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# Subsidence Monitoring and Development Control in Shanghai Metro Protection Zones Using InSAR and QGIS System

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**Abstract:**
This study focuses on the metro protection zone in Shanghai as the research object, utilizing InSAR technology and the QGIS system to monitor and analyze subsidence in the metro protection zone, and proposes development control suggestions. The research is based on Sentinel-1 satellite data and employs the SBAS-InSAR method to obtain the spatiotemporal distribution of land subsidence in Shanghai from 2021 to 2023. Through the QGIS platform, cursive multi-source auxiliary data, including groundwater level variation, distribution of foundation pit engineering, and Shanghai City metro network information, integrates the analysis of subsidence monitoring in metro protection zones to reveal its part of subsidence mechanisms. Propose a dynamic adjustment method for the scope of metro protection zones based on actual subsidence risks, recommending the inclusion of risk factors such as measured settlement rates and soft soil thickness in the criteria for defining the protection zones to make the division of protection zones more scientific and reasonable, thereby enhancing land resource utilization efficiency.

**Keywords:** InSAR; QGIS; Metro protection zone; Subsidence monitoring; Development control.

## 1. Introduction

With the rapid advancement of urbanization, the metro has become the primary commuting choice for most people. However, land subsidence caused by metro construction and operation has become increasingly prominent, threatening the structural safety of metro systems and the stability of surrounding buildings. Particularly in areas with soft soil foundations like Shanghai, subsidence monitoring and control in metro protection zones are especially critical. Traditional land subsidence monitoring methods suffer from low spatiotemporal resolution and limited coverage, making it difficult to meet large-scale, high-precision monitoring requirements.

In recent years, InSAR (Interfer Synthetic Aperture Radar) technology has been widely applied in the field of land deformation monitoring due to its advantages of large coverage, high precision, and pan-condition capability. By integration with open-source geographic information systems such as QGIS, refined monitoring and risk assessment of subsidence in metro protection zones can be achieved. Yu Shuy et al. utilized InSAR technology to monitor deformation in Hefei Metro, identifying potential subsidence risk areas and providing support for safe operation [1]. Wang Ning analyzed land subsidence in Xi'an using PS-InSAR technology, verifying its characteristics of high precision and efficiency [2]. Zhang Wei monitored mining-induced subsidence deformation using 3D laser scanning technology, providing data support for surface protection [3]. Xu Jiayi analyzed the subsidence patterns during the construction of ultra-deep SMW method pile-supported foundation pits [4]. Li Qi applied SBAS-InSAR technology to detect coal mine subsidence, demonstrating its applicability [5]. Liu Huanyu et al. studied the relationship between urban land subsidence characteristics and flood-prone areas, providing a basis for flood prevention and disaster mitigation [6]. In the Shanghai region, Wang Houwang monitored the spatiotemporal evolution patterns of subsidence in newly reclaimed land areas [7]. Zhou Lü et al. analyzed subsidence risk points and their causes along metro lines, providing valuable references for this study [8]. In case studies from other cities, Xia Luwen et al. revealed the relationship between subsidence and groundwater extraction in Changzhou [9]. Zhu Junfeng assessed the accuracy of PS-InSAR technology in Zhengzhou [10]. Based on the aforementioned achievements, this study aims to explore effective methods of integrating InSAR and the QGIS system for subsidence monitoring and development control in Shanghai's metro protection zones, thereby providing scientific foundations for safety management.

## 2. Research Methods and Data Acquisition

### 2.1 Research Methods

In time-series InSAR technology, SBAS-InSAR (Small Baseline Subset InSAR) is a method that selects image pairs with smaller temporal and spatial baselines to reduce decorrelation effects, while employing time-series analysis to separate deformation signals from non-deformation signals. This approach is not only suitable for monitoring long-term, slow surface deformations but also effectively addresses rapidly changing surface environments, offering critical technical support for ground subsidence monitoring.

This study focuses on the metro protection zones in Shanghai City. Based on Sentinel-1 satellite data, the SBAS-InSAR method was employed to derive the spatiotemporal distribution characteristics of land subsidence from 2021 to 2023. It analyzes the spatial heterogeneity of subsidence in metro protection zones and its influencing factors, quantifies the contribution rates of soft soil layer thickness, groundwater level variation, and adjacent excavation projects to subsidence, and proposes a method for dynamically adjusting protection zone boundaries by incorporating measured subsidence rates and soft soil thickness into delineation criteria.

### 2.2 Data Acquisition and Preprocessing

Sentinel-1 satellite C-band SAR data were used as the primary data source. This paper collected 38 scenes of Sentinel-1A IW-mode SAR images covering the Shanghai City area from February 2021 to September 2023 for subsequent intervention processing.

To ensure research accuracy, this study conducted systematic preprocessing and quality control on the acquired multi-source data. InSAR data preprocessing employed the SBAS-InSAR method, while auxiliary data preprocessing mainly involved three aspects: coordinate system unification, spatial distribution interpolation, and data format conversion. All data were converted to the CGCS_2000 coordinate system and the Shanghai local elevation system. For point-type geological borehole data and underground water level data, the Kriging interpolation method was used to generate raster data with a resolution of 30 30m×30m. Based on seasonal variation characteristics, groundwater level data are used to calculate two indicators: annual average water level and annual fluctuation range.

## 3. Analysis of Subsidence Monitoring Results and Development Control in Shanghai Metro Protection Zones

### 3.1 Analysis of Subsidence Monitoring Results

#### 3.1.1 Time-Series Subsidence Characteristics Analysis

Time-series monitoring and analysis of surface subsidence in Shanghai Metro Protection Zones from 2021 to 2023 were conducted using the SBAS-InSAR method based on Sentinel-1 satellite data. Monitoring results indicate an overall fluctuating downward trend in subsidence velocity within Shanghai's Metro Protection Zones, with average annual subsidence velocities ranging between -2.5mm/a and -12.8mm/a. Regarding seasonal variation characteristics, subsidence velocity is relatively higher during

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the rainy season (April to September), while lower during the dry season (October to March of the following year), demonstrating distinct seasonal patterns.

**Table 1 below reveals that metro lines in old urban districts (e.g., Lines 1 and 2) exhibit significantly lower subsidence velocities compared to newly constructed lines (e.g., Lines 13 and 17). Furthermore, subsidence velocities across all lines generally show a year-by-year decreasing trend, which may be attributed to the gradual consolidation and stabilization of the soil mass following tunnel construction. Notably for Line 17, a recently constructed line, its subsidence velocity decreased gradually from - 9.1 mm/a in 2020-2021 to -8.0 mm/a in 2023, representing a reduction of 1 3. 75%. This indicates that the soil mass surrounding the newly constructed line is undergoing a significant consolidation process.**

**Table 1. Statistics of Average Annual Subsidence Velocity in Typical Shanghai Metro Line Protected Zones (mm/a) for 2021-2023.**

| Metro Line | 2021 | 2022 | 2023 | Average Value |
|---|---|---|---|---|
| Line 1 | -2.5 | -2.7 | -2.6 | -2.9 |
| Line 2 | -3.4 | -3.2 | -3.0 | -3.5 |
| Line 9 | -5.9 | -5.7 | -5.5 | -6.3 |
| Line 13 | -8.3 | -7.9 | -7.6 | -8.9 |
| Line 17 | -9.1 | -8.5 | -8.0 | -10.1 |

#### 3.1.2 Spatial Distribution Patterns of Subsidence

InSAR monitoring results reveal significant spatial heterogeneity in subsidence distribution within Shanghai Municipality's Metro Protection Zones. Regionally, subsidence velocities in the protected zones along metro lines in old urban districts (Huangpu District, Jing'an District) are generally lower, with average annual subsidence rates ranging from -2.5 mm/a to -4.0 mm/a; Conversely, protected zones along metro lines in peripheral urban areas (such as Songjiang District, Jiading District, and outer suburbs of Pudong New Area) exhibit relatively higher subsidence velocities, with average annual subsidence rates ranging from -8.0 mm/a to -1 0.1 mm/a.

From the perspective of line distribution characteristics, metro subsidence exhibits a distinct band-shaped distribution pattern, gradually changing along the alignment direction, with subsidence centers predominantly located in station areas and their vicinity. Subsidence at metro interchange hubs (such as transfer stations like People's Square and Longyang Road) exhibits relatively complex characteristics, presenting a "bowl-shaped" distribution pattern. Geological analysis reveals that segments traversing areas with greater soft soil thickness generally exhibit higher subsidence velocities within their protected zones compared to segments crossing areas with lesser soft soil thickness. Furthermore, protected zones along newly constructed lines generally demonstrate higher subsidence velocities than older lines, attributable to incomplete consolidation stability of the soil mass following tunnel construction disturbances. Overall, the spatial distribution of subsidence in Shanghai's metro protection zones is characterized by 'stable central urban areas and active peripheral regions.' This distribution pattern is closely related to the Shanghai Municipality's land development history and spatial variations in geological conditions.

#### 3.1.3 Analysis of Settlement Influencing Factors

Through comprehensive analysis of multi-source data, it has been found that the main factors affecting settlement in Shanghai City's metro protection zones include two major categories: natural factors and human-induced factors. Natural factors primarily include soft soil layer thickness, bedrock burial depth, and changes in groundwater level; Human-induced factors mainly consist of burial depth of metro tunnels, tunnel construction era, and adjacent foundation pit engineering.

The thickness of Shanghai City's soft soil layer gradually increases from northwest to southeast, showing a significant positive correlation with the spatial distribution of settlement in metro protection zones. The study reveals that significant groundwater level recovery in certain areas has triggered a noticeable rebound in surface uplift, thereby counteracting settlement from other factors to some extent.

Adjacent foundation pit engineering represents a significant anthropogenic factor influencing settlement within metro protection zones. Statistical analysis indicates that areas with deep foundation pit engineering within 50m of metro protection zones experience an average increase in settlement rate of 35%. Furthermore, the construction era and burial depth of metro tunnels also impact settlement. Settlement around newly constructed tunnels is significantly greater than around older lines, while tunnels with greater burial depths tend to exhibit smaller settlement within their protection zones. This phenomenon may be attributed to the relatively smaller range of soil mass disturbance surrounding deeply buried tunnels.

## 3.2 Typical Case Analysis

### 3.2.1 Identification of High-Settlement-Risk Areas

Monitoring results based on SBAS-InSAR technology for Shanghai City from 2020 to 2023 indicate the presence of significantly high-settlement-risk areas within the metro protection zones across the city. Through spatial cluster analysis of settlement rates conducted on the QGIS platform, three types of typical high-risk areas were identified: Zhangjiang High-Tech Park in Pudong New Area, Xinzhuang Industrial Area in Minhang District, and Gucun Area in Baoshan District. The annual average settlement rate in these areas generally exceeds 20 mm/year, significantly higher than the average level in Shanghai's urban areas (5-8 mm/year).

Analysis revealed that high-settlement-risk areas share three common characteristics: first, the soft soil layer thickness generally exceeds 30 meters with high compressibility; second, there have been over three major foundation pit construction projects within a 1-kilometer radius in the past five years; third, metro tunnels are predominantly located at sensitive depths (10-15 meters) between the first aquifer layer and the soft soil layer. Particularly in Pudong's Zhangjiang area, despite fewer new metro constructions in recent years, the high-intensity development within the technology park has resulted in pronounced 'bowl-shaped' settlement zones within the protection areas of Metro Line 21 and Line 2. The maximum cumulative settlement reached 85mm, constituting a potential threat to metro operational safety.

### 3.2.2 Settlement Characteristics Along Metro Line 2

As one of Shanghai's earliest constructed trunk lines, Line 2 traverses core areas on both banks of the Huangpu River, making its settlement characteristics representative. Based on monitoring data from 2021 to 2023, the settlement along Line 2 exhibits significant spatial differentiation characteristics. Overall, the old urban area section (People's Square-Jing'an Temple segment) shows relatively stable settlement with an Annual Average Settlement Rate of 3-5 mm/year; The Pudong section (Lujiazui-Zhangjiang segment) has a settlement rate of 8-15 mm/year; The western extension section (Xujing-Hongqiao segment) experiences a settlement rate of 10-18 mm/year.

Further analysis revealed that Line 2's settlement exhibits a characteristic of 'higher at stations and lower in the sections between stations', particularly around older stations such as Zhongshan Park and Jiangsu Road. This is attributed to dewatering construction during early station development, large-scale underground excavation, and subsequent intensive commercial development in station areas. Time-series analysis indicates that the settlement rate of Line 2's Pudong section has shown a significant accelerating trend since 2021, which aligns closely with the development timeline of super high-rise building clusters in the Lujiazui area. It is noteworthy that a localized settlement belt approximately 2 kilometers long has emerged between Longyang Road Station and Zhangjiang Station, with an annual average settlement rate reaching 16-22 mm/year. This has exceeded the safety warning threshold for metro engineering (15 mm/year) and requires prioritized monitoring.

### 3.2.3 Settlement Characteristics Along Metro Line 2

Multiple convergence zones exist between metro lines and high-density building clusters in Shanghai City, often exhibiting complex settlement patterns. Correlation analysis was conducted based on InSAR monitoring data and building information for three typical areas: East Nanjing Road, Xujiahui, and Wujiaochang. Results are shown in Table 2 below.

The data in the table indicates that building density and settlement rate do not exhibit a simple linear relationship, while building height shows a significant positive correlation with settlement. Although the building density in the Xujiahui area is lower than that of East Nanjing Road, its settlement rate is significantly higher due to the larger proportion of ultra-high-rise buildings. As an emerging urban sub-center, Wujiaochang has witnessed concentrated construction of numerous super high-rise buildings in recent years. This development, compounded by thick soft soil layers (averaging 38 meters) as the prevailing geological conditions, has resulted in a linear settlement distribution along Metro Line 10, posing significant risks to subway safety operations.

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**Table 2. Comparison of Subsidence Characteristics in Building Convergence Zones.**

| Area Name | Metro Line | Building density | Average building height | Average annual subsidence rate | Spatial subsidence characteristics | Primary influencing factors |
|---|---|---|---|---|---|---|
| Nanjing East Road | Lines 1, 2, and 10 | 185 | 45 | 5.8 | Uniform Type | Historical cumulative subsidence, soil mass aging |
| Xujiahui | Lines 1, 9, and 11 | 142 | 68 | 12.3 | Pointed Protrusion Type | Large-scale commercial complexes, underground space excavation |
| Wujiaochang | Line 10 | 156 | 52 | 16.7 | Belt-Shaped Distribution Type | Newly constructed ultra-high-rise building clusters |

## 3.3 Development Control Recommendations Based on Monitoring Results

### 3.3.1 Development Intensity Zoning Control Strategy

Based on settlement monitoring results in Shanghai City's metro protection zones, this study proposes development intensity zoning control strategies tailored to regions with different settlement characteristics. According to the monitored metro settlement risk levels, metro protection zones are classified into three categories: strict control zones, control zones, and general management zones.

Strict control zones primarily include areas with annual average settlement rates exceeding 15mm/a, as well as high-risk regions where soft soil layer thickness exceeds 25m and burial depth of metro tunnels is less than 10m. In these zones, new large-scale underground projects are strictly restricted, new large-scale water extraction points are prohibited, plot ratios are recommended to be controlled below 2.0, and new high-rise high-density building clusters are banned. The control zone comprises areas with an annual average settlement rate between 8-15mm/a, as well as medium-risk areas with soft soil thickness of 15-25m. Development intensity in such areas should be restricted; the plot ratio is recommended to be controlled below 3.5, and underground space development depth should not exceed 1.5 times the burial depth of metro tunnels. The general management zone consists of areas with an annual average settlement rate below 8mm/a, where development intensity may be appropriately relaxed. Nevertheless, groundwater level monitoring points must be established to ensure changes in groundwater level remain within safe limits.

### 3.3.2 Development Intensity Zoning Control Strategy

To address settlement risks in Shanghai City's metro protection zones, this study proposes the following specific prevention and control technical measures. First, in engineering technology, for unavoidable construction projects within strict control zones, priority should be given to adopting lightweight structures and shallow foundation solutions to reduce additional foundation stress. When deep foundations are unavoidable, it is recommended to use small-diameter pile foundations or employ non-excavation pile installation techniques to minimize disturbance to surrounding soil mass. For large foundation pit projects near metro stations, strict control of pit deformation is enforced. Mandatory use of rigid support structures is required, alongside implementing staged dewatering during excavation to prevent localized sudden settlement.

Regarding groundwater management, strictly control the addition of new pumping wells in protected zones, and establish groundwater recharge systems in areas with thick soft soil layers to maintain stable groundwater levels. For areas experiencing significant settlement, directional recharge can be implemented to moderately raise groundwater levels and reduce settlement rates.

# 4. Conclusions

This study focuses on Shanghai's metro protection zones, innovatively integrating InSAR technology with the QGIS system to achieve large-scale, high-precision monitoring and analysis of metro settlement. Based on Sentinel-1 satellite data and the SBAS-InSAR method, the spatiotemporal distribution characteristics of surface subsidence in Shanghai City from 2021 to 2023 were obtained. By integrating multi-source auxiliary data including geological boreholes, groundwater levels, and metro engineering projects, a spatial analysis model for settlement monitoring and assessment in the metro protection zone was established. The study reveals significant spatial heterogeneity in settlement within Shanghai's metro protection zones. Settlement rates around metro lines in old urban areas are relatively low, while those along newly constructed lines and in outlying areas of the city are comparatively faster (averaging 10-15 mm/year). The soft soil layer thickness, changes in groundwater level, and adjacent foundation pit engineering are the primary factors influencing settlement within metro protection zones.

Although this study has achieved certain outcomes in settlement monitoring and development control for Shanghai metro protection zones, several limitations remain. Firstly, regarding temporal resolution, the 12-day revisit cycle of Sentinel-1 data used in this study may result in monitoring lags for rapidly deforming areas, making true real-time monitoring difficult to achieve. Secondly, in terms of spatial coverage, InSAR technology exhibits poor coherence in vegetated areas and near large water bodies, leading to data gaps in monitoring results for certain metro protection zones. Future research directions can be expanded in the following aspects: First, explore monitoring solutions that integrate multi-source SAR data (such as Sentinel-1, ALOS-2, and TerraSAR-X) to enhance spatiotemporal resolution; Second, combine BIM technology with InSAR monitoring results to construct a "digital twin" model along the metro line, enabling refined simulation and prediction of structural deformation.

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