

Multi-temporal InSAR Analysis of Land Subsidence in the Shaqu Coal Mine Based on a Hybrid Cloud Processing Framework

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Abstract: This study addresses the demand for monitoring intensive surface subsidence in the Shaqu No. 1 and No. 2 coal mines, Shanxi Province, by implementing a hybrid cloud-based InSAR analytical framework. The workflow utilizes the ASF Hyp3 cloud platform for automated Sentinel-1 data preprocessing, including interferogram generation and phase unwrapping, integrated with the open-source MintPy toolbox for Small Baseline Subset time-series modeling. The results demonstrate that this approach significantly reduces the dependency on local computational resources while effectively capturing the spatiotemporal evolution of moving subsidence basins. The findings provide critical technical support for operational safety and geohazard mitigation in complex mining environments.

Keywords: Surface Subsidence; InSAR; Hyp3; MintPy; Hybrid Cloud Architecture; Time-series Analysis.

1. Introduction

In the context of peak carbon and carbon neutrality, the Shaqu No. 1 and No. 2 mining areas in Shanxi serve as vital national coking coal production bases. Monitoring surface subsidence induced by high-intensity mining in these areas is of paramount importance for both operational safety and ecological restoration. The Shaqu mining area is characterized by complex geological conditions and typical repeated mining of close-distance coal seams, leading to rapid evolution of surface subsidence basins and large deformation gradients. Traditional ground-based leveling and GNSS monitoring, constrained by sparse point distribution, high labor costs, and limited coverage, fail to meet the requirements of modern mines for large-area, high-spatiotemporal-resolution dynamic deformation sensing.

While Interferometric Synthetic Aperture Radar (InSAR) technology has become a mainstream tool for mine disaster monitoring due to its all-weather, long-term, and high-precision advantages, traditional InSAR processing workflows, such as SNAP or Gamma face significant technical bottlenecks.[1]These include high local computational resource consumption, slow downloads of precise orbits and SLC data [2], and low efficiency in registration and phase unwrapping when processing massive Sentinel-1 datasets.

To address these issues, this paper proposes a processing architecture based on a Hybrid Cloud approach. The front-end leverages the Hyp3 cloud processing platform provided by NASA ASF, utilizing elastic computing resources to automatically complete precise alignment of SAR images, interferogram generation, and SNAPHU-based phase unwrapping. The back-end employs the open-source time-series analysis tool MintPy, which performs multi-temporal modeling on the cloud-generated interferometric stacks based on the Small Baseline Subset (SBAS) theory, while incorporating the ERA5 meteorological model for tropospheric delay correction.

This model significantly enhances the conversion

efficiency from raw data to deformation rate products while drastically reducing local data storage pressure, by more than 90%. This study aims to use this framework to conduct a quantitative analysis of surface subsidence characteristics in the Shaqu mining area from 2017 to 2025, verifying the reliability and timeliness of the hybrid cloud architecture for monitoring complex mining areas and providing a scientific basis for disaster prevention and reduction.

2. Study Region and Methodology

The Shaqu mining area represents a critical coking coal production base in China. Given the complex geological conditions characterized by high gas content and high ground pressure, monitoring surface deformation induced by intensive mining is essential for infrastructure integrity and ecological restoration. Traditional geodetic methods, such as leveling and GNSS, are often limited by sparse sampling and high labor costs. While Interferometric Synthetic Aperture Radar (InSAR) offers broad spatial coverage, conventional local processing chains face bottlenecks in data storage and computational efficiency when handling large-scale Sentinel-1 datasets[3]. To overcome these challenges, this study proposes a hybrid cloud architecture. By leveraging the Hyp3 platform for elastic cloud-based preprocessing and MintPy for refined time-series inversion[4], this framework achieves a lightweight yet high-throughput workflow. This paper analyzes the dynamic subsidence patterns in the Shaqu mine from 2017 to 2025 to evaluate the reliability of the proposed method.

$$\Phi_{x,y}^k = \varphi_{\text{top},x,y}^k + \varphi_{\text{def},x,y}^k + \varphi_{\text{orb},x,y}^k + \varphi_{\text{atm},x,y}^k + \varphi_{\text{noi},x,y}^k \quad (1)$$

To extract motion information precisely from Sentinel-1 interferometric pairs, the total observed phase of a pixel in interferogram is decomposed into a linear superposition of physical components. φ_{def} represents the line-of-sight deformation phase of the primary research target, φ_{topo} accounts for the residual topographic phase resulting from the precision limitations of the external digital elevation model,

and ϕ_{atm} denotes the atmospheric delay phase influenced by water vapor and pressure[5], ϕ_{orb} refers to systematic phase shifts caused by errors in satellite orbital parameters, while ϕ_{noise} encompasses random noise phase arising from spatiotemporal decorrelation and system thermal noise. The effective isolation and modeling of these distinct components through the MintPy time-series inversion algorithm provides a fundamental basis for obtaining high-precision velocity fields. The research implements a cloud-to-local hybrid framework designed to optimize large-scale processing. Sentinel-1 Single Look Complex (SLC) stacks are processed

on the ASF-Hyp3 platform using the ISCE2 processor. This stage automates the generation of interferograms, including precise co-registration, multi-looking (5x1 ratio), and topographic phase removal using the Copernicus GLO-30 DEM. The resulting interferometric stacks are ingested into MintPy. A small baseline network is constructed, 30-day temporal, 300m spatial baseline thresholds, to mitigate decorrelation. Interferograms with an average coherence below 0.1 were excluded to ensure the robustness of the inversion. The weighted least squares (WLS) method is then applied to the unwrapped phases to reconstruct the raw Line-of-Sight (LOS) displacement history[6].

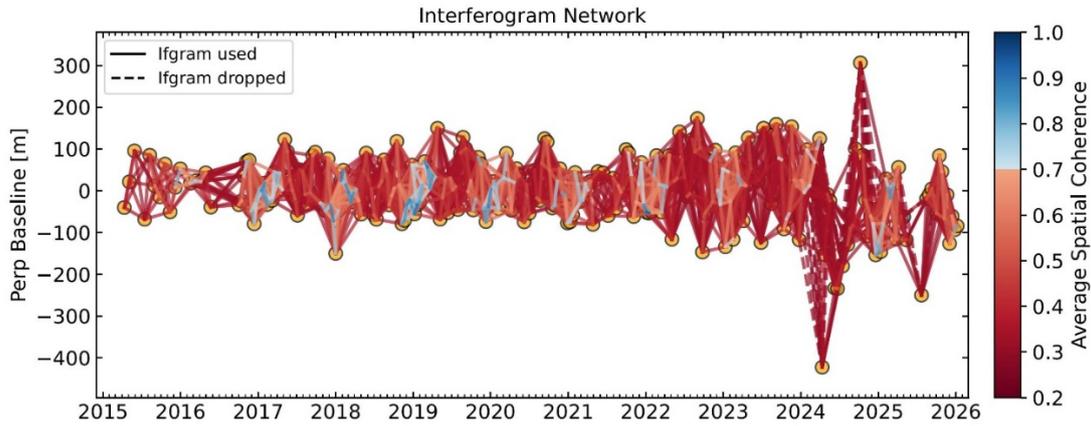


Figure 1. InSAR Network Connection Diagram for Shaqu Mining Area

3. Result

Utilizing a hybrid cloud-based architecture integrating Hyp3 and MintPy, this study derived the long-term annual average surface deformation velocity map for the Shaqu mining area spanning 2015 to 2025. The results characterize multiple prominent subsidence funnels within the mine boundaries, with deformation exhibiting significant spatial heterogeneity. These areas are primarily concentrated in the central and eastern sectors of the mine, demonstrating a high degree of spatial correlation with the advancement of

underground longwall mining faces. In terms of magnitude, the surface deformation rates across the study area range from -0.0492 m/year to 0.0406 m/year. Specifically, the regions indicated in blue represent distinct subsidence centers, with a maximum subsidence rate of approximately 4.9 cm/year, while the peripheral green areas remain largely stable with velocity rates approaching zero. The subsidence basins manifest as elliptical or irregular shapes, reflecting the non-uniform movement patterns of the overlying strata under the influence of mining activities.

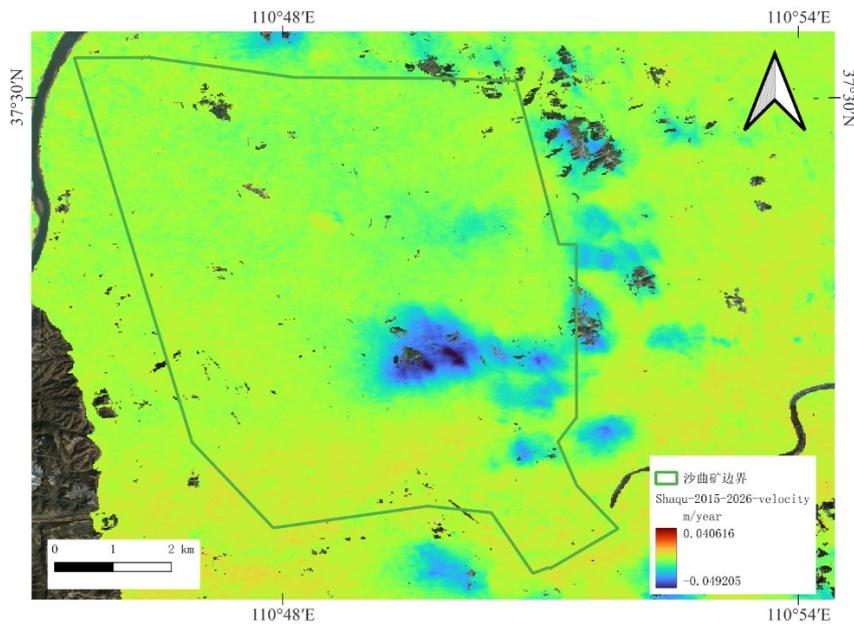


Figure 2. Deformation time series from 2017 to 2025 in the Shaqu mining area obtained through SBAS-InSAR inversion

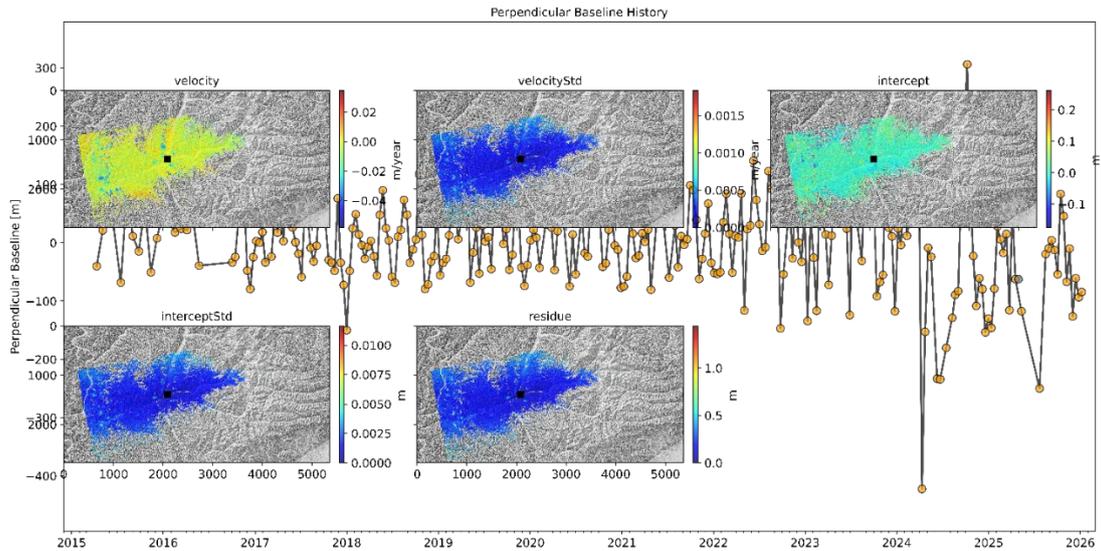


Figure 3. Different rates and error results obtained from InSAR inversion in Shaqu mining area

Analysis integrated with the mine boundary (indicated by the solid green line) identifies the most intense subsidence within the core mining zone in the central sector, where a continuous deformation belt has formed. The imagery reveals a notable dual-center subsidence structure, suggesting the simultaneous or sequential operation of two primary active working faces during this period. Furthermore, several secondary deformation centers are scattered near the eastern boundary, indicating that mining-induced impacts have extended to the periphery of the mine area. Owing to the application of the Small Baseline Subset (SBAS) inversion technique within MintPy, the velocity map maintains robust spatial continuity even in loess gully regions with dense vegetation cover. This high-spatial-resolution distribution not only facilitates the precise identification of the subsidence extent in the Shaqu mine but also elucidates the potential correlation between subsidence gradients and mining depths, providing a quantitative data foundation for assessing the impact of mining on surface structures and the geomorphology of the loess gully region.

4. Discussion

Based on the derived deformation maps of the Shaqu mine, surface movements exhibit significant spatial heterogeneity, which can be categorized into three distinct levels. First, high-magnitude deformation zones (velocity < -4 cm/year) are primarily concentrated in the dark blue regions of the map. These correspond to working faces currently under active extraction, where large-scale coal removal triggers intense overlying strata collapse that rapidly propagates to the surface. Second, low-to-moderate deformation zones (velocities between -1 and -3 cm/year) are distributed along the periphery of primary subsidence basins. These represent the expansion of subsidence basin boundaries or residual settlement effects from abandoned gobs. Finally, stable zones (velocities approaching zero) are extensively distributed across the loess plateau outside the mining boundaries. This gradient characteristic, decreasing from the center toward the periphery, reveals the propagation process of the mining-induced stress field through the loess overburden.

The reliability of the findings in this study is substantiated through three dimensions. First, spatial correlation: the coordinates of the deformation centers extracted via InSAR precisely coincide with the planned locations of the Shaqu

mines working faces. Furthermore, the orientation of the major axes of these deformation zones aligns with the direction of face advancement, providing direct empirical evidence. Second, logical temporal evolution: analysis of the time-series displacement scatter plots shows that monitoring points remain stable during the pre-mining phase, followed by linear subsidence as the working face approaches, and eventually enter a non-linear acceleration phase. This evolutionary pattern is entirely consistent with the "subsidence basin development model" in mining subsidence engineering. Third, technical stability: the time-series inversion performed via MintPy effectively mitigated atmospheric phases identified by the ERA5 meteorological model, maintaining velocity fluctuations in stable areas within 5 mm. Such low background noise levels ensure a high signal-to-noise ratio for identifying subtle deformations. Although some areas exhibit "data voids" caused by phase decorrelation due to loess plateau vegetation, the integration of advanced Gamma filtering algorithms on the Hyp3 cloud and weighted least squares (WLS) inversion in MintPy maximized the consistency of the deformation phase. In summary, the proposed hybrid cloud InSAR monitoring framework demonstrates high robustness in the Shaqu mine, accurately reconstructing the dynamic surface displacement field.

5. Conclusion

This study successfully developed and applied a hybrid cloud InSAR processing architecture based on Hyp3 and MintPy to address the challenges of monitoring surface subsidence in the complex geological conditions of the Shaqu mine, Shanxi Province. The research conclusions are as follows: First, the efficiency of the proposed technical path was validated. By leveraging the powerful cloud computing capabilities of the Hyp3 platform for the interferometric preprocessing of Sentinel-1 data, combined with local MintPy for Small Baseline Subset (SBAS) modeling, the approach reduced local storage requirements by over 90% while significantly enhancing data conversion efficiency. This provides a lightweight, high-throughput solution for the dynamic monitoring of mining areas. Second, the deformation inversion results accurately captured the surface dynamic evolution characteristics of the Shaqu No. 1 and No. 2 mining areas from 2017 to 2025. The study identified subsidence

basins with a maximum sinking rate of 4.9 cm/year. The spatial distribution of these basins showed a high degree of consistency with the locations of underground retreating working faces, proving that the proposed scheme maintains excellent spatial continuity and reliability in complex loess gully regions. Third, the time-series deformation characteristics clearly reflected the physical process of "initiation–acceleration–stabilization" under the influence of mining. This provides a scientific, quantitative basis for mining authorities to determine the boundaries of mining impacts, ensure the safety of ground infrastructure, and plan subsequent land reclamation. In summary, the hybrid model of "cloud-based preprocessing + local refined modeling" not only overcomes the dependence of traditional InSAR on high-performance local hardware resources but also achieves an optimal balance between precision and timeliness, demonstrating significant potential for widespread industrial application.

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