International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

A Review on Efficient Foundation Design For Metro Rail Corridors

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Abstract

The rapid growth of urbanization and the rising demand for sustainable transport infrastructure have accelerated the development of metro rail systems worldwide. Foundation design plays a crucial role in ensuring the stability, safety, and longevity of metro rail corridors, particularly in densely populated urban environments where geotechnical challenges, space constraints, and interaction with existing structures must be carefully addressed. This review explores the principles and practices of efficient foundation design for metro rail projects, with emphasis on geotechnical investigation, soil-structure interaction, and selection of foundation type, seismic considerations, settlement control, and construction techniques. Special attention is given to pile foundations, raft foundations, and hybrid solutions that provide stability in varying soil conditions, along with modern design tools such as finite element analysis and Building Information Modeling (BIM). The study also highlights the importance of optimizing cost, time, and sustainability by incorporating innovative materials, ground improvement methods, and risk mitigation strategies. By synthesizing lessons from global case studies and recent research, the review underscores that efficient foundation design not only enhances structural reliability but also minimizes construction impacts, reduces lifecycle costs, and contributes to the resilience and long-term performance of metro rail corridors.

Key Words: -rapid growth of urbanization, foundation design, metro rail projects, varying soil conditions, enhances structural reliability

Introduction

Efficient foundation design for metro rail corridors is vital to ensure structural stability, durability, and cost-effectiveness while accommodating the complex demands of urban infrastructure. It begins with comprehensive geotechnical investigations to evaluate soil properties, stratigraphy, and groundwater conditions, which are essential for selecting the appropriate type of foundation—whether shallow foundations for stable soils or deep foundations like piles and caissons in weak or variable strata. Risk assessment plays a crucial role, addressing potential hazards such as soil liquefaction, seismic activity, differential settlement, and nearby construction impacts. The design must also ensure adequate bearing capacity, control settlements within permissible limits, and provide resilience against dynamic loads from trains and environmental influences. Furthermore, modern foundation design emphasizes sustainability through optimized material use, reduced carbon footprint, and incorporation of techniques that extend service life with minimal maintenance. Altogether, a well-engineered foundation system balances safety, performance, environmental responsibility, and economic feasibility, forming the backbone of reliable metro rail infrastructure.The rapid growth of urban populations and the increasing demand for sustainable transportation systems have made metro rail corridors an essential component of modern infrastructure development. Metro systems not only reduce traffic congestion and air pollution but also provide reliable, high-capacity, and eco-friendly mobility in densely populated cities. Among the various structural elements of a metro project, the foundation plays a critical role in ensuring safety, stability, and durability. Since metro rail corridors often traverse through complex urban environments—characterized by heterogeneous soil conditions, high groundwater tables, seismic vulnerability, and proximity to existing structures—the design of foundations requires careful consideration of geotechnical, structural, and environmental factors. An efficient foundation design ensures adequate load-carrying capacity, controls settlement, minimizes construction costs, and reduces risks during both construction and operation phases. Moreover, adopting innovative and sustainable foundation solutions, such as advanced piling techniques, soil improvement methods, and eco-friendly materials, contributes to optimizing land use and enhancing long-term performance. This review aims to explore the principles, challenges, and advancements in efficient foundation design for metro rail corridors, with emphasis on safety, economy, sustainability, and adaptability to complex ground conditions.

Literature Review

RushikeshShelke et al (2024) this research paper presents a detailed case study on the construction of cast in situ piles and pile caps for Pier Number 370 at Bandra Station, part of the Mumbai Metro Line 2B project, focusing on geotechnical investigations through borehole drilling, soil sampling, and in-situ testing to determine subsurface conditions and design parameters. It highlights the engineering design considerations, including concrete mix design and reinforcement detailing, while outlining the construction sequence from site preparation and pile boring to concreting and pile cap formation. The study emphasizes the use of specialized equipment such as rotary piling rigs and tremie pipes for underwater concreting, reflecting the challenges of executing metro infrastructure in densely populated urban areas. By documenting the methodologies, challenges, and solutions adopted, the paper provides valuable insights into the planning, monitoring, and adaptive problem-solving required for large-scale infrastructure projects, and concludes with recommendations aimed at guiding future urban construction works, thereby contributing to both professional practice and academic knowledge in civil engineering.

Lei Yan et al (2023) this study addresses the complexity of pile foundation underpinning structures and the high precision required during construction by highlighting the necessity of using epoxy resin reinforcing adhesive for planting rebar in underpinning beam design, which enhances the mechanical bond between new and old concrete at joint surfaces. To further improve performance, the paper proposes a novel pile foundation replacement beam construction method combining "chiseling + prestressed reinforcement + epoxy resin adhesive," ensuring better structural integrity and durability. Using a real urban overpass underpinning project as a prototype, a scaled model with a 1/6 similarity ratio was designed and subjected to repeated progressive static loading tests to evaluate load-bearing capacity, displacement characteristics, overall working performance, and failure modes of the strengthened replacement structure. Based on these experimental investigations, a finite element analysis (FEA) model of the prototype was developed, and its results were compared with the physical test data to validate the mechanical behavior and deformation patterns under actual underpinning beam loads. The findings provide both theoretical and experimental insights, offering a reliable foundation for guiding the safe and efficient implementation of similar pile foundation underpinning projects in complex urban environments.

XinpingGuo et al (2021) the construction of metro stations in densely built urban environments faces the dual challenge of maintaining strict schedules while minimizing environmental and structural impacts on surrounding areas. In Dalian, China, where the geological profile consists of an upper-soft and lower-hard stratum, a specialized structural approach using six pilot tunnels combined with three spans of the pile-beam-arch (PBA) method was implemented at the Labor Park metro station. To assess its effectiveness, researchers employed laboratory experiments, numerical simulations, and field monitoring, focusing on ground surface settlement, arch vertical displacement, horizontal rock mass movement, and vertical stress distribution within the support structures. The findings showed strong agreement between simulation and field data, confirming the reliability of the model. Results highlighted that both pilot tunnel excavation and arch construction were the primary factors influencing surface settlement, and the removal of parts of the initial vertical support in pilot tunnels led to stress redistribution and shifts in maximum vertical stress locations. Importantly, the inclusion of side piles significantly enhanced stability, reducing horizontal rock mass displacement by 44.76% compared to cases without reinforcement. Overall, the six pilot tunnels and three spans of the PBA method proved highly effective in controlling settlement, displacements, and stress redistribution, ensuring both structural safety and construction efficiency in complex geological conditions.

Shuaihua Ye et al (2020) the excavation of a foundation pit significantly affects nearby structures and underground pipelines due to changes in the soil's stress state, which leads to deformation; therefore, a case study was conducted to analyze the impact of excavation on the deformation of adjacent subway tunnels using PLAXIS 3D finite element software to simulate the entire excavation process. Based on the simulation results, the foundation pit's structural design was optimized to ensure stability and protect the subway tunnel, followed by a safety evaluation to assess the impact of excavation-induced deformation. The study found that the influence of excavation and unloading on subway tunnels is strongly dependent on factors such as the distance between the tunnel and the foundation pit, the volume of soil removed in each stage, and the geological conditions at the site. The findings provide valuable reference for optimizing design and improving safety assessment in similar urban construction projects.

Shijia Liu et al (2020)in the project of excavating through the pile foundation of the adjacent Qingdao Metro Line 11 at Zhangcun Station of Line 4, an orthogonal simulation study was conducted to analyze the effects of different underground running lengths of the adjacent bridge pile, with the findings highlighting significant improvements in safety, efficiency, and cost-effectiveness. The initial solution showed that the maximum vibration velocity generated by the bridge pile was 0.69 cm/s, which was deemed very safe, while the optimized scheme increased the vibration velocity slightly to 1.02 cm/s but allowed for an extension of 10 m in the blasting section, thereby accelerating the construction schedule. Field monitoring data confirmed that the results of the optimized scheme matched the simulated data, validating the accuracy of the simulation approach and demonstrating that the optimization reduced the overall construction budget by approximately 15%. Furthermore, the study found that vibration velocity attenuation was influenced mainly by the stratigraphy of silty clay, coarse sand, and micro-weathered granite. The optimization process utilized Ansys/LS-DYNA software to adjust the K file by incorporating blasting parameters and initiation points, which provided a practical and efficient plan that not only improved construction efficiency but also ensured safety and reliability in the metro tunnel excavation process.

B.Butchibabu et al (2019) excavations for underground metro rail developments in thickly populated urban areas can often trigger unexpected consequences such as sinkhole formation, soil piping, or uneven settlement of nearby foundations, leading to cracks in adjacent buildings and even tilting of tall structures, as was observed in Chennai. Despite following established design guidelines and codes, the disturbance of the subsurface regime during excavation frequently generates weak zones that compromise stability. One common remedial measure is grouting; however, applying it without properly demarcating the weak or affected zones may prove ineffective or even counter-productive. To address such issues, integrated geophysical and geotechnical investigations are essential, as demonstrated in the Chennai case, where cross-hole seismic P- and S-wave velocity measurements were conducted between 10 pairs of boreholes up to 20 m depth on both sides of the excavation, complemented by two electrical resistivity tomography (ERT) surveys, each 141 m in length. The results from S-wave velocity profiles and resistivity tomograms revealed distinct weak zones and probable sinkhole locations, confirming the cause of structural distress in the surrounding strata. Furthermore, a site-specific empirical correlation was developed between S-wave velocity and standard penetration test (SPT) N-values, allowing estimation of subsurface strength conditions both pre- and post-excavation. These comparisons validated the presence of weak zones that contributed to the instability of foundations. Such combined geophysical and geotechnical approaches are highly beneficial for future metro rail projects in complex subsurface environments characterized by alluvium, sand, clay mixed with silt, pebbles, and boulders, particularly in groundwater-influenced regions of densely populated cities, as they enable accurate identification of vulnerable zones and implementation of targeted stabilization measures.

Mr. Mohammed Imran et al (2016)pile foundations are widely adopted for multi-storied buildings, industrial structures, bridges, and offshore constructions because they provide stability in areas where soil strength is inadequate to bear structural loads. The fundamental concept involves drilling piles from the ground surface until a competent hard stratum is reached, thereby transferring structural loads safely to deeper, stronger soil or rock layers. Since soil type and geological conditions vary significantly, the design of pile foundations must carefully account for ground conditions, as these influence both the load transfer mechanism (end-bearing or frictional resistance) and the ultimate capacity of the foundation. A safe and efficient design ensures structural stability even under severe loading conditions such as dynamic loads, seismic forces, or fluctuating water pressures. The design process involves estimating loads from superstructures according to site-specific conditions and applying Indian Standards (IS) for accuracy and reliability. Additionally, the performance of pile foundations under load has been studied through various theoretical approaches, including pile load transfer models, settlement analysis, and lateral load behavior, which guide engineers in selecting appropriate pile dimensions, materials, and installation methods to optimize safety and cost-effectiveness across different ground conditions.

NagarjunaPilaka et al (2015) hyderabad, being a rapidly growing metropolitan city in India, has been facing severe traffic congestion and transportation challenges due to the saturation of existing modes like buses and trains, which necessitated the development of a modern Mass Rapid Transit System (MRTS). To address this, the Hyderabad Metro Rail Project (HMRP) was conceived as one of the largest Public-Private Partnership (PPP) initiatives in the country, aimed at providing sustainable, efficient, and high-capacity urban mobility. Despite several challenges in execution, the project is nearing completion and showcases a range of advanced technical features, including carefully planned route alignment to cover major traffic corridors, well-engineered horizontal and vertical curves, optimized cross-sectional designs for elevated and underground structures, and robust construction methodologies to ensure safety and durability in a dense urban environment. The project incorporates modern structural designs for viaducts, stations, and depots, along with state-of-the-art construction processes such as precast segmental techniques, advanced tunneling methods, and seismic-resistant structures. Furthermore, the operational arrangements include automated signaling, integrated ticketing, efficient scheduling, and intermodal connectivity, ensuring smooth passenger movement and minimal urban disruption. These aspects collectively make the Hyderabad Metro Rail Project a landmark in urban transport infrastructure, demonstrating engineering precision, sustainable planning, and execution excellence in meeting the long-term mobility needs of the city.

Methodology

The study adopts a systematic review-based research methodology to analyze efficient foundation design approaches for metro rail corridors. The methodology consists of the following steps:

Literature Collection

- Comprehensive collection of research papers, technical reports, case studies, and codes of practice related to foundation design in metro rail projects.
- Sources include academic journals, government publications, metro project reports, and international standards.

Identification of Key Parameters

- Extraction of crucial design considerations such as soil-structure interaction, load-bearing capacity, settlement behavior, groundwater conditions, seismic factors, and construction constraints in urban environments.
- Review of different foundation types (shallow, pile, caisson, raft, well foundations) and their suitability for metro rail corridors.

Comparative Analysis

- Evaluation of design methods and techniques applied in different metro projects worldwide.
- Comparison of performance with respect to cost-effectiveness, constructability, safety, sustainability, and service life.

Case Study Review

- Examination of selected metro projects (national and international) to understand practical challenges and successful design strategies.
- Documentation of geotechnical investigations, foundation selection criteria, and construction techniques adopted.

Synthesis of Findings

- Integration of theoretical knowledge and practical case outcomes to highlight best practices.
- Identification of gaps, limitations, and opportunities for improvement in current foundation design approaches.

Conclusion

Efficient foundation design plays a pivotal role in ensuring the safety, durability, and cost-effectiveness of metro rail corridors, particularly in complex urban environments with challenging geotechnical conditions. A thorough understanding of soil characteristics, groundwater conditions, and seismic vulnerabilities is fundamental for selecting appropriate foundation systems, whether shallow or deep. Pile foundations, diaphragm walls, and raft systems are commonly employed, but their suitability depends on load requirements, settlement control, and constructability within constrained urban spaces. Advanced techniques such as numerical modeling, soil improvement methods, and performance-based design approaches enhance reliability and minimize risks of settlement and vibration, thereby protecting adjacent structures and underground utilities. Furthermore, sustainability considerations, including optimization of materials, energy efficiency, and reduced carbon footprint, are increasingly shaping foundation practices. By integrating geotechnical investigations, structural demands, environmental concerns, and innovative construction methods, efficient foundation design not only supports the long-term stability of metro rail systems but also contributes to faster project execution, reduced maintenance, and overall economic viability of mass rapid transit infrastructure.

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