Building Deformation Monitoring and Safety Risk Assessment Based on PSI Technology

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Abstract

Based on traditional PS-InSAR technology, this study proposes a building elevation estimation method based on long and short baseline iteration. It utilizes long-temporal SAR images for multiple iterations to calculate building heights, which are used as prior information. Combined with the Interferometric Point Target Analysis (IPTA) method, it inverts building deformation information. The K-means clustering method is employed for PS point clustering analysis, classifying PS points with similar deformation trends and mapping them to buildings. A building safety risk assessment system is established, which comprehensively evaluates the cumulative deformation amount and deformation rate of both the building structure and its foundation. In this paper, the feasibility of the above method is verified by an example. The deformation of 9442 buildings is extracted in the study area, of which 245 buildings are in a high security risk state, and 2 buildings are in a high security risk state. Through this study, it can provide comprehensive auxiliary decision-making reference data covering macro wide-area and micro single buildings for urban construction management departments.

1. Introduction

In recent years, with the acceleration of urban development, the development scale of underground space such as urban super high-rise buildings and subway tunnels has surged (Li N Y,2022,Zhang, Peng,2024). Due to the superposition of multiple factors such as geological conditions, underground space development and long-term load, the potential safety hazards such as building foundation deformation and structural damage have become prominent, which has become a key risk source threatening urban public safety and infrastructure operation and maintenance. Especially in old urban areas, there are many early-stage buildings that are subject to issues such as outdated design standards, aging materials, and unauthorized renovations, making their safety risks even more in need of systematic monitoring.

The early identification and precise monitoring of building deformation are core components in achieving urban safety risk pre-control. However, traditional monitoring methods, such as total station observations, level gauge measurements, and Lidar scanning, can only acquire deformation data for small areas and discrete points. They struggle to capture the overall distribution characteristics and evolution patterns of the deformation field at the macro scale of cities, thus failing to meet the practical needs of modern urban fine management and macro safety control.

Many scholars have utilized the Permanent Scatter Interferometry (PSI) method to achieve the inversion and analysis of building deformation in large-scale urban areas. This method boasts high spatial resolution, wide coverage, and all-weather monitoring capabilities, enabling time-series tracking and quantitative description of building deformation (Ferretti A,2001, LI Naiyi,2018). However, this method still has significant limitations in practical applications. On the one hand, the PSI method relies on permanent scatterers (PS points) distributed on the surface of buildings to obtain deformation information. However, due to differences in building materials, limitations in observation angles, and environmental interference, PS points often exhibit characteristics of "sparse distribution and discrete fragmentation", especially in areas with low-rise buildings and complex structural structures, where data gaps are easily formed. On the other hand, the key to retrieving deformation information using PSI technology lies in phase unwrapping. Due to the large phase gradient of high-rise buildings, jumps often occur during the unwrapping process, which can affect the ability to meet the unwrapping requirements and lead to inaccurate retrieval of building deformation information. In addition, most scholars assess the safety risk level of buildings using their annual average deformation rate and cumulative deformation, without comprehensively considering the impact of the foundation in the building area. This restricts the reliability of monitoring results in management decision-making.

In view of the above problems, this paper explores building deformation monitoring and safety assessment methods based on PSI technology, employing baseline iterative estimation for elevation information. This elevation data is then used as prior information in the coherent point target analysis method to invert building deformation values. Through PS point aggregation analysis, it fills in the monitoring blind spots caused by the absence of local PS points. It assesses the safety risk level of buildings from four dimensions: foundation deformation (rate) and building deformation (rate), achieving a shift from subjective assessment based on a single indicator to scientific assessment based on comprehensive indicators.

2. Methodology

2.1 Building deformation monitoring based on PSI

2.1.1 Long-short baseline iterative estimation of building height: Due to the significant elevation phase gradient of the building, phase unwrapping often results in phase jumps, leading to failure in deformation information estimation. If accurate elevation information can be estimated and used as a priori value in the calculation, the phase jump problem can be

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resolved. The principle of the long-short baseline iteration method is to determine the number of iterations according to the length of the baseline, calculate the building elevation information through iteration, and use the elevation information of the previous iteration as a priori information to make up for the phase gradient difference in the latter iteration, and then invert the building elevation information.

The length of the spatial baseline is highly correlated with the elevation ambiguity (Li N Y.,2022). According to the formula (1), the larger the vertical baseline, the smaller the elevation ambiguity, indicating that the elevation information obtained is more accurate. The smaller the vertical baseline is, the greater the elevation ambiguity is, indicating that the accuracy of elevation information is low.

$$h_{2\pi} = -\frac{\lambda R_1 \sin\theta}{2B_\perp} \tag{1}$$

Where $h_{2\pi}$ is the elevation ambiguity
λ is the radar wavelength
R_1 is the distance from the radar to the sensor
θ is the incident angle
$B_\perp$ represents the vertical baseline.

Therefore, this method controls the accuracy of elevation estimation by adjusting the length of the baseline. When the time baseline is short, the deformation caused by the terrain is relatively small, so the deformation phase information can be ignored. Therefore, the two-dimensional model is transformed into a one-dimensional model, and the elevation phase value of the building is calculated. The one-dimensional regression model is publicized as follows:

$$\Delta\phi_{i,j}^{k} = C_B \cdot B^{(k)} \cdot \Delta\varepsilon_{i,j} + a^{(k)} + n^{(k)} \tag{2}$$

This method realizes the accurate estimation of building elevation through multiple iterations of long-short baselines. Firstly, the initial elevation information of the building is estimated and the elevation phase is simulated by using the short baseline combination calculation and the one-dimensional model regression analysis. Then, the initial elevation value is taken as a priori information, the spatial baseline condition is increased, and the second iteration calculation is carried out. In the calculation process, the initial elevation component is subtracted, and the elevation correction value is calculated. Then the spatial baseline condition is increased, and the new elevation value is substituted into a new round of iterative calculation. As the spatial baseline gradually increases, iterative calculations are progressively performed to reduce the phase gradient, thereby obtaining the elevation values of the target building under long baseline conditions. This effectively solves the phase jump problem caused by excessive elevation differences in high-rise buildings. The technical route as shown in Figure 1.

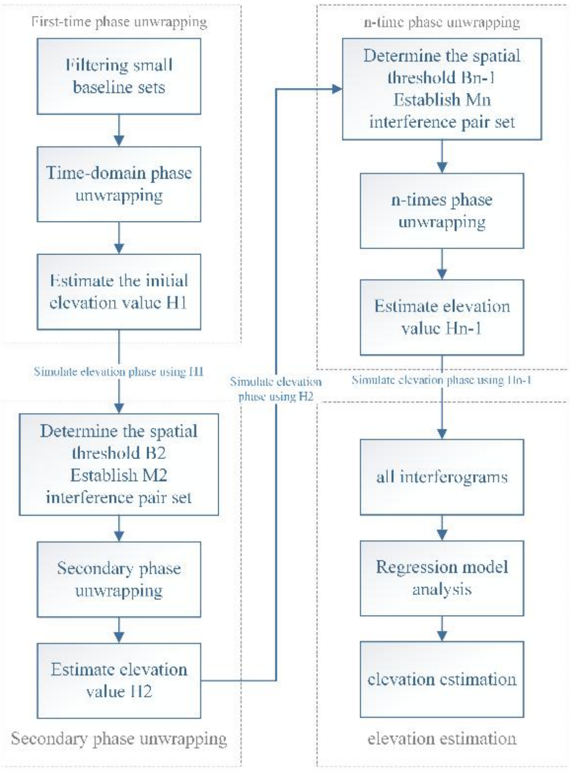

Figure1.Elevation baseline iterative estimation technical route

2.1.2 Interferometric Point Target Analysis （IPTA）：

Interference Point Target Analysis (IPTA) is a method of extracting terrain features that are not affected by time and space and have stable backscattering coefficients from long-term images, a Denauney triangulation network is established, and iterative calculations are performed in turn. After phase unwrapping, the atmospheric delay phase and residual phase are further eliminated (Zhang L.,2023). Finally, the deformation information of the point target is obtained.The technical route as shown in Figure 2.

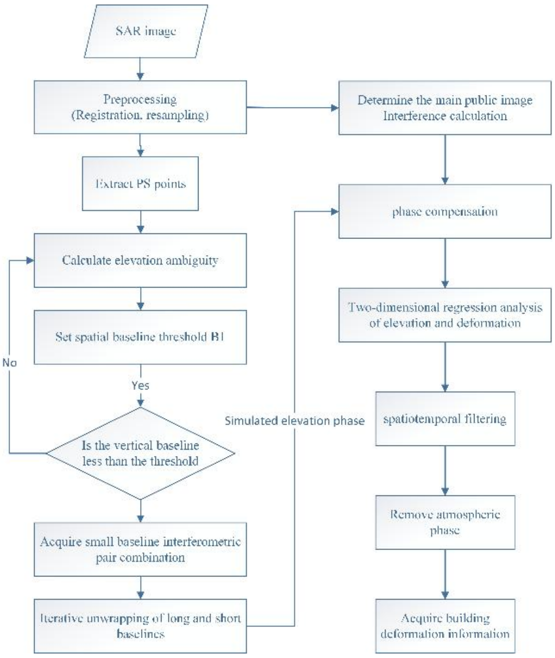

Figure2.Technical route of IPTA method

The IPTA method uses spatially and temporally stable coherent points to characterize ground objects, and analyzes the deformation information of ground objects through a two-dimensional regression model in time and space. For the selected target, two-dimensional regression analysis in spatial domain and time domain is carried out. The spatial domain uses the irregular network flow method to unwrap the wrapped phase to obtain the real phase. The time domain is to use the regression analysis method to analyze the time series change of the phase after unwrapping, and the SVD decomposition and its linearization model are mostly used. Through multiple iterations of two-dimensional regression analysis, the phase caused by linear deformation rate and elevation error, and the remaining residual phase are obtained. The residual phase includes the line-of-sight non-deformed phase, the atmospheric delay phase and the system noise phase. The specific model is as follows:

$$\phi_{\mathrm{unw}}=-2k\pi+\phi_{line}+\phi_{topo\_res}+\phi_{non}+\phi_{atm}+\phi_{noise} \tag{3}$$

Where ϕ_{unw} is the unwrapping phase

ϕ_{line} is the line-of-sight linear phase

ϕ_{topo_res} is the terrain residual phase

ϕ_{non} is a nonlinear variable phase

ϕ_{atm} is atmospheric phase

ϕ_{noise} is the noise phase.

In the phase of surface deformation, there are both linear and nonlinear deformation phases of coherent points. Therefore, equation 4 can be used to calculate the phase value of ground deformation, thereby obtaining the deformation amount and deformation rate.

$$\phi_{def}=\phi_{line}+\phi_{non}=\frac{4\pi}{\lambda}v_{line}+\frac{4\pi}{\lambda}D_{non} \tag{4}$$

Where ϕ_{def} is Deformation phase

v_{line} is linear deformation rate

D_{non} is Nonlinear deformation variables.

2.2 PS point cluster analysis

In this paper, K -means clustering method is used to map PS points of buildings (Liu, X.,2023,Zhu, J.,2021). The core principle is that the deformation trend and type of a building are the same, so the PS points with the same deformation are extracted by cluster analysis to express the building body.

K -means clustering method is an unsupervised machine learning algorithm that can iteratively extract time series and PS points with similar deformation dynamics from disordered PS points, and divide them into the same category. Then, the PS points with the same change trend are aggregated into a cluster point to characterize the building deformation.

Assume that a data set, a specified number of clusters K , and a set of cluster centers are given. Calculate the distance between the data point and the cluster center:

$$D(x_i,c_j)=\sqrt{\sum_{K=1}^{d}(x_{ik}-c_{jk})^2} \tag{5}$$

Among them, d represents the dimensionality of the data points. Assign each data point to the nearest cluster center (Equation 6), and then update the cluster center to the mean of all data points within that cluster (Equation 7).

$$k_i=\arg\min_{j} D(x_i,c_j) \tag{6}$$

$$c_j=\frac{1}{|S_j|}\sum_{x_i\in S_j}x_i \tag{7}$$

Where S_j is the set of all data belonging to cluster j . By iterating the above steps.

K -means clustering algorithm continuously optimizes the cluster centers, making the distribution of data points more compact and the within-class similarity higher. In this paper, we will use K -means clustering to preliminarily classify PS points, and thereby map the architectural PS points. By aggregating PS points from the same building through K -means clustering, statistical averaging of multiple observations and outlier removal are achieved, effectively suppressing single-point random noise.

2.3 Building safety risk level assessment

Building safety risks include building deformation risk and foundation settlement risk. This paper will establish the key parameters of building deformation from the two dimensions of building body and building foundation, and calculate the annual average deformation rate and cumulative deformation respectively to form four indicators for comprehensive judgment of building safety risk level,as shown in Table 1.

Parameter	Meaning
Ld_{3y}	Maximum cumulative settlement of foundation
LV_{1y}	Annual average settlement rate of foundation
Bd_{3y}	Accumulated maximum deformation of the building
BV_{1y}	Annual average deformation rate of buildings

Table 1 Construction risk assessment indicators

Based on the deformation inversion results of each building, according to the four key deformation indicators, the risk level is evaluated according to the risk evaluation criteria. The building is evaluated as four levels : I (Low risk), II (General risk), III (Higher risk) and IV (Very high risk), and the interval value of the evaluation index is designed, as shown in Table 2. This study believes that any indicator reaches a IV （very high risk） level, that is, the building is defined as a very high risk hidden danger building.

Level	Ld_{3y}/Bd_{3y} (mm)	LV_{1y}/BV_{1y} (mm/y)
Ⅰ	<18	<12
Ⅱ	18-24	12-24
Ⅲ	24-48	24-32
Ⅳ	>48	>32

Table 2 Deformation evaluation index value interval

3. Experimental scheme

3.1 Data and scope of study

In this experiment, 44 COSMO-SkyMed images from January 2022 to July 2025 were used as SAR image sources, X-band, spatial resolution of 3 meters, and the study area is about 55.56 km^2, as shown in Figure3. In this paper, the inversion of regional building deformation information will be carried out in this area, and the hidden danger of building safety risk will be analyzed and evaluated.

Figure3.Study area

3.2 Building elevation iteration results

In this experiment, the data time baseline and the spatial baseline are longer as shown in Figure4, so four long and short baseline iterations are performed.

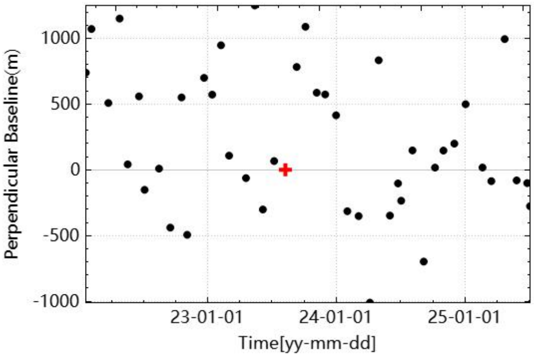

Figure4. Spatial-temporal baseline

Total of 182,000 PS points were extracted in the study area. According to the length of the spatial baseline, four elevation information iterations were performed, and the regional building elevation information was finally estimated,as shown in Figure5.

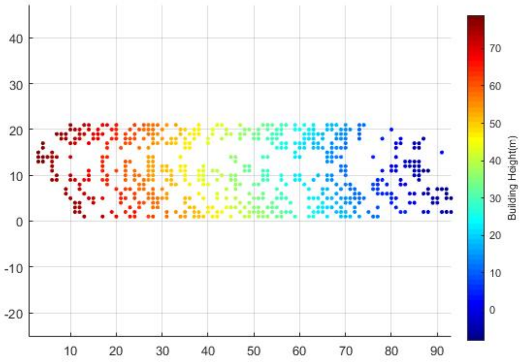

Figure5.Example of iterative results of building elevation (LOS Direction)

After calculation, the standard deviation of elevation estimation is 0.12 m, indicating that the long-short baseline iteration method can accurately estimate the building height.

3.3 Regional surface deformation monitoring results

Based on 182,000 PS points, the regional surface deformation information is inverted. It is calculated by the IPTA method that from January 2022 to July 2025, the cumulative average deformation in the region for three and a half years is about −15.84mm,as shown in Figure6, and the annual average deformation rate is about −4.22mm/y,as shown in Figure7.

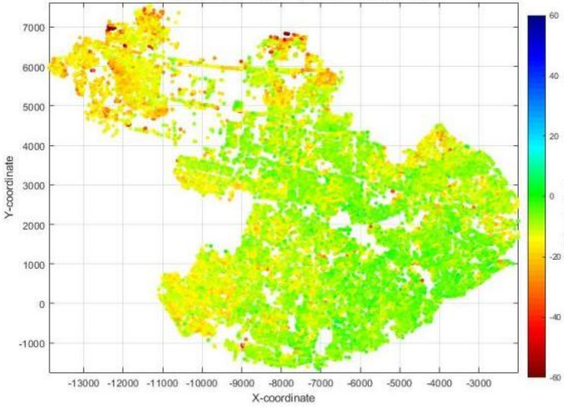

Figure6.Regional surface cumulative deformation

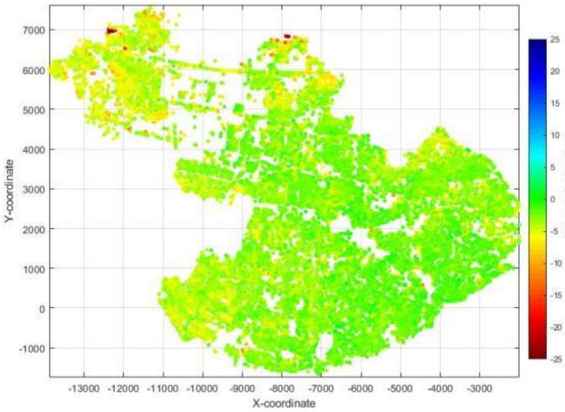

Figure7.Regional average annual surface deformation rate

The inversion results show that there are obvious subsidence funnels in the northwest, north and southwest regions of the region. The overall surface subsidence is relatively balanced and stable, and there is no obvious uplift trend in the region.

3.4 Building deformation monitoring and risk assessment

Utilize iterative elevation information to perform building deformation inversion. Through K-means clustering analysis, 73,700 PS points representing buildings and 40,700 PS points representing building foundations were identified, mapping out the annual average deformation rate and cumulative deformation amount for 9,442 buildings.

According to statistics, the cumulative average deformation of all buildings in three and a half years is about −15.85mm, as shown in Figure8, and the annual average deformation rate is about −4.23 mm/y, as shown in Figure9. which is basically consistent with the trend of surface deformation. After calculation, the standard deviation of the cumulative deformation of the building is 0.044 mm, and the standard deviation of the annual average deformation rate is 0.013 mm/y. The dispersion of the overall inversion results is low and the results are reliable.

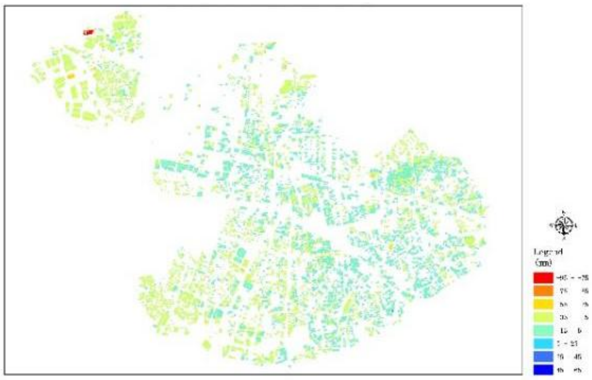

Figure8.Cumulative deformation of regional buildings

Figure9.Average annual deformation rate of regional buildings

According to the inversion of building deformation, the safety risk level of 9442 buildings is evaluated, and the thematic map of regional building safety risk is formed, as shown in Figure10.

Figure10.Regional building safety risk level

3.5 Safety level analysis of high-risk building deformation

According to the results of risk assessment, the overall state of the buildings in the experimental area is good, and there are 8670 buildings with low risk, accounting for 91.82 %. There are 525 buildings with general risk hidden dangers, accounting for 5.56%. There are 245 buildings in the state of high safety risk, accounting for 2.59%, and the cumulative deformation value in the past three years is [-48mm, -24mm]. Two buildings are in a state of high safety risk, accounting for 0.02%, and the cumulative deformation value in the past three years is greater than -48mm.

Taking one of the high-risk buildings as an example for multi-dimensional analysis. According to the optical image, the high-risk building is the construction factory,as shown in Figure11.

Figure11.High-risk building optical images

Through experimental analysis, the settlement index of the building body and foundation is shown in the Table3. According to the index value, the building is comprehensively judged to be grade IV (very high risk).

Parameter	Value	Level
Ld_{3y}	-83.57mm	IV
LV_{1y}	-24.35mm/y	III
Bd_{3y}	-50.09mm	IV
BV_{1y}	-14.45mm/y	II

Table3.High-risk building deformation information

From the analysis of the deformation trend, the building deformation curve and the maximum subsidence deformation rate curve are shown in the Figure12, and the deformation rate is accelerating as shown in Figure13.

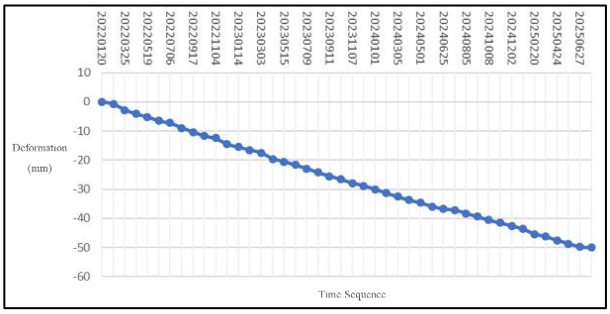

Figure12.The trend of building time series deformation

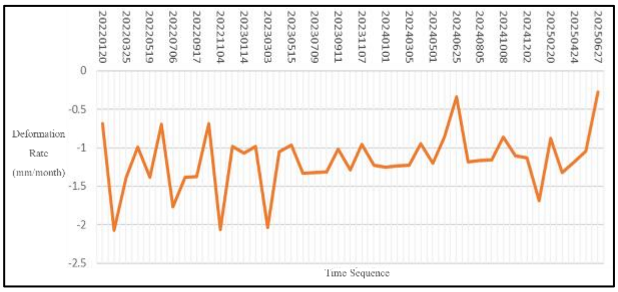

Figure13.The trend of building time series deformation rate

4. Conclusions

In this paper, the method of PSI inversion deformation information for urban buildings is studied. The phase jump problem caused by large height difference is solved by long and short baseline iteration. The IPTA method is used to solve the deformation information of surface and ground objects in macro area, which solves the problems of long period, discontinuity, discrete monitoring results and high cost of ground object deformation monitoring in large area.

Based on the results of PSI inversion, the K -means clustering method is used to cluster all PS points, and the PS points with the same deformation trend and type are extracted. The PS points are mapped to the building body through the three-dimensional space (x, y, h) information, which solves the problem of building PS point coefficient dispersion and data fault.

Through the PS point cluster analysis, the building deformation data is obtained, and the construction safety risk level evaluation system is established according to the requirements of urban construction safety operation and management. The construction safety risk is comprehensively graded by Ld_{3y}, Bd_{3y}, LV_{1y} and BV_{1y} and the construction safety risk is evaluated as I-IV according to the index value.

To verify the feasibility of the above methods and systems, this paper selects urban building-intensive areas for experiments. Through verification and analysis, the algorithm proposed in this paper can invert the regional deformation information, and extract the 3-year cumulative deformation of 9442 buildings is −15.85 mm, and the annual average deformation rate is about −4.23 mm/y. After comprehensive evaluation, 245 buildings in this area are in a higher security risk state, and 2 buildings are in a very high security risk state. For one of the high-risk buildings, through the analysis of the time series deformation trend, it is found that the building has an accelerated deformation trend and needs to be maintained and managed as soon as possible.

Through method research and experimental verification, this paper comprehensively evaluates building deformation information and foundation settlement information, and obtains the evaluation results of regional building safety risk level, which provides technical support for urban building safety management and scientific maintenance.

5. Prospect

In the follow-up study, considering the deformation error caused by the influence of temperature on building materials, the temperature information is added to improve the rationality of the deformation results when inverting the deformation information. In addition, the assessment of building safety level also needs to consider factors such as time series deformation trend, land use type, geological impact and surrounding environment. In the future, multi-source information will be combined with ground measurement results for verification and analysis, and the accuracy and scientific of building safety risk assessment will be further improved.

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