Surface deformation monitoring of subway before and during construction based on PS-InSAR

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Abstract. The construction of urban subways induces ground surface deformation, and regional surface deformations harm subway construction. Measuring the surface deformation of the project area before and during construction is necessary. The construction of the Tianjin Metro Line 6 Lushuidao Station–Shuanggang Station section was used as the study case. A total of 6028 permanent scatterers (PSs) in 2.5 km² of the project area were detected using persistent scatterer interferometric synthetic aperture radar (PS-InSAR). The distribution of PSs, the regional surface deformation rate around the station and along the tunnel, and the time-series deformation of individual PSs were analyzed. Results show that the PSs are mainly distributed on buildings. Few PSs are distributed on roads and natural ground surface, and almost no PSs are found on vegetation-covered and river areas. PS-InSAR deformation monitoring accuracy could achieve millimeter level. Moreover, the ground around Lushuidao Station is more stable than that around Shuanggang Station. Before the construction, the maximum settlement occurred on building 12 with a value of 13.98 mm, and the maximum lifting occurred on building 17 with a value of 15.85 mm. Finally, building 4 and ground on the east side adjacent to buildings 12 and 13 were affected by the construction of the pit. The PSs on them showed a significant settlement trend after the excavation.

1. Introduction

With the development of society and the expansion of cities, subways have become a popular transport system with the advantages of fast, convenient, economical, and safe, easing traffic burdens in cities. Regional surface deformation can adversely affect buildings, roads, and other facilities. Subway construction may worsen this process. In recent years, accidents caused by subway construction have increased and caused different degrees of damage to surrounding areas. Therefore, the historical surface deformation in the project area must be analyzed before any subway construction. During the construction, monitoring and providing timely feedback on the surface and building deformation in the project area are crucial to ensure the safety of the surroundings.
At present, studies on the ground settlement pattern caused by subway construction are thorough. Tan et al. [1] investigated the responses of six pre-existing buildings to an adjacent deep subway station excavated by the covered semi-top-down method based on field data. He [2] discussed the surrounding environment monitoring plan and layout of monitoring points, items, and the predetermined warning values based on a deep foundation pit excavation of the Juizizhou Station in Changsha. In the study of ground settlement caused by shield tunneling, Peck [3] proposed the Peck formula by generalizing a large amount of measured data. In this formula, the volume of the excavation process without soil drainage and settlement trough is assumed to be equal to the volume of soil loss, and the surface settlement trough shows a Gaussian curve distribution. Liu et al. [4] analyzed the ground settlement caused by the shield tunneling of Guangzhou Metro Line 2 by combining field monitoring data and numerical simulation and summarized the ground settlement pattern. Huang et al. [5] summarized the surface settlement caused by several classic shield tunneling cases, introduced the content of on-site monitoring at different stages of shield tunneling, and analyzed the monitoring data with actual engineering cases. At present, in subway construction, the traditional monitoring and analysis methods of subway construction have been relatively mature. The typical monitoring instruments are total station, level, and so on. However, the number of measurement points of the traditional monitoring method is limited. Thus, the deformation of the entire project area and the historical deformation of the same area are difficult to obtain. However, historical deformation plays a vital role in identifying the risk sources and optimizing the layout of measurement points. The urban subway is a linear project. Thus, arranging many measurement points along the subway for surface settlement monitoring is costly.

Synthetic aperture radar interferometry (InSAR) is a new remote sensing technology initially used for surface elevation measurements [6][7]. Later developed differential synthetic aperture radar interferometry and permanent scatterer-synthetic aperture radar interferometry (PS-InSAR) can measure surface deformation [8][9]. Many significant results have been achieved in surface deformation monitoring in recent years [10][11]. Heleno et al. [12] studied the ground settlement data of the metro in Lisbon City from 1992 to 2003 by using PS-InSAR and analyzed the settlement characteristics in combination with groundwater and faults. Ge et al. [13] used high-resolution COSMO-SkyMed data and PS-InSAR to analyze the spatial and temporal evolution of ground settlement during the construction and operation periods of Shanghai Metro Line 10. They obtained the settlement characteristics of the metro line in the cross-sectional and longitudinal directions. Jiang et al. [14] used COSMO-SkyMed data covering Tianjin City from 2011 to 2015 to obtain settlement information of highly coherent targets along the Tianjin metro line and compared it with the level point data of the same period. Wang et al. [15] used PS-InSAR to monitor the ground subsidence of the Guangzhou subway network and analyzed the Spatio-Temporal development of ground subsidence due to subway construction. Reinders et al. [16] investigated if, when, and how satellite InSAR can evaluate surface settlements caused by shield construction. At present, many studies focused on subway operation settlement from a macro perspective. Few studies performed regional surface deformation rate monitoring, deformation monitoring before construction, and construction influence analysis.

In this paper, the newly constructed Tianjin Metro Line 6 Lushuidao Station–Shuanggang Station was used as the study case. The deformation in the project area from July 2017 to February 2021 was obtained using PS-InSAR. The deformation rate of the entire project area and the cumulative deformation of the ground surface and buildings around the subway were analyzed. The impact of pit construction on the surrounding buildings and ground surface and the impact of shield construction on the road were analyzed by using the time-series deformation of individual PSs. Moreover, the deformation monitoring accuracy of PS-InSAR was verified.

2. PS-InSAR for monitoring subway surface deformation

A Ferretti et al. [9] first proposed PS-InSAR, which focuses on PSs or the points in Synthetic Aperture Radar (SAR) images that maintain high coherence in time-series. The PSs can be artificial buildings, artificially placed corner reflectors, lighthouses, rocks, concrete dikes, and so on. In urban areas, the density of PSs can reach thousands per square kilometer. The main steps of PS-InSAR for surface
deformation monitoring include differential interferogram generation, PS selection, and deformation solution.

In differential interferogram generation, one image will be selected as the master image among all the N SAR images, and the master image selection mainly considers the temporal coherence, spatial coherence, doppler coherence, and thermal noise coherence, and the overall coherence coefficient is used as the basis for selecting the master image. The overall coherence factor is the basis for selecting the master image, as shown in Equation (1).

\[
\rho_{\text{total}} = \rho_{\text{temporal}} \rho_{\text{spatial}} \rho_{\text{doppler}} \rho_{\text{thermal}} \approx \left( 1 - f \left( \frac{T}{T_C} \right) \right) \left( 1 - f \left( \frac{B_{\perp}}{B_{DC}} \right) \right) \left( 1 - f \left( \frac{B_{DC}}{T_{DC}} \right) \right) \rho_{\text{thermal}}
\]

(1)

where \( \rho_{\text{total}} \) is the overall coherence coefficient, \( \rho_{\text{temporal}} \), \( \rho_{\text{spatial}} \), \( \rho_{\text{doppler}} \), and \( \rho_{\text{thermal}} \) are the time, space, doppler, and thermal noise coherence coefficients, respectively. \( T \) and \( T_C \) are the time baseline and critical time baseline, respectively. \( B_{\perp} \) and \( B_{DC} \) are the spatial baseline and the critical spatial baseline, respectively. \( B_{DC} \) and \( T_{DC} \) are the doppler frequency and limiting doppler frequency, respectively.

The rest of the SAR images are registered with the master image separately to form M interferometric pairs. Differential processing is performed on each of them to obtain M differential interferograms. The interferometric phase \( \varphi_{\text{int}} \) is mainly composed of five components \cite{17}, including the phase \( \varphi_{\text{flat}} \) generated by the reference ellipsoid, the phase \( \varphi_{\text{topo}} \) generated by the ground object elevation, the phase \( \varphi_{\text{def}} \) generated by the surface deformation, the atmospheric delay effect phase \( \varphi_{\text{atmo}} \), and the system noise phase \( \varphi_{\text{noise}} \), as shown in Equation (2):

\[
\varphi_{\text{int}} = \varphi_{\text{flat}} + \varphi_{\text{topo}} + \varphi_{\text{def}} + \varphi_{\text{atmo}} + \varphi_{\text{noise}}
\]

(2)

In PS selection, pixels with strong and stable scattering characteristics are selected from \( N + 1 \) images. The main methods are correlation coefficient threshold method, amplitude dispersion index threshold method, phase dispersion index threshold method, phase dispersion index threshold method, and so on.

Finally, based on the selected PSs, a Delaunay triangulation network is constructed to establish the functional relationship model of the phase difference between two adjacent points, deformation rate, and elevation correction. Each phase component can be solved by the model solution. Finally, the deformation component can be determined.

![Image of Metro surface deformation monitoring using PS-InSAR](image.png)
Further processing of PSs is required using PS-InSAR results for subway surface deformation analysis. The PSs in the entire project area must be extracted for regional historical settlement analysis. The deformation rate and values of PSs can be visualized on Arcgis, as shown in Figure 1. For analysis of individual PSs, the 3D position and time-series deformation of the PSs must be obtained to determine whether or not they have been affected by construction.

3. Data set

3.1. SAR images. The Sentinel-1 (Sentinel-1) satellite is an Earth observation satellite in the Copernicus program (GMES) of the European Space Agency, carrying a C-band synthetic aperture radar. Sentinel-1A can provide SAR images of the same area on a 12-day cycle. The 107 Sentinel images covering the Tianjin area from July 2, 2017 to February 21, 2021 were selected for this processing. The data type is Single-Looking Complex. The acquisition mode is Interferometric Wide swath.

3.2. PS-InSAR monitoring results and their applications. The PS-InSAR results contain the deformation rate of the PSs, spatial location information, cumulative deformation of each period in monitoring, and time-series deformation information, as shown in Table 1. The 3D location information can be used to locate PSs and determine whether they are in buildings or on the ground surface. The deformation rate can be used to analyze the rate of surface deformation. In addition, the time-series deformation can show the historical deformation pattern of the PS and indicate whether or not the point has been affected by construction.

Table 1. Data provided by PS-InSAR monitoring results and their applications

| Information provided by PS-InSAR results | Application in surface deformation monitoring |
|----------------------------------------|-----------------------------------------------|
| Spatial location information of PSs     | Location of the PSs (On buildings or on the ground) |
| Deformation rate of PSs                 | Deformation rate of the ground/building |
| Cumulative settlement at different times during the monitoring time range | Cumulative settlement of the ground/buildings before construction |
| Time-series deformation of for each PS  | The historical deformation pattern of the PS and whether it was affected by the construction |

3.3. PS-InSAR deformation monitoring accuracy verification. During the construction, the level monitoring method was used to monitor the ground surface deformation caused by shield tunneling. Two PSs above the right tunnel are selected for accuracy. The nearby level points are located above ring 732 and ring 838 of the right tunnel. Specific locations of the PSs and level points are shown in Figure 2.
The monitoring data of PS1 and PS2 and the corresponding leveling points are shown in Figure 3, and the gray vertical lines indicate the shield passage. The following conclusions can be drawn from the figure: InSAR data and level monitoring data showed high consistency in settlement occurrence time and a slight difference in values.

Figure 3. PS-InSAR and level monitoring data

The deformation of these two PSs during the same period in 2017 and 2019 was analyzed, as shown in Table 2, to determine that the settlement of the PSs was caused by tunneling. The deformations in history were small. Therefore, the settlement of the PSs from 2020.12.01 to 2021.1.24 was assumed to be caused by tunneling. PS-InSAR deformation monitoring accuracy could reach millimeter level.

Table 2. Accumulated settlement in different years (The same period)

| Data source and time                  | Settlement of Point 1 (mm) | Settlement of Point 2 (mm) |
|---------------------------------------|----------------------------|----------------------------|
| Level Monitoring (2020.12.01–2021.1.24)| −8.3                       | −11.4                      |
| InSAR data (2020.12.01–2021.1.24)    | −13.1                      | −12.9                      |
| InSAR data (2019.12.01–2020.1.24)    | 2.1                        | 0.8                        |
| InSAR data (2017.12.01–2018.1.24)    | −2.3                       | 1.0                        |

4. PS-InSAR deformation monitoring results

4.1. Distribution of PSs and regional surface deformation rates. PS-InSAR results were visualized by Arcgis, as shown in Figure 4, to facilitate the analysis. The color of the PSs in the figure represents the deformation rate. Positive values represent the uplifting trend of the surface, whereas negative values represent the subsidence trend of the surface. We conducted statistical analysis and visual interpretation of the distribution of PSs and deformation rates in the study area and obtained the following conclusions.

4.1.1. Distribution of PSs. As shown in Figure 4, the PSs are mainly distributed on the buildings. The buildings around Shuanggang Station are dense, and the density of the PSs is high. The buildings around Lushuidao Station are relatively few, the density of the PSs is relatively low, and almost no PSs are found in some areas without buildings. The tunnel is mainly located under the road, and the figure shows few PSs on the road. Moreover, almost no PSs are found in the area of vegetation and rivers.

4.1.2. Regional surface deformation rate around the station. The ground surface deformation rate around the foundation pit of Shuanggang Station varies greatly. In the northern part of the station pit, the west side surface of the pit mainly shows an uplift trend, and the deformation rates of the PSs are mostly between −0.36 and 6.94 mm/year. The east and north sides also show an uplift trend, and the deformation values of the PSs are mostly between 0.56 and 13.90 mm/year. In the southern part of the Shuanggang Station pit, the west and south sides are relatively stable, and the deformation rates of PSs are mostly between 0.568 and 6.94 mm/year. The east side shows a slightly uplift trend, and the deformation rates are mostly between 0.568 and 6.94 mm/year. The ground surface around the
foundation pit of Lushuidao Station is relatively stable. The deformation rates of the PSs on the west side are between $-1.58$ and $4.54$ mm/year, those on the east side are between $-4.91$ and $6.94$ mm/year, with a slight uplift trend, and those on the south side are between $-1.58$ and $6.94$ mm/year.

4.1.3. Regional surface deformation along the tunnel. From Shuanggang Station to Chilong Street, the ground surface shows an uplifting trend. From Chilong Street to the Outer Ring River, the uplifting trend decreases, with a local subsidence trend. From Wihuan River to Lushuidao Station, the ground surface shows a slightly subsiding trend, with a slightly local uplifting trend.

4.2. Cumulative settlement of the ground/buildings before construction. The accumulated settlements of the ground surface around the station before construction are shown in Figure 6. Moreover, we numbered the buildings for convenient analysis. Around the foundation pit of Lushuidao Station, the PSs adjacent to buildings 1 and 2 showed small settlements, with values ranging from $-3.36$ mm to $-0.76$ mm. The PSs adjacent to buildings 4, 5, 6, 8, 9, and 10 showed uplifts, with values ranging from 5.60 mm to 19.20 mm. The PSs on buildings 4, 7, and 11 mainly had settlements and uplifts. Further analysis of the time-series deformation of these PSs showed that the maximum settlement occurred on building No. 7 with a value of 5.51 mm, and the maximum uplift occurred at the surface near building No. 8 with a value of 12.36 mm. Around Shuanggang Station, the accumulated deformation of PSs on buildings 13 to 19 ranged from $-3.36$ mm to 10.38 mm. The PSs on buildings 14, 16, 17, and 19 mainly had settlements, and the PSs on the rest of the buildings had settlements and uplifts. The maximum settlement occurred on building 12 with a value of 13.98 mm, and the maximum lifting occurred on building 17 with a value of 15.85 mm.
4.3. Time-series deformation analysis of individual PSs. Several points affected by the construction were found by analyzing the time-series deformation of the PSs. PS1 and PS2 were located on building No. 4, near Lushuidao Station, and the linear distance from the pit is 30 m. PS3 and PS4 are located on the surface around Shuanggang Station, adjacent to buildings 12 and 13, 20 m away from the pit. As shown in Figure 6, PS1 and PS2 had regular fluctuations before the excavation of the pit. After excavation of the pit, they showed a settlement trend and lasted for a long time. The maximum settlement exceeded 15 mm compared with the beginning of the construction. PS3 had a trend of slow uplift before the excavation. It exhibited a settlement trend after excavation. PS4 was relatively stable before excavation and exhibited a settlement trend after excavation.

5. Conclusion

The methods of measuring surface deformation and analyzing subway surface deformation using PS-InSAR are introduced. The following conclusions can be drawn:

1. PS-InSAR can detect high-density PSs in urban areas. In this experiment, 6028 PSs were acquired in 2.5 km² of the project area. PSs are mainly distributed on buildings. The denser the buildings, the higher the density of PSs. Few PSs are found on roads and natural ground surface, and almost no PSs are observed on vegetation-covered and river areas.

2. PS-InSAR results provide high-density PSs and multiple types of data. The main types are the deformation rate of PSs, spatial location, time-series deformation, and cumulative surface deformation for each monitoring time. The deformation rate of the PSs can be used to analyze the regional surface deformation rate. The historical monitoring data can be used to analyze the pre-work surface deformation. The spatial location information of the PSs can determine their locations. The time-series deformation of individual PSs can be used to obtain their historical deformation patterns and to analyze whether and to what extent the construction has affected them.

3. The ground surface deformation rate around the pit of Shuanggang Station varies greatly. The ground surface around the pit of Lushuidao Station is relatively stable. Before the construction, the maximum settlement occurred on building 12 with a value of 13.98 mm, and the maximum lifting occurred on building 17 with a value of 15.85 mm. Building 4 and ground on the east side adjacent to buildings 12 and 13 were affected by the construction of the pit, and the PSs on them showed a significant settlement trend after the excavation.
(4) The accuracy of PS-InSAR results was verified using the monitoring data of ground-level points. InSAR data and level monitoring data showed high consistency in settlement occurrence time and settlement values. The results showed that PS-InSAR monitoring accuracy could achieve millimeter level.

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References
[1] Tan Y, Huang R and Kang Z 2016 Covered semi–top–down excavation of subway station surrounded by closely spaced buildings in downtown Shanghai: Building response J. Perform. Constr. Facil. 30 6 04016040.
[2] He W, Pan X Y and Zhang J 2013 Monitoring and environmental impact analysis of deep excavation of subway stations in river islands Chin. J. Geotech. Eng. 35 S1 pp 478–483.
[3] PECK R B 1969 Deep excavations and tunnelling in soft ground Proceeding of the 7th Int. Conf. on Soil Mechanics and Foundation Engineering (Mexico: Mexico City) pp 225–290.
[4] Liu Z W, Wang M S and Dong X P 2003 Analysis of ground surface subsidence of metro Chin. J. Rock. Mech. Eng. 22 8 pp 1297–1301.
[5] Huang H W and Zhang D M 2001 Shield tunnelling induced surface settlement and in–site monitoring Chin. J. Rock. Mech. Eng. 20 pp 1814–1820.
[6] Zebker H A and Goldstein R M 1986 Topographic Mappingfrom Interferometric Synthetic Aperture Radar Observations J. Geophys. Res. Solid Earth B5 pp 4993–4999.
[7] Gabriel A K, Goldstein R M and Zebker H A 1989 Mapping Small Elevation Changes over Large Areas: Differential Radar Interferometry J. Geophys. Res. Solid Earth 94 B7 pp 9183–9191.
[8] Massonnet D, Feigl K and Rossi M 1994 Radar Interferometric Mapping of Deformation in the Year after the Landers Earthquake Nature 369 6477 pp 227–230.
[9] Freretti A, Prati C and Rocca F 2001 Permanent scatterers in SAR interferometry IEEE Trans. Geosci. Remote Sens. 39 1 pp 8–20.
[10] Zhu J J, Li Z W and Hu J 2017 Research progress and methods of InSAR for deformation monitoring Acta Geod. et Cartogr. Sin. 46 10 pp 1717–1733.
[11] Crosetto M, Monserrat O and Cuevas–González M 2016 Persistent scatterer interferometry: A review ISPRS–J. Photogramm. Remote Sens. 115 pp 78–89.
[12] Heleno S I, Oliveira L G and Henriques M J 2011 Persistent scatterers interferometry detects and measures groundsubsidence in Lisbon Remote Sens. Environ. 115 8 pp 2152–2167.
[13] Ge D Q, Zhang L, Wang Y, Li and Liu B 2014 Monitoring subsidence on Shanghai Metro line 10 during construction and operation using high–resolution InSAR Shanghai Land. Res. 35 04 pp 62–67.
[14] Jiang D C, Zhang Y H, Zhang J X, Wu H A and Kang Y H 2017 Uneven land subsidence along tianjin subway lines monitored by InSAR technology Remot. Sens. Inf. 32 06 pp 27–32.
[15] Wang H, Feng G and Xu B 2017 Deriving spatio–temporal development of ground subsidence due to subway construction and operation in delta regions with PS–InSAR data: A case study in Guangzhou, China Remote Sens. 9 10 p1004.
[16] Reinders K J, Hanssen R F and van Leijen F J 2021 Augmented satellite InSAR for assessing short–term and long–term surface deformation due to shield tunnelling Tunn. Undergr. Sp. Tech. 110 103745.
[17] Hanssen R F 2001 Radar Interferometry: Data Interpretationand Error Analysis (Netherlands: Springer).