Monitoring and Analysis of Ground Deformation in Mining Area Based on SBAS Technology

Qianwen Li\textsuperscript{1,2*}, Qianqian Yan\textsuperscript{1,2} and Tongkang Zhang\textsuperscript{1,2}

\textsuperscript{1} College of Geometrics, Xi'an University of Science and Technology, Xi'an 710054, China
\textsuperscript{2} Key Laboratory of Coal Resources Exploration and Comprehensive Utilization, Ministry of Natural Resources, Xi'an 710021, China
Email: 952123162@qq.com

Abstract. In view of the serious harm and significant economic loss caused by large-scale surface subsidence in Huangling Mining area. Firstly, the surface deformation information was obtained by using the Small Baseline technology during 2007-2009 (ALOS-1) and 2018-2019 (Sentinel-1A), and then the deformation position and magnitude changes were compared in these two different periods, finally, the time series analysis of the surface subsidence funnel in the mining area was performed. The results showed that: (1) The average annual deformation rate respectively reached 360 mm/a and 480 mm/a during 2007-2009 and 2018-2019. It was found that compared with 2007-2009, the deformation position moved up in 2018-2019, and the deformation area and magnitude increased. Combined with the analysis of the mining area data, the Huangling mining area was in the early stage of mining from 2007 to 2009. As the advance of mining working face and the passage of time, the deformation position would move up in 2018-2019. (2) From 2018 to 2019, the most serious surface subsidence in the Huangling mining area was located in the northwest of Shuanglong Town, including Huangling No. 2 Coal Mine. The maximum cumulative subsidence reached 300mm. The results of the study indicated that the main cause of subsidence in this area was underground coal mining. The analysis of the deformation law provides a decision basis for the subsequent rational mining and treatment of the mining area.

Keywords. Huangling mining area, small baseline set technology, deformation extraction, time series analysis, underground coal mining.

1. Introduction
"Rich coal" is the main feature of China's energy resources, and Shaanxi is one of the main provinces of China's coal resources. Irrational mining of coal resources will destroy the geological structure, leading to subsidence or uplift of the surface of the mine, and in serious cases will induce landslides, collapses and other geological disasters \cite{1}. Therefore, it is urgent to efficiently monitor and analyze the surface deformation of the mining area, grasp the geological damage in the mining area in time, and formulate emergency measures.

The traditional levelling, total station, GPS measuring methods have the advantages of reliable accuracy and easy operation in monitoring ground deformation, but there are disadvantages: (1) The monitoring range is limited, the measurement points are sparse, and the "point"-based monitoring
doesn’t comprehensively monitor the deformation of the entire mining area; (2) It requires a lot of manpower to set up the site, which is difficult to do when the environment is bad, even endangers personal safety and costs a lot of money; (3) The measurement points are easy to damage, cannot be monitored for a long time, which makes it impossible to analyze the deformation patterns in time series. After more than 50 years of development, Interferometry Synthetic Aperture Radar (InSAR) has become an effective and commonly used method of earth observation, with all-weather, all-weather, large-scale, high-resolution, high-precision, continuous coverage. It is not restricted by weather and climate, has good application potential in terrain mapping, disaster prevention and mitigation and other fields, and can accurately monitor the surface of mining areas in real time [2]. Subsequently, the differential radar interferometric technology (Differential InSAR, D-InSAR) was proved to be able to extract small surface deformations with an accuracy of up to mm, but there are constraints such as decoherence, atmospheric effects, and orbital errors [3-4].

In order to solve the problems of D-InSAR technology, domestic and foreign researchers have proposed time series InSAR technologies such as Small Baseline Subsat InSAR [5] (Small Baseline Subsat InSAR, SBAS-InSAR), which widely used in mining areas and cities for slow surface deformation monitoring. In 2006, Casu et al. [6] extracted the standard deviation of the surface deformation rate of Naples Bay in Italy and Los Angeles in the United States based on SBAS technology to be about 1mm/a, and verified the reliability by leveling and GPS data. In 2007, Lanari et al. [7] confirmed that SBAS technology can detect large-scale surface deformation. In 2012, based on ENVISAT ASAR data, Xuedong Zhang, Daqing Ge, and Lixin Wu [8] used SBAS technology to successfully obtain linear and nonlinear surface deformations in the mining city Tangshan based on ENVISAT ASAR data. The monitoring results are consistent with the existing level data, indicating that the feasibility of this technology in surface deformation monitoring of mining cities. In 2018, Da Li, Kazhong Deng [9] et al, based on TerraSAR-X (2012-2013) data, compared SBAS and D-InSAR technologies to monitor settlement values, verifying the effectiveness of SBAS technology on mining area monitoring. The above studies all showed the reliability of SBAS technology in surface deformation monitoring, but the application of SBAS in surface deformation monitoring in mining areas is less. At the same time, lack of comparative analysis of deformation locations, magnitude of SAR data changes and causes, it is very necessary to conduct in-depth research.

In this paper, based on GAMMA [10] software, SBAS technology was ursed to extract the annual average deformation rate and time series cumulative subsidence information of ALOS-1 (2007-2009) and Sentinel-1a (2018-2019) data in Huangling mining area, Shaanxi Province. Compared and analyzed the development changes and causes of surface deformation in mining areas in two different periods, and the deformation laws of typical settlement funnels was analyzed in section.

2. Small Baseline Subsat Method
SBAS technology was proposed in 2002. The core idea is to reduce the impact of spatio-temporal decoherence, using multi-master images, setting spatiotemporal baseline thresholds to form interference pairs, and using least squares method to solve temporal deformation information. Among them, the singular value decomposition (SVD) method is used to obtain the deformation rate and time series deformation.

• Pretreatment. To address the particularity of the Sentinel-1a data in the study area, firstly, only the SLC of IW2 and IW3 extracted, and then the study area cropped out by extracting the common burst (6-9) to improve the processing speed and efficiency.

• Select N+1 SAR images and set a reasonable spatiotemporal baseline threshold. The spatiotemporal baseline network connection was shown in figure 1, combined into M differential interferograms, and M satisfies:
Assuming that the j-th scene interferogram is generated from the master-slave images acquired at two times $t_A$, $t_B$ ($t_B > t_A$), the interference phase at any point after removing the flat ground and terrain phase can be expressed as:

$$\delta \varphi_j = \varphi_{t_A} - \varphi_{t_B} \approx \varphi_{j_{\text{def}}} + \varphi_{j_{\text{atm}}} + \varphi_{j_{\text{noise}}}$$  \hspace{1cm} (2)

where $\varphi_{j_{\text{def}}}$ is the directional deformation of the radar line of sight (LOS) during $t_A$ and $t_B$, $\varphi_{j_{\text{atm}}}$, $\varphi_{j_{\text{noise}}}$ are the phase difference caused by the elevation error, atmospheric error, and noise in the time period. Where $\varphi_{j_{\text{def}}}$, $\varphi_{j_{\text{atm}}}$, $\varphi_{j_{\text{noise}}}$ can be specifically expressed as:

$$\begin{align*}
\varphi_{j_{\text{def}}} &= \frac{4\pi}{\lambda} (d_{t_A} - d_{t_B}) \\
\varphi_{j_{\text{atm}}} &= \frac{4\pi}{\lambda} \frac{B}{R \sin \theta} \Delta h \\
\varphi_{j_{\text{noise}}} &= \varphi_{j_{\text{atm}}} - \varphi_{j_{\text{atm}}}
\end{align*}$$  \hspace{1cm} (3)

where $\lambda$ is the radar wavelength, $R$ is the slope distance, $B$ is the vertical baseline, and $H$ is the elevation difference.

Adaptive filtering of the differential interferogram (Goldstein) [11], taking the house in Caojiayu Village, Dantou Town, Huangling County as a reference point for stable unwrapping, with a coherence of 96%, using the minimum cost flow (mcf) method for unwrapping. The interference phase after removing the elevation, atmosphere, and noise error phase is the deformation phase value in the line of sight direction, namely:

$$\delta \varphi_{(\text{def,atm})} = \frac{4\pi}{\lambda} [d(t_{A,r},t_r) - d(t_{B,r},t_r)]$$  \hspace{1cm} (4)
The average annual deformation phase rate is:

\[ v^j = \frac{\phi_{n,j} - \phi_{n-1,j}}{t_n - t_{n-1}} \]

(5)

Then the deformation phase value of the j-th scene interferogram is:

\[ \delta \phi_j = \sum_{i=1}^{j} (t_{i} - t_{i-1})v_i = AV \]

(6)

The specific technical route is shown in figure 2.

---

3. Research Area and Data

3.1. Research Area Overview
The Huangling mining area is located in Huangling County, Yan'an City, Shaanxi Province, with an area of about 2,600 km² and convenient transportation. The specific overview is shown in figure 3(a). The topography of the mining area is high in the northwest and low in the southeast, and the vegetation is very dense, which is a typical of the loess plateau landscape and low mountain forest area. The thickness of the collapsible loess is large. In addition, the coal seams in the mining area are widely exposed and shallowly buried, which expands the scope of surface subsidence in the mine when it encounters rain erosion. Among them, the Hulu River, Ju River and Nanchuan River have large flow rate, and coal mining is affected, especially in the coal mines located in the middle of the mining area, accidents of surface water flooding into the mine often occur, and water prevention and control has become the top priority in mine mining [12-13]. Huangling mining area is very rich in coal resources, with a long history, with a recoverable reserve of 1.4Gt, 8 state-owned coal mines, and more than 160 township and individual coal mines, as shown in figure 3(b). Among them, Huangling No. 1 (area: 197 km²) and No. 2 coal mine (area: 352 km²) are the main parts of the large coal bases in northern Shaanxi and Huanglong planned by the state. There are many large and small coal mines. Predatory mining destroys the surface structure of the loess. Coal mining has become a major factor in frequent occurrence of surface subsidence, cracks, and landslides [14].
Figure 3. Geographical location of the study area and distribution of mining areas.

3.2. Data Source
The ascending data of ALOS-1 and Sentinel-1a were selected to cover the study area. The basic data parameters were shown in Table 1. In order to reduce the orbit error, the precise orbit ephemeris data of Sentinel-1a data was obtained from the website (https://qc.sentinel1.eo.esa.int/aux_poeorb), and the accuracy is within 5cm, generally preferred. In order to better remove the flat ground and terrain effects in the interference processing, the external DEM data selected the 30-meter resolution SRTM provided by NASA. In this study, GAMMA software was used to monitor the surface deformation of Huangling mining area, and ArcGIS and Origin software were used for profile analysis and mapping.

Table 1. Basic parameters of SAR data in the study area.

| Parameter                | ALOS-1               | Sentinel-1a          |
|--------------------------|----------------------|----------------------|
| Coverage time range      | 2007.1.13-2009.1.18  | 2018.10.2-2019.3.19  |
| Number of images         | 12                   | 15                   |
| Path, Frame              | (463, 700)           | (84, 110)            |
| Heavy workshop cycle /d  | 46                   | 12                   |
| Width /km                | 70                   | 250                  |
| Spatial resolution /m²   | 10×14                | 5×20                 |
| Radar wavelength /cm     | 23.6                 | 5.6                  |
| Working band             | L                    | C                    |

4. Result Analysis

4.1. Analysis of Annual Average Deformation Rate
Using the above mentioned SBAS timing technology, the annual average deformation rates of the Huangling mining area from 2007 to 2009 and 2018 to 2019 were obtained, which reached 360 mm/a and 480 mm/a respectively, as shown in figure 4 and figure 5. On the whole, the deformation rate from January 2007 to January 2009 was smaller than the deformation rate from October 2018 to March 2019 because the Huangling No. 1 and No. 2 coal mines, Hongshiyan and other coal mines from January 2007 to January 2009 It has just been put into production and was in the early stage of mining. With the passage of coal mining time and the increase in mining, the deformation rate increased from October 2018 to March 2019.
It can be seen from figure 4 that the surface deformation of the Huangling mine was represented by six distinct deformation areas: A, B, C, D, E and F. Area A contains Huangling No. 2 Coal Mine, which is located in the northwest of Shuanglong Town, with the largest deformation range and...
magnitude. Area B contains Huangling No. 1 Coal Mine and Shuanglong Coal Mine, located near the center of Shuanglong Town, Huangling County. Area C contains Hongshiyuan and Shiniugou coal mines, which are located near Jixian Village and Checun Huaishuzhuang in Diantou Town, respectively. Area D contains the Cangcun Coal Mine, which is located near Cangcun Township, Longfang Town, Huangling County. Area E is located near Dingzhou Village in Diantou Town and Gelai Temple in Longfang Town. Through research and analysis of six deformation areas, it is found that the deformation positions from January 2007 to January 2009 and October 2018 to March 2019 are almost inconsistent. Combined with the analysis of the mining data in this mining area, it can be obtained: As the mining time passed, the deformation position shifted from south to north, and the deformation area was newly added, and the magnitude increased, indicating that coal mining is the main cause of surface subsidence in the Huangling mining area.

4.2. Analysis of Time Series Deformation Law

In view of the wide impact of the cumulative subsidence from October 2018 to March 2019 and the large amount of subsidence, it is necessary to conduct a time series analysis of the surface subsidence law during this period to provide a reference for coal mines to develop mining plans. Figure 5 uses the first scene image (20181002) as the starting time, assuming that the settlement at the starting time was 0, and the rest images was cumulative deformation values that gradually increase over time. It was intuitively concluded that the surface deformation area and subsidence of Huangling mining area were slowly increasing, and it was manifested in six obvious subsidence areas, as shown in table 2 below.

| Subsidence area number | Mine name              | Territory                  | The maximum subsidence value (mm) | Subsidence area ( km² ) |
|------------------------|------------------------|----------------------------|-----------------------------------|-------------------------|
| A                      | Huangling No. 2 Coal Mine | Shuanglong Town           | 300                               | 4.3                     |
| B                      | Huangling No. 1 Coal Mine | Shuanglong Town           | 214                               | 2.5                     |
| C                      | Shiniugou Coal Mine     | Diantou Town               | 144                               | 0.4                     |
| D                      | Hongshiyuan Coal Mine   | Diantou Town               | 110                               | 0.5                     |
| E                      | Cangcun Coal Mine       | Cangcun Township, Diantou Town | 189                               | 1.4                     |
| F                      | unknown                 | Diantou Town and Longfang Town | 222                               | 1.6                     |

In order to analyze the pattern of subsidence funnel in the mining area, by drawing the L profile in arcgis (figure 6), the local surface subsidence value of Huangling No. 2 Coal Mine was obtained, as shown in figure 6. From October 1, 2018 to December 13, 2018, the maximum cumulative subsidence in this area has dropped from 34 mm to 196 mm. From December 13, 2018 to March 19, 2019, the maximum cumulative subsidence has reached 240mm, which clearly yields a greater rate of subsidence from October 1, 2018 to December 13, 2018 than from December 13, 2018 to March 19, 2019, indicating that the surface subsidence rate is slowing down and the subsidence value is still slowly increasing. The overall development trend of the curve is consistent with that shown in figure 5. The initial settlement is small. As the working face advances, the settlement value gradually increases with the passage of time, forming an obvious settlement funnel.
In order to accurately analyze the law of surface subsidence in the Huangling mining area, P1, P2 (Huangling No. 2 Coal Mine), P3 (Huangling No. 1 Coal Mine), and P4 (Hongshiyan Coal Mine) are selected in areas A, B, D, E, and F respectively. P5 (Cangcun coal mine), P6 (unknown coal mine) six settlement center characteristic points for time series analysis. As shown in figure 7, the surface settlement of P1 and P2 is the most severe. The cumulative settlement values of P1 and P2 are respectively reaching 290mm and 240mm. From October 2, 2018 to January 18, 2019, the cumulative settlement value of P1 is less than P2. After that, the subsidence rate of P1 is accelerated, and the cumulative settlement value is greater than the accumulated settlement value of P2. The surface settlement of P6 is slight, with a cumulative settlement value of 103 mm. The accumulated settlement values of points P3, P4, and P5 from October 2, 2018 to March 19, 2019 are 206 mm, 160 mm, and 205 mm respectively. Overall, the cumulative settlement value of the six characteristic points gradually increased from October 2, 2018 to March 19, 2019. The results show that this is consistent with the advancement of the working face, mining time, and mining conditions, and conforms to the mining subsidence law.

85% of the rainfall in the Huangling mining area is concentrated from May to September. During this period, the rainfall will infiltrate into the rock and soil, which will aggravate the surface subsidence. The study time is from October to March 2018, which is in the freezing period. The impact of the amount on the surface settlement is negligible, which further verifies that the surface settlement of the mining area during this period was mainly caused by mining.

5. Result Analysis
This paper used ALOS-1 (January 2007 to January 2009) and Sentinel-1a (October 2018 to March 2019) data. The SBAS time series technology used to obtain the large-scale annual average deformation rate and time series cumulative settlement value of the Huangling mining area, and comprehensively analyzed the temporal and spatial variation laws and causes of the surface deformation of the study area in two different periods, and the following conclusions obtained:

- Compared with the traditional leveling and GPS measurement methods, SBAS time series technology can realize large-scale, high-precision surface settlement monitoring in mining areas. SBAS monitoring results show the settlement of one surface and can monitor some unknown surface settlements.
- It was discovered that from January 2007 to January 2009, from October 2018 to March 2019, at least 5 new subsidence areas were added to the Huangling mining area. About 20 subsidence areas had been formed, mainly distributed in Shuanglong Town, Diantou Town, Longfang Town, and Cangcun Township, the surface subsidence of Shuanglong Town was the
most serious because it was located in the goaf area of Huangling No. 1 and No. 2 coal mines. The subsidence trend was consistent with the mining subsidence law, and the maximum cumulative settlement value was up to 214 mm, 300 mm.

- The surface subsidence in Huangling mining area is mainly caused by underground coal mining. According to the investigation, the mining geological condition parameters such as mining depth, mining thickness, and working face width are the main factors affecting the surface settlement in this area. The surface settlement and ground fissures interact with each other, which causes great harm. Time series analysis shows that the current range and magnitude of surface subsidence in the Huangling mining area are slowly increasing. This situation requires special attention from mining personnel, so that corresponding measures can be taken for reasonable mining.

References

[1] Guo H, Lun Y, Geng L, et al. 1994 Mining Subsidence Xuzhou: China University of Mining and Technology Press.
[2] Bamler R and Hartl P J 1998 Synthetic aperture radar interferometry Inverse Problems 14(4) R1-R54.
[3] Gabriel, Andrew K, Goldstein, Richard M, Zebker and Howard A J 1989 Mapping small elevation changes over large areas: Differential radar interferometry Journal of Geophysical Research Solid Earth 94(B7) 9183-9191.
[4] Jianjun Z, Zhiwei L and Jun H J 2017 In SAR deformation monitoring methods and research progress Journal of Surveying and Mapping 46(10) 1717-1733.
[5] Berardino P, Fornaro G, Lanari R, et al. 2002 A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms IEEE Transactions on Geoscience and Remote Sensing 40(11) 2375-2383.
[6] Casu F, Manzo M and Lanari R J 2006 A quantitative assessment of the SBAS algorithm performance for surface deformation retrieval from DInSAR data Remote Sensing of Environment 102(3-4) 195-210.
[7] Lanari R, Casu F, Manzo M, et al. 2007 An overview of the small base-line subset algorithm: A DInSAR technique for surface deformation analysis Pure and Applied Geophysics 164(4) 637-661.
[8] Xue Z, Da G, Li W, Ling Z, Yan W, Guo X F, Li M and Yu X H 2012 Research on land subsidence monitoring of mining cities based on coherent target short baseline InSAR Journal of China Coal Society 37(10) 1606-1611.
[9] Da L, Ka D, Xiao G and Hai N J 2018 Monitoring and analysis of ground subsidence in mining areas based on SBAS-InSAR Journal of Wuhan University: Information Science Edition 43(10) 1531-1537.
[10] Werner C, Wegmüller U, Stroazzi T, et al. 2000 Gamma SAR and interferometric processing software Proceedings of the ERS-ENVISAT Symposium Gothenburg, Sweden.
[11] Goldstein R M and Werner C L 1998 Radar interferogram filtering for geophysical applications Geophysical Research Letters 25(21) 4035-4038.
[12] Yanni Z J 2020 The hidden disaster-causing factors and prevention measures of coal mines in Huangling mining area Shaanxi Coal 39(01) 172-175.
[13] Yongfeng W D 2019 Detection of Water Conducting Fissure Zone and Prediction of Fracture Safety in Huangling Mining Area Xi'an: Xi'an University of Science and Technology.
[14] Zhenyu D D 2010 Research on the Characteristics of Surface Subsidence and Overburden Failure Law of Coal Mining Face in Huangling Mining Area Xi'an: Xi'an University of Science and Technology.