Temporal and Spatial Evolution Characteristics Analysis of Beijing Land Subsidence Based on InSAR

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Abstract. Land subsidence is one of the main geological disasters in the Beijing Plain. Accurate and quantitative monitoring of the evolution of land subsidence will help scientifically guide the prevention and control of land subsidence. We use PS-InSAR technology and TerraSAR 3m resolution images as our data source to study the temporal and spatial evolution characteristics of Beijing’s land subsidence from 2012 to 2015. The research indicates that, from a spatial perspective, the land subsidence presents a funnel shape, the central area of the settlement funnel is maintained at 112.5km\textsuperscript{2}, and the total land subsidence area remains basically unchanged. From the temporal point of view, the central area of the ground subsidence funnel subsides at a rate of 110mm/y, the ground subsidence rate in other areas decreases as it far away from the settlement center.

1. Introduction
Land subsidence is a geological phenomenon that causes the consolidation and compression of loose sediments and reduces the ground elevation in a certain area. It is often induced by natural factors and human engineering activities, and belongs to a slowly changing geological disaster [1]. Land subsidence is a global disaster. More than 150 cities around the world have experienced serious land subsidence problems caused by excessive groundwater exploitation [2]. Beijing is also one of the few large cities in the world that uses groundwater as the main water supply source. Groundwater has always accounted for about 2/3 of the city's total water supply.

Beijing is located in the northern part of the North China Plain, with geographic coordinates of 115°25′-117°35′ east longitude and 39°28′-41°05′ north latitude. Affected by the excessive exploitation of groundwater, the land subsidence of the Beijing Plain has successively experienced the formation stage (1955-1973), the development stage (1973-1983), the expansion stage (1983-1999), and the current rapid development stage (1999- now)[3]. A series of environmental geological problems such as elevation loss caused by land subsidence have become one of the important factors affecting the urban planning and construction of Beijing and the sustainable development of regional economy. Quantitative
monitoring of the impact range and size of land subsidence and analysis of its evolution characteristics have important reference value for the prevention and control of land subsidence.

At present, the monitoring methods of land subsidence are mainly based on leveling, stratification, and GPS measurement. Although these methods have high monitoring accuracy, they can only obtain land subsidence information in the form of points and cannot be adapted to continuous and large-scale surface settlement monitoring, and high maintenance costs. With the development of space-to-earth observation technology, Interferometric Synthetic Aperture Radar (InSAR) has been applied to land subsidence monitoring for its large-scale area monitoring, unaffected by weather, and high monitoring accuracy. Especially Permanent Scatter InSAR (PS-InSAR), which is developed on the basis of InSAR technology, extracts interference by registering and differentially interfering multiple SAR images covering the same area. The strong scatterer points with strong scattering characteristics and relatively stable phase information in the figure can effectively remove the influence of atmospheric, time and spatial decoherence, and finally obtain millimeter-level ground subsidence information.

This paper selects TerraSAR 3m resolution images covering areas with severe land subsidence in Chaoyang District and Tongzhou District in Beijing. The PS-InSAR technology was used to obtain the land subsidence information of the area from 2012 to 2015, and the evolution characteristics of the cumulative land subsidence in the four years were analyzed in inter-annual units, which provided a reference for further improving the monitoring and prevention of land subsidence in Beijing.

2. Materials and Methods

This paper selects 3 m resolution images of the TerraSAR satellite of 40 scenes from November 6, 2011 to December 11, 2015 as the data source. Since the imaging time of the first phase of 2012 was on February 2, 2012, this paper assigns the subsidence from November 6, 2011 to 2012 to make up for the lack of subsidence information before February 2012, and get the complete annual land subsidence. The TerraSAR radar satellite was launched on June 15, 2007. It is a high-resolution radar satellite developed by Germany. It carries a high-frequency X-band synthetic aperture radar sensor with a variety of polarization methods.

The research area of this article is shown in Figure 1. The red solid line in the figure is the administrative boundary of Beijing, and the blue square is the intersection area of 40 scenes, which is the study area of this article. The research area is about 693km², covering part of the south of Chaoyang District, the west of Tongzhou District, the northwest of Daxing District, the west of Fengtai District, the east of Xicheng District and most of Dongcheng District.

PS-InSAR technology was first proposed by Ferretti in 2000. The core idea of this method is to use multiple SAR images acquired from the same area within a certain period of time, and use statistical analysis methods to detect targets with high time correlation in the imaging area, that is, permanent
scatterers. Then model based on the phase time series of these permanent scatterers to separate the deformed phase and the atmospheric delay phase [4].

For N time series SAR images covering the same area, one image is selected as the master image and the remaining slave images are registered with the master image and sampled to the same pixel space. Differential processing is performed on each slave image and the master image to form M interferograms (M=N-1) [5]. At this time, the interference phase composition on each resolution unit is shown in the following formula (1):

\[
\phi = \phi_{flat} + \phi_{topo} + \phi_{defo} + \phi_{atmo} + \phi_{noise}
\]

is the total interference phase of the resolution unit, \(\phi_{flat}\) is the flat-ground phase caused by the reference ellipsoid, \(\phi_{topo}\) is the topographic phase caused by topographic undulation, \(\phi_{defo}\) is the deformation phase caused by interference on the surface displacement in the time interval of the two images affecting the imaging, \(\phi_{atmo}\) is the delayed phase caused by the inconsistency of atmospheric conditions when imaging the two images by interference, \(\phi_{noise}\) is the phase caused by random noise [6]. Among them, the flat-ground phase can be removed according to the satellite's precise orbit parameters and interference geometric relations; The topographic phase can be partially removed based on the satellite's precise orbit parameters and external DEM data. Due to a certain error in the external DEM data, it is necessary to further remove the residual topographic phase [7]. At this time, for any pixel \((x, y)\) in the interferogram, the phase value on the i-th differential interferogram can be expressed by formula (2):

\[
\Phi_i(x, y; T_i) = \frac{4\pi}{\lambda} \cdot B_i \cdot \sin \theta \cdot \epsilon(x, y) + \frac{4\pi}{\lambda} \cdot T_i \cdot \nu(x, y) + \phi_{i\text{res}}(x, y; T_i)
\]

\(B_i\) represents the spatial vertical baseline of the interference pair i; \(T_i\) represents the time baseline.

\(\lambda\) is the wavelength, \(R\) is the distance from the sensor to the target, and \(\theta\) is the radar incident angle. The first factor is the residual topographic phase. The second factor is the linear deformation phase. The third factor is the residual phase, which includes nonlinear deformation phase, atmospheric phase, and noise phase. In order to suppress and weaken the influence of the atmosphere on the solution of the deformation parameters, according to the spatial autocorrelation properties of the atmosphere, the adjacent PS points are differentially processed, and the following formula (3) can be obtained:

\[
\Delta \Phi_i(x_i, y_i; x_p, y_p; T_i) = \frac{4\pi}{\lambda} \cdot \bar{B}_i \cdot \Delta \epsilon(x_i, y_i; x_p, y_p) + \frac{4\pi}{\lambda} \cdot T_i \cdot \Delta \nu(x_i, y_i; x_p, y_p) + \Delta \phi_{i\text{res}}(x_i, y_i; x_p, y_p; T_i)
\]

\(\bar{B}_i\), \(\bar{R}\) and \(\bar{\theta}\) are the average values of the corresponding parameters of adjacent PS points; \(\Delta \epsilon\) and \(\Delta \nu\) are the elevation error increment and linear deformation rate increment between adjacent PS points respectively; \(\Delta \phi_{i\text{res}}\) is the residual phase increment between adjacent PS points. Through the least square method, the elevation correction value and linear deformation rate of each PS point can be solved. By further analyzing the signal characteristics of the residual phase in the time domain and the space domain, the atmospheric delay phase, the noise phase and the nonlinear deformation phase can be separated, and finally the PS point deformation variable can be obtained. The specific flow chart of PS-InSAR technology in this article is shown in Figure 2.
3. Results & Discussion

In this paper, 344129 stable PS points with a coherence greater than 0.7 are obtained through PS-InSAR technology, and the average annual subsidence rate map shown in Figure 3 is obtained by interpolating the average annual subsidence rate of each PS point. As shown in Figure 3, the area with severe subsidence is located in the western part of Tongzhou District and the southeastern part of Chaoyang District. The average annual subsidence rate from 2012 to 2015 reached a maximum of -110mm/y. The area was the center of the settlement funnel and radiated to the surrounding area. The black triangle in Figure 3 is the benchmark points, which records the cumulative land subsidence of this point from 2012 to 2015. This paper takes the benchmark points as the center, establishes a 200-meter buffer zone and extracts the cumulative land subsidence of the PS points in the buffer zone for accuracy verification. The comparison between the cumulative settlement of the PS points and the cumulative settlement recorded at the corresponding benchmark points is shown in Table 1. It can be seen from Table 1 that the average error of land subsidence obtained by the PS-InSAR technique in this paper is 4.4mm, which can be used for subsequent analysis.

![Figure 3: 2012-2015 average land subsidence rate chart.](image-url)
Table 1: Settlement comparison between benchmarks and PS-InSAR (mm).

| Benchmarks Number | Leveling Measurement | PS-InSAR | Difference |
|-------------------|----------------------|----------|------------|
| BM1               | 16                   | 13.2     | 2.8        |
| BM2               | 21                   | 18.5     | 2.5        |
| BM3               | -354                 | -360.1   | 6.1        |
| BM4               | 17                   | 12.4     | 4.6        |
| BM5               | -465                 | -473.2   | 8.2        |
| BM6               | 3                    | 7.7      | 4.7        |
| BM7               | -20                  | -17.8    | 2.2        |
| Mean              |                      |          | 4.4        |

In order to study the temporal and spatial evolution characteristics of land subsidence, this paper selects the cumulative subsidence corresponding to the imaging time of the last phase of each year from 2012 to 2015 as the cumulative subsidence of that year (the imaging time of the last phase of each year is December). Through interpolation and classification, the inter-annual cumulative land subsidence distribution map shown in Figure 4 is obtained. It can be seen from Figure 4 that the maximum cumulative land subsidence from 2012 to 2015 is 457mm, and the maximum ground uplift is 22mm. Considering that the maximum settlement rate is 110mm/y, in order to better show the change of the cumulative settlement between years better, this paper divides the cumulative land subsidence into five categories based on 100mm as the boundary, and the ground uplift is classified into one category separately.

It can be clearly seen that the ground subsidence in the study area is in a rapid development stage. With the connecting part of Chaoyang District and Tongzhou District as the center of the subsidence funnel, the surrounding ground subsidence is increasing. Figure 5 shows the corresponding areas of different types of accumulated land subsidence in each year from 2012 to 2015. The abscissa is the corresponding year, the ordinate is the area, and the legend shows the accumulated land subsidence of each type divided.

The scope of the study area is unchanged. According to Figure 5, it can be seen that the area of the non-land subsidence area (the area of ground uplift) changed very little from 2012 to 2015. Based on this, it can be seen that the area of land subsidence changed little in the spatial range from 2012 to 2015. The average area of the land subsidence area during the year was 647 km², and the change is reflected in the increase in the degree of land subsidence. Combining Figures 4 and 5, it can be found that the center area of the settlement funnel is about 112.5km², and from Figure 3, it can be known that the area continued to settle at a rate of 110mm/y from 2012 to 2015.
4. Conclusions
This paper uses PS-InSAR technology to obtain land subsidence information from 2012 to 2015, which partially covers areas with severe land subsidence in Chaoyang District and Tongzhou District, Beijing, and analyzes the temporal and spatial evolution characteristics of accumulated land subsidence in each year on an interannual basis. In terms of spatial, the area of the ground subsidence area in the study area has not changed significantly during the four years, and the ground subsidence presents a "funnel" shape, and the severity of land subsidence spreads around the center. In terms of temporal, the center of the ground subsidence funnel continued to experience ground subsidence at a rate of 110 mm/y.

The research results of this paper are helpful to quantitatively evaluate the distribution and evolution of land subsidence in Beijing, so as to prevent and control land subsidence scientifically and effectively and reduce the disasters caused by land subsidence.
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