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Study on Overlying Rock Deformation and Surface Subsidence Prediction under Layered Grouting Filling Conditions

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Abstract: To investigate the movement mechanism of overlying rock and surface under layered filling extraction conditions, scientifically evaluate the applicability of traditional prediction models under layered filling conditions, and improve the accuracy of surface subsidence prediction parameters, this paper takes the 1605 layered filling working face of Guhanshan Coal Mine as the engineering background. A comprehensive approach combining long-term field precise levelling measurements, non-contact microwave remote sensing (SBAS-InSAR) monitoring, and parameter optimisation inversion using the probability integral method was employed to conduct an in-depth study of overlying rock and surface movement patterns under layered filling. The study shows that under the disturbance of filling excavation, surface deformation exhibits distinct staged evolution characteristics of "grouting disturbance," "dynamic pressure balance," and finally "rheological stability." The high-pressure grouting filling area shows significant local atypical settlement different from the traditional caving method. SBAS-InSAR technology was used to obtain multi-dimensional surface deformation monitoring results for the entire field, achieving a leap from "point-line" unidirectional control to full "area" coverage in mining area settlement monitoring. On this basis, the limitations of the probability integral method in layered filling mining were explored, and an equivalent mining thickness correction model and optimisation fitting inversion algorithm were established. Engineering verification shows that the corrected probability integral model after parameter inversion can highly fit the measured scatter points, successfully achieving refined prediction of the atypical surface subsidence under layered filling, providing scientific data support for disaster prevention, loss reduction, and optimisation of filling parameters in mining areas.

Keywords: Layered filling, surface movement patterns, SBAS-InSAR monitoring, probability integral method, parameter inversion.

1. Introduction

Coal resources, as an important basic energy source for the development of China's national economy, are mined with high intensity and on a large scale. While ensuring the supply of energy, this has also caused a series of severe ecological and environmental problems in mining areas, among which the large-scale surface subsidence caused by the collapse of overlying rock layers in goaf areas is particularly prominent. Surface subsidence not only leads to extensive waterlogging, salinization, and desertification of farmland, but also causes cracking of buildings, deformation of roads, and damage to groundwater systems around mining areas, severely restricting the sustainable development of the mining area's economy and ecological civilization construction [1-2]. In order to effectively control surface subsidence and achieve green and efficient mining of coal resources, various subsidence-reducing mining technologies have emerged in recent years. Among them, overlying rock layer grouting and filling technology, as a green mining process that reduces loss at the source, has gained increasingly wide application in the control of subsidence in deep coal mining due to its advantages of flexible system layout, relatively low filling cost, and significant subsidence reduction effect [3-4]. The core mechanism of this technology is as follows: after coal mining, before the overlying hard rock breaks, a separation space forms beneath it. Through surface drilling, high-pressure injection of mixed slurry such as fly ash and gangue powder is carried out into this space. The slurry solidifies in the separation space to form a filling body with certain strength. This filling body can provide effective active support for the key overlying layers, alter the stress transmission path within the rock layers, block the upward development of water-conducting fracture zones, and effectively buffer the severe surface disturbance caused by direct roof collapse, ultimately achieving the goal of reducing surface subsidence [5-6]. However, compared to traditional all-collapse mining methods, the movement process of overlying strata and the surface under delamination filling conditions is extremely complex, influenced by multiple factors such as grouting pressure, filling material ratio, grouting timing, delamination space development height, and overlying strata structure [7]. This multivariate coupling effect leads to significantly atypical patterns in surface subsidence basins, deformation characteristics, and spatiotemporal evolution laws under delamination filling conditions, making traditional collapse-based mining subsidence theories and empirical formulas inadequate for accurately describing this intricate process [8-9]. Currently, the probability integration method, the most widely applied mining subsidence prediction technique in China, lacks unified standards for its applicability and parameter selection under delamination grouting filling conditions. Traditional empirical parameters often result in overestimations at basin edges and underestimations at basin centers, failing to meet the high-precision subsidence control requirements for mining areas [10-11]. Additionally, conventional surface movement monitoring relies heavily on precise leveling surveys, which, despite their high accuracy, are limited by high labor costs, long observation cycles, and the ability to only obtain discrete point-line data, making it difficult to comprehensively capture the full-field, micro-level deformation characteristics induced by delamination filling [12-13]. Consequently, introducing advanced non-contact microwave remote sensing (InSAR) technology in conjunction with ground-measured data to conduct full-field deformation monitoring and refine predictive models has become a current research focus and challenge [14-15]. Given this context, this paper takes the delamination filling working face of Guhanshan Coal Mine as the research background, employing long-term leveling measurements and SBAS-InSAR technology to thoroughly analyze the atypical patterns of surface movement under delamination filling conditions. It further constructs an optimal inversion model for probability integration method prediction parameters suitable for this scenario, aiming to provide robust theoretical support and technical guidance for green mining and refined surface subsidence control under similar geological conditions.

2. Construction of Detached Layer Filling Overburden and Surface Movement Prediction Model

2.1. Mechanical Mechanism of Detached Layer Filling Subsidence Reduction and Characteristics of Overburden Movement

After coal seam extraction, the overlying rock layers move, deform and fracture under their own weight and the load from above. During the overburden movement, due to differences in lithology, thickness and mechanical strength of various rock layers, the bending and subsidence of adjacent layers are not synchronised, resulting in interlayer voids between hard rock layers and weak rock layers, known as "detached layers". Detached layer filling technology captures this spatiotemporal evolution feature by injecting slurry into the detached layer through a high-pressure surface pumping station before the detached layer reaches its maximum development height and closes. From a mechanical perspective, the injected slurry not only physically fills the detached layer space but also forms a high-pressure fluid support pad within the enclosed space. As the slurry dehydrates and consolidates, the filling body gradually gains bearing capacity. At this stage, the key layer changes from the stressed state of a cantilever or end-supported beam to that of a continuous beam supported by an elastic foundation at the base. This active support force significantly reduces the bending moment and shear force of the key layer, preventing its fracture and rotational instability. Therefore, damage to the overburden is confined below the detached layer, with movement of the overlying strata predominantly being overall bending subsidence rather than severe collapse or fracture. This mechanism enhances the continuity of surface movement, smooths the edges of subsidence basins, and greatly reduces overall settlement.

The probability integral method is the industry standard approach for subsidence prediction in China. Its theoretical basis is the theory of stochastic media, treating the rock mass as a granular structure and using integral operations to determine the surface movement and deformation caused by the extraction of finite mining units. Its basic subsidence formula is:

$$W(x) = \frac{W_0}{2}[\mathrm{erf}(\frac{\sqrt{\pi}}{r}x) + 1]$$

Here, $W_0 = m \cdot q \cdot cos\,\alpha$ represents the maximum subsidence, $r = \frac{H}{tan\,\beta}$ is the main influence radius, q is the subsidence coefficient, and tanβ is the tangent of the main influence angle. In traditional caving mining, this model can fit the surface subsidence basin well. However, under the conditions of a caving and filling layer, directly applying the traditional model has the following limitations: First, the physical meaning of the subsidence coefficient q changes. In the caving method, q mainly reflects the fragmentation and swelling characteristics of the overlying strata above the goaf; in caving and filling, the magnitude of q is directly controlled by the grout filling rate and the compressibility of the filling body. Using traditional empirical values for caving and filling prediction will lead to excessively high predicted values. Second, it is difficult to accurately define the main influence radius parameter tanβ. Caving and filling alters the stress transfer path, and the unbroken state of the key layer expands the affected range of mining towards the periphery, resulting in a larger but gentler surface movement basin. This means the actual tanβ value is usually greater than that in the caving method; without correction, the predicted basin edge will be too steep and cannot reflect the real atypical subsidence characteristics. Finally, local heave or minor surface uplift caused by grouting disturbance cannot be directly described by the pure subsidence model of the probabilistic integral method. Therefore, it is necessary to make in-depth theoretical revisions and parameter reconstruction to the traditional model.

2.2. Construction of the Ground Subsidence Prediction Model for Layered Filling

2.2.1. Theoretical Basis of the Prediction Model

In the study of coal mining subsidence prediction, in order to quantitatively describe the restraining effect of layered grouting filling on ground movement, this paper establishes a mathematical relationship between the filling rate (ϕ) and the subsidence coefficient (q). The theoretical derivation is mainly based on the "Equivalent Mining Height Method" and the "Spatial Compensation Theory".

The equivalent mining height theory holds that the core of layered filling is that the filling body occupies the space originally released by the subsidence of the overlying strata, thereby reducing the displacement transmitted to the surface. The maximum subsidence value of the filled ground surface can be expressed as:

$$W_{max} = M \cdot q_c$$

Where: M is the original mining height; qc is the equivalent settlement coefficient after filling.

2.2.2. Derivation of the settlement coefficient under off-layer filling conditions

Under off-layer filling conditions, the settlement coefficient qfill can be regarded as a function of the original caving method settlement coefficient and the filling efficiency. Based on the overburden space compensation logic, its mathematical expression is as follows:

$$q_{fill} = q_0 - (k_{scp} \cdot \emptyset \cdot \mu)$$

The physical meanings of the parameters are as follows:

q0 (subsidence coefficient under the caving method): refers to the basic constant determined by factors such as the overlying rock lithology and mining depth of the mining area under unfilled conditions. In the research scenario of this study, the subsidence coefficient under the caving method is 0.78.

ϕ (filling rate of the goaf): the ratio of the volume of injected slurry to the volume of the goaf space. In the research scenario of this study, the filling rate is 50%.

kscp (goaf development coefficient): represents the proportion of total goaf space generated by overlying rock movement to the mining height, reflecting the degree of space development under key layer structures.

μ (pressure reduction rate of the filling body): considers the compressive deformation of the filling body under long-term overlying rock pressure. Under the condition of relatively high slurry solidification strength, μ is usually taken as ≈1.

2.2.3. Analysis and Correction of Model Parameters

Based on the data obtained from the experiment, the formula is applied for reverse analysis. If kscp deviates from the empirical value range in conventional calculations, it indicates that the reduction of the settlement coefficient under this model is not only due to the physical filling of the infill material but also stems from the collaborative support of the delaminated infill on the stability of the key layer structure.

To enhance the applicability of the model, this paper proposes the final prediction correction formula:

$$q_{fill} = q_0 \cdot [1 - \frac{V_{fill}}{M \cdot A \cdot \gamma}]$$

3. Overview of 1605 Working Face at Guhan Mountain Mine and On-Surface Subsidence Measurement Analysis

3.1. Overview of Geological Mining and Filling Conditions at 1605 Working Face

The Guhan Shan coal mine is located in a typical high-water-level, deep mining area in China. Its 1605 working face is the core experimental face for implementing interlayer grouting and filling to reduce subsidence. The coal seam at the working face is stable, with an average mining thickness of 6m. The working face extends approximately 1200m in length and the average mining depth reaches 600m. The structural characteristics of the overlying rock formation are key to implementing interlayer filling. According to geological borehole data, the overlying rock layers of the 1605 working face mainly consist of alternating mudstone, sandy mudstone, and fine- to medium-grained sandstone. At distances of around 180m and 320m from the coal seam roof, there are hard, massive fine-grained sandstone layers and coarse sandstone layers measuring up to 25m and 38m thick, respectively. These two hard rock layers form the main sub-critical layers of the overburden. After coal extraction, the lower part of these key layers is prone to forming wide interlayer spaces. Based on this, the mine designed a multi-porous linked surface grouting system, using a mixed slurry primarily of fly ash with cement as an auxiliary material. During the advancement of the working face, the slurry is injected into the two main interlayer zones via a high-pressure pumping station with a delayed tracking method, with a designed grouting pressure of around 35MPa, aiming to maximize control over surface subsidence.

3.2. Surface Movement Observation Station Deployment and Levelling Measurement Data Analysis

To accurately capture the surface movement patterns over the entire mining cycle of the 1605 working face, high-grade observation stations were deployed on the surface above the working face. According to the 'Coal Mine Surveying Regulations' and the geometric characteristics of the mining area, four main observation lines, J, D, C, and S, were set up. The survey stations included multiple control points and a series of working survey points. The spacing between points was set between 30m and 50m, and second-order levelling accuracy was used for long-term, high-frequency tracking observation. After nearly two years of continuous observation and data calculation, the subsidence characteristic parameters of each survey line were extracted and subsidence curves were plotted. Data analysis indicates that the surface movement of the filled goaf exhibited three distinctive evolutionary stages: Grouting Disturbance Period: When the working face had just passed the survey points, the goaf space had initially formed, and high-pressure grouting had commenced, the downward velocity of some points dramatically slowed due to the strong lifting effect of the grout, with a few points on line J showing minor reverse uplift of 1-3mm. This confirms the effective active support exerted by high-pressure grouting on the overlying strata. Dynamic Pressure Balance Period: As the working face continued to advance, the load above increased, and the fill began to consolidate under pressure, resulting in stable surface subsidence. The subsidence rate remained around 1~2mm/d, with no sudden acceleration of subsidence typically observed in caving methods. Rheological Stabilisation Period: After mining ceased and grouting was completed, the surface entered a prolonged stage of slow settlement, mainly induced by the long-term creep of the fill. The maximum surface subsidence measured at the 1605 working face was only about 157mm, representing a reduction rate of over 95% compared with the theoretical expected subsidence in the non-grouted caving method. Additionally, the measured advance influence distance and angle parameters show that the surface basin covers a wider area, yet the deformation is extremely gentle, with no noticeable surface cracks.

3.3. Full-field Deformation Monitoring and Processing Based on SBAS-InSAR

Although levelling surveys are highly accurate, they are limited by point distribution and cannot provide a panoramic view of the spatial morphology of subsidence basins. To address this, this paper introduces the Sentinel-1A SAR satellite imagery dataset and employs Small Baseline Subset (SBAS-InSAR) microwave remote sensing technology for full-process interferometric processing of the 1605 working face and surrounding areas. The SBAS-InSAR technique overcomes the spatiotemporal decorrelation issues of traditional D-InSAR by limiting the spatial and temporal baselines and combining multiple SAR images into small baseline subsets. The specific processing steps are as follows:

(1) Generation of connectivity graph and image registration: 35 Sentinel-1A images covering the mining period were selected, with a temporal baseline threshold of 60 days and spatial baseline threshold of 150 m, to generate the optimal interferometric pair connectivity graph. Sub-pixel high-precision registration was then achieved using geometric

registration based on precise orbit ephemerides and DEMs.

(2) Differential interferometry and phase unwrapping: The SRTM 30 m DEM was used to remove topographic phase and generate differential interferograms. Phase unwrapping was performed using the Minimum Cost Flow (MCF) algorithm combined with coherence thresholds to extract the true deformation phase.

(3) Orbit refinement and flattening: High-coherence stable points far from the subsidence centre were selected as Ground Control Points (GCPs), and a quadratic polynomial model was used to remove orbit errors and residual topographic phase.

(4) Deformation rate inversion and geocoding: Singular Value Decomposition (SVD) was applied to the small baseline subsets to invert cumulative subsidence and deformation rates over the time series. Finally, the deformation results in the radar coordinate system were projected to the WGS84 geographic coordinate system to produce a full-field deformation map of the mine.

3.4. Surface Atypical Deformation Patterns Under Combined Leveling and InSAR Monitoring

The cumulative subsidence field and vertical subsidence rate maps obtained from SBAS-InSAR analysis were cross-validated with high precision against leveling measurement points. Spatially, the InSAR results clearly depict an elliptical, gently subsiding basin above the 1605 working face, with the long axis along the strike measuring approximately 150m and the short axis about 220m. Comparing the validation points, the time-series subsidence curves extracted from InSAR show a high degree of consistency with the measured leveling curves, with the root mean square error (RMSE) controlled within 12.5mm, demonstrating the high reliability of SBAS-InSAR technology in monitoring backfill.

Full-field combined monitoring further revealed the overall synergistic suppression effect of backfilling: the peak values of surface tilt deformation and curvature deformation in the area are significantly weakened, and the edges of the subsidence funnel show extremely smooth transition characteristics. This "surface" type of coverage data not only intuitively displays the effect of distant layer grouting on settlement control at the scale of the entire mine, but also provides a significant guarantee in terms of data dimensions for the subsequent three-dimensional spatial optimisation inversion of the probabilistic integral method parameters.

4. Application and Engineering Verification of Prediction Model in Face 1605

4.1. Optimisation Inversion of Subsidence Prediction Parameters for Face 1605

Based on the optimisation inversion system constructed in Chapter 2 and the high-precision joint monitoring data obtained in Chapter 3, this section systematically inverts the parameters of the probability integration method for Face 1605 of the Guhanshan Mine.

The key parameters for backfill mining of the Guhanshan Mine Face 1605 obtained from the inversion are as follows:

Table 1. Predicted Parameter Results

Subsidence coefficient q	Mining Impact Propagation Angle θ_0 (°)	Main impact Angle tangent tanβ	Offset distance of turning point S_0 (m)	Horizontal movement Coefficient b	Full mobilization influence factor γ
0.078	90°-0.6α	2.06	20	0.3	0.56

These parameters directly confirm the mechanical role of the grouting fill numerically: the significant decrease in q indicates that the equivalent mining thickness has been greatly compressed, and the fill effectively supports the roof; whereas the increase in tanβ conforms to the theoretical expectation that stress should transfer and extend towards the boundaries of the mined-out area on both sides before the key layer fractures.

4.2. Analysis of the Fit Between Corrected Model Predictions and Measured Data

To verify the engineering applicability of the correction probability integral model parameters obtained based on the least squares inversion principle, this study reintroduced the optimal parameter combination obtained from the inversion in the previous section into the constructed mathematical computation domain for surface movement prediction, and conducted forward settlement prediction calculations based on calculus formulas. Forty-four measurement points arranged above the 1605 working face in the Guhan Mountain mining area were selected as a reference for comparison. The analytically calculated anticipated settlement distribution curve was spatially fitted and compared with the concurrently measured levelling settlement data. The results are shown in the figure:

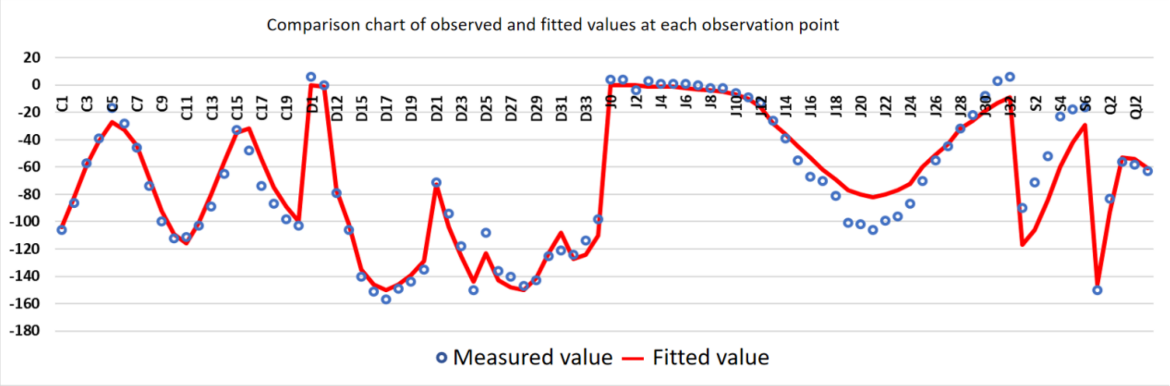

Figure 1. Comparison chart of observed and fitted values at each observation point

4.3. Evaluation of Predictive Model Accuracy and Error Analysis

To scientifically and objectively quantify the reliability and expected accuracy of the surface movement prediction model for layer backfilling constructed in this study, the subsidence fitting error rate σ is introduced as an absolute metric for verification. The specific mathematical formula for calculating the fitting error is as follows:

$$\sigma = \frac{\sqrt{\frac{1}{n}\sum_{i-1}^{n}(P_i - R_i)^2}}{W_{max}} \times 100\%$$

In the formula: Pi is the fitted subsidence value of the ith observation point calculated by the model's forward analysis; Ri is the actual measured subsidence value at that point; n is the total number of valid comparison observation points; Wmax is the maximum subsidence value actually monitored. The corresponding comparison data on each major observation line were substituted into the above formula for systematic computation and comprehensive statistics. The results show that the absolute deviation of the maximum subsidence point on each observation line is effectively controlled within a very small range. After calculation, the comprehensive subsidence fitting error σ was reduced to 7.3%, and the overall prediction accuracy reached 92.78%. This high precision not only far exceeds the theoretical deviation caused by directly applying the traditional probability integral method, but also fully meets the strict engineering requirements of China's 'three-down' coal mining regulations for refined surface deformation prediction, directly demonstrating the robustness and high reliability of the modified theoretical model under complex filling conditions.

5. Conclusion

This paper focuses on the complex green mining condition of layer-separation grouting backfilling, taking the 1605 working face of Guhanshan Mine as the research object. Through multi-source monitoring and theoretical modelling, the following main conclusions are drawn:

(1) Under the conditions of stope-backfill mining, surface movement exhibits significant atypical characteristics. Measured data reveal that surface deformation undergoes three stages: "grouting disturbance", "dynamic pressure balance", and "rheological stability", with high-pressure grouting even causing slight local surface uplift. The active support of the backfill effectively suppresses roof collapse, resulting in subsidence basins that are wide, shallow and gentle, with a subsidence reduction rate of over 95%.

(2) A monitoring system integrating SBAS-InSAR based on Sentinel-1A imagery with precise levelling has been established. This system compensates for the limitations of single levelling measurements in spatial resolution, providing high-precision, comprehensive characterisation of large-scale deformation dominated by stope-backfill, offering solid data support for revealing the subsidence reduction mechanism and correcting predictive models.

(3) The limitations of the traditional probabilistic integration method under stope-backfill conditions have been analysed in depth, and a predictive model has been proposed. A nonlinear parameter optimisation inversion system was established, successfully inverting characteristic parameters suitable for the backfill material, and mathematically explaining the mechanical effects of the backfill.

(4) Engineering verification shows that the revised predictive model fits the measured subsidence curves closely, effectively eliminating estimation deviations at basin edges caused by traditional algorithms. This model accurately predicts the extreme values of surface anisotropic deformation, providing a scientific basis and technical guidance for the protection of mine structures and the dynamic optimisation and precise control of backfill grouting parameters.

References

[1] Lan, J. (2019). Research on the Transformation and Upgrading of China's Coal Industry and Optimization of Spatial Layout [Master's thesis]. China University of Geosciences (Beijing).

[2] Qian, M. G., Xu, J. L., & Miao, X. X. (2003). Green mining technology of coal mines. Journal of China University of Mining and Technology, (4), 5–10.

[3] Kang, H. P. (2021). The development and prospect of surrounding rock control technology in Chinese coal mine tunnels for 70 years. Chinese Journal of Rock Mechanics and Engineering, 40(1), 1–30.

[4] Hu, Z. Q., Long, J. H., & Wang, X. J. (2014). On the self-repair, natural repair and artificial repair of the ecological environment in coal mining areas. Journal of China Coal Society, 39(8), 1751–1757.

[5] Guo, W. B., Bai, E. H., & Zhao, G. B. (2020). Current status and progress of surface damage and prevention technology in high-intensity mining overlying rock. Journal of China Coal Society, 45(2), 509–523.

[6] Srivastava, V., & Jha, K. P. (2025). Environmental impacts of coal mining and mitigation measures: a review. Environmental Monitoring and Assessment, 197(5), 545. https://doi.org/10.1007/s10661-025-13212-9

[7] Xu, J. L. (2020). 20 Years of research and progress on green mining in coal mines. Coal Science and Technology, 48(9), 1–15.

[8] Guo, W. B., Yang, W. Q., Ma, X. C., et al. (n.d.). Research Status and Progress of Grouting Subsidence Reduction Technology in Overlying Strata of Coal Mines in China. Journal of China Coal Society. Retrieved April 8, 2026, from the online version.

[9] Sun, X. K. (2020). Current status and prospects of green filling mining in mines. Coal Science and Technology, 48(9), 48–55.

[10] Zhang, J. X., & Miao, X. X. (2006). Research on underground treatment of coal mine gangue. Journal of China University of Mining and Technology, (2), 197–200.

[11] V. P. (2003). Formation of fractured zones in overburden due to longwall mining. Environmental Geology, 44(1), 28–38. https://doi.org/10.1007/s00254-003-0785-2

[12] Zhou, Y. B. (2021). Research on the Deformation Law of Overlying Rock Continuous Movement during Fill Mining and Settlement Prediction [Master's thesis]. China University of Mining and Technology (Beijing).

[13] Singh, M. M. (1992). Mine subsidence. In SME mining engineering handbook (Vol. 2, pp. 923–952).

[14] He, G. Q. (1991). Study on Mine Subsidence. China University of Mining and Technology Press.

[15] Zhu, J. J., Li, Z. W., & Hu, J. (2017). InSAR Deformation Monitoring Methods and Research Advances. Journal of Surveying and Mapping, 46(10), 1717–1733.