced probabilistic and deterministic seismic hazard assessment methods are employed to generate site-specific ground motion parameters, including spectral accelerations and time histories. These parameters are then used to develop design spectra and ground motion time series for different return periods, tailored to the specific location and characteristics of the metro infrastructure. The site-specific approach ensures that the seismic design of the metro system is optimized for local conditions, potentially leading to more cost-effective and resilient structures. This level of detailed analysis is essential for safeguarding critical urban infrastructure against seismic risks and ensuring public safety in earthquake-prone regions.

### ***Designing for varied seismic performance requirements***

Designing for varied seismic performance requirements presents a significant engineering challenge, as different components of the network demand distinct seismic resilience criteria. Tunnels, stations, and above-ground structures each have unique structural characteristics and operational importance, necessitating tailored seismic design approaches. Underground tunnels, for instance, generally experience less severe seismic loading than surface structures but must withstand ground deformations. Stations, serving as critical junctions and evacuation points, require higher performance standards to ensure post-earthquake functionality. Above-ground structures, such as elevated tracks or depots, are more vulnerable to ground shaking and thus demand robust seismic resistance. The challenge lies in integrating these varied design requirements into a cohesive system that performs uniformly during seismic events. Engineers must employ a range of analytical tools and design strategies, including dynamic analysis, performance-based design, and advanced structural systems like base isolation or damping devices, to meet the specific needs of each component. Simultaneously, they must ensure that transitions between different structural elements do not create weak points in the system. This comprehensive approach to seismic design requires careful coordination among various engineering disciplines and often involves iterative design processes to achieve an optimal balance between safety, functionality, and cost-effectiveness across the entire metro network.

## **CASE STUDIES**

The construction of Dhaka's underground metro system faced numerous geotechnical and logistical challenges. The densely populated urban environment with limited open space posed difficulties for excavation and construction activities. Soil conditions varied significantly along the proposed route, requiring careful analysis and selection of appropriate tunneling methods. In areas with softer clay soils, there were concerns about ground settlement and stability. The high water table in parts of Dhaka also complicated excavation and waterproofing efforts. Existing buildings and infrastructure near the alignment necessitated extra precautions to avoid damage from tunneling-induced ground movements. The lack of prior experience with large-scale underground construction in Bangladesh meant that additional training and capacity building was required. Traffic congestion and the need to minimize disruption to the city during construction added further complexity. Careful planning and sequencing of activities, along with extensive geotechnical investigation and modeling, was crucial to overcoming these multifaceted challenges and successfully implementing Dhaka's first underground metro system [5].

During the construction of the Kolkata Metro, several significant challenges were encountered. One of the primary difficulties was the highly congested urban environment through which the metro had to be built. The initial metro line, constructed between 1975 and 1995, mostly employed the cut-and-cover method, except for a short stretch that required shield tunneling with compressed air due to its proximity to a railway yard. This method had to navigate through busy urban areas where underground construction technology

was not as advanced as it is today. The East-West Corridor, another significant part of the Kolkata Metro, posed its unique challenges. This section required tunneling below the Hooghly River, demanding advanced technology and careful planning. The use of tunnel boring machines (TBMs) was essential to go approximately 10 meters below the riverbed and then continue beneath the central business district of Kolkata. This intricate work required extensive soil testing and the development of robust design parameters for the large-diameter piles, which had to reach depths of 35-40 meters. Moreover, the geotechnical conditions in Kolkata complicated the construction efforts. The subsoil consisted of weak cohesive strata in the upper layers, with silty clay and clayey silt particularly soft in the top 12-15 meters. The groundwater table was also fairly high, rising almost to the ground surface during the monsoon season. This necessitated dewatering in some areas, adding another layer of complexity to the construction process. Financial constraints further exacerbated the difficulties. The reliance on foreign funding introduced additional administrative overheads and extended construction timelines, although efforts were made to increasingly utilize internal resources for infrastructure development. Despite these challenges, modern design techniques and field instrumentation have helped ensure the quality and safety of the construction process in densely populated urban areas [7]. Figure 3 shows the typical construction of metro in Chittaranjan Avenue in Kolkata.



**Figure 3.** Cut and cover construction through Chittaranjan Avenue (Som, 2017).

The construction of the Delhi Metro presented numerous engineering and logistical challenges in a dense urban environment. Tunneling beneath existing structures and infrastructure required careful planning and monitoring to avoid damage. For example, when tunneling under an existing viaduct, extensive ground strengthening was performed using TAM grouting to stabilize the soil between support pillars. Sensitive instrumentation was installed to measure minute ground movements during tunneling. When passing beneath a canal, special precautions were taken due to weathered canal lining and muddy ground conditions. Tunneling through varying soil conditions, from sandy silt to clay, necessitated adapting excavation techniques. The presence of high groundwater tables in some areas further complicated underground work. Shifting of numerous utilities like water pipelines and electrical lines had to be coordinated before construction could proceed in many locations. Minimizing disruption to traffic and daily city life required strategic planning of work sites and schedules. The project team had to constantly balance the speed of construction with safety precautions to protect adjacent buildings and infrastructure. Overall, the successful completion of the metro system through such a complex urban landscape stands as a significant engineering achievement [10].

## **RESULTS AND DISCUSSIONS**

Case studies from diverse urban settings reveal common geotechnical challenges in metro construction, often related to complex soil conditions and dense urban environments. Key solutions include comprehensive monitoring systems, advanced tunneling techniques like EPB TBMs, and ground improvement methods like TAM grouting. These cases emphasize the importance of adapting construction approaches to local geological and urban contexts, highlighting the need for thorough pre-construction investigations and flexible engineering strategies.

The urban metro project tackled complex geotechnical challenges through a multi-faceted approach. Cutting-edge mapping technologies like 3D utility scans and ground-penetrating radar were crucial in navigating the underground maze. Tunnel boring machines (TBMs) proved superior to cut-and-cover methods, minimizing disruption above ground. Water management can be addressed via dual-layer waterproof membranes and strategic grouting, while real-time monitoring systems allow swift responses to ground movements.

In sensitive zones, particularly near historical landmarks, tunnel diameters can be reduced to lessen the impact. Injection piles provide quick stabilization when needed. Each solution brought unique advantages and drawbacks. TBMs, while efficient, demanded hefty initial outlays. The waterproofing strategy is highly effective but adds complexity to the construction. Grouting and injection techniques offered speed but required precise execution to avoid complications.

The project's success hinged on the strategic combination of these methods, carefully adapted to each location's specific challenges. This tailored approach effectively mitigated the varied geotechnical hurdles encountered, demonstrating the power of innovative, context-specific problem-solving in urban infrastructure development.

In tackling the urban metro's construction challenges, a trio of innovative solutions proved pivotal. Off-site prefabrication revolutionized the approach to tunnel supports and station components, alleviating logistical bottlenecks in the congested cityscape. Ground stability issues can be addressed through the deployment of Fiber Reinforced Polymer (FRP) piles, offering unparalleled strength and corrosion resistance in weak soils. Secant piling emerged as the go-to technique for robust earth retention and water management in problematic areas. Each method brought unique strengths: prefabrication excelled in constrained spaces, FRP piles shone in corrosive environments, and secant piling proved invaluable in water-sensitive zones. The project's success ultimately stemmed from the strategic integration of these techniques, tailored to each section's specific demands, demonstrating the power of adaptive problem-solving in complex urban infrastructure development.

The urban metro project tackled seismic challenges through a comprehensive strategy rooted in site-specific probabilistic hazard analysis. This approach enabled precise peak ground acceleration calculations, guiding the implementation of tailored solutions along the geologically diverse route. Key interventions included micro piles and vibro compaction in liquefaction-prone areas, base isolation systems, hydraulic dampers at critical junctures, and innovative tunnel lining with bolt-anchored concrete segments. Each method brought distinct advantages: probabilistic assessment provided nuanced risk insights, ground improvements enhanced soil stability, and specialized structural elements offered superior seismic resistance. The effectiveness varied by location, with vibro compaction excelling in high-liquefaction zones and base isolation proving particularly valuable for station structures. This adaptive, multi-pronged approach successfully met diverse seismic performance requirements, ensuring the metro's resilience across varied geological landscapes.

## Conclusions

The urban metro construction project demonstrated the critical importance of innovative engineering solutions and adaptive methodologies in addressing complex geotechnical and seismic challenges. By integrating advanced technologies such as 3D mapping and tunnel boring machines (TBMs) with advanced techniques like fiber-reinforced polymer (FRP) piles and prefabrication, the project successfully navigated site-specific obstacles across diverse geological conditions. Precise numerical modeling emerged as a key strategy for predicting and mitigating potential risks, significantly enhancing project efficiency and safety. The research highlights the most important significance of comprehensive site investigations, flexible construction approaches, and interdisciplinary collaboration. Ultimately, this project shows how the strategic synthesis of cutting-edge technologies and established engineering practices can effectively overcome the complex challenges inherent in urban infrastructure development, providing valuable insights for future metropolitan underground construction endeavors.

The authors declare no conflict of interest.

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