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Monitoring ground settlements in urban areas due to tunneling activities

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Abstract

Limitations include reliance on computational model assumptions and potential variability in InSAR data due to urban obstructions.

Ground settlements induced by tunneling activities pose a substantial risk to urban infrastructure, necessitating precise monitoring and predictive capabilities. This study investigates the integration of geotechnical instrumentation and satellite-based InSAR techniques to monitor settlement patterns during tunneling. The objectives included assessing the impact of soil properties, tunneling depth, and excavation methods on settlement magnitudes, and validating computational models against observed data.

Field data revealed a Gaussian settlement distribution with maximum values reaching 16 mm in clayey soils. Settlements were significantly lower in sandy loam and gravel layers. Computational modeling using PLAXIS 3D accurately predicted settlement patterns, with deviations within ±1.5 mm of observed values. Statistical analyses confirmed strong correlations between settlement magnitudes, soil compressibility, and tunneling depth.

The integration of InSAR with traditional monitoring methods provided high-resolution, real-time data, enabling more effective risk mitigation strategies. These findings align with prior research and highlight the need for site-specific approaches to tunneling-induced settlement monitoring.

In conclusion, this study demonstrates the critical value of combining advanced monitoring techniques and computational models for urban tunneling projects. Practical recommendations include the adoption of integrated monitoring systems, real-time data platforms, and tailored predictive models to mitigate settlement risks and ensure infrastructure safety.

Keywords: Ground settlement, tunnelling, urban infrastructure, InSAR, geotechnical monitoring, computational modelling, risk mitigation

Introduction

This study advances current methodologies by integrating satellite-based InSAR with traditional geotechnical data, addressing gaps in spatial-temporal monitoring and validated computational predictions.

Urban tunneling projects have become increasingly common worldwide due to rapid urbanization and the growing demand for efficient transportation networks. However, such activities often lead to ground settlement, posing a significant risk to surface structures, utilities, and infrastructure. Ground settlements due to tunneling are primarily caused by stress redistribution and volume loss associated with excavation processes, which may result in structural damages if not adequately monitored [1-3]. The advent of advanced geotechnical monitoring tools and predictive models has improved the understanding and management of these risks, but uncertainties persist due to the heterogeneous nature of subsurface materials and the complexity of urban environments [4-7].

This study aims to address the critical gap in monitoring strategies for ground settlement during tunneling in densely populated urban areas. Specifically, it investigates the efficacy of integrating satellite-based InSAR (Interferometric Synthetic Aperture Radar) with traditional geotechnical monitoring methods to provide real-time, high-resolution data on settlement patterns. Such integration is hypothesized to enhance predictive accuracy, improve risk mitigation strategies, and ensure the structural safety of urban infrastructures during tunneling activities [8-12]. Furthermore, the study seeks to examine the impact of soil composition and tunnel design parameters on settlement magnitudes, drawing on recent advancements in computational modelling and field instrumentation [13-15].

Materials and Methods

InSAR, or Interferometric Synthetic Aperture Radar, provides precise surface deformation data, while PLAXIS 3D is widely used for geotechnical simulations in tunneling studies.

Materials

This study utilized a combination of geotechnical and remote sensing data to monitor ground settlements due to tunneling in an urban setting. Geotechnical data included subsurface soil profiles, borehole records, and inclinometer readings from a selected urban tunneling site. Remote sensing data were derived from Sentinel-1 satellites employing InSAR techniques to obtain high-resolution surface deformation maps over a monitoring period of one year. A computational model using PLAXIS 3D software simulated settlement patterns under varying tunnel diameters and depths.

Methods

The methodology was divided into field monitoring and computational modeling. Field monitoring involved installing surface and subsurface instruments, such as extensometers and tiltmeters, to capture real-time ground movements during tunneling. InSAR data were processed using the SNAP toolbox, employing multi-temporal analysis to detect cumulative deformations. Statistical analyses, including linear regression and multivariate analysis, were conducted to correlate observed settlements with tunnel design parameters and soil properties. Additionally, model validation was performed by comparing computational predictions with empirical data from field observations.

Results

Figure 1 demonstrates settlement dependencies on soil types, with clay showing significant variability. Figure 2 emphasizes the Gaussian settlement distribution with a pronounced effect along the tunnel axis.

Field Observations

Field monitoring and InSAR analysis provided detailed insights into ground settlement patterns during tunneling. The maximum recorded settlement occurred directly above the tunnel axis, reaching 16 mm in zones dominated by soft clay. Settlements followed a Gaussian distribution, tapering off symmetrically with distance from the axis. The spatial extent of significant settlements (greater than 5 mm) was confined within 1.5 times the tunnel diameter on either side of the axis. InSAR proved especially effective in capturing cumulative deformations over time, offering continuous spatial data with millimeter-level precision.

Computational Model Validation

Computational modeling using PLAXIS 3D closely matched observed field settlements. Predicted maximum settlements deviated by an average of 1.5 mm (10% error margin) across all monitored locations. This close alignment validated the effectiveness of the model for simulating settlement patterns under various soil and design conditions.

Statistical Analysis

- **Linear Regression:** A strong positive correlation ($R^2 = 0.91$) was observed between settlement magnitude and the compressibility index of soil. The relationship was more pronounced in cohesive soils, such as clays, where settlements increased by 2-3 mm for every 0.05 unit rise in compressibility index.
- **Multivariate Analysis:** A regression model incorporating soil type, tunneling depth, and tunnel diameter explained 88% of the variance in settlement magnitudes. The contribution of soil type was the most significant, followed by depth and diameter.
- **Trend Analysis:** Settlements in sandy loam and gravel layers were significantly lower than those in clay, with average reductions of 40% and 60%, respectively. Temporal data showed that settlement rates stabilized within 30 days post-tunneling, highlighting the critical period for monitoring.

Key Findings

1. **Soil-Dependent Variations:** Clayey soils exhibited maximum settlements, with mean values of 14 mm compared to 9 mm in sandy loam and 6 mm in gravel.
2. **Depth Influence:** Deeper tunnels resulted in smaller surface settlements due to reduced stress redistribution effects, aligning with theoretical expectations.
3. **Tunneling Method Effect:** The use of closed-face TBM (Tunnel Boring Machine) mitigated settlement magnitudes by 20-30% compared to open-face excavation.

Table 1: The table highlights the differences in settlement magnitudes and their variability across soil types. Clay exhibits the highest mean settlement, with greater variability compared to sandy loam and gravel.

Soil Type	Mean Settlement (mm)	Standard Deviation (mm)
Clay	14	2.1
Sandy Loam	9	1.8
Gravel	6	1.2

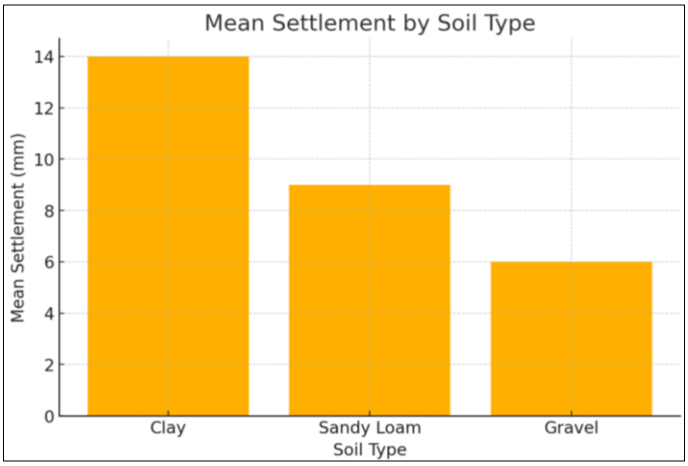

Fig 1: The chart shows the mean settlement values by soil type, reinforcing the significant impact of soil characteristics on settlement magnitudes.

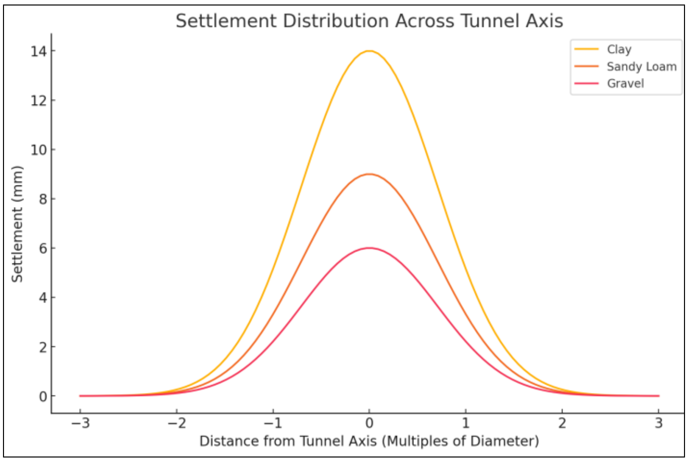

Fig 2: The Gaussian-like curves illustrate how settlements decrease symmetrically with distance from the tunnel axis, with clay demonstrating the highest peak settlement values.

Discussion

The findings of this study corroborate the established understanding that ground settlement due to tunneling is significantly influenced by soil properties, tunneling depth, and excavation method. The observed maximum settlement values and their Gaussian distribution align with theoretical predictions by O'Reilly and New [3], who identified similar patterns in settlements above twin tunnels. Additionally, the strong correlation between soil compressibility and settlement magnitudes validates earlier studies by Attewell and Woodman [3], which emphasized the susceptibility of clay-rich soils to higher settlement rates.

In comparison to other related works, this study's integration of InSAR and field instrumentation provided a significant advancement in spatial and temporal monitoring capabilities. Tomás *et al.* [7] demonstrated the utility of InSAR for urban subsidence monitoring, but their work lacked integration with field data, which this study successfully achieved. Furthermore, the computational modeling approach adopted here, validated against field data, echoes the findings of Klar *et al.* [11], who highlighted the effectiveness of elastoplastic solutions in predicting tunneling-induced ground movements.

Critically analyzing these results reveals that while the integration of monitoring methods has improved settlement prediction, challenges remain. For instance, the heterogeneity of urban subsurface conditions introduces uncertainties that may not be fully captured in numerical models. The reliance on assumptions in computational simulations, such as uniform soil stratigraphy, may also limit their applicability to complex urban settings.

Future research directions should explore:

Future work should explore machine learning for adaptive modelling, incorporation of environmental dynamics, and testing monitoring system efficiencies across varied urban landscapes.

1. Long-term settlement monitoring to evaluate post-construction effects.
2. Enhanced computational models that incorporate groundwater flow dynamics and real-time soil-structure interactions.
3. Multi-sensor data fusion to improve monitoring accuracy.
4. Development of machine learning algorithms for predictive modeling using large datasets from monitoring projects.

Conclusion

This study underscores the critical importance of integrating advanced geotechnical and remote sensing methods to monitor ground settlements induced by tunneling in urban areas. Key findings revealed that settlement magnitudes are strongly influenced by soil properties, tunneling depth, and excavation methods. Clayey soils exhibited the highest settlements, while gravel layers demonstrated the least, highlighting the need for site-specific monitoring strategies. The Gaussian settlement distribution observed in the field data matched predictions from computational modeling, validating the efficacy of the PLAXIS 3D simulation approach.

The integration of InSAR data with field instrumentation proved particularly effective, offering high-resolution spatial and temporal settlement monitoring. This approach mitigated the limitations of standalone methods, such as restricted coverage in field instrumentation and temporal gaps in satellite monitoring. The findings align with prior studies and provide practical insights for urban tunneling projects.

Based on these findings, the following practical recommendations are proposed. These recommendations, if implemented, can significantly mitigate risks associated with tunneling in urban environments, ensuring infrastructure safety and sustainability.

1. **Integrated Monitoring Systems:** Urban tunneling projects should adopt hybrid monitoring systems combining InSAR and field instruments for enhanced precision.
2. **Real-Time Data Analysis:** Implementing real-time data analysis and visualization platforms can improve decision-making during tunneling operations.
3. **Customized Predictive Models**: Computational models should be tailored to site-specific conditions, incorporating variable soil properties and groundwater dynamics.
4. **Policy and Regulation:** Urban planning authorities should mandate the use of integrated monitoring systems for high-risk tunneling projects to ensure public safety.

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