Using SBAS-InSAR to Detect Surface Movement above Old Mining Areas after Mine Closure

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Abstract. The impact of underground coal mining on the surface is not only manifested in the period of coal mining, but also after the coal mining stops and after the coal mine closes down, there will still be residual settlement, or the opposite movement - surface uplift. With the continuous development of microwave earth observation technology, time series InSAR technology has become one of the important means of surface deformation observation in mining areas. In this paper, SBAS-InSAR technology is applied to study the surface deformation movement in Lingzi coal mine, Shandong Province. The time series observations of Sentinel-1A/B data acquired from March 2015 to August 2019 were analyzed, it is found that the seasonal variation of atmosphere is more obvious under the short revisit period and long time series of satellite data, especially in mountainous areas. Considering this effect, the polynomial method is used to fit the observed results. The results show that the surface deformation in Lingzi coal mine is diverse. Some areas continue to uplift, with the maximum uplift of 69 mm. Others first subsidence and then uplift, with the maximum subsidence of -80 mm. The process of subsidence and uplift is based on different mechanisms. The subsidence is the residual subsidence of underground caving caused by coal mining, and the process of uplift is related to the recharge of groundwater.

1. Introduction

Surface deformation caused by coal mining is a long-term concern, even after the closure of the coal mine, this effect still exists, including the residual subsidence of the surface or the reverse process caused by groundwater recharge - surface uplift. The existence of these deformations increases the potential risk of the surface. For a long time, people have been using various means and methods to monitor and analyze the surface deformation, such as GPS or leveling. These technologies can accurately and quickly obtain the surface deformation data, and are the traditional means of monitoring the surface deformation in mining areas. However, these methods are based on sparse point-like distribution targets, and it is difficult to obtain detailed information of surface deformation. In recent years, using D-insar technology to monitor the surface deformation has become a new monitoring method. It has the advantages of high monitoring accuracy (up to millimeter level) (Wang R et al., 2015; Xie R et al., 2015), wide coverage, high efficiency, low cost, simple data processing (Hanssen R F, 2001), can obtain more detailed surface deformation information. However, D-insar technology has some problems, such as spatiotemporal mismatch and atmospheric delay (Zebker H A et al., 1992), which make the deformation detection accuracy lower. SBAS-InSAR
technology uses long time series interferometric synthetic aperture radar images to improve measurement accuracy, which can effectively overcome the spatial and temporal de-correlation of D-InSAR and weaken the impact of atmospheric delay. A large number of scholars have studied the feasibility of SBAS-InSAR technology in mapping cumulative mine deformation (Bateson L et al., 2015; Du Z et al., 2016; Ma C et al., 2016).

In this paper, the surface deformation in Lingzi coal mine is observed by using SBAS-InSAR technology and Sentinel-1A/B radar satellite data. It is found that under the short revisit period and long time series of Sentinel-1A/B data, the annual effect of atmospheric delay is prominent, which affects the results of deformation monitoring. In this paper, polynomial method is used to fit the time series results to weaken the effect of atmospheric delay. Finally, this paper analyse the spatial distribution characteristics and temporal development of surface deformation, which provides a basis for the study and governance of surface environmental decision-making in mining areas.

2. Study area and experimental data

2.1. Overview of the study area

The topography of the study area is an Intermountain depression, which belongs to the low hills and residual mountains of the piedmont tectonic erosion. The southern part is the ancient Cambrian and Ordovician mountains, the northern part is a mountain range composed of Jurassic strata and basic magmatic rocks, and the central part is a coal-bearing stratum of Carboniferous-Permian. The ground elevation is 90-350m.

The main coal mine in the study area is Lingzi coal mine, which is divided into two minefields with F6 fault as the boundary. The Yihao minefield is to the east of the fault and the Baoshan minefield is to the west, as shown in Figure 1. Other small coal mines are scattered in and around Lingzi coal mine.

There are abundant groundwater in the mining area, and the output of coal mine water is large, and the clay mine distributes more in the mining area. After nearly 60 years of mining, the mine resources in the mining area are gradually exhausted. The mines have been closed since the decade of the 21st century, and the Yihaojing in Lingzi coal mine was closed in November 2015.

![Figure 1. Location of study area. The red solid line is the research area, the black dotted line is the boundary of Lingzi coal mine, and the black solid-ticks line in the middle of the mining area is F6 fault.](image-url)
2.2. The selected data

Sentinel-1 is the Earth observation satellite of the European Space Agency's Copernicus Program (GMES). It consists of two satellites and carries a C-band SAR. Single satellite maps the world once every 12 days, and the period of double constellation revisit is shortened to 6 days. However, in this study area, the main revisit period is 12 days, the width of the IW mode is 250 km, and the ground resolution is 5*20 m, which can be used for high-precision surface deformation monitoring. The data selected in this paper are 119 Sentinel 1-A/B data covering the research area during the period of 2015.03.08-2019.08. The orbital data are AUX_POEORB, and the selected external reference DEM is SRTM data at a resolution of 1 arc-second, that is, 30 m. See Table 1 for details on satellite data.

Table 1. The list of the selected data, including 36 Sentinel1-A and 83 Sentinel1-B satellite radar data, orbit number is 149, descending.

| No. | Date       | No. | Date       | No. | Date       | No. | Date       |
|-----|------------|-----|------------|-----|------------|-----|------------|
| 1   | 20150308   | 8   | 20150730   | 15  | 20151103   | 22  | 20160126   |
| 2   | 20150401   | 9   | 20150811   | 16  | 20151115   | 23  | 20160207   |
| 3   | 20150519   | 10  | 20150823   | 17  | 20151127   | 24  | 20160219   |
| 4   | 20150612   | 11  | 20150916   | 18  | 20151209   | 25  | 20160302   |
| 5   | 20150624   | 12  | 20150928   | 19  | 20151221   | 26  | 20160314   |
| 6   | 20150706   | 13  | 20151010   | 20  | 20160102   | 27  | 20160326   |
| 7   | 20150718   | 14  | 20151022   | 21  | 20160114   | 28  | 20160407   |

| No. | Date       | No. | Date       | No. | Date       | No. | Date       |
|-----|------------|-----|------------|-----|------------|-----|------------|
| 1   | 20160928   | 17  | 20170408   | 33  | 20171029   | 50  | 20180521   |
| 2   | 20161010   | 18  | 20170502   | 34  | 20171110   | 51  | 20180602   |
| 3   | 20161022   | 19  | 20170514   | 35  | 20171222   | 52  | 20180614   |
| 4   | 20161103   | 20  | 20170526   | 36  | 20171204   | 53  | 20180626   |
| 5   | 20161115   | 21  | 20170607   | 37  | 20171216   | 54  | 20180708   |
| 6   | 20161127   | 22  | 20170619   | 38  | 20171228   | 55  | 20180720   |
| 7   | 20161209   | 23  | 20170701   | 39  | 20180109   | 56  | 20180801   |
| 8   | 20161221   | 24  | 20170713   | 40  | 20180121   | 57  | 20180825   |
| 9   | 20170102   | 25  | 20170725   | 41  | 20180202   | 58  | 20181012   |
| 10  | 20170114   | 26  | 20170806   | 42  | 20180214   | 59  | 20181024   |
| 11  | 20170126   | 27  | 20170818   | 43  | 20180226   | 60  | 20181105   |
| 12  | 20170207   | 28  | 20170830   | 44  | 20180310   | 61  | 20181117   |
| 13  | 20170219   | 29  | 20170911   | 45  | 20180322   | 62  | 20181129   |
| 14  | 20170303   | 30  | 20170923   | 46  | 20180403   | 63  | 20181211   |
| 15  | 20170315   | 31  | 20171005   | 47  | 20180415   | 64  | 20181223   |
| 16  | 20170327   | 32  | 20171017   | 48  | 20180427   | 65  | 20190104   |

3. SBAS timing analysis method

3.1. Principles of SBAS-InSAR technology

SBAS-InSAR is an InSAR time series method with multiple master images (Berardino P et al., 2002). This method uses the method of small baseline to avoid spatial de-correlation and reduce the influence of terrain on the difference. It combines several small baseline subsets data to obtain all available
small baseline interferograms simply and effectively. This combination is based on the minimum deformation rate criterion, and then the minimum deformation rate is obtained by singular value decomposition (SVD). Small baseline set technology increases the time sampling rate. Compared with PS-InSAR (Ferretti A et al., 2001) technology, it needs fewer SAR images and can obtain more deformable reflectors (Zhu J et al., 2017). The deformation obtained is more continuous in space. In this study, 119 Sentinel 1-A/B data in the study area were processed by SBAS-InSAR technology. The software used for data processing is ISCE and GiaNT. The processing steps are shown in Figure 2.

![Flowchart of SBAS algorithm](image)

Figure 2. Flowchart of SBAS algorithm

In this paper, we design a spatial threshold of 150 m for small baselines and 72 days for time baselines. Figure 3 shows the spatial-temporal baselines of small baseline sets processed. Reference point is selected in Linchi Town in the north of the study area, with coordinates 117.779801°E, 36.717253°N. The processing results are shown in Figure 4.

![Spatial-temporal baselines of interferograms](image)

Figure 3. Spatial-temporal baselines of interferograms
3.2. Annual cycle impact of atmospheric delay

Atmospheric delay is one of the main constraints of InSAR surface deformation monitoring. It has high spatial correlation and low time correlation. It can be eliminated or weakened through the processing of low-pass filtering in spatial domain and high-pass filtering in time domain (Berardino P et al., 2002). However, under the short revisit period and long time series of satellite data, the annual cycle effect of atmospheric delay begins to emerge, especially in mountainous areas. Point 1 in Figure 5 is located on the southwest mountain area of the study area. Although the surface of the area is relatively stable, it can be seen from the obtained time series data that there is an annual fluctuation of 8-9 mm, which is mainly caused by the seasonal difference of atmospheric delay between the reference point and the observation area (Bekaert D P S et al., 2015).

![Figure 4. Cumulative deformation of the study area](image-url)
Deformation time series of the point 3

Deformation time series of the point 4

Figure 5. Deformation time series of the ground points. The blue triangle symbols are the original data and the black solid line are the data after polynomial fitting.

In this study area, three points were selected with the largest deformation from 2 to 4, as shown in Figure 5. It can be seen that besides the long-period deformation characteristics, the annual variation of atmospheric delay can also be observed. In order to weaken this effect, the polynomial method is used to fit the time series observation results. The fitting results are also shown in Figure 5.

4. Results and analysis

The deformation results show that the surface deformation of Lingzi coal mine area presents diversity. Baoshan mining area is characterized by surface up lift. The maximum uplift during observation period is 59 mm, equivalent to 13 mm/a. The northern side of Yihaojing mining area generally shows uplift, but the time series results of Figure 5-2 show that the deformation is divided into two stages: first subsidence and then uplift, with the time limit of 2015.11.15. The cumulative settlement in subsidence stage is -6 mm, equivalent to -8 mm/a, and the cumulative uplift in uplift stage is 69 mm, equivalent to 19 mm/a. The southern side of Yihaojing mine area generally shows settlement, and its deformation is also divided into two stages: first subsidence and later uplift, with the time limit of 2017.11.22. The cumulative settlement in subsidence stage is -80 mm, equivalent to -30 mm/a, and the cumulative uplift in uplift stage is 17 mm, equivalent to 6 mm/a. According to the investigation of the mining area, the surface subsidence is mainly the residual subsidence after the closure of the mine. At the same time, the amount of groundwater in the mining area is large. After the closure of the coal mine, the groundwater stops pumping, the water level rises, and the underground pore pressure increases, which causes the surface uplift.

The area is also rich in clay minerals. After water encounter, clay minerals expand, which further leads to surface uplift. With the further rise of groundwater level, it is estimated that the surface on the south side of yihaojing mining area will continue to rise until the water level restores to its original state. Next, further observations and studies are still needed to explain the detailed mechanism of the surface deformation and evaluate its potential impact on the surface.

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