Subway Line Settlement Monitoring and Analysis Based on PS-InSAR Technology and Wavelet Packet Decomposition

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Keywords: PS-InSAR, Wavelet Packet Decomposition, Subway, Structural Deformation.

Abstract

Ground subsidence induced by metro construction and operation can lead to structural deformation, posing significant threats to the safety of urban infrastructure. The Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) technique enables high-precision monitoring of ground subsidence by extracting the interferometric phase of persistent scatterer (PS) points, demonstrating remarkable advantages in metro subsidence monitoring. However, due to the superimposed influence of multiple factors on the displacement signals of PS points, structural deformation signals are often obscured. Currently, there is a lack of effective methods for identifying structural deformation signals along metro lines. To address this, this study proposes a PS point analysis method based on Wavelet Packet Decomposition (WPD), which decomposes the time series of PS points into structural and non-structural deformation components, focusing on structural deformation induced by metro construction and operation. Using 32 Radarsat-2 images acquired from April 2019 to February 2023, ground deformation along Beijing Metro Line 16 was monitored and analyzed. The results demonstrate that the proposed method effectively captures structural deformation signals, revealing deformation characteristics associated with metro construction and operation. The study finds that structural deformation predominantly occurs during the construction phase, with ground subsidence showing a deceleration trend as operational time increases.

1. Introduction

With the continuous development of subway construction and operation, ground subsidence has become a significant threat to the safety of urban infrastructure (Lyu et al., 2020). Subsidence not only affects the subway lines themselves but may also have serious impacts on surrounding buildings and underground networks. During the construction phase, underground excavation and construction activities are often direct causes of ground subsidence, while in the operational phase, prolonged load effects exacerbate the subsidence phenomenon (Edmonds, 2018). Therefore, effectively monitoring and mitigating this subsidence is crucial to ensuring the long-term stability and safety of subway systems.

Traditional ground subsidence monitoring methods, such as leveling (Zhouet al., 2023), GPS measurements (Lingyun et al., 2014), and geological surveys (Okada, 2021), although capable of providing certain data for subsidence monitoring, are limited in their precision and spatial coverage, making them inadequate for large-scale, high-precision subsidence monitoring. In recent years, Synthetic Aperture Radar Interferometry (InSAR) technology has made significant progress, with Permanent Scatterer InSAR (PS-InSAR) emerging as one of the main techniques for urban ground subsidence monitoring due to its high precision, all-weather capabilities, and large-scale monitoring advantages (Ramirez and Kwon, 2022). The PS-InSAR technology extracts stable Permanent Scatterer (PS) points and uses their time-series data for ground deformation analysis, effectively identifying subsidence features along subway lines and surrounding areas.

However, the displacement signals of PS points are typically influenced by various factors (Ramirez and Kwon, 2022), especially along subway lines, where the overlap of structural and non-structural deformation signals often complicates the extraction of deformation signals. Structural deformation is usually caused by human activities such as construction, traffic flow, or changes in other infrastructure, manifesting as rapid changes in the ground over a short period (Wang, 2022). In contrast, non-structural deformation is primarily caused by natural factors such as geological movements, climate changes, or fluctuations in groundwater levels, typically resulting in slow and long-term changes in the ground (Solano-Rojas., 2020). While both types of deformation contribute to ground movement, structural deformation usually presents more severe risks. Subway construction and operation often lead to large-scale underground structural subsidence or uneven subsidence, and such rapid and intense deformation may jeopardize the safety of subway structures and even directly threaten surrounding buildings, roads, and other infrastructures. Therefore, effectively distinguishing and extracting structural deformation signals related to subway construction and operation has become a critical research topic in ground subsidence monitoring.

Commonly used PS point signal decomposition methods include traditional time-series analysis methods (Schlögl, 2021), model-based decomposition methods, and wavelet transform-based decomposition methods. Traditional time-series analysis methods, such as linear regression and polynomial fitting, typically extract deformation trends by fitting the time-series of PS points. However, these methods have limited capacity to handle nonlinear and non-stationary subsidence signals and are easily affected by noise. Model-based decomposition methods, such as Small Baseline Subset (SBAS) and least squares inversion, can fit signals by assuming a model and are suitable for simpler subsidence scenarios (Lauknes et al., 2011). However, these methods are often constrained by model selection and data processing limitations, making them ineffective at capturing nonlinear deformations in complex geological conditions and large-scale data sets. In contrast, wavelet transform, particularly Wavelet Packet Decomposition (WPD), is effective at handling non-stationary and nonlinear features in time-series data. WPD decomposes signals into multiple scales, breaking them into sub-signals across different frequency bands, thus capturing both structural and non-structural deformations in ground subsidence with greater precision (Rhifal, 2019). Compared to traditional methods, WPD not only effectively filters noise and enhances signal extraction accuracy but also reveals detailed changes in the subsidence process through multi-scale analysis, especially during subway construction and operation, enabling more precise identification of subsidence features related to underground construction (Guo et al., 2022). Therefore, the application of WPD in subway subsidence monitoring offers high precision and robustness, making it an effective solution to the limitations of traditional methods.

To this end, this paper proposes a PS point analysis technique based on WPD, which decomposes the time-series signals of PS points into two components: structural and non-structural deformation signals. This allows for a more precise extraction of subsidence features related to subway construction and operation. Using this method, the study conducted systematic monitoring of ground subsidence along Beijing Subway Line 16. The results demonstrate that the method can effectively identify subsidence features during both the construction and operational phases of the subway, providing strong support for further improving the accuracy and reliability of subway subsidence monitoring.

2. Study Area and Dataset

2.1 Study Area

Beijing Subway Line 16 is located in the southeastern part of Beijing, connecting Chaoyang District and Fengtai District. The line starts at Beianhe Station in Haidian District and ends at Wanpingcheng Station in Fengtai District, with a total length of approximately 50 kilometers. It passes through several key commercial and residential areas, making it an important part of Beijing's transportation network. Figure 1 shows the location of Beijing Subway Line 16.

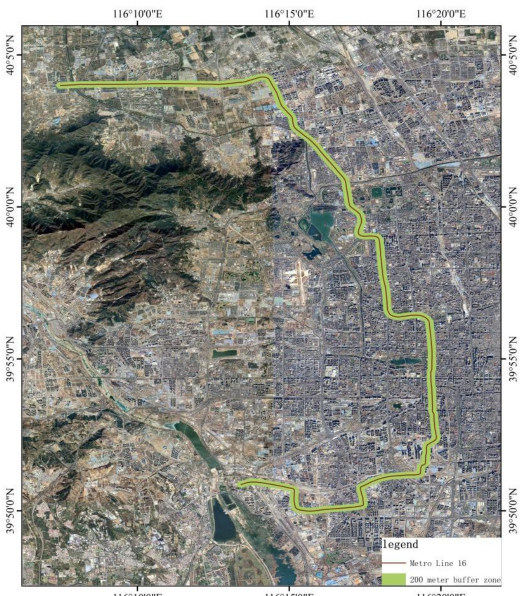

Figure 1. Study area geographic location

2.2 Dataset

This study selected 32 scenes of Radarsat-2 data with a resolution of 5 meters for deformation monitoring, covering the period from April 2019 to February 2023. The spatiotemporal baseline is shown in Figure 2, with the main image date of November 17, 2020. Detailed information on the dataset is provided in Table 1. The Radarsat-2 imagery, provided by the Canadian company MDA, is SAR data widely used in ground monitoring and environmental change analysis. The satellite has a revisit cycle of 24 days and operates in the C-band, offering high spatial and temporal resolution, making it suitable for dynamic monitoring along subway lines. To eliminate the influence of topographic phase, the study also obtained 30-meter resolution Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) data.

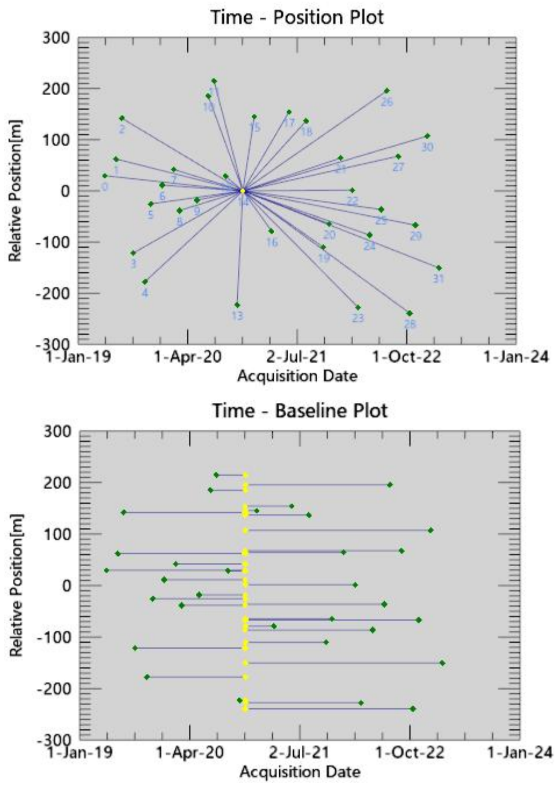

Figure 2. Time space baseline connection diagram

No.	Sampling Date	No.	Sampling Date
1	2019/04/21	17	2021/03/17
2	2019/06/08	18	2021/05/28
3	2019/07/02	19	2021/08/08
4	2019/08/19	20	2021/10/19
5	2019/10/06	21	2021/11/12
6	2019/10/30	22	2021/12/30
7	2019/12/17	23	2022/02/16
8	2020/02/03	24	2022/03/12
9	2020/02/27	25	2022/04/29
10	2020/05/09	26	2022/06/16
11	2020/06/26	27	2022/07/10
12	2020/07/20	28	2022/08/27
13	2020/09/06	29	2022/10/14
14	2020/10/24	30	2022/11/07
15	2020/11/17	31	2022/12/25
16	2021/01/04	32	2023/02/11

Table 1. Data list of the Radarsat-2 images

3. Method

This study employs PS-InSAR technology combined with WPD to monitor and analyze ground subsidence along Beijing Subway Line 16. The overall process is shown in Figure 3.

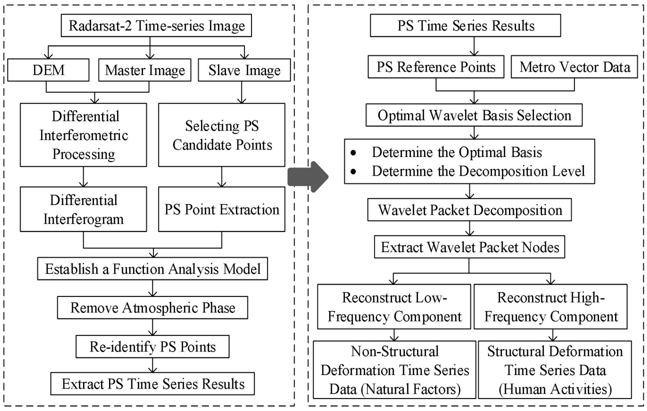

Figure 3. Overall technical process

3.1 PS-InSAR Data Processing Technique

In 2001, Ferretti et al. introduced the PS-InSAR method to address the issues of temporal and spatial decorrelation and atmospheric effects inherent in traditional InSAR techniques (Ferretti et al., 2002). This method selects a master image from multiple SAR images covering the same area, generating a time-series interferogram, and identifying PS points with stable phases and strong scattering, which are used to represent ground subsidence information. Based on this, subsidence information is obtained through modeling and solving, while effectively reducing the effects of temporal and spatial decorrelation and atmospheric delays. Differential interferometric processing of the images allows for the selection of stable PS points, thus providing continuous and reliable surface deformation data.

The principle of PS-InSAR is to use $N+1$ SAR images of the same area, selecting one as the master image and the remaining N images as slave images. The phase values of the corresponding PS pixels in the slave images are subtracted from those in the master image, resulting in N differential interferograms (Colesanti et al., 2003).

$$\phi_{ins} = \phi_{def} + \phi_{\varepsilon} + \phi_{atm} + \phi_{orb} + \phi_{noi} \quad (1)$$

The differential interferometric phase in InSAR contains multiple phase components. These include ϕ_{ins} for the pixel interferometric phase, ϕ_{def} for the deformation phase along the radar line of sight, ϕ_{ε} for the topographic phase caused by DEM errors, ϕ_{atm} for the atmospheric delay phase, ϕ_{orb} for the orbital error phase, and ϕ_{noi} for error components caused by noise and the registration process. Based on the PS point network and the spatiotemporal characteristics of each phase component, it is possible to estimate the phase components of atmospheric fault, DEM residuals, surface deformation, and orbital deformation. These can then be sequentially removed to extract the deformation phase reflecting surface displacement changes.

The key steps for ground deformation monitoring using PS-InSAR technology are as follows:

1. Selection of the Common Master Image: In the PS-InSAR interferometric processing, the selection of the common master image is crucial. It requires comprehensive consideration of the temporal baseline, spatial baseline, and Doppler centroid frequency baseline. The master image should be selected from the middle of the time series to reduce temporal decorrelation; the image pair with the smallest spatial baseline should be chosen to reduce spatial decorrelation; and the pair with the smallest Doppler centroid frequency baseline should be selected to ensure high coherence and improve interferogram quality. These principles can minimize the negative effects on interferometric phase quality and improve the accuracy of deformation inversion.

2. Image Registration: To obtain clear interferometric fringes, precise image registration is required. The registration process includes coarse registration and fine registration. Coarse registration searches for target pixels over a large area to obtain an initial offset, while fine registration involves interpolation at the sub-pixel level to obtain a more accurate offset. The registration accuracy is typically required to be 0.2 pixels or better to ensure the accuracy of the interferometric phase, thereby improving the precision of ground deformation analysis.

3. PS Point Identification and Selection: Identifying PS points is a key step in PS-InSAR technology, typically selecting stable and strong-scattering features, such as buildings and rocks. The selection methods for PS points include the single-threshold method and the double-threshold method. The double-threshold method combines coherence coefficient and amplitude deviation index, which improves the reliability of the selection. This process requires careful threshold setting to ensure the accurate selection of PS points.

4. Deformation Information Extraction: In PS-InSAR, PS points are first identified and their interferometric phases are unwrapped to obtain elevation information. However, atmospheric disturbances and decorrelation may affect the clarity of the interferometric fringes. To address this issue, the method proposed by Ferretti et al. is typically used, which eliminates the topographic effect through external DEM and employs optimization techniques to separate deformation rates and elevation errors. The remaining nonlinear deformations, atmospheric delays, and noise are removed through spatiotemporal analysis and filtering, ultimately obtaining accurate deformation rates and cumulative deformation values.

3.2 Wavelet Packet Decomposition Technique

Wavelet Packet Analysis is based on wavelet theory and, through the scaling and translation of wavelet basis functions, enables the subdivision of time in the high-frequency range and frequency in the low-frequency range, achieving localized analysis of signals in both time and frequency domains (Cui and Song, 2006). Compared to traditional dyadic wavelets, wavelet packets provide higher resolution for the high-frequency components of signals and introduce the concept of optimal basis selection on top of wavelet theory. After multi-level decomposition of the original frequency band using wavelet packets, frequency band information can be adaptively selected according to the characteristics of the analyzed signal, matching it to the signal and improving the analysis capability. The schematic diagram of wavelet packet three-level decomposition is shown in Figure 4, where U represents the original signal, A represents the low-frequency component, and B represents the high-frequency component. AAA, AAB...BBB represent the wavelet packet nodes from the three-level decomposition.

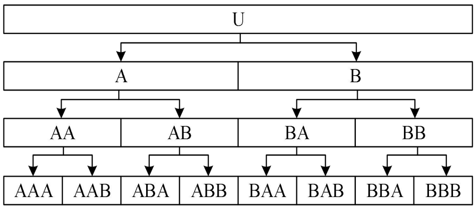

Figure 4. Schematic diagram of wavelet packet decomposition

The definition of wavelet packet is given by the following formula:

$$u_{2n}(t) = \sqrt{2} \sum_{k \in Z} h_{0k} u_n(2t-k) \quad (2)$$

$$u_{2n+1}(t) = \sqrt{2} \sum_{k \in Z} h_{1k} u_n(2t-k) \quad (3)$$

The defined function set $\{u_n(t)\}$, $n = 2,1,\cdots$ is the wavelet packet determined by $u_0(t) = \varphi(t)$. Since $\varphi(t)$ and h_k are uniquely determined, $\{u_n(t)\}$, $n = 2,1,\cdots$ is referred to as the orthogonal wavelet packet related to the $\{h_k\}$ sequence. In this case, $u_0(t)$ and $u_1(t)$ degenerate into the scaling function $\phi(t)$ and the wavelet basis function $\psi(t)$, respectively.

The original time series of length n is decomposed using wavelet packet decomposition, resulting in $2k$ subsequences of length $(n/2k)$ at the k-th level. These shorter subsequences can be subjected to more specific nonlinear computations, such as recursive analysis, which are not only reasonable and fast in computation but also more effective under the assumption of stationarity at multiple wavelet scales.

The orthogonal wavelet decomposition algorithm in multi-resolution analysis is extended to wavelet packets, resulting in the recursive formulas for wavelet packet decomposition and reconstruction:

$$d_k^{2m} = \sum_n h_{0(n-2k)} d_n^m \quad (4)$$

$$d_k^{2m+1} = \sum_n h_{1(n-2k)} d_n^m \quad (5)$$

$$d_n^m = \sum_k g_{0(n-2k)} d_k^{2m} + \sum_k g_{1(n-2k)} d_k^{2m+1} \quad (6)$$

After wavelet packet decomposition, the signal is transformed into several time series of different sizes, with each sequence corresponding to a certain frequency band component of the original signal. Based on the spectral characteristics of the original signal, certain sequences can be selectively chosen for detailed analysis.

4. Result and Discussion

4.1 PS-InSAR Experimental Results

Using PS-InSAR technology, ground deformation monitoring was conducted over the entire study area, resulting in 36,858 PS points. To better observe the subsidence along the subway line, a 200-meter buffer zone was created around Beijing Subway Line 16 to obtain PS points along the surrounding areas. The experimental results are shown in Figure 5. Within the time span from April 2019 to February 2023, most sections of Line 16 experienced excavation and construction activities. The results indicate that subsidence is present along the entire Line 16, with varying degrees of subsidence, and the average subsidence rate is concentrated between -12.649 and 6.293.

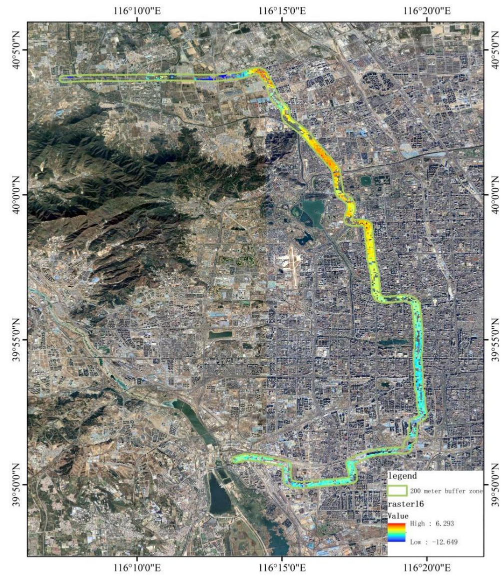

Figure 5. Settlement results of Metro Line 16

The deformation signal of each PS point is simultaneously influenced by both natural factors and human activities, which increases the complexity of the signal. This makes it difficult to accurately identify areas of structural deformation caused by human activities solely based on the raw PS point data. Specifically, the PS point signals not only contain low-frequency deformation components related to natural factors such as geological changes and climate fluctuations, but also mix in high-frequency deformation components caused by human activities such as urban construction and traffic flow. To improve analysis accuracy and accurately identify structural deformation, it is necessary to effectively decompose the PS point signals and focus on analyzing the structural deformation caused by human activities.

4.2 Separation of Structural and Non-structural Deformations

After obtaining the PS point time-series results for Beijing Subway Line 16, the optimal wavelet basis method was used to determine the best wavelet basis for this study area as sym4, and three levels were identified as the optimal decomposition depth. Wavelet packet decomposition was performed on the study area to carry out a three-level decomposition, with low-frequency dominant bands (AAA, AAB, ABA, ABB, BAA) and high-frequency dominant bands (BAB, BBA, BBB) reconstructed separately. The low-frequency components primarily represent long-term, slow ground deformation caused by natural factors such as geological changes and climate fluctuations, which are associated with non-structural subsidence. In contrast, the high-frequency components reflect rapid and intense ground deformation caused by human activities, typically related to subway construction, traffic flow, etc., and are classified as structural subsidence. The decomposition results are shown in Figure 6. To verify the accuracy of this method, two evaluation metrics, Energy Separation and Mutual Information (MI) (Batina, 2011), were used to validate the decomposition results, as shown in Table 2. Energy Separation is an indicator used to assess the independence of energy distribution between the modes generated by the decomposition method. Energy

Separation should approach 1, indicating a more independent energy distribution between the modes. MI measures the degree of information sharing between components, assessing whether the information of one component can be inferred from other components. The closer the MI value is to 0, the less information is shared between the components, indicating greater independence between them.

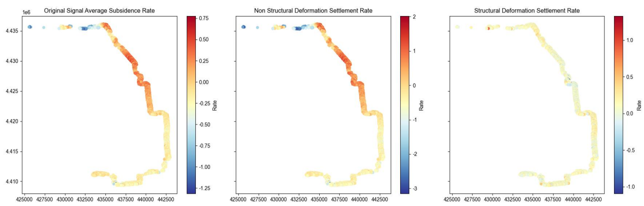

Figure 6. Settlement rate chart before and after decomposition

Method	Energy Separation	MI
WPD	0.738299	0.325816

Table 2. Evaluation metric results

In the PS point signals, when structural deformation dominates, it often leads to severe ground subsidence incidents. By examining the proportion of high-frequency components in the original PS point deformation rates (Figure 7), it can be observed that the contribution of structural deformation varies for each PS point. This study extracted the PS points where structural subsidence dominates (i.e., high-frequency component proportion > 50%) and highlighted them in Figure 8 for further analysis.

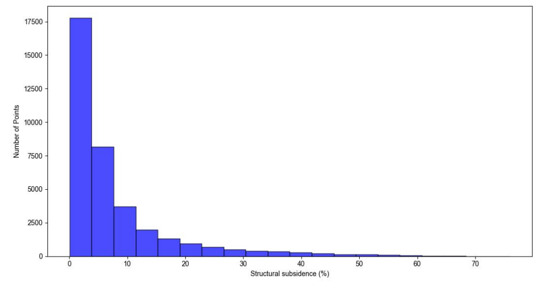

Figure 7. The proportion of structural settlement in the original deformation rate results

4.3 Structural Deformation Analysis of Metro Line 16

According to Figure 8, the PS points dominated by structural deformation are mainly concentrated in three areas, which are highlighted in red boxes in the figure. The analysis of the three areas is as follows:

Area 1: Structural deformation is mainly concentrated in the section between Yongfeng Station and Maliandao Station on Line 16, with fewer PS points. This section opened for operation on December 31, 2016, along with the northern part of Line 16. Since there has been no new subway construction in this section from April 2019 to February 2023, the structural deformation may mainly be related to vibrations during subway operation, underground pipeline construction, and soil consolidation after subway construction. Therefore, this area requires special attention.

Area 2: Structural deformation is mainly concentrated in the section between Xiyuan Station and Muxidi Station on Line 16, with a higher concentration of PS points. The section from Xiyuan Station to Suzhou Street Station underwent shield tunneling construction from March 2018 to December 2019, and trial operation began on December 31, 2020. From April 2019 to February 2023, this area went through the subway construction and initial operation stages. Excavation, tunnel boring, and other activities during construction, as well as train vibrations during the early stages of trial operation, were the main factors causing subsidence.

Area 3: Structural deformation is mainly concentrated in the section between Dongguantou South Station and Wanpingcheng Station on Line 16, with PS points evenly distributed along the subway line. The section from Yushuzhuang Station to Wanpingcheng Station underwent shield tunneling construction from early 2021 to January 2022 and is scheduled to begin trial operation on December 30, 2023. During the period from April 2019 to February 2023, this area was mainly in the construction phase. Shield tunneling, tunnel excavation, and other activities were the primary causes of the subsidence phenomenon.

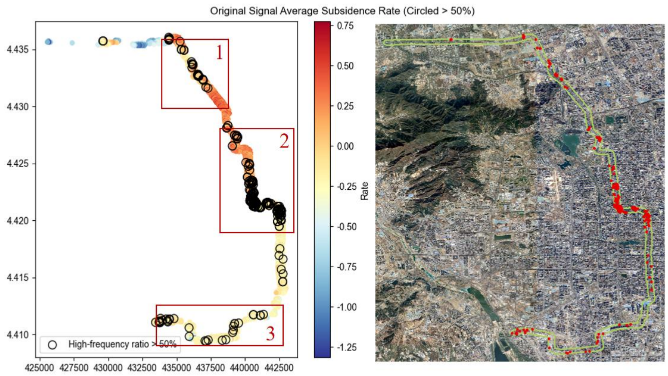

Figure 8. PS Points Dominated by Structural Deformation

5. Conclusions

This paper proposes a method for subway line subsidence monitoring and analysis by combining PS-InSAR technology with WPD. Using 32 scenes of Radarsat-2 radar imagery data from April 2019 to February 2023, ground subsidence along Beijing Subway Line 16 was monitored and analyzed. The results show that the proposed method effectively separates structural and non-structural deformation signals, offering significant advantages over traditional methods.

PS-InSAR technology provides large-scale, high-precision ground subsidence monitoring capabilities, making it a crucial tool for urban infrastructure monitoring. However, traditional methods struggle to effectively differentiate between structural and non-structural subsidence signals, as ground subsidence is influenced by various factors. By introducing the WPD method, the time series of PS points can be decomposed into structural and non-structural deformation components, allowing for the accurate extraction of subsidence features caused by subway construction and operation. The WPD method is effective at handling non-stationary and nonlinear signals, especially suitable for rapid and intense ground deformation during subway construction and operation, offering better resolution. Compared to traditional methods, WPD not only improves the accuracy of deformation signal extraction but also reveals detailed changes in the subsidence process through multi-scale analysis, accurately identifying PS points dominated by structural deformation. Therefore, the WPD method demonstrates higher accuracy and robustness in subway subsidence monitoring, providing an effective tool to overcome the limitations of traditional methods.

The research results indicate that structural deformation along Line 16 primarily occurs during the construction phase, with subsidence rates gradually slowing down as the operation time increases. Furthermore, the combined WPD and PS-InSAR analysis method provides more accurate subsidence hotspot identification, aiding in prioritizing areas that require close monitoring. This method also assesses the long-term impact of subway operations on the surrounding environment, offering valuable insights for urban planning and infrastructure management.

Although this method performs excellently in improving monitoring accuracy, the increased computational workload when handling large-scale data may affect analysis efficiency. Future research should focus on enhancing algorithm efficiency and explore other approaches to further improve processing speed and result precision.

In summary, the combination of PS-InSAR and WPD not only enhances subsidence monitoring accuracy but also provides a powerful tool for distinguishing different types of subsidence signals. This has significant applications for ensuring the safety and stability of urban infrastructure, particularly in large-scale subway construction projects. Future research could further optimize algorithm efficiency and integrate multi-source data to address more complex monitoring needs.

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