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# A model for extracting large deformation mining subsidence using D-InSAR technique and probability integral method

Hong-dong FAN[1,2], Wei GU[1], Yong QIN[2], Ji-qun XUE[3], Bing-qian CHEN [1]

1. Jiangsu Key Laboratory of Resources and Environmental Information Engineering, China University of Mining and Technology, Xuzhou 221116, China;
2. School of Resources and Geosciences, China University of Mining and Technology, Xuzhou 221116, China;
3. Zhejiang Geological Prospecting Institute, China Chemical Geology and Mine Bureau, Hangzhou 310002, China

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**Abstract:** Due to the difficulties in obtaining large deformation mining subsidence using differential Interferometric Synthetic Aperture Radar (D-InSAR) alone, a new algorithm was proposed to extract large deformation mining subsidence using D-InSAR technique and probability integral method. The details of the algorithm are as follows: the control points set, containing correct phase unwrapping points on the subsidence basin edge generated by D-InSAR and several observation points (near the maximum subsidence and inflection points), was established at first; genetic algorithm (GA) was then used to optimize the parameters of probability integral method; at last, the surface subsidence was deduced according to the optimum parameters. The results of the experiment in Huaibei mining area, China, show that the presented method can generate the correct mining subsidence basin with a few surface observations, and the relative error of maximum subsidence point is about 8.3%, which is much better than that of conventional D-InSAR (relative error is 68.0%).

**Key words:** D-InSAR; genetic algorithm; probability integral method; mining subsidence

## 1 Introduction

As the dominant part of the energy production and consumption in China, coal occupies about 70% of primary consumption. Due to the high-intensity and wide-spread mining, most mining areas are confronted with the serious problem of ground subsidence. Although the classical monitoring methods, such as geodesy, precise leveling, close range photogrammetry, GPS and laser 3D scanning, have high accuracies, there are also many disadvantages such as heavy workload, high cost, difficult to keep the monitoring points in a long time, and difficult to obtain the three-dimensional deformation information of space and a long temporal domain [1,2]. Differential interferometric synthetic aperture radar (D-InSAR) technique, as the research topic in the earth observation field, can solve these problems to some extent [3]. Moreover, D-InSAR has been widely applied in the mining subsidence monitoring [4].

As we known, the mining subsidence is different from that in the cities. Many researches presented that some problems existed in monitoring mining subsidence by D-InSAR. These problems can be summed as follows: 1) The mining subsidence area usually has characteristics of abundant vegetation, fast subsidence velocity, and serious geological hazards [5], which easily induces the loss of coherence between two SAR images, and more, causes phase unwrapping error or obtains the wrong deformation [6]; 2) Calculating errors are usually contained in the subsidence values obtained by D-InSAR, thus, the monitoring values could not accurately match the real mining subsidence [7]; 3) The subsidence models of multi-baseline InSAR technique [8], such as PS-InSAR, SBAS, are commonly designed for small deformation monitoring, so it is difficult to obtain the large deformation of the mining subsidence [9,10].

In order to resolve these problems, this work

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**Corresponding author:** Wei GU; Tel:+86-13775898958; E-mail: guweicumt@163.com
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presents a new model for extracting large deformation mining subsidence using D-InSAR technique and probability integral method. The simulating computation and real data test are performed to evaluate the performance of the proposed model.

## 2 Parameters of probability integral method

### 2.1 Probability integral method

Probability integral method is widely used in predicting mining subsidence at present. The method regards the rock mass studied in mining subsidence as a non-continuum model, which is similar to granulosis medium, so the movement laws of rock mass and surface caused by the two models are nearly the same in macroscopic view [11]. According to the principle of probability integral method, the subsidence of any surface point (*x, y*) caused by mining can be expressed as [12]

$$\begin{cases} W(x,y)=mq\cos\alpha\iint W_{\text{eoi}}(x,y)\mathrm{d}x\mathrm{d}y \\ W_{\text{eoi}}(x,y)=\dfrac{1}{r^2}\exp\left(\dfrac{-\pi(x-x_i)^2}{r^2}\right)\cdot \\ \qquad\exp\left(\dfrac{-\pi(y-y_i+H_i\mathrm{ctg}\theta)^2}{r^2}\right) \end{cases} \tag{1}$$

where $q$ is the subsidence coefficient; $r$ is the main influence radius, $r=H_0/\tan\beta$; $H_0$ is the average mining depth; $\theta$ is the mining influence angle; $\tan\beta$ is the tangent of main influence angle; $(x_i, y_i)$ is the plane coordinate of mining unit $i$; $(x, y)$ is the coordinate of any surface point.

Probability integral method can predict the mining subsidence correctly, and the main predicting parameters are usually deduced by many observations of mining subsidence. However, the damage or loss of the observation points often takes place, which will result in cost increasing and cannot ensure the predicting accuracy. While, D-InSAR technique can present many points' subsidence data instead of actual observations, and increase the points' quantity on the basin edge to deduce the parameters. So, when the probability integral method is used in the prediction, the problem of the rapid convergence in the edge of subsidence basin can be solved to some extent [13].

### 2.2 Parameters of probability integral method deduced by D-InSAR and GA

Genetic algorithm (GA) [14] was proposed by J. HOLLAND in 1975, which simulated the natural selection and genetic mechanism of organisms in nature. The basic idea of GA is as follows: a group of chromosome population is generated at first; according to survival of the fittest principle, some chromosome is selected to generate new chromosome population by copying, intercross and aberrance; finally, the chromosome population which most adapts the environment is sought by evolution. GA can provide the most optimized solution for the problem.

Thanks to the advantages of GA in parameter deducing, it had been widely applied to parameters analysis in rock and soil mechanics [15,16]. Several experimental results showed that parameters of probability integral method could be deduced precisely by GA. To resolve the problems of D-InSAR used in mining subsidence, a new algorithm that combines D-InSAR and probability integral method to obtain large deformation subsidence is proposed. The processing steps involved in the proposed method are shown in Fig. 1.

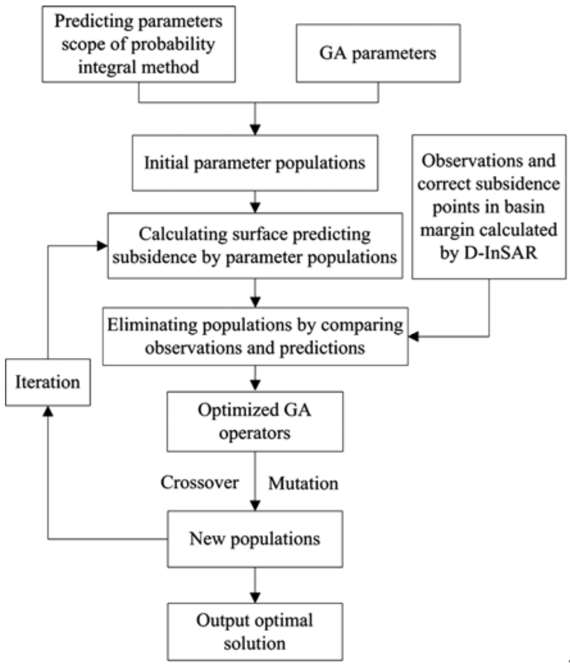


**Fig. 1** Flowchart of deducing probability integral method parameters by D-InSAR and GA

## 3 Experimental analysis

### 3.1 Simulation analysis

In order to test the ability of subsidence monitoring by D-InSAR, according to the parameters of the simulated working face and probability integral method in Tables 1 and 2, land subsidence basin could be deduced as shown in Fig. 2(a), where the white rectangular frame was the work face. Then, the subsidence value is converted into phase shown in Fig. 2(b) according to the parameters of the ERS or ENVISAT data (i.e., the wavelength is 56 mm, resolution is about 20 m). After that, the phase is wrapped (Fig. 2(c)). Finally, the wrapped phase is unwrapped by minimum cost network flow algorithm [17,18], as shown in Fig. 2(d).

From Figs. 2(b) and (d), it can be seen that, in this mining condition, the true subsidence can be obtained correctly by D-InSAR when the subsidence coefficient is 0.05. When the subsidence coefficient becomes 0.1, and the other parameters are the same, the simulated phase and unwrapped phase are shown in Fig. 3. From Fig. 3, it can be seen that, in this mining condition, it is difficult for D-InSAR to obtain the true subsidence.

**Table 1** Parameters of simulated working face

| Strike length/m | Dip length/m | Mining depth/m | Average coal thickness/m | Dip angle/(°) |
|---|---|---|---|---|
| 400 | 200 | 300 | 2 | 0 |

**Table 2** Parameters of probability integral method

| Subsidence coefficient | Tangent of main influence angle (tan $\beta$) | Mining influence angle, $\theta$/(°) | Offset distances of left, right, up and down inflection points, $S_l$, $S_r$, $S_u$, $S_d$/m |
|---|---|---|---|
| 0.05 | 2.0 | 90 | 20 |

The unwrapped phase shows that the subsidence of basin edge can be obtained correctly, so these correct unwrapped phase points can be combined with a few observations to deduce the parameters of probability integral method by GA, and then the whole subsidence basin can be calculated by the optimized parameters. This method can not only reduce the number of observation points and monitoring cost, but also solve the difficulty in obtaining the large deformation mining subsidence by D-InSAR.

### 3.2 Real data test

3.2.1 Work face and SAR data

The work face in this example is II3720 located in Huaibei City, China. The coal seam thickness is 2.7 m, the dip angle is about 5°−15°, and the mining depth is about 300 m. This work face was exploited from 2008-02-12 to 2009-08-22, and the longwall natural collapse method was used. The surface movement observation points were established above II3720 work face, and the movements of these points were measured by GPS, total station measuring system, and leveling. The plane distributions of monitoring points (red crosses) above II3720 work face are shown in Fig. 4.

Two ALOS/PALSAR images with high resolution captured in 2008-04-09 and 2009-01-10, and SRTM3 DEM were used. In this example, standard "two-pass" D-InSAR method was used to obtain the surface

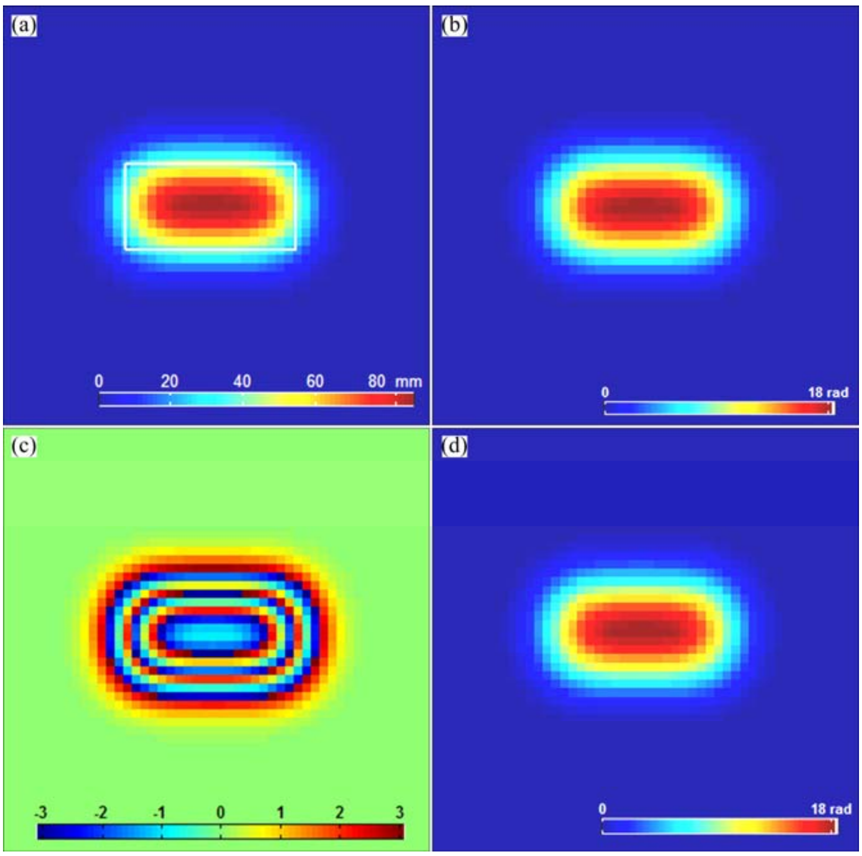


**Fig. 2** Simulated phase images (subsidence coefficient is 0.05): (a) Simulated subsidence basin; (b) Simulated phase of subsidence basin; (c) Wrapped phase; (d) Unwrapped phase

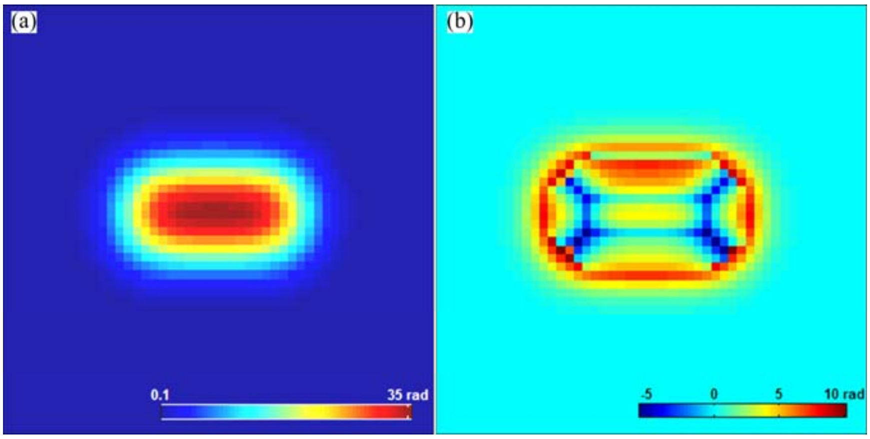


**Fig. 3** Simulated phase images (subsidence coefficient is 0.1): (a) Simulated phase of subsidence basin; (b) Unwrapped phase

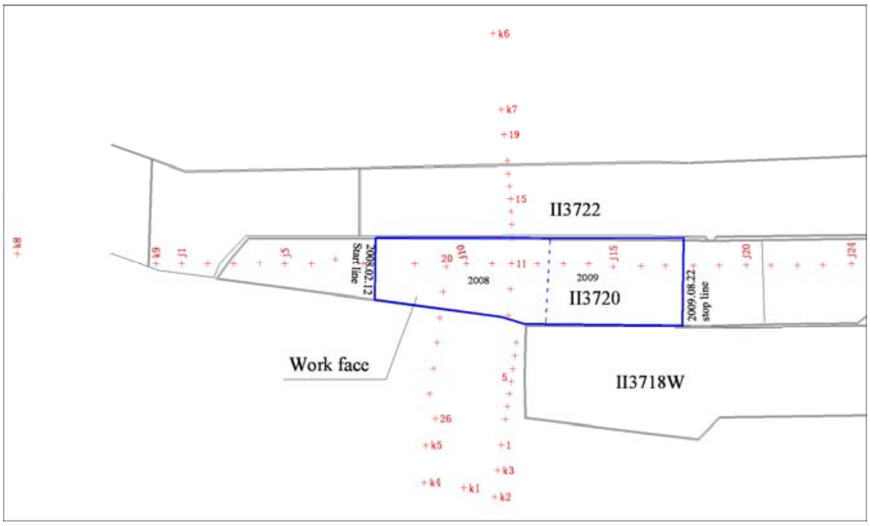


**Fig. 4** Plane distributions of monitoring points above II3720 work face

subsidence. In 2008-04-09, the advance distance of work face was about 30 m, and according to the mining subsidence theory analysis, there was no surface subsidence. To 2009-01-10, the advance distance of work face was about 240 m. Although the subsidence basin was not stable, the model of probability integral method could also obtain the correct mining subsidence.

3.2.2 Data process and analysis

The maximum subsidence calculated by D-InSAR technique is only about 300 mm in this example, but the observation value is about 937 mm. To enhance the performance of InSAR technique, according to the method proposed in this work, the points whose coherence is over 0.5 in the basin edge are selected, and combined with 4 control points (Table 3, near the maximum subsidence and inflection points) to deduce the parameters of probability integral method by GA. Finally, the parameters calculated by this method are as follows: $q$=0.464, tan $\beta$=2.392, $\theta$=83.964°, $S_l$=−32.677 m, $S_r$=24.424 m, $S_u$=15.750 m, $S_d$=0.504 m.

**Table 3** Point information used in monitoring subsidence basin in mining process

| No. | $x$/pixel | $y$/pixel | Coherence | Subsidence/mm | Note |
|---|---|---|---|---|---|
| 1 | 625 | 1026 | 0.69 | 15.30 | D-InSAR |
| 2 | 865 | 946 | 0.60 | 34.61 | D-InSAR |
| 3 | 465 | 916 | 0.64 | 21.71 | D-InSAR |
| 4 | 865 | 906 | 0.70 | 53.54 | D-InSAR |
| 5 | 465 | 886 | 0.55 | 24.36 | D-InSAR |
| 6 | 465 | 876 | 0.51 | 20.94 | D-InSAR |
| 7 | 875 | 846 | 0.58 | 32.37 | D-InSAR |
| 8 | 455 | 836 | 0.53 | 13.24 | D-InSAR |
| 9 | 885 | 836 | 0.73 | 17.99 | D-InSAR |
| 10 | 455 | 816 | 0.62 | 13.87 | D-InSAR |
| 11 | 505 | 796 | 0.53 | 33.35 | D-InSAR |
| 12 | 525 | 786 | 0.52 | 57.16 | D-InSAR |
| 13 | 576 | 844 | − | 486 | Observation |
| 14 | 806 | 845 | − | 430 | Observation |
| 15 | 705 | 839 | − | 937 | Observation |
| 16 | 776 | 844 | − | 640 | Observation |

The subsidence basin (Fig. 5) is predicted by the parameters. It can be seen that the basin lags behind the distance of work face, and the main subsidence section in strike direction deviates to downhill direction, which accords with the law of mining subsidence. Comparing with the observations of surface monitoring control points (Fig. 6), the average error is about 31 mm, and the absolute error of the maximum subsidence point is about 83 mm, and the relative error is about 8.3%, which is much better than the results of D-InSAR (relative error is 68.0%). Therefore, the method proposed in this work can be used to monitor the mining subsidence effectively.

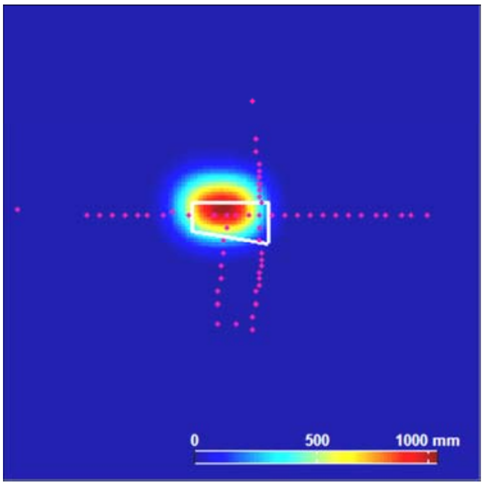


**Fig. 5** Predicted mining subsidence basin

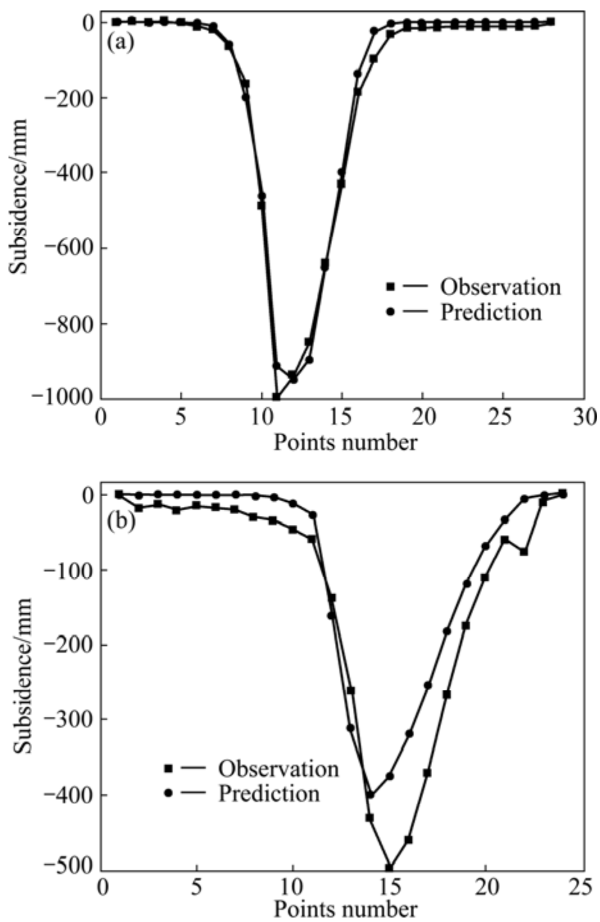


**Fig. 6** Comparison of measured values with predicted values: (a) Observations in strike direction; (b) Observations in dip direction

## 4 Conclusions

1) A new algorithm was proposed to extract large deformation mining subsidence using D-InSAR technique and probability integral method. The real data test indicated that it is feasible to deduce the mining subsidence basin, and the relative error of the maximum subsidence point in the example is about 8.3%, which is much better than the results of D-InSAR (relative error is 68.0%).

2) The surface observations number can be decreased when D-InSAR technique is used. Meanwhile, the number of edge points involved in the prediction of subsidence basin is increased. Therefore, the problem of the rapid convergence of probability integral method in subsidence basin edge can be solved.

3) In this example, the workface was mining when the image was captured, and the land surface above the workface was not stable at that time. So, how to generate the final land subsidence by this method will be studied in the future.

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# 基于 D-InSAR 和概率积分法的矿区大变形地表沉降提取方法

范洪冬[1,2]，顾 伟[1]，秦 勇[2]，薛继群[3]，陈炳乾[1]

1. 中国矿业大学 江苏省资源环境信息工程重点实验室，徐州 221116；
2. 中国矿业大学 资源与地球科学学院，徐州 221116；
3. 中化地质矿山总局 浙江地质勘查院，杭州 310002

**摘　要**：针对差分合成孔径雷达干涉测量（D-InSAR）技术无法正确获取矿区地表大沉降量的问题，提出 D-InSAR 及概率积分法联合获取矿区沉降量的新方法。具体过程为：由 D-InSAR 技术得到下沉盆地，选取盆地边缘相干系数较大而下沉量较小的点，再加入最大下沉点和拐点附近的少量实测点作为解算控制点；然后采用遗传算法对概率积分法参数不断进行优化；最后，由解算的最优参数反算地表下沉盆地。实例表明，该方法能够在减少地面监测点数量的情况下获取较为准确的地表沉降场，最大下沉的相对误差为 8.3%，优于 D-InSAR 的监测结果(相对误差约 68.0%)。

**关键词**：D-InSAR；遗传算法(GA)；概率积分法；开采沉陷

**(Edited by Sai-qian YUAN)**