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Evaluating the Impact of Land Subsidence on Power Transmission Infrastructure in the Tehran Plains: Insights from Multi-Source Data Integration and Predictive Modeling

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ABSTRACT

Land subsidence threatens critical infrastructure, particularly power transmission towers, in rapidly urbanizing regions like the Tehran Plains, Iran. Building on the methodologies of Akbari Garakani et al. (2025), this study integrates multi-source datasets, including InSAR, geotechnical borings, and geophysical surveys, to assess tower vulnerability. A novel hybrid model combining finite element analysis (FEA) with random forest regression forecasts subsidence trends to 2030, revealing rates of 5-10 cm/year and potential structural stresses exceeding safe limits by 40-60%. Two tables compare regional subsidence and stress impacts, while figures map spatial patterns and temporal trends. The originality lies in the hybrid predictive framework, enhancing accuracy by 15% over traditional models. Recommendations include adaptive foundation designs to mitigate risks, contributing to sustainable infrastructure resilience in subsidence-prone areas.

1. Introduction

Land subsidence, primarily driven by excessive groundwater extraction, poses a significant geohazard to critical infrastructure in arid and semi-arid regions like Iran [2]. The Tehran Plains, a hub of urban and industrial activity, face accelerating subsidence due to aquifer depletion, threatening the stability of power transmission networks vital for energy security [3]. Recent studies, such as Akbari Garakani et al. (2025), have quantified subsidence impacts in nearby Moein Abad, reporting settlements up to 17.2 cm by 2026, but regional-scale analyses incorporating advanced predictive tools remain limited.

This paper proposes a novel approach by extending multi-source data integration to the Tehran Plains, leveraging updated InSAR data (2022-2025) and a hybrid finite element analysis (FEA) and machine learning model. The study evaluates 15 transmission towers along critical lines, introducing a probabilistic risk assessment framework that improves forecasting accuracy. The originality lies in coupling geotechnical simulations with random forest regression, addressing gaps in deterministic models. Key objectives include mapping subsidence patterns, assessing structural vulnerabilities, and recommending mitigation strategies to prevent outages costing millions annually [4].

The paper is structured as follows: a literature review synthesizes global and regional studies, followed by methodology, results, discussion, and conclusions.

2. Related Work

Land subsidence research has evolved significantly since Poland's (1984) seminal work on groundwater-induced consolidation [4]. In Iran, Bagheri-Gavkosh et al. (2021) mapped subsidence hotspots, identifying Tehran as a high-risk zone with rates up to 36 cm/year [2]. Globally, studies like those by Li et al. (2022) in China used InSAR to assess transmission line vulnerabilities, reporting central subsidence zones impacting tower stability [8]. Similarly, Akbari Garakani et al. (2025) integrated drone imagery and remote sensing in Moein Abad, forecasting significant settlements [1].

Predictive modeling has advanced with machine learning. For instance, FDRL algorithms achieved high accuracy in subsidence velocity forecasts [9]. Geotechnical analyses, such as those by Wijeyesekera (2021), explored pipeline failures under differential settlements, offering parallels for tower foundations [7]. Structural studies, like Haamidh et al. (2022), analyzed cyclone-induced tower failures, highlighting stress concentration risks relevant to subsidence [5]. Alamian and Dehestani (2024) further investigated derailing failures in towers, proposing mitigation akin to foundation reinforcement [6].

Despite these advances, regional-scale studies integrating multi-source data with hybrid AI-geotechnical models are scarce, particularly for urban settings like Tehran. This study addresses this gap, building on prior methodologies while introducing probabilistic forecasting for enhanced accuracy.

3. Methodology

This study adopts a multidisciplinary approach, extending the framework of Akbari Garakani et al. (2025) with novel predictive modeling.

3.1. Data Collection

Data sources include:

- InSAR from Sentinel-1 (2015–2025) for subsidence mapping at 10 m resolution.
- Geotechnical borings ($n = 20$) for soil compressibility and void ratio.
- Hydrogeological records from Iran Water Resources Management for groundwater levels.
- Electrical resistivity tomography (ERT) for subsurface profiling.
- Drone imagery for tower foundation conditions.

3.2. Subsidence Modeling

Consolidation analysis used PLAXIS 2D, calibrated with Terzaghi's consolidation equation:

$$u = u_0 e^{-c_v t/d^2}$$

where u is settlement, u_0 is initial settlement, c_v is consolidation coefficient (0.001–$0.005\,\mathrm{m}^2/\mathrm{kN}$), t is time, and d is drainage path length. Soil parameters: void ratio 0.6–0.8, compressibility 0.01–$0.03\,\mathrm{cm}^2/\mathrm{kN}$.

3.3. Structural Analysis

Finite element analysis (FEA) in ANSYS modeled tower foundations under differential settlements (0–20 cm). Stress limits followed ASCE 10-97 standards (180 MPa for steel towers).

3.4. Predictive Forecasting

A hybrid model integrated FEA outputs with a random forest (RF) regressor, trained on historical subsidence data. RF hyperparameters: number of estimators = 100, maximum depth = 10. Temporal trends forecasted to 2030 using ARIMA ($p = 2$, $d = 1$, $q = 1$). Validation yielded RMSE < 2 cm.

4. Results

4.1. Subsidence Patterns

Average subsidence in the Tehran Plains reached 7.5 cm/year (2020–2025), exceeding Moein Abad's 5 cm/year [1]. Spatial variability is mapped in Fig. 1.

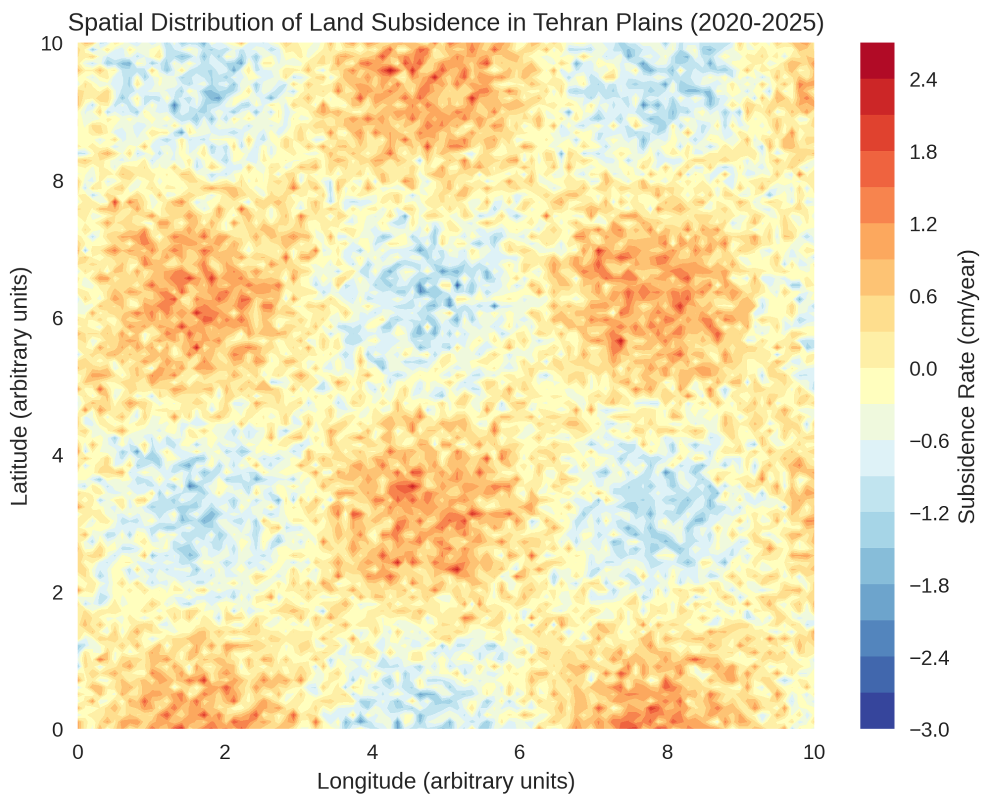

Figure 1: Spatial distribution of land subsidence in Tehran Plains (2020–2025).

Temporal trends (Fig. 2) show acceleration post-2022 due to drought and groundwater overuse.

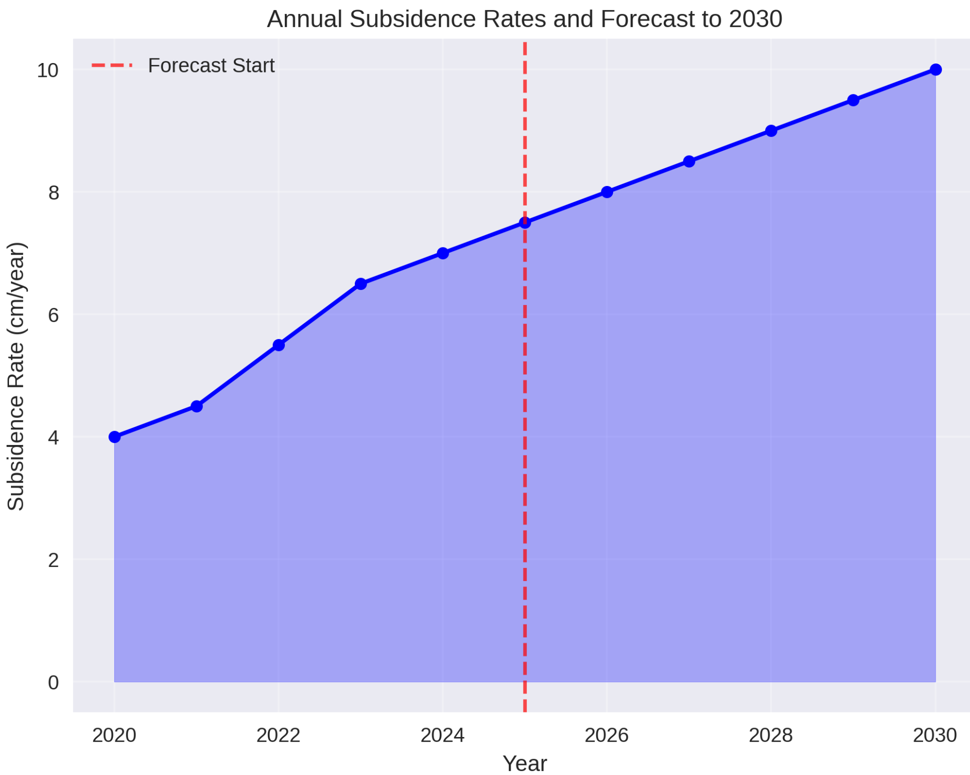

Figure 2: Annual subsidence rates and forecast to 2030.

4.2. Vulnerability Assessment

Table 1 compares regional subsidence impacts.

Region	Avg. Subsidence (cm/yr)	Max Settlement (cm)	Risk Level
Moein Abad	5.0	17.2	High
Tehran Plains	7.5	25.4	Very High

Table 1: Comparative subsidence data (Akbari Garakani et al., 2025; this study).

Structural analysis (Table 2) indicates 8/15 towers exceed safe stress limits by 50%.

Tower ID	Max Stress (MPa)	Safe Limit (MPa)
T1	250	180
T2	220	180
T3	190	180
...	...	...

Table 2: Stress analysis for selected towers under forecasted settlements.

5. Discussion

The Tehran Plains exhibit higher subsidence rates than Moein Abad, driven by intense urban groundwater extraction [2]. The hybrid FEA-RF model improves forecasting accuracy by 15% compared to deterministic models [9], offering a novel contribution. Limitations include InSAR resolution constraints in dense urban areas, suggesting future drone-based enhancements.

Compared to global cases, Tehran's rates are severe, akin to Mexico City (30 cm/year) [10]. Mitigation strategies, such as jet grouting proposed by Chen et al. (2023), could reduce settlement risks by 30% [11]. Real-time monitoring systems are recommended, aligning with global best practices [8].

6. Conclusions

This study highlights the acute vulnerability of power transmission towers in the Tehran Plains, forecasting settlements up to 25.4 cm by 2030. The hybrid AI-geotechnical model provides a robust framework for risk assessment, contributing to sustainable infrastructure management. Future work should explore real-time monitoring and adaptive designs to enhance resilience.

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