Slope of Large-scale Open-pit Mine Monitoring Deformations by Using Ground-Based Interferometry

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ABSTRACT:

A real-time, accurate measurement of slope of open pit could provide reliable information for slope management and the warning system, directly related to the economic benefits and production continuity in the open pit. This paper proposed an innovative technique, based on synthetic aperture radar interferometry and implemented using ground-based instrumentation, has been applied for monitoring slope of open pit. Compared to conventional measurements, The proposed technique presents high spatial resolution and accuracy, generates a topography-free interferogram, provides multi-temporal displacement and velocity map, supplies a deformation field of slope, which represents reliable information for the interpretation of slope kinematics and short-term evolution. The experiment shows that the new technique is reliable for monitoring slope of open pit.

1. INTRODUCTION

Elevating slope angle is an important means of fully recycling resources, reducing production costs and increasing mining efficiency in open pit, along with the increase of slope disasters. Thus, it's essential to process real-time deformation monitoring by monitoring, to master slope disasters, development and change process, to analyze by certain data processing methods and to establish early warning system. Although the total station, electronic level and measuring robots and other traditional measure techniques has been widely used in practice [1], but vulnerable to climate,intervisibility and other conditions. GPS can overcome many shortcomings of traditional measurements [2,3,4], and can well apply in deformation monitoring. But, the number and distribution of visible satellites received a certain geometric constraints by a large open-pit slope angle, which affected GPS positioning accuracy, reliability or even its feasibility [3]. Traditional measurement techniques and GPS access to high-precision displacement, but difficult to reflect the overall trend due to complexity of slope movement. And these measurement are contact measurement, difficult to implement dangerous observation in slope .In recent years, the newly developed three-dimensional laser scanning technology [5] with point cloud observation , not only can get a single point of deformation information, but can reflect the overall observed deformation of the target. While, there is a short-distance observation, - dust impact and low-precision observation. So, there are some limitations in open pit slope monitoring.

Synthetic Aperture Radar (SAR) is an amicrowave sensor, all-weather, all-time, and some penetrating and other unique advantages. Interferometric Synthetic Aperture Radar (InSAR) is an important application of SAR, and received rapid development. To extract ground elevation information from phase information of InSAR data, mainly in ground DEM and surface deformation monitoring [6,7], The monitoring precision in the direction of radar line reached to millimeter level. Airborne-Based Synthetic Aperture Radar Interferometry(AB_InSAR) and Ground-Based Synthetic Aperture Radar Interferometry(GB_InSAR) are two forms of InSAR.

Airborne-Based Synthetic Aperture Radar (AB_SAR) can access to data range, apply to large areas of surface subsidence monitoring. Despite many examples demonstrated in the domestic the feasibility of space-based synthetic aperture radar interferometry in slope monitoring [8-11]. However, due to space-based synthetic aperture radar fixed return period, stance and low spatial resolution, it is not suitable for slope monitoring. GB_InSAR is a great addition to AB_InSAR with best attitude and continuous observation ability. It is a non-contact measurement, no manual observation points, and can monitor the implementation of the dangerous slope. In recent years, some foreign scholars have already researched in the GB_InSAR. Tarchi D, who first proposed the use of artificial structures GB_InSAR deformation monitoring [12], followed by several scholars of this technology in decline [13-16], ice [17 -18], volcanic [19] monitoring, but no scholars GB_InSAR used in open pit slope monitoring studies. Domestic scholars have not started GB_InSAR research.

This paper described GB_InSAR principle, evaluated the feasibility of GB_InSAR in open pit slope monitoring, and applied this technology into an open pit slope monitoring, and get consistent results with total station. Demonstration proved the feasibility of this technology in open pit slope monitoring .

2. GB_INSAR PRINCIPLE

2.1 GB_InSAR

GB_InSAR stemmed from AB_InSAR technology, which is the implementation of AB_SAR on the ground, including Synthetic Aperture Radar(SAR) and Differential Radar Interferometry,but slightly difference with AB_InSAR in techniques .

There are difference between Ground-based synthetic aperture radar and space-based synthetic aperture radar in principle.

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Space-based synthetic aperture radar with linear FM signal from the pulse compression for high resolution satellite orbital motion by the sensor to achieve the synthetic aperture techniques to achieve high azimuth resolution; which the former one appliedStepped Frequency-Continous Wave(SF-CW),which can achieve high range resolution [20], and can ensure the long-range radar transmission. The resolution expressed as follows:

$$\Delta R = \frac{c}{2B} \qquad (1)$$

Formula (1) showed the radar pulse width of B, C is the speed of light. Seen from equation (1), the high range resolution, the high pulse width. B is , range resolution is 0.5m.

Radar achieve a linear synthetic aperture techniques by sliding rails,which fixed on the ground .The direction of resolution expressed as followed.

$$\Delta\varphi = \frac{\lambda}{2L} \qquad (2)$$

In Formula (2), L is synthesized antenna aperture, is the radar wavelength. Using Ku frequency band (18 ~ 12.5GHz) for radar, highest resolution 4.17mrad can get.

By combination of synthetic aperture radar (SAR) and stepped frequency continuous wave technology (SF-CW). Many two-dimensiona monitoring region is splitted. into small units, As shown in Figure(1).

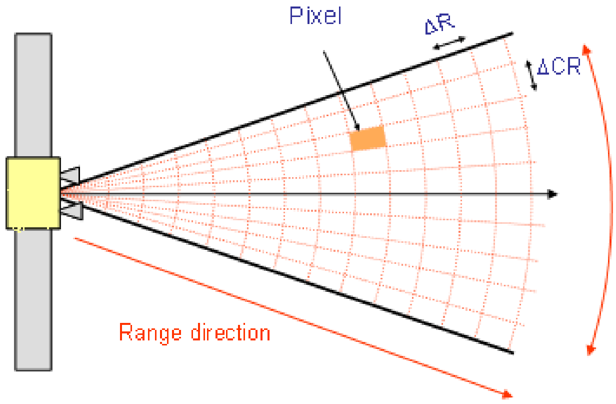

Fig 1.Spatial resolution unit of GB_InSAR

2.2 Ground-based radar differential interferometry

DInSAR is a measure technique through differential treatment by two surface deformation differential interference image processing in an area . Differential space-based radar interferometry affected by the loss of coherence in the application with many limitations:

1) Two SAR images with interferometry are not in the same imaging position. Then, the loss of coherent geometric effect will exist. If there is no precise orbital parameter, the phase error will be introduced to the track.

2) Twice change of scattering target in repeat track during the observation time caused coherence. Time is a non-coherent measurement, and mixed with noise.

3) The uneven delay impact of atmospheric phase, due to the heterogeneity of atmosphere itself and different atmospheric conditions at different times, especial for interferometric pair in different seasons. Atmosphere cannot be avoided in differential interference phase.

Same as air-based radar, ground-based radar with high coherence between images is also suitable for interference analysis. While, GB_SAR flexible imaging attitude can achieve independent differential interferometer. As long as two consecutive radar images can be associated with the deformation phase. The reason as followed.

1) High sampling can guarantee the same scattering properties during observation period, can reduce the coherence of time and some atmospheric delay;

2) Fixed observation geometry gesture can truly receive zero baseline measurements, in addition to the geometric loss of phase coherence. The deformation in sight line is shown as followed:

$$d_{los} = -\frac{\lambda}{4\pi}\Delta\varphi \qquad (3)$$

$\Delta\varphi$ is the interferogram phase, formula (3) is deformation of sight line , which can be decomposed into vertical and horizontal deformation based on geometric profile.

3. RESEARCH METHOD

In order to verify the effectiveness of GB_InSAR in open pit slope monitoring, a Italian IBIS-M microwave interferometer was used in a open pit slope in China .This system consists of two parts as shown in Figure (2) .

1. Radar System; Ku-band (16.6-16.9GHz) radar sensors, generate, transmit and receive radar waves.
2. Linear slide parts; a 2.5m-long aluminum track,radar sensors slide under the control of stepper motor .

Fig 2. A sketch map of GB-SAR

Research methods including data acquisition and data processing.

3.1 Data Acquisition

Monitoring equipment was installed on a stable area opposite slope. As shown, the average distance from the monitor slope is 2050m. Radar beam width is 35°. In order to ensure that monitoring of the slope, the distance resolution is 0.5m under these conditions ;the azimuth resolution is between 7-10m; the monitoring accuracy of sight line is 0.1mm.The images obtained with 9-minute interval , 40-hour continuous observation , 266 landscape images, to compose of time series as pairs.

In GB_InSAR monitoring period, three-dimensional laser scanner obtained accurate DEM of slope, and then projected obtained image onto DEM to get results, finally identify deformation area. Placed five reflective film on the slope,then DEM and GB_SAR can be unified to the same coordinate system by RTK measurements and GB_SAR position.

After 20-hour's GB_InSAR monitoring, placed three prisms in significant displacement area in upper leftslope, and then using total station observations to measure in every 2 hours until the end of the experiment to verify accuracy.

3.2 Data Processing

Using first image as the main image, and interfere with other 265 images respectively. In order to get accurate and reliable measurement results based on pixel coherence, such as formula (4), setting the threshold value of 0.9 to cover up bad points, coherence images shown in formula (3), received more than 40,000 permanent scatterers. After treatment, interference deformation map, deformation speed chart, deformation history graph of each permanent scattering point and regional deformation history graph can received.

$$\gamma = \frac{E[ms^*]}{\sqrt{E[|m|^2]E[|s|^2]}} \qquad (4)$$

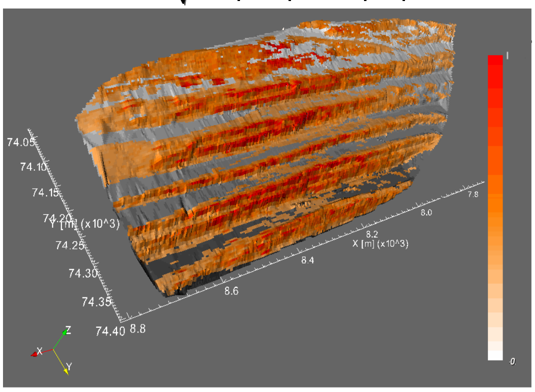

Fig 3. Interferometric coherence combined with DEM

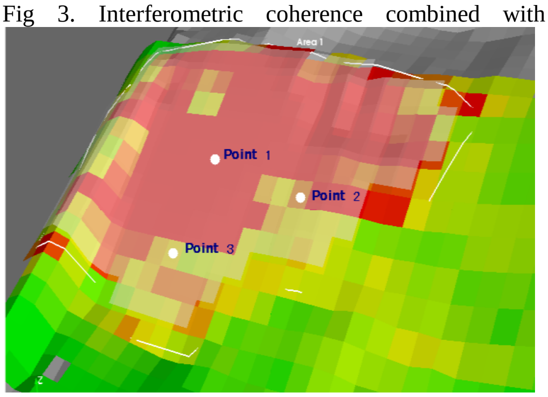

Fig 4. The main slip and benchmark

4. RESULT AND DISCUSSION

Short- time image received at an interval (9 minutes), then the impact of Dielectric constant and atmospheric delay can be ignored. But for mutation changes in the weather, the impact of atmospheric delay cannot be neglected. The differential phase can directly transfer into sight-line deformation based on equation (3). Figure (5) is a time series with eight deformed differential images .The time range is 37 hours. Deformation direction corresponds to the movement of slope in the direction of sight line; negative values indicate the decrease of distance, namely, the movement is moving towards the observer. Seen from Figure (5), before 20 hours, the slope remained stable, with no significant deformation zone; 20 hours later, the upper left corner had a significant regional deformation. Deformation zone extended from the center to the periphery. There are also relatively large deformation in other regions, due to the impact of speckle noise caused by SAR image. So, it is not complete to only consider the coherence between images by selection of high-quality point.

To learn more about the movement of the deformation zone, this paper did a time-series analysis for deformation zone. The selected area was shown in Figure (3), taking the mean value of the shape variables as the value of regional deformation, which can show significant deformation speed linear trend. According to the regional deformation and deformation to the deformation should speed images, as shown in Figure (6) shows, this area can be seen from the figure, the overall deformation was 5.08mm, the deformation rate remained -0.026mm / h in the 40-hour monitoring. While, using the value of first 30 hours as the deformation values to calculate deformation equation based on linear regression analysis; the last 10 hours of deformation values can further test fitting accuracy, with 0.081mm of fitting error, less than ground-based synthetic aperture radar interferometry measurement accuracy (0.1mm). So, linear deformation equation after fitting is reliable, can predict deformation values. Linear deformation rate equation can also be fitted by same method.

Time-series analysis was made on the three points in the placement of Prism on the regional deformation. Seen from Figure (7-9), each point of deformation and deformation rate images can be shown. Three points indicated the trend of linear deformation. But compared with the regional deformation trend, there is always abnormal deformation of individual values. Therefore, ordinary linear regression analysis was not available. This paper adopted two measures to fit linear trends, robust linear regression analysis [21] and low-pass filtered time dimension linear regression analysis [22] respectively. Two methods can remove the impact of crude almost through comparative analysis.

Ground-based synthetic aperture radar interferometry is the deformation value in sight line; while total station is the vertical deformation values. Based on radar imaging geometry, although the form of sight line can be divided as a variable vertical deformation. But, due to the complexity of the terrain slope, the result of vertical deformation is uncertain.

Seen from graph, it remained consistent with the obtained results. The biggest difference is 0.5mm. The distribution of 3 points showed, point 1 is in the center of regional deformation, and the deformation is reached to 6.95mm in 40-hour monitoring period; As for point 2 and 3, they are 6mm and 4.79mm respectively, followed by the deformation rate were-0.029mm / h,-0.022mm / h and 0.016mm / h .

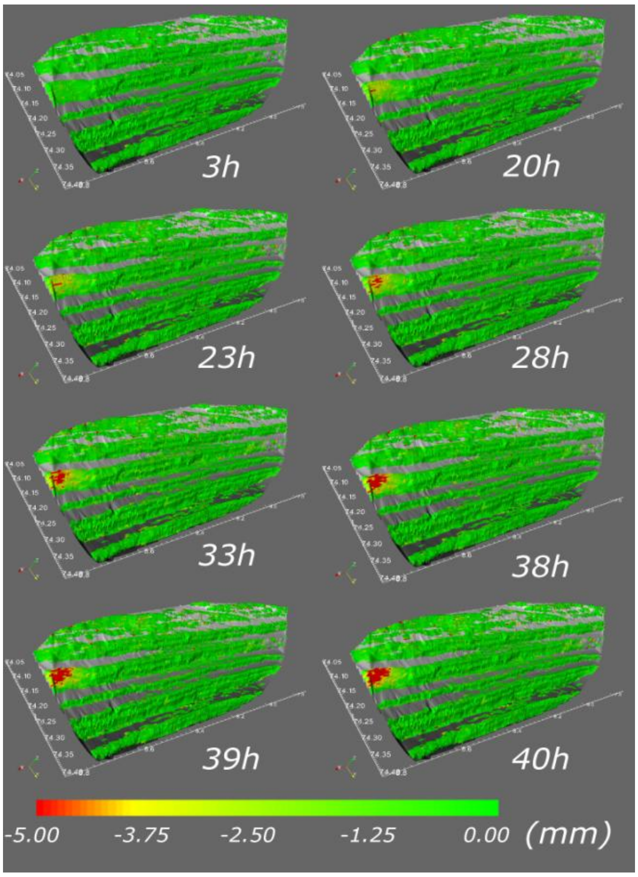

Fig 5. Sequence of Displacement map between the 15:33 12/09/2010 and 06:29 14/09/2010

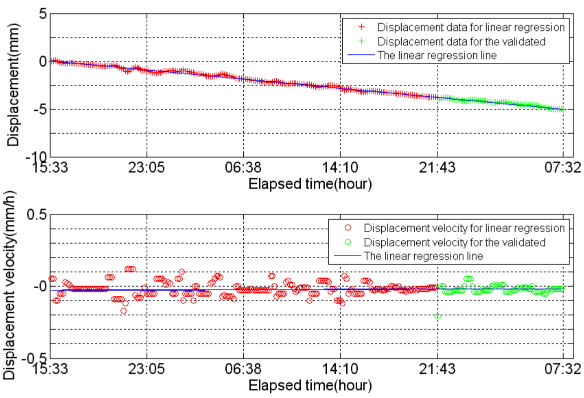

Fig 6. Displacement and velocity time series of the main slip

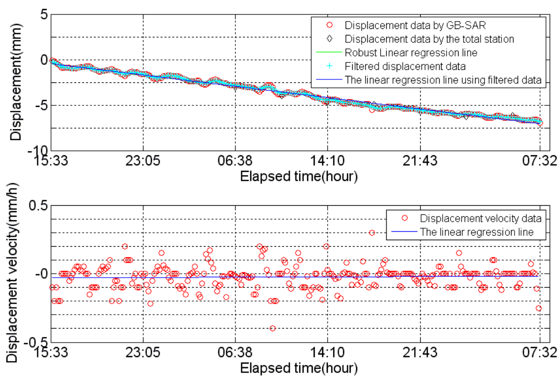

Fig 7. Displacement and velocity time series of point 1

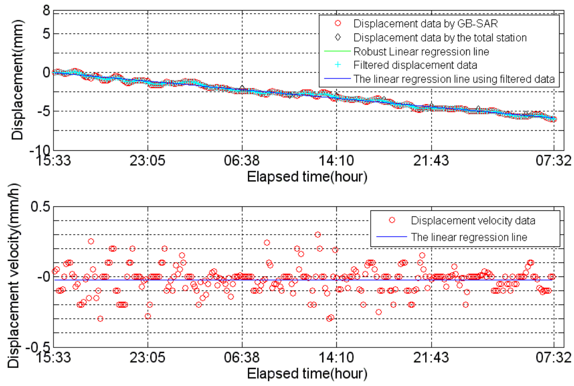

Fig 8. Displacement and velocity time series of point 2

The results of this experiment can assess the accuracy of ground synthetic aperture radar interferometer. Regional deformation monitoring accuracy is about 1.5mm; single-point accuracy is 1.7mm. As regional deformation value received by the average of deformation zone. Therefore, deformation monitoring accuracy is slightly higher than the single-point accuracy.

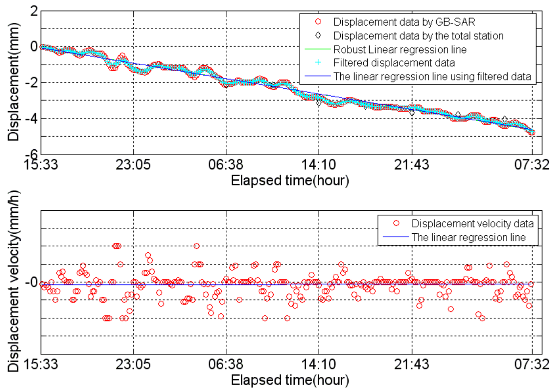

Fig 9. Displacement and velocity time series of point 3

5. CONCLUSION

In this paper, GB_InSAR was used in open pit slope monitoring through the verification of experimental in open pit slope monitoring. Experiments show that, GB_InSAR monitoring in remote sensing way with high spatial resolution, millimeter-level monitoring accuracy, high data sampling frequency, can get real-time slope deformation images that reflect the movement of the slope during the monitoring process, in order to facilitate follow-up slope deformation analysis. Compared with conventional monitoring, GB_InSAR can not only get single deformation information, but can grasp unstable region information in overall deformation; GB_InSAR, a non-contact measurement, can achieve the monitoring of dangerous slope. With stable weather and low-coverage in slope during monitoring, differential interference can get good results by ignorance of atmospheric effects and loss of coherence in time. For the changeable weather, air pollution will affect the shape variables. Therefore, GB_InSAR would be used for in-depth theoretical and applied research instead of that of relatively unreliable differential interferometer.

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