Challenges and Innovations in Deep Excavation in Urban Areas: Integrated Design and Construction Practices

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Abstract: The rapid pace of urbanization and demand for high-rise developments have intensified the need for deep excavations to accommodate underground infrastructure. Executing such projects in dense urban areas is challenging due to complex soil–structure interactions, limited space, nearby lifelines, and strict deformation control requirements. Conventional support-of-excavation (SOE) systems often fall short under these conditions. This paper presents an integrated design and construction methodology combining field data, numerical modeling, and real-time monitoring to address these challenges. Case studies from Tehran with excavation depths of 19.5–43 m highlight key innovations in soil nail wall systems and hybrid shoring. A major finding is that post-construction deformations, often underestimated, can rise by 69–222% beyond initial values, exceeding standard guidelines. Incorporating a Load Relaxation Factor (LRF) into PLAXIS 2D analysis improves prediction accuracy, while AI-assisted monitoring and adaptive design enable safer, more economical, and sustainable deep excavation solutions in complex urban settings.

Keywords: ***Deep excavation, Soil nail walls, Numerical modeling, Real-Time monitoring, Load relaxation factor, Hybrid support systems, Urban geotechnics.***

Introduction

Urban densification increasingly drives infrastructure underground, with excavations often exceeding 30 m and facing challenges such as limited space, nearby structures, variable ground conditions, and strict deformation limits (Peck, 1969). In cities like Tehran, weak fills, irregular geology, and aging utilities intensify these issues. Traditional SOE systems like braced walls often fail to manage complex soil–structure interactions, leading to greater use of adaptable methods like soil nailing (Lazarte et al., 2003). Yet, uncertainties remain in predicting long-term deformation. This study addresses that gap through an integrated methodology combining advanced modeling, instrumentation, and field data, introducing the Load Relaxation Factor (LRF) to improve post-construction deformation prediction.

Integrated Methodology for Design and Construction

A successful deep excavation project in dense urban areas requires a robust, multidisciplinary approach. This study adopts a structured Engineering–Procurement–Construction (EPC) framework with four key phases. It begins with comprehensive site characterization through subsurface investigations, in-situ testing, and mapping of nearby lifelines to establish a geotechnical baseline. Next, optimized SOE selection is carried out, evaluating advanced systems like soil nail walls and hybrid solutions combining nailing with anchorage or jet grouting. The core of design is advanced numerical modeling using Plaxis 2D and staged construction simulations. A key innovation is the Load Relaxation Factor (LRF), which quantifies residual forces after excavation stages — a major driver of post-construction deformation often ignored in conventional design. Finally, real-time monitoring and adaptive design close the loop. Continuous data from instruments such as inclinometers and total stations, integrated with AI-based analytics, support back-analysis and proactive adjustments to construction sequencing and support systems.

Case Studies and Technical Challenges

The proposed methodology was applied to several deep excavation projects in Tehran, each with distinct challenges. At the Niayesh Complex (43 m), proximity to buried pipelines required deep cast-in-place piles, multi-level tiebacks, and staged excavation guided by real-time instrumentation. The Amir Kabir Complex (31 m) faced geological variability; irregular rock inclusions were mitigated by denser soil nailing, longer anchors, and reinforced facings. In the Vanak Tower (33 m) project, lateral displacements reached 82.5 mm, stabilized through additional anchors, buttressing, and improved drainage, highlighting the need for flexible design. Data from the Yas and Baran projects (19.5–29.3 m) showed post-construction displacements increased by 69–222%, far exceeding the 15% limit in FHWA guidelines and emphasizing the importance of accounting for time-dependent soil–structure interaction. Results also showed that deformation rates depend not only on ground conditions but also significantly on design parameters such as nail density, spacing, and length.

Modeling, Monitoring, and the Load Relaxation Factor (LRF)

Conventional numerical models often assume deformations stabilize once construction ends. Field data contradict this, revealing significant ongoing movements. The Load Relaxation Factor (LRF) quantifies unbalanced forces remaining after each excavation stage, which drives post-construction displacements.

PLAXIS 2D models incorporating the LRF showed significantly better agreement with field data. In the Y1 project (29.3 m), displacement grew from 16 mm at completion to 35 mm after nine months; a model with LRF = 67% predicted 35.4 mm. Across projects, LRF ranged from 22% to 67%, confirming residual load effects are substantial and must be addressed. Variations in soil nail design directly influenced LRF, showing that optimizing parameters can reduce long-term deformation and improve support system performance.

Innovations in Monitoring and Adaptive Risk Management

Modern monitoring has evolved from passive verification to proactive decision-making. Integrating AI and predictive analytics enables early detection of behavioral trends and interventions before critical limits are reached — a shift essential for complex urban excavations.

Projects using hybrid support systems demonstrate these benefits. In the Vanak and Sohanak projects, real-time data guided mid-construction measures such as adding anchors and improving drainage to control displacements and address performance issues. Continuous feedback, combined with LRF-based modeling, forms an iterative process that enhances predictive reliability and supports dynamic, adaptive project strategies (Yasrebi et al., 2022).

Conclusions and Recommendations

Deep urban excavations require approaches beyond conventional design. This study shows that long-term support system behavior is controlled by construction sequencing, structural design, and post-construction effects, challenging the assumption of immediate deformation stabilization.

The LRF is a key contribution, linking model predictions with field observations of time-dependent wall behavior. Post-construction deformations rising by 69–222% demand a shift in design and risk assessment practices.

We recommend practitioners:

- Adopt an integrated EPC framework uniting investigation, modeling, and monitoring.
- Incorporate LRF into analyses for accurate long-term predictions.
- Make real-time instrumentation and data analytics core components of risk management.
- Optimize support system design holistically, as structural parameters strongly influence long-term performance.
- The synergy of LRF-based modeling, real-time monitoring, and adaptive design underpins safer, more economical, and reliable deep excavation projects in complex urban environments.

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