Deformation monitoring of photovoltaic power stations and substations in Yangquan using time-series InSAR

Jianjun Jia1, *, Haifei Yang1, Hao Gong2,3, Xianbing Ke2,3, Xiao Guo2,3, Shiguang Bie2,3, Nian Wu2,3

1State Grid Yangquan Power Supply Company, Yangquan, 045000, China
2NARI Group Corporation/State Grid Electric Power Research Institute, Nanjing 211106, China
3Wuhan NARI Limited Liability Company, State Grid Electric Power Research Institute, Wuhan 430074, China

*Corresponding author email: jianjunjia@sgcc.com.cn

Abstract. Yangquan is rich in coal resources, and coal mining activities are frequent, which usually causes significant subsidence in the mining area. Substations and power stations around the mining area may be affected by subsidence. In this paper, the time series SAR images of the 25 Sentinel-1A satellite in Yangquan from January to November 2019 are obtained to monitor the deformation of substations and photovoltaic power stations by using the SBAS-InSAR technology. The results show that the deformation range of the study area is between -23.8cm and 11.2cm. In addition, there are multiple subsidence “bowl” due to coal mining. The deformation range of the feature points of the five substations in Wenchi, Niangziguan, Changling, Luhu and Ceshi is between -1cm and 1cm, which are in a stable state. However, there is a continuous linear subsidence phenomenon in Ququcheng photovoltaic power station. Among the Ququcheng three subsidence feature points, the maximum annual subsidence reaches more than 4cm. The main reasons for the subsidence are the gravity component of soil and the increased ground load caused by the power generation device in this area.

1. Introduction
Substation and power tower are the link to ensure the smooth flow of electricity and play a pivotal role in economic and social activities [1]. Yangquan area is rich in coal resources and the terrain is dominated by hills and mountains. Due to its complex terrain environment, coal mining activities are likely to affect the stability of surrounding substations and power stations, causing surface subsidence and geological disasters [2]. In addition, the self-weight stress of substation and power station is also an important factor causing surface deformation. Therefore, it is of great significance to accurately monitor and analyze the surface deformation characteristics of substations and power stations in Yangquan.

Traditional monitoring methods (Precision leveling and GNSS measurement) observe discrete point positions. For large areas, a large number of elevation control points need to be set up, and the observation time is long. At present, D-InSAR (Differential Interferometric SAR) has achieved remarkable results in the monitoring and research of surface deformation. However, it suffers from temporal and spatial decoherence problems. Berardino et al. [3] proposed the SBAS technology, which
combines a series of short spatial baseline differential interferograms, can effectively overcome the phenomenon of spatial decoherence and increase sampling rate in time and high-density deformation measurement in space. The SBAS method has been successfully applied in ground deformation monitoring, such as coal mining area, landslides, and power transmission facilities. Han Xiaoyan [4] used SAR images and D-InSAR technology to monitor the surface deformation of the 500kV substation in Ganzi, Sichuan. Xiao Xingquan et al. [5] used JS-InSAR technology to conduct deformation monitoring on two 500kV large substations of Jianshan and Jiujiang in Chengdu. Yang Xie et al. [6] used the SBAS method to monitor the deformation characteristics of the mining area. Zhang Jinying et al. [7] use Sentinel-1 data combined with SBAS technology to monitor large-scale surface subsidence in the Yellow River Delta.

Based on Sentinel-1A SAR images, this paper uses the SBAS method to monitor the deformation of the photovoltaic power station and substations in Yangquan. The time series deformation characteristics in the study area are revealed and the causes of subsidence are analyzed. Finally, reasonable suggestions are given.

2. Method

The SBAS technology forms a small baseline interference pair by setting the threshold of the spatial baseline and the temporal baseline. Then, based on the minimum norm criterion, the deformation velocity and time series of the coherent target are obtained by the singular value decomposition (SVD) method. Specific steps are as follows [8]:

1. Obtain \( N + 1 \) SAR images arranged in time sequence \( t_0, \ldots, t_N \), and select one of them as the main image, and the other slave images are registered to the master image.

2. For the differential interferogram generated by the main image \( B \) and the slave image \( A \), the interference phase of pixel \((x, r)\) can be written as:

\[
\delta \Phi_j(x, r) = \Phi_B(x, r) - \Phi_A(x, r)
\]

\[
\approx \frac{4\pi}{\lambda} [d(t_B, x, r) - d(t_A, x, r)] + \Delta \Phi_{\text{topo}}^j(x, r) + \Delta \Phi_{\text{AS}}^j(t_B, t_A, x, r) + \Delta \Phi_n^j(x, r)
\]

where \( j \in (1, ..., M) \), \( x \) and \( r \) are azimuth and distance coordinates. \( \lambda \) is the central wavelength of the signal. \( d(t_B, x, r) \) and \( d(t_A, x, r) \) are the radar line-of-sight deformation relative to \( d(t_0, x, r) \) at time \( t_B \) and \( t_A \). \( \Delta \Phi_{\text{topo}}^j(x, r) \) is the residual phase due to the DEM errors. If the DEM introduced is of high accuracy, the \( \Delta \Phi_{\text{topo}}^j(x, r) \) can be ignored. \( \Delta \Phi_{\text{AS}}^j(t_B, t_A, x, r) \) represents the atmospheric artifacts phase. \( \Delta \Phi_n^j(x, r) \) is the noise phase term. Without considering the phase of residual terrain, atmospheric artifacts and noise, equation (1) (2) (3) can be simplified as:

\[
\delta \Phi_j(x, r) = \Phi_B(x, r) - \Phi_A(x, r)
\]

\[
\approx \frac{4\pi}{\lambda} [d(t_B, x, r) - d(t_A, x, r)]
\]

3. In order to obtain a subsidence sequence with physical significance, the phase in equation (4) (5) is expressed as the product of the average phase velocity and the time interval. The phase of the interferogram can be written as:

\[
\sum_{k=t_A+1}^{t_B} (t_k - t_{k-1}) v_k = \delta \Phi_j
\]
where \( v_k \) is the average phase velocity, and \((t_k - t_{k-1})\) represents the time interval.

The SVD method is used to obtain the minimum norm solution of the velocity vector, and finally the deformation of the whole time period can be obtained through the integration of the velocity in each time period.

The SBAS method is based on differential interferograms with small spatial and temporal baseline. The main technical feature of this method is to make full use of all the highly coherent pixels in SAR data, which improves the time sampling rate of deformation and the spatial coverage of the study area and effectively eliminates the atmospheric artifacts phase. The process of SBAS method is shown in Figure 1.

![Figure 1. SBAS processing flow chart.](image)

3. Study area and data processing

3.1. Study area
Yangquan is located in the east of the Loess Plateau, where the landform is dominated by mountains and the rest by hills and plains. The original topography creates poor geological conditions in this area, which can easily cause various geological disasters. Otherwise, Yangquan is an important coal mining city in Shanxi Province, and coal mining has the characteristics of wide distribution, long time, and depth. Coal mining has formed a large number of underground mined-out areas, which have induced ground cracks, ground collapse, slope collapse, landslides and other geological disasters [9]. The locations of photovoltaic power Ququcheng and the substations of Wenchi, Niangziguan, Changling, Luhu and Ceshi are shown in Figure 2 (a).
The data set used in this paper is the 25 SAR data (VV) acquired by the ESA Sentinel-1A satellite from January 3 to November 23, 2019. At the same time, precision orbit data and 30m resolution DEM data are used as auxiliary data. The specific SAR image parameters are shown in Table 1.
Table 1. SAR image parameters.

| Image number | Product type        | Acquisition time | Orbit mode | Polarization mode |
|--------------|---------------------|------------------|------------|-------------------|
| 1            | SENTINEL1_SLC_IW    | 19/01/03         | Ascending  | VV                |
| 2            | SENTINEL1_SLC_IW    | 19/01/15         | Ascending  | VV                |
| 3            | SENTINEL1_SLC_IW    | 19/01/27         | Ascending  | VV                |
| 4            | SENTINEL1_SLC_IW    | 19/02/08         | Ascending  | VV                |
| 5            | SENTINEL1_SLC_IW    | 19/02/20         | Ascending  | VV                |
| 6            | SENTINEL1_SLC_IW    | 19/03/04         | Ascending  | VV                |
| 7            | SENTINEL1_SLC_IW    | 19/03/16         | Ascending  | VV                |
| 8            | SENTINEL1_SLC_IW    | 19/03/28         | Ascending  | VV                |
| 9            | SENTINEL1_SLC_IW    | 19/04/09         | Ascending  | VV                |
| 10           | SENTINEL1_SLC_IW    | 19/04/21         | Ascending  | VV                |
| 11           | SENTINEL1_SLC_IW    | 19/05/03         | Ascending  | VV                |
| 12           | SENTINEL1_SLC_IW    | 19/05/15         | Ascending  | VV                |
| 13           | SENTINEL1_SLC_IW    | 19/05/27         | Ascending  | VV                |
| 14           | SENTINEL1_SLC_IW    | 19/06/08         | Ascending  | VV                |
| 15           | SENTINEL1_SLC_IW    | 19/06/20         | Ascending  | VV                |
| 16           | SENTINEL1_SLC_IW    | 19/07/14         | Ascending  | VV                |
| 17           | SENTINEL1_SLC_IW    | 19/08/19         | Ascending  | VV                |
| 18           | SENTINEL1_SLC_IW    | 19/08/31         | Ascending  | VV                |
| 19           | SENTINEL1_SLC_IW    | 19/09/12         | Ascending  | VV                |
| 20           | SENTINEL1_SLC_IW    | 19/09/24         | Ascending  | VV                |
| 21           | SENTINEL1_SLC_IW    | 19/10/06         | Ascending  | VV                |
| 22           | SENTINEL1_SLC_IW    | 19/10/18         | Ascending  | VV                |
| 23           | SENTINEL1_SLC_IW    | 19/10/30         | Ascending  | VV                |
| 24           | SENTINEL1_SLC_IW    | 19/11/11         | Ascending  | VV                |
| 25           | SENTINEL1_SLC_IW    | 19/11/23         | Ascending  | VV                |

3.2. The processing results

With the help of SARscape software, this paper generates a connection diagram by setting a maximum 50% critical spatial baseline and a 60d maximum temporal baseline threshold, and the combination of interference pairs is shown in Figure 3. Then the data pair is interfered, and the remaining images are registered to the super main image (March 4, 2019). A series of steps including interferogram generation, flattening, adaptive filtering, coherence diagram generation and phase unwrapping of minimum cost flow are completed. After that, the phase diagram, coherence diagram and phase unwrapping result generated after the filtering can be observed, and the connection diagram with obvious atmospheric phase and poor flattening effect can be removed. Then, the interferogram with better flattening and filtering result is selected as the reference image, and more than 20 GCPS are selected in the region with better coherence and no residual topographic and deformation fringes for orbit refining and re-flattening. In addition, two inversion steps need to be performed. The first step is to estimate the deformation velocity and residual terrain, and the second step is to calculate the displacement on the time series, estimate and eliminate atmospheric phase, and obtain a purer displacement result of the time series. Finally, geocoding is executed to obtain the average deformation velocity diagram (Figure 4).
According to the deformation velocity diagram of Yangquan from January to November 2019 generated by the SBAS-InSAR method, it can be seen that the annual deformation range is probably between -23.8cm and 11.2cm.

There is much subsidence “bowl” in the Figure 4, most of which are caused by mining. In addition, the substations of Ceshi (point 1), Luhu (point 2), Changling (point 3), Niangziguan (point 4) and Wenchi (point 5) are in a stable state, which are not affected by the mining area. However, the photovoltaic power station of Ququcheng (point 6) has obvious large area of subsidence.

Figure 3. Distribution of images for the Sentinel-1A data set. The lines connecting image pairs indicate the interferograms generated.

Figure 4. Deformation velocity diagram in the study area.
3.3. Result analysis

In order to quantitatively analyze the subsidence characteristics of the study area, one feature point is selected for each substation of Wenchi, Niangziguan, Changling, Luhu and Ceshi, and three subsidence feature points are selected for the Ququcheng photovoltaic power station.

The deformation of Wenchi, Niangziguan, Changling, Luhu and Ceshi ranges from -1cm to 1cm in Figure 5, which is in a stable state, and not affected by the mining in the surrounding mining areas. For Ququcheng photovoltaic power station, Figure 6 shows obvious linear subsidence at three feature points, of which the maximum subsidence exceeds 4cm. In addition, this photovoltaic power station is far away from the mining area and is less likely to be affected by mining. Therefore, it can be speculated that the subsidence is mainly caused by the construction pressure of the 100 MW photovoltaic power station project and the pressure of the power generation device in this area.

![Fig 5. Time series of subsidence feature points deformation of substations.](image1)

![Fig 6. Time series of subsidence feature points deformation of photovoltaic power station.](image2)
4. Conclusion
This paper uses SBAS-InSAR technology to monitor the ground deformation of the five substations in Wenchi, Niangziguan, Changling, Luhu and Ceshi and the Ququcheng Photovoltaic Power Station in Yangquan from January 2019 to November 2019. The causes of the main subsidence areas are analyzed according to the results.

The results show that the annual deformation of the whole study area is about -23.8cm~11.2cm, and there are many subsidence funnies, most of which are caused by mining. What’s more, the maximum deformation of Wenchi, Niangziguan, Changling, Luhu and Ceshi substations is about 1cm/year, which means these substations are in a stable state. However, the Ququcheng photovoltaic power station presents obvious subsidence phenomenon. The three subsidence feature points show linear subsidence from January 3 to November 23, 2019, with the maximum subsidence of 4cm/year, which is mainly caused by the gravity component of soil and the power generation device in this area. The subsidence area of photovoltaic power station has a trend of continuous linear subsidence, which may cause slow slope slip. Therefore, preventive measures should be taken in advance to avoid economic losses.

In future work, multi-source data should be combined with analysis to improve the accuracy of the results.

Acknowledgment
This work was financially supported by Science and Technology Project of Shanxi Electric Power Company (5205c018005f).

References
[1] LIU Ming, LI Yonggao, ZHANG Houqi, et al, Safety analysis of typical transmission tower in geologic disaster zone[J]. Electric Power, 2012, 45(5): 34–38.
[2] Wu Liping, Gong Hao, Zhao Xiaolong, Fan Peng, Wu Baojun, Zhou Yuantao, Deformation monitoring and analysis of Yangquan mining area based on DInSAR technology[J]. Safety in Coal Mines, 2018, 49(07): 193-197.
[3] Berardino P, Fornaro G, et al, A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms.IEEE Transactions on Geoscience and Remote Sensing, 2002, 40(11): 2375- 2383.
[4] Han Xiaoyan, Bu Xianghang, Research and application of monitoring technology for slow surface settlement in 500 kV substations[J]. Sichuan Electric Power Technology, 2017, 40(02): 46-50.
[5] XIAO Xingquan et al. The application of JSInSAR technology in substation and power tower deformation monitoring. Electric Power, 2018, 51(11):45-52.
[6] YANG Xie et al. Application of SBAS-InSAR deformation feature monitoring in damage identification and analysis of mining area [J]. Safety in Coal Mines, 2020, 51(6): 174-178, 183.
[7] Zhang Jinying, Cui Liang, Liu Zengmin, Wang Xintian, Lin Lin, Xu Fengling. Large-area surface deformation monitoring using Sentinel-1 SAR data and SBAS technology [J]. Bulletin of Surveying and Mapping, 2020(07): 125-129.
[8] Mingsheng Liao, Teng Wang. Technology and application of Time series InSAR. Beijing Science Press,2014.
[9] Cao Yanni, Liu Wei, Xu Motao, Wang Aijun, Zhao Yang. Division of Geological Disaster Prone Areas in Yangquan Mining Area[J]. China Manganese Industry, 2018, 36(06): 171-175.