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Large-scale deformation monitoring in mining area by D-InSAR and 3D laser scanning technology integration

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ABSTRACT

Large-scale deformation can not be detected by traditional D-InSAR technique because of the limit of its detectable deformation gradient, we propose a method that combines SAR data with point cloud data obtained by 3D laser scanning to improve the gradient of deformation detection. The proposed method takes advantage of high-density of 3D laser scanning point cloud data and its high precision of point positioning after 3D modeling. The specific process can be described as follows: first, large-scale deformation points in the interferogram are masked out based on interferometric coherence; second, the interferogram with holes is unwrapped to obtain a deformation map with holes, and last, the holes in the deformation map are filled with point cloud data using inverse distance weighting algorithm, which will achieve seamless connection of monitoring region. We took the embankment dam above working face of a certain mining area in Shandong province as an example to study large-scale deformation in mining area using the proposed method. The results show that the maximum absolute error is 64 mm, relative error of maximum subsidence value is 4.95%, and they are consistent with leveling data of ground observation stations, which confirms the feasibility of this method. The method we presented provides new ways and means for achieving large-scale deformation monitoring by D-InSAR in mining area.

1. Introduction

Coal is China's main energy and is also indispensable material basis for economic and social development. The problems of ground subsidence and environmental hazards caused by high intensity and large areas exploiting coal resources become more and more serious. It is reported that total nationwide mining subsidence area is over 700 thousand hectare and results in loss of more than 50 billion Yuan, of which an average of one hundred and five thousand mu is developed in North China and East China each year. In order to reduce mining subsidence disasters, domestic and foreign scholars have conducted extensive research and achieved fruitful achievements [1–8]. Due to the complexity of the mining strata, most studies in mining subsidence are currently based on observed data, and also traditional mining subsidence is mostly monitored using triangulation, leveling and GPS measurements, i.e., to establish the observation lines on the main sectional plane of the subsidence basin, observe regularly and obtain deformation information through data processing and analysis. However, these methods cost large amount of human and material resources, meanwhile these methods are all point wise measurements, lack of area information.

The appearance of InSAR (Interferometric Synthetic Aperture Radar) technique provides a new method for ground subsidence monitoring. The technique utilizes the relationship between the phase difference and spatial distance difference of complex data obtained in two observations to extract three-dimensional information and elevation change information of ground surface. D-InSAR (Differential Interferometry Synthetic Aperture Radar) technique is a means of detection of small surface displacement, which is developed on the basis of InSAR technique. According to the working principle of D-InSAR, D-InSAR technology can get small deformation of ground resolution cell and reach millimeter accuracy in theory [9]. Due to its outstanding advantages of high-precision, all-time, all-weather and large areas, it makes up for the deficiencies of the traditional monitoring methods to a large extent. Also, there are a lot of successful examples in subsidence monitoring for mining areas using D-InSAR technology [10–14]. But for the surface of mining area suffering severe deformation (such as ground collapse) cases, deformation gradient exceeds the maximum detectable deformation gradient of D-InSAR, interferogram will show a series of close interferometric fringes and also image sampling rate will not satisfy the Nyquist rule requirement, which will cause interferometric phase aliasing [15].

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Moreover, deformation gradient is so large that it will inevitably cause changes of scatterer characteristics resulting in SAR (Synthetic Aperture Radar) images temporal decorrelation. Both interferometric phase aliasing and coherence reduction will lead to the final phase unwrapping errors. Reference [16] proposed a method of interpolation multi-looks to improve detectable deformation gradient and Reference [17] used a method of full resolution interferogram to improve the gradient of deformation detection. But both of their improvements are limited, they can not resolve the problem of large-scale deformation (such as meter-scale deformation) in mining area fundamentally.

As mentioned above, large-scale deformation of mining area has hardly ever been monitored by D-InSAR technology until now, therefore, in this paper, we presented a method that combined SAR data with point cloud data using inverse distance weighting algorithm to improve the gradient of deformation detection, which took advantage of high-density of 3D laser scanning point cloud data and its high precision of point positioning after 3D modeling. Finally, we took the embankment dam above working face of a certain mining area in Shandong province as an example to validate the method we proposed. Furthermore, we did a contrastive analysis between experimental results and leveling data.

2. Detectable deformation gradient function models of D-InSAR

The deformation caused by ground motion shows a series of interferometric fringes in InSAR interferogram, and each stripe corresponds to the changes of half the radar wavelength along the line of sight, e.g., ERS sensor with radar wavelength 5.6 cm, each stripe represents changes of 2.8 cm along the line of sight. In 1992, Zebker et al. gave the fundamental condition for interferometry carried out smoothly [18]:

$$\mu \cdot (\mathrm{Sin}\theta_1 - \mathrm{Sin}\theta_2) < \frac{\lambda}{2} \tag{1}$$

where μ represents the pixel size, λ the radar wavelength, θ_1 and θ_2 the angles of center incidence corresponding to the same resolution cell in the first and second images, respectively. From Eq. (1), it is seen that the maximum deformation value along the line of sight in a unit pixel can not be greater than half a wavelength, or these deformation can not recover from InSAR Interferogram. According to the definition mentioned above, Massonnet et al. firstly proposed the concept of deformation gradient and gave the formula theoretically for the maximum detectable deformation gradient of D-InSAR [19]:

$$d_{\max} = \frac{\lambda}{2\mu} \tag{2}$$

where $d_{\max}$ is the maximum detectable deformation gradient value of D-InSAR. According to Eq. (2), we can know that there is a big difference for maximum detectable deformation gradient values between different sensors, e.g., the maximum detectable deformation gradient is 1.4 mm/m (pixel resolution 20 m $\times$ 20 m with 5 looks) for Envisat (Environmental Satellite) sensor and 11.5 mm/m (pixel resolution 10 m $\times$ 10 m with 3 looks) for ALOS (Advanced Land Observing Satellite) sensor after multi-looking processing, therefore, sensors of long-wave band and high-resolution images have the advantages of monitoring greater deformation gradient in theory.

Massonnet's deformation gradient model did not consider the influence of external source errors, i.e., assuming there is no noise in the radar images. However, in practical applications, the detectable deformation gradient of D-InSAR is always smaller than theoretical value as the influence of various decorrelation factors such as temporal decorrelation, spatial baseline decorrelation, thermal noise decorrelation, Doppler cancroids dispersion and atmospheric delay, etc., and more and less, noise in interferogram [20]. Therefore, this ideal model of the deformation gradient can not meet the needs of practice.

In 2005, Baran et al. studied the relationship between deformation gradient and coherence through simulated experiments, meanwhile, they established a functional model of deformation gradient using empirical statistics method, in which coherence is independent variable [21]:

$$D_{\max} = d_{\max} + 0.002(\gamma - 1) \tag{3}$$

where $D_{\max}$ represents the maximum detectable deformation gradient value, $\gamma \in [0, 1]$ the coherence of the interferogram and it is the quantitative evaluation criteria of echo signal affected by a variety of decorrelation factors. It can be seen from the above equation, the maximum detectable deformation gradient of D-InSAR is a linear function of the coherence, which generally increases with coherence increasing. When the coherence is equal to 1, the model becomes the theoretical formula of Massonnet's maximum deformation gradient.

3. Data integration based on inverse distance weighting algorithm

According to the analysis above we can know that the maximum detectable deformation gradient of D-InSAR is limited within a certain range because of the constraint of hardware, e.g., for sensor constraint etc., which leads to the deformation beyond the range of detectable deformation gradient not being monitored by D-InSAR technique. Because it is difficult to overcome those constraint conditions from mechanism of D-InSAR and data processing itself, so we consider integration of SAR data with other source data to solve the deformation gradient problem.

3D laser scanning technology is a new technology emerged in the mid-1990s, and its point cloud data has the characteristics of high-density and high-precision, etc. The point cloud density from a few millimeters to tens of millimeters and its point positioning accuracy can reach millimeter under close observation (less than 100 m) [22–24]. Therefore, we attempt to combine cloud data with SAR data, which takes advantages of high-density and high precision of cloud data, to improve the detectable deformation gradient of D-InSAR.

3.1. Principle of integration algorithm

The resolution of radar image is generally at meter-scale, while the density of point cloud data is commonly at centimeter-level or even millimeter-scale, which means the footprint of one radar pixel typically including dozens or even hundreds of point cloud data, so the spatial resolution of radar data and point cloud data must be effectively unified for data integration. In this paper, inverse distance weighting algorithm is introduced [25]. We think that any point cloud observations within the spatial dimension of a pixel in radar image will affect center point and the impact decreases with distance increasing, therefore, we endow cloud data with different weights according to the distance from point cloud to center point.

Assume that Z represents arbitrary missing point in the masked deformation field obtained by D-InSAR technology, $Z(X, Y)$ on behalf of deformation value of missing point Z, point (X_i, Y_i) represents plane coordinate of arbitrary point i in point cloud deformation field, $Z_i(X_i, Y_i)$ represents deformation value of point i. Inequality $|X - X_i| < m$ and $|Y - Y_i| < n$ are used to determine inverse distance weighted window size, of which the value of m and n are determined based on the resolution of SAR image and density of point cloud of 3D laser scanning (Fig. 1). According to the