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Numerical simulation of dynamic surface deformation based on DInSAR monitoring

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Abstract: Differential interferometric synthetic aperture radar (DInSAR) technology is a new method to monitor the dynamic surface subsidence. It can monitor the large scope of dynamic deformation process of surface subsidence basin and better reflect the surface subsidence form in different stages. But under the influence of factors such as noise and other factors, the tilt and horizontal deformation curves regularity calculated by DInSAR data are poorer and the actual deviation is larger. The tilt and horizontal deformations are the important indices for the safety of surface objects protection. Numerical simulation method was used to study the dynamic deformation of LW32 of West Cliff colliery in Australia based on the DInSAR monitoring data. The result indicates that the subsidence curves of two methods fit well and the correlation coefficient is more than 95%. The other deformations calculated by numerical simulation results are close to the theory form. Therefore, considering the influence, the surface and its subsidiary structures and buildings due to mining, the numerical simulation method based on the DInSAR data can reveal the distribution rules of the surface dynamic deformation values and supply the shortcomings of DInSAR technology. The research shows that the method has good applicability and can provide reference for similar situation.
Key words: DInSAR monitoring; numerical simulation; dynamic surface deformation; supplement

1 Introduction

In Australia, most underground coal mines that operate at a depth greater than 300 m mostly employ the longwall mining technique [1]. However, compared with room and pillar mining and other mining ways, longwall mining brings the serious surface deformation and threats the environment, the structures and buildings, railways and ancillary facilities. It affects the normal production of people life. Surface movement and deformation is a dynamic process. Therefore, it is very important to understand the rules of dynamic surface deformation due to longwall mining.

DInSAR is a new deformation monitoring technology in recent years. It is able to provide a large scope of deformation information of continuous surface in a short period. The accuracy can reach centimeter, even millimeter [2−5]. There have been many studies showing that the subsidence curves measured by DInSAR are consistent with the actual condition and the subsidence basin can be obtained. But in fact, the other deformation values (such as tilt, curvature and horizontal deformation) are the key to the most important protected objects. Usually, DInSAR data are influenced by noise and other factors and their deformation and actual curve have great deflection. So it is hard to actual application. Under this circumstance of no other actual measurement data, to reveal the surface dynamic deformation rules to protect the surface objects, other ways must be found to supply the shortcomings of DInSAR. The scholars both at home and abroad use Knothe function [6−9] and numerical simulation method [10−13] to study dynamic rules. But the parameter choice of these methods is mostly relying on the experience. No measured data could be referenced. So, based on DInSAR actual

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monitoring, dynamic mining of LW32 of West Cliff colliery in Australia is taken to study numerical simulation analysis of dynamic surface deformation.

2 Geology and coal seam condition of West Cliff colliery

The test area extracted by West Cliff colliery belongs to the southern coalfield in Australia, one part of the Sydney−Gunnadah Basin. There are several Permian period coal seams in this area and the top coal seam is Bulli seam. From the typical stratigraphic section of Southern Coalfield [14], the overlying rocks are major sandstone interbedded with other rocks and though shales and claystones are quite extensive in places, the sandstone predominates whose properties usually belong to the medium hard rock.

The longwall plan of West Cliff colliery is extracted from Bulli seam [1] shown in Fig. 1 [15]. LW31 was completed in February 2007. LW32 was mined from 12 February 2007 to 08 June 2008. The mining speed was slower before the middle May 2007 (around 23−30 m per week). The speed was accelerated from middle May 2007 (around 32−45 m per week). LW33 was started from the end of July 2008. The length of LW32 was 3222 m and the width was 305 m. The depth was 470−540 m; the thickness was 2.2−2.8 m; the dip angle is 2°. The mining method was the longwall mining.

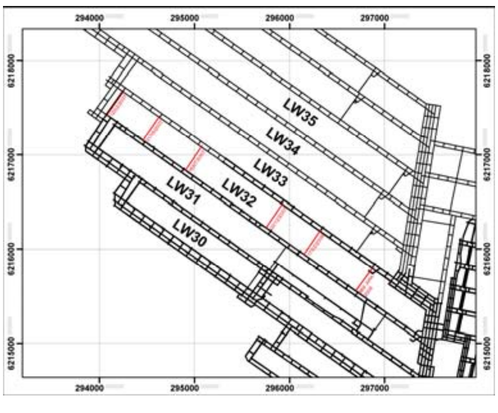

Fig.1 Longwall plan of West Cliff colliery (unit: mm)

3 DInSAR results about studying area

In order to study the ground movement of LW32 in West Cliff colliery, ten ALOS PALSAR data acquired from 29 June 2007 to 01 October 2008 were used. Nine differential interferograms were generated with temporal baseline of one revisiting cycle (46 d) except the last pair (92 d). The 2-pass method [5] was used for data processing. The interferograms including deformation phase were generated by two repeat orbit SAR images. Then an external high precision digital elevation model (DEM) was subtracted from the interferogram. The track parameters are shown in Table 1 and the deformation value is calculated.

Table 1 ALOS PALSAR data condition (Ascending)

Pair	Date		Orbit	Perpendicular baseline/m
	Image 1	Image 2		
1	29/06/2007	14/08/2007	370	45
2	14/08/2007	29/09/2007	370	−501
3	29/09/2007	14/11/2007	370	−110
4	14/11/2007	30/12/2007	370	−735
5	30/12/2007	14/02/2008	370	24
6	14/02/2008	31/03/2008	370	629
7	31/03/2008	16/05/2008	370	39
8	16/05/2008	01/07/2008	370	2851
9	01/07/2008	01/10/2008	370	1788

25 m resolution DEM provided by the New South Wales land bureau in Australia was used and the different stages of DInSAR results in line-of-sight (LOS) direction are shown in Fig. 2 [15]. The negative value indicates the subsidence.

4 Numerical simulation analyses

4.1 Model description

In order to ensure rapid and accurate simulation calculation, considering the typical stratigraphic section and the dimensions of the LW31 and LW32 (Table 2), the model with dimensions of 4000 m in longitudinal (x) direction, 2000 m in transverse (y) direction and 500 m in vertical (z) direction was selected as the initial geometry (Fig. 3). The entire model was divided by brick element, and the whole calculation modeling had a total of 332800 zones and 391245 grid points. Four sides of model have displacement boundary conditions, four vertical boundary faces and undersides were fixed, and the surface was free. The Mohr−Coulomb yield criterion of the rock mass destruction judgment was adopted [12]. The calculation parameters of the lithology and coal characteristics used in the model were chosen according to the geological investigation and similar projects.

To compare the subsidence with the DInSAR measured results, the mining distances need to be equal to the actual mining distance at different time stages. The residual subsidence influence of LW31 could not be ignored when LW32 was extracted. However, the information on the extraction time for LW31 was not available, therefore the calculation extracted speed was uniform velocity which was 200 m per month.

4.2 Modelling results

Using the software ArcGIS, the dynamic surface

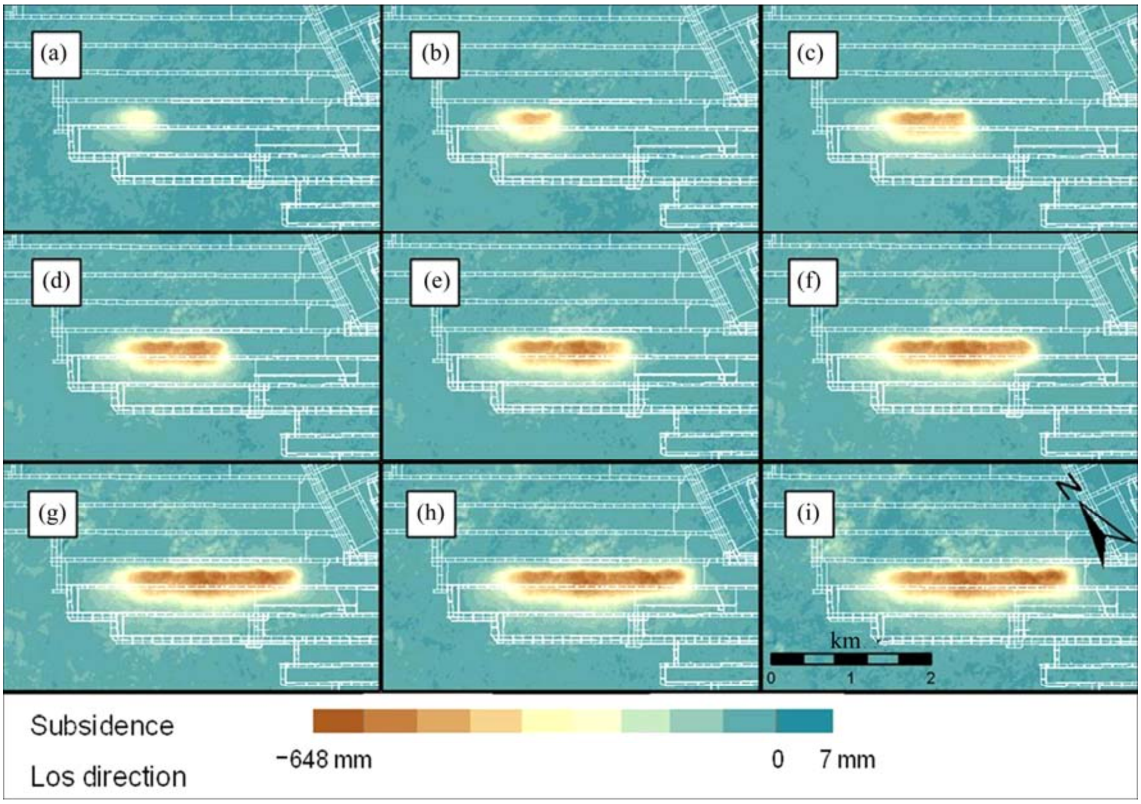

Fig. 2 Subsidence in LOS direction measured by DInSAR computing time started from 29/06/2007 to 14/08/2007 (a), 29/09/2007 (b), 14/11/2007 (c), 30/12/2007 (d), 14/02/2008 (e), 31/03/2008 (f), 16/05/2008 (g), 01/07/2008 (h) and 01/10/2008 (i)

Table 2 Dimensions of longwalls 31 and 32

Longwall	Length/m	Width/m
LW31	2270	300
	1250	200
LW32	3225	305

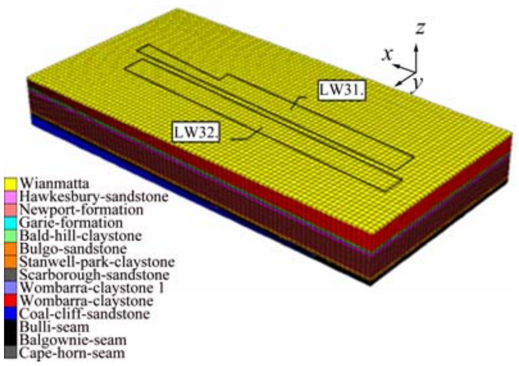

Fig. 3 Initial geometry model and position of workface of West Cliff colliery

deformation process extracted in LW32 could be achieved. The vertical subsidence and the surface horizontal movement along the longitudinal and transverse directions at different time stages can be calculated as shown in Fig. 4. The black box is the relevant mining area.

5 Comparison between DInSAR and modeling results

The displacement measured from DInSAR is in LOS direction. Therefore, the 3D displacements calculated from modeling need to project into the same direction to compare with the DInSAR measurements. Figure 5 shows the modeling displacement along the LOS direction of LW32 at different time stages calculated using the following equation [16]:

$$[\mathrm{con}\,\theta \quad -\sin\theta\cos\alpha \quad \sin\theta\sin\alpha]\begin{bmatrix} D_{\mathrm{U}} \\ D_{\mathrm{E}} \\ D_{\mathrm{N}} \end{bmatrix} = \Delta R$$

where θ is the incidence angle at the target point; α is the satellite heading vector angle (positive clockwise from north); D_{U} is the vertical displacement; D_{E} is the easting displacement; D_{N} is the northing displacement; ΔR is the ground displacement between two acquisitions along LOS direction.

The subsidence curves of DInSAR and numerical modeling along the longitudinal and transverse directions at different mining stages are shown in Fig. 6 [15]. As can be seen from the graph, good correlations between displacements along the longitudinal and transverse

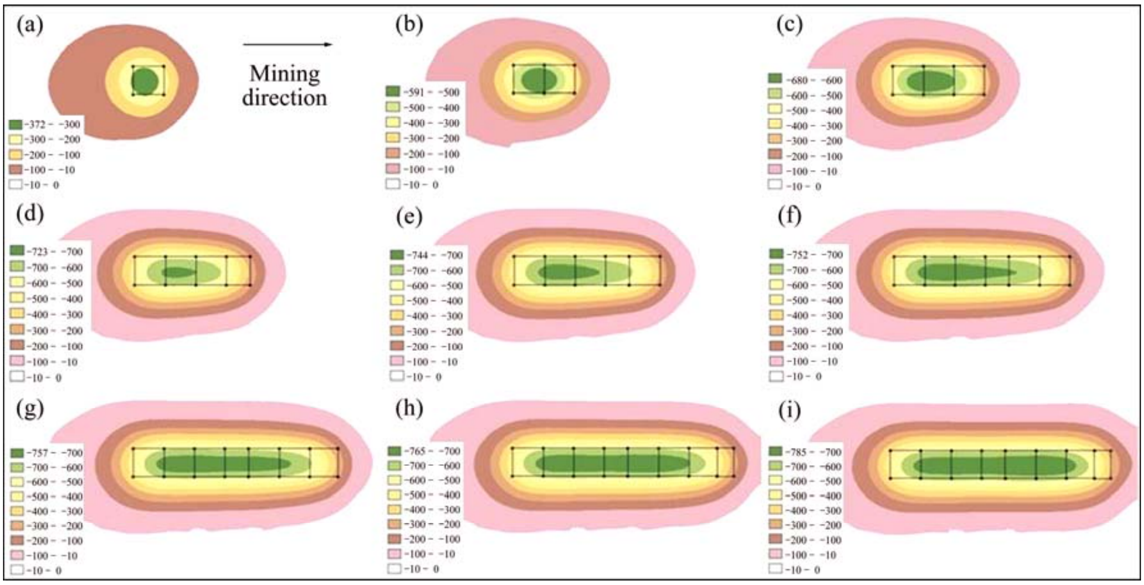

Fig. 4 Vertical subsidence of LW32 of modeling results computing time started from 29/06/2007 to 14/08/2007 (a), 29/09/2007 (b), 14/11/2007 (c), 30/12/2007 (d), 14/02/2008 (e), 31/03/2008 (f), 16/05/2008 (g), 01/07/2008 (h) and 01/10/2008 (i) (unit: mm)

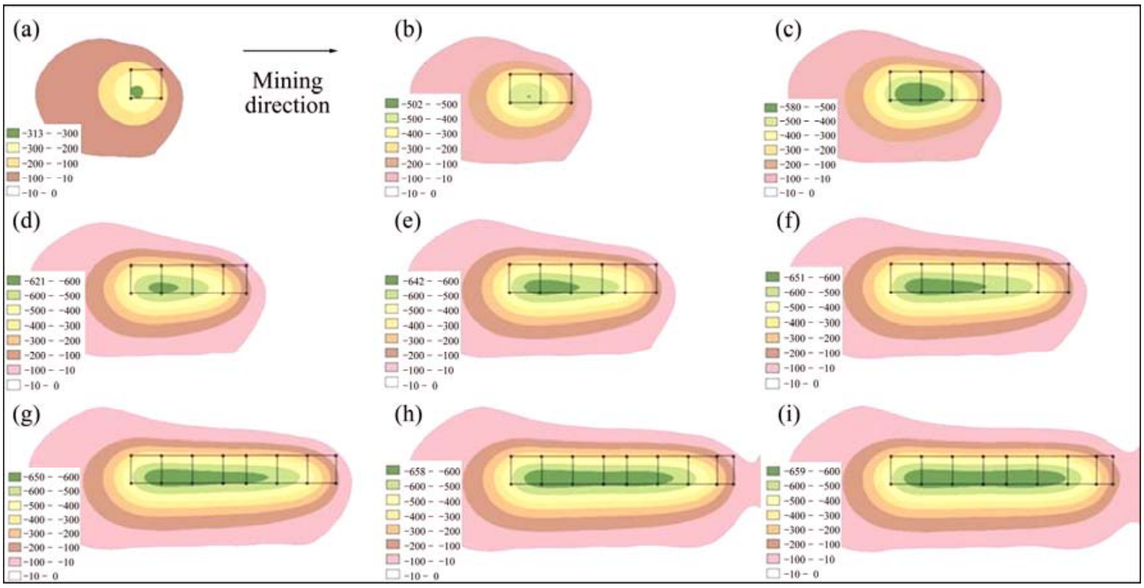

Fig. 5 Modelling displacement along LOS direction computing time started from 29/06/2007 to 14/08/2007 (a), 29/09/2007 (b), 14/11/2007 (c), 30/12/2007 (d), 14/02/2008 (e), 31/03/2008 (f), 16/05/2008 (g), 01/07/2008 (h) and 01/10/2008 (i) (unit: mm)

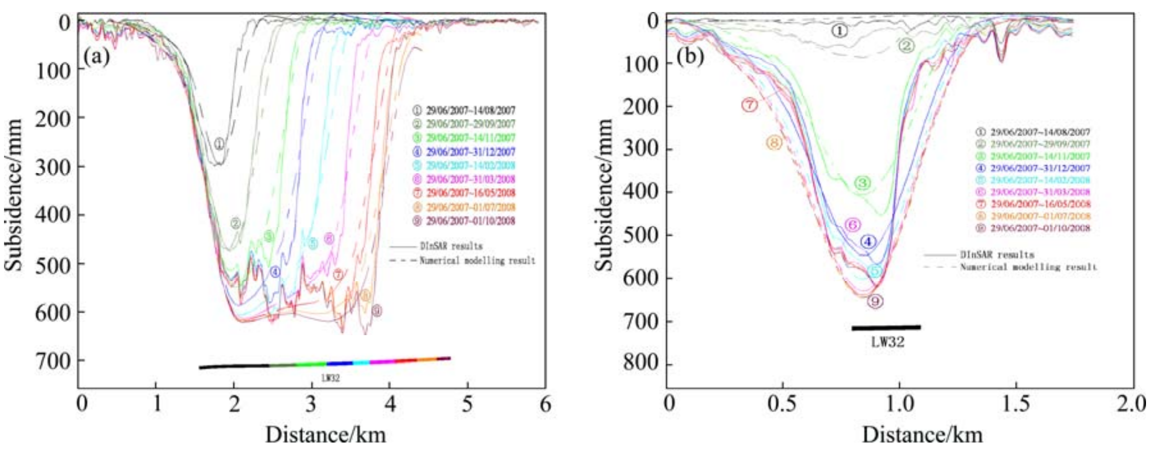

Fig. 6 Comparison of DInSAR and modeling subsidence: (a) Along longitudinal direction; (b) Along transverse direction

directions estimated from both methods were observed. The correlation coefficient is more than 95%. The boundary angle is 45°. It is also indicated that the results of numerical modeling are the same with actual condition.

Tilt is an first order derivative of subsidence. The tilt contrast of DInSAR and numerical simulation along the longitudinal and transverse directions are shown in Fig. 7. With the working face advancing, the maximum tilt value of open-off cut located at the same position increases gradually, and finally tends to be stable. The results of DInSAR and numerical simulation show performance for the deformation value gradually increasing with face of advance, and the maximum deformation value and the effects range between results are closer along two directions. The tilt deformation curves of numerical simulation are similar with theory distribution. But tilt deformation curves distribution of DInSAR have large fluctuations. The maximum tilt is always at the middle of the workface. This cannot reflect the actual surface deformation, and regularity is not apparent. Measured and theoretical tilt deformation and distributions should be consistent if there are no special geological and geomorphologic conditions in the study area. It is due to mainly noise and other factors that cause the phenomenon of inconsistent.

Curvature is second derivative of subsidence. Figure 8 shows curvature deformation comparison chart of DInSAR and numerical simulation along the transverse directions. The curvature values of DInSAR deviated from the theoretical ones are large along the transverse main sections. The maximum curvature value is not stable and there are no regular rules to be found. But the results of numerical simulation are closer to the theoretical form. From Fig. 8(b), there are three areas on the surface. The tensile deformation zones are on both sides and the compressive deformation zone is in the middle of mining-out area. Being affected by LW31 mining, the maximum curvature value of this side is less than the other side, but the influence range is increased.

The numerical simulation with the appropriate parameters can well reflect the dynamic surface subsidence based on DInSAR monitoring data. But due to the noise and other factors impact on DInSAR data, its analysis of dynamic deformation of tilt and curvature is a little poor than numerical simulation. It is difficult to evaluate the surface deformation and the buildings of the safety implications only with DInSAR data. Therefore, when researching on the surface and its subsidiary structures and buildings and calculating other surface deformation parameters due to longwall mining, the numerical simulation method can supply the

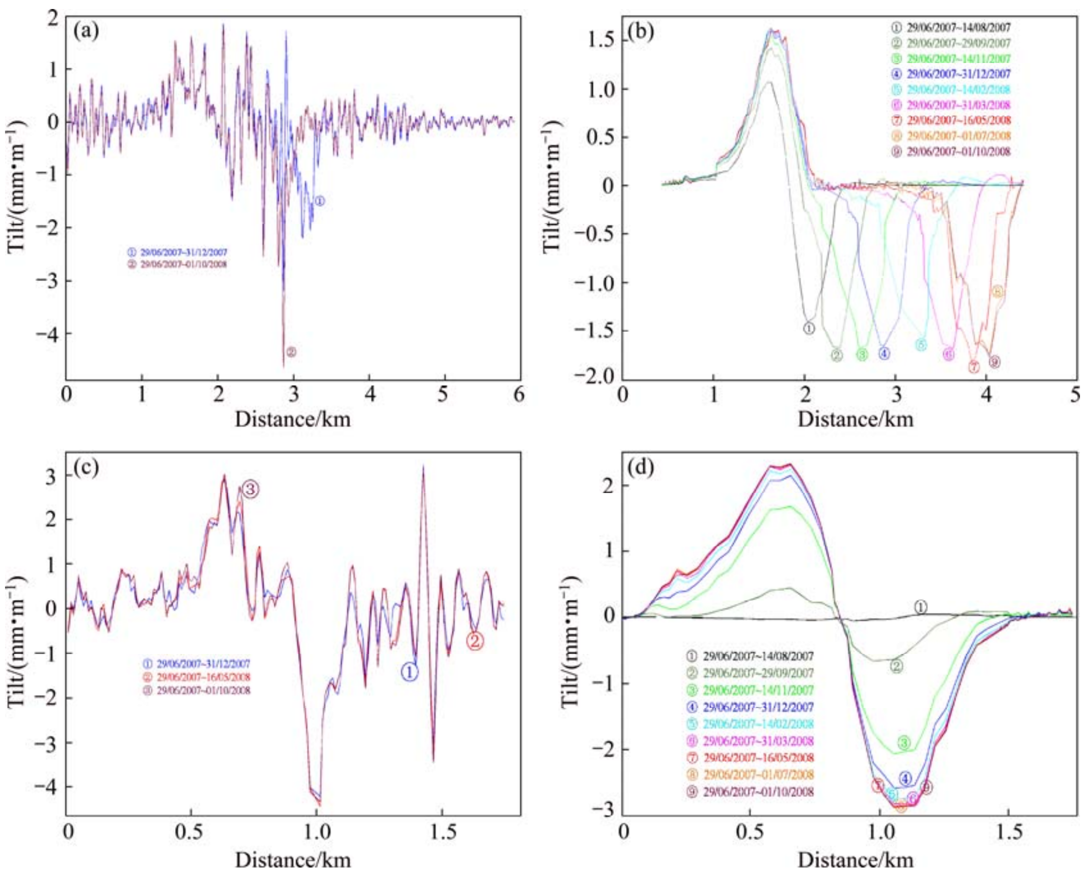

Fig. 7 Tilt comparison of DInSAR and modeling: (a) DInSAR tilt along longitudinal direction; (b) Modeling tilt along longitudinal direction; (c) DInSAR tilt along transverse direction; (d) Modeling tilt along transverse direction

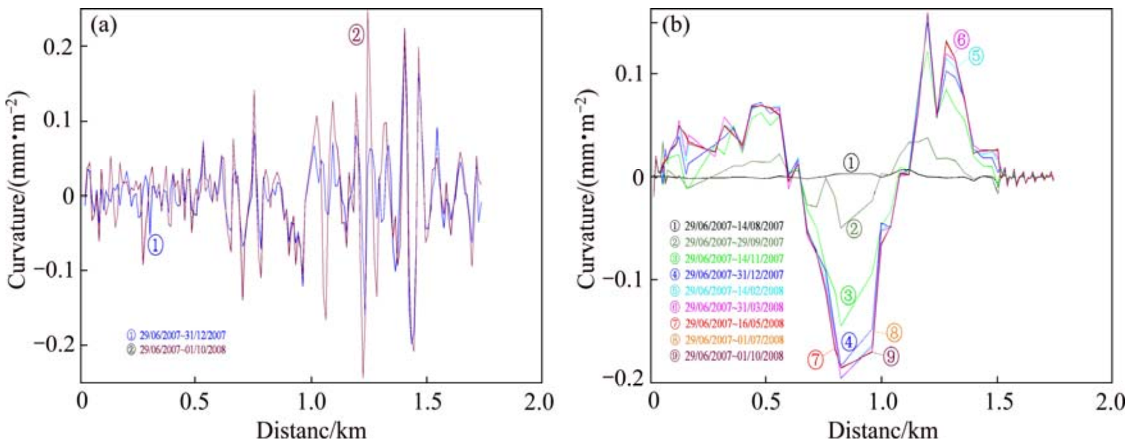

Fig. 8 Curvature comparison of DInSAR and modeling: (a) DInSAR curvature along transverse direction; (b) Modeling curvature along transverse direction

shortcomings of DInSAR technology. Both unions can better describe the dynamic surface movement deformation and provide the basis for safe mining under buildings.

6 Conclusions

1) DInSAR technology can reflect the actual dynamic surface subsidence with all weather and 24-hours. But due to the noise and other factors, the DInSAR monitoring results are difficult to reflect the actual surface tilt and curvature deformation.

2) The numerical simulation method is used for modeling dynamic surface deformation based on DInSAR monitoring data. The subsidence correlation between simulation and DInSAR results is high, and the tilt and curvature deformations calculated from modeling are consistent with theory form.

3) When the tilt and curvature deformations need to be calculated based on DInSAR data, the numerical simulation method can supply the shortcomings of DInSAR technology.

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基于 DInSAR 监测的动态地表移动变形数值模拟分析

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摘　要：合成孔径雷达干涉测量(DInSAR)技术是监测动态地表沉陷的新方法，能够大范围地监测地表下沉盆地的动态演化过程，可以较好地反映各阶段的地表下沉形态。但是受到噪声等因素的影响，基于 DInSAR 数据计算的倾斜、水平变形等曲线规律性较差，与实际偏差较大，而倾斜、水平变形又是研究地表受护对象是否安全的重要指标。基于 DInSAR 监测数据，采用数值模拟方法，对澳大利亚 West Cliff 煤矿长壁工作面 32 开采动态地表移动变形进行分析研究。结果表明，数值模拟得到的下沉曲线与 DInSAR 实测数据比较吻合，相关系数可达 95%以上，且数值模拟方法求算的地表倾斜、曲率和水平变形与理论形态一致。因此，进行矿区地表及其附属建（构）筑物受采动影响分析时，应以 DInSAR 实测数据为基础确定模型参数，结合数值模拟方法揭示地表动态其他移动变形值的分布规律。研究表明，该方法具有良好的适用性，可为类似的情况提供参考。

关键词：DInSAR 监测；数值模拟；动态地表移动变形；补充

(Edited by Hua YANG)