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Calculation of maximum ground movement and deformation caused by mining

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Abstract: In order to know the maximum mining ground deformation of arbitrary surface point, directions of the maximum surface tilt, curvature, horizontal displacement and horizontal deformation caused by multi-working faces were deduced based on probability integral method. The distribution forms of surface deformations in all direction $\varphi\in[0, 2\pi]$ were obtained and also equations of maximum deformations were given based on calculation of mining ground deformation in direction φ. A mining subsidence analysis system was developed with VB6.0. The system implements the probability integral mining subsidence prediction with direct integration method, and it can avoid errors of arbitrary shaped working face subdivision of traditional method, and accuracy of mining subsidence prediction can be improved with the direct integral method. The system implements the contour chart and profile chart and also data analysis automation by manipulation of the SURFER kernel function and it complements the defect of existing subsidence prediction software. Calculation of maximum deformations caused by multi-working faces mining in a coal mine of Xuzhou, China was shown as application example. Engineering application indicates that maximum deformation of mining ground surface can be calculated and analyzed by the system. The research provides a theoretical basis and calculation tool for mining subsidence prediction and analysis.

Key words: mining subsidence; probability integral method; movement and deformation; system development

1 Introduction

Probability integration is the most widely used method in mining subsidence prediction [1] and one of the recommended methods in the regulation of the National Coal Bureau [2]. The deformation of surface movement is a value related to its direction; they are different in different directions even the same point. It has important significance to safety mining, deformation resistant structure design and protection in mining area and mining damage identification to determine the maximum deformation and main (or maximum) deformation direction.

At present, the most of the mining subsidence prediction software can be used to calculate ground movement and deformation along a specified direction caused by rectangular mine working faces. But there are also the following defects [3−11].

1) Only deformation and movement along specified directions can be calculated, but the maximum deformation and its direction known as the most important values can not be; or only a single mining working face subsidence can be calculated, which greatly limits the accuracy of mining subsidence prediction and range of application.

2) Information of working faces and ground movement parameters need to enter manually when calculation of mining subsidence affectively, it is complex to prepare the data files.

3) Generally, non-rectangular working faces are divided into rectangular or approximate rectangular ones, it involves issues such as coordinate transformation and small working faces correction which increases the complexity of calculation and reduces the accuracy.

4) Most programs have great defect on visualization. In order to obtain accurate ground movement and deformation, maximum value of arbitrary point mining

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subsidence caused by multi-working face was derived according to basic principles of probability integral method; the accurate distribution of surface movement was analyzed and the probability integral method mining subsidence prediction was actualized with a double integral directly. Mining subsidence prediction and analysis system based on the probability integral method was developed with Active X Automation technology in SURFER software which combine the visualization data processing and results expression together. It realized the visual expression of mining subsidence calculation and result analysis.

2 Fundamental theory of probability integral method

Fundamental theory of mining subsidence prediction is probability integral method based on the stochastic medium theory. According to the basic theory of probability integral method, the surface subsidence, ground tilt, curvature, horizontal displacement and deformation can be calculated with double integrals as shown in Eqs. (1−5).

$$W(x,y)=\sum_{j=1}^{n}\iint_{D_j} W_0 W_e(x,y)\mathrm{d}s\mathrm{d}t=\sum_{j=1}^{n}\iint_{D_j}\frac{W_0}{r_j^2}\exp\left(-\pi\frac{(x-s)^2+(y-t)^2}{r_j^2}\right)\mathrm{d}s\mathrm{d}t \quad (1)$$

$$i(x,y,\varphi)=\frac{\partial W(x,y)}{\partial x}\cos\varphi+\frac{\partial W(x,y)}{\partial y}\sin\varphi=\sum_{j=1}^{n}\iint_{D_j}\frac{-2\pi W_0}{r_j^4}\left\{[(x-s)\cos\varphi+(y-t)\sin\varphi]\exp\left(-\pi\frac{(x-s)^2+(y-t)^2}{r_j^2}\right)\right\}\mathrm{d}s\mathrm{d}t \quad (2)$$

$$K(x,y,\varphi)=\frac{\partial i(x,y,\varphi)}{\partial x}\cos\varphi+\frac{\partial i(x,y,\varphi)}{\partial y}\sin\varphi=\sum_{j=1}^{n}\iint_{D_j}\left[\frac{-2\pi W_0}{r_j^4}\{1-\frac{2\pi}{r_j^2}[(x-s)\cos\varphi+(y-t)\sin\varphi]^2\}\exp\left(-\pi\frac{(x-s)^2+(y-t)^2}{r_j^2}\right)\right]\mathrm{d}s\mathrm{d}t \quad (3)$$

$$U(x,y,\varphi)=\sum_{j=1}^{n}\iint_{D_j}\frac{-2\pi bW_0}{r_j^3}\left\{[(x-s)\cos\varphi+(y-t)\sin\varphi]\exp\left(-\pi\frac{(x-s)^2+(y-t)^2}{r_j^2}\right)\right\}\mathrm{d}s\mathrm{d}t \quad (4)$$

$$\varepsilon(x,y,\varphi)=\sum_{j=1}^{n}\iint_{D_j}\left[\frac{-2\pi bW_0}{r_j^3}\{1-\frac{2\pi}{r_j^2}[(x-s)\cos\varphi+(y-t)\sin\varphi]^2\}\exp\left(-\pi\frac{(x-s)^2+(y-t)^2}{r_j^2}\right)\right]\mathrm{d}s\mathrm{d}t \quad (5)$$

where $W(x, y)$ is the mining subsidence of point (x, y), n is the number of working faces; W_0 is the maximum subsidence, $W_0=mq\cos\alpha$; m is mining thickness; q is subsidence factor; α is dip angle of coal seam; D_j is the jth mining area, $W_e(x, y)$ is subsidence of unit mining of point (x, y); r_j is the main influence radius of the jth mining area, $r_j=H_j/\tan\beta$; H_j is mining depth of the jth mining area; $\tan\beta$ is tangent of main effect angle; b is displacement factor; $i(x, y, \varphi)$ is the surface tilt of point (x, y) along the direction φ; $K(x, y, \varphi)$ is the surface curvature; $U(x, y, \varphi)$ is the surface horizontal displacement; $\varepsilon(x, y, \varphi)$ is the surface deformation.

3 Calculation and distribution form of maximum surface movement and deformation caused by mining

3.1 Direction of maximum deformation

3.1.1 Direction of maximum surface tilt and horizontal displacement deformation

Due to the proportional of horizontal displacement and surface tilt, they have the same maximum deformations direction, and then only the surface tilt was shown as example. Assume that the direction of maximum surface tilt (or horizontal displacement) of an arbitrary point $A(x, y)$ is φ_i. Seeking partial derivative of Eq. (2) and let it equals to zero, as shown in Eq. (6).

$$\left.\frac{\partial i(x,y,\varphi)}{\partial\varphi}\right|_{\varphi=\varphi_i}=0 \quad (6)$$

Eq. (7) can be obtained with solution of Eq. (6).

$$\varphi_i=\arctan\frac{\sum_{j=1}^{n}\iint_{D_j}\frac{W_0}{r_j^4}(y-t)\exp\left(-\pi\frac{(x-s)^2+(y-t)^2}{r_j^2}\right)\mathrm{d}s\mathrm{d}t}{\sum_{j=1}^{n}\iint_{D_j}\frac{W_0}{r_j^4}(x-s)\exp\left(-\pi\frac{(x-s)^2+(y-t)^2}{r_j^2}\right)\mathrm{d}s\mathrm{d}t} \quad (7)$$

where φ_i is the direction of the maximum surface tilt (or maximum horizontal displacement). The maximum surface tilt of point A can be calculated by putting the φ_i of Eq. (7) into the Eq. (2). In the similar way, the maximum horizontal displacement of point A can be calculated by putting it into the Eq. (4).

3.1.2 Direction of maximum surface curvature and horizontal deformation

Due to the proportional of surface curvature and horizontal deformation, the maximum deformations have the same direction, and then only the curvature was shown as example. Assume that the direction of maximum curvature (or horizontal deformation) of an arbitrary point $A(x, y)$ is φ_K. Seeking partial derivative of Eq. (3) and let it equals to zero, as shown in Eq. (8).

$$\left.\frac{\partial K(x,y,\varphi)}{\partial\varphi}\right|_{\varphi=\varphi_k}=0 \tag{8}$$

Eq. (9) can be obtained with solution of Eq. (8).

$$\varphi_k=\frac{1}{2}\arctan\left\{2\sum_{j=1}^{n}\iint_{D_j}\left[\frac{W_0}{r_j^6}(x-s)(y-t)\times \exp\left(-\pi\frac{(x-s)^2+(y-t)^2}{r_j^2}\right)\right]\mathrm{d}s\mathrm{d}t\right\}\Big/ \left\{\sum_{j=1}^{n}\iint_{D_j}\left[\frac{W_0}{r_j^6}[(x-s)^2-(y-t)^2]\times \exp\left(-\pi\frac{(x-s)^2+(y-t)^2}{r_j^2}\right)\right]\mathrm{d}s\mathrm{d}t\right\} \tag{9}$$

where φ_K is the direction of the maximum surface curvature (or maximum horizontal deformation).

The maximum curvature of point A can be calculated by putting φ_K of Eq. (9) into the Eq. (3). In the similar way, the maximum horizontal deformation of point A can be calculated by putting it into Eq. (5).

3.2 Calculation of maximum surface movement and deformation

In chapter 3.1, through superposition calculation of multiple working faces, the directions of maximum ground movement and deformation of arbitrary point caused by multi-faces mining were given using higher mathematics' knowledge. In process of protection of mining subsidence, deformation resistant structure design and protection in mining area and mining damage identification, the maximum value of deformation is the mainly concern value but not its direction. According to fundamental theory of probability integral method, some meaningful conclusions were got by further calculation of Eqs. (2−5).

3.2.1 Calculation of surface tilt and horizontal displacement

For the arbitrary point $A(x, y)$ in the affected area of multiple working face mining subsidence, its coordinate is determined. The tilt of point A along the arbitrary direction φ can be expressed as Eq. (10).

$$i(x,y,\varphi)=\sum_{j=1}^{n}\iint_{D_i}-2\pi W_0\frac{1}{r_j^4}\left\{[(x-s)\cos\varphi+(y-t)\sin\varphi]\exp\left(-\pi\frac{(x-s)^2+(y-t)^2}{r_j^2}\right)\right\}\mathrm{d}s\mathrm{d}t$$

$$\Rightarrow i(\varphi)=\cos\varphi\sum_{j=1}^{n}\iint_{D_n}\frac{-2\pi W_0}{r_j^4}(x-s)\mathrm{d}s\mathrm{d}t+\sin\varphi\sum_{j=1}^{n}\iint_{D_n}\frac{-2\pi W_0}{r_j^4}(y-t)\mathrm{d}s\mathrm{d}t \tag{10}$$

If $A=\sum_{j=1}^{n}\iint_{D_j}\frac{-2\pi W_0}{r_j^4}(x-s)\mathrm{d}s\mathrm{d}t$,

$B=\sum_{j=1}^{n}\iint_{D_j}\frac{-2\pi W_0}{r_j^4}(y-t)\mathrm{d}s\mathrm{d}t$, and then Eq. (10) can be expressed as Eq. (11).

$$i(\varphi)=A\cos\varphi+B\sin\varphi=\sqrt{A^2+B^2}\times\left(\frac{A}{\sqrt{A^2+B^2}}\cos\varphi+\frac{B}{\sqrt{A^2+B^2}}\sin\varphi\right) \tag{11}$$

Angle θ meets the requirements of Eqs. (12−13).

$$\cos\theta=\frac{A}{\sqrt{A^2+B^2}} \tag{12}$$

$$\sin\theta=\frac{B}{\sqrt{A^2+B^2}} \tag{13}$$

Eq. (10) can be expressed as:

$$i(\varphi)=A\cos\varphi+B\sin\varphi=\sqrt{A^2+B^2}(\cos\theta\cos\varphi+\sin\theta\sin\varphi)=\sqrt{A^2+B^2}\cos(\varphi-\theta) \tag{14}$$

As known in Eq. (14), range of surface tilt of arbitrary point along the arbitrary direction is between $[-\sqrt{A^2+B^2},\sqrt{A^2+B^2}]$; there are two equal and opposite maximum surface tilt $\sqrt{A^2+B^2}$. The values associated with the location of the point only but nothing relationship with directions.

The maximum value of horizontal displacement is similar, and in which the maximum horizontal displacement of $A(x, y)$ is shown in Eq. (15).

$$\left\{\left[\sum_{j=1}^{n}\iint_{D_j}\frac{-2\pi bW_0}{r_j^3}(x-s)\mathrm{d}s\mathrm{d}t\right]^2+\left[\sum_{j=1}^{n}\iint_{D_j}\frac{-2\pi bW_0}{r_j^3}(y-t)\exp\left(-\pi\frac{(x-s)^2+(y-t)^2}{r_j^2}\right)\mathrm{d}s\mathrm{d}t\right]^2\right\}^{1/2} \tag{15}$$

The values associated with the location of the point only and have nothing relationship with directions.

With calculation method above, if the direction of the maximum surface tilt (or horizontal displacement) needs not to know, maximum value of surface tilt (or horizontal displacement) can be calculated directly. Take $\varphi\in[0, 2\pi]$ in Eq. (14), distribution figure can be got as shown in Fig. 1 (dashed denotes the negative values). The surface tilt (or horizontal displacement) of arbitrary point in mining affecting area all has the distribution form shown as Fig. 1.

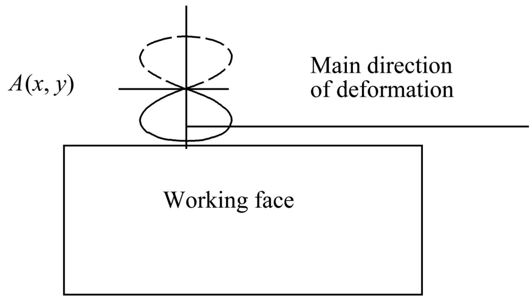

Fig. 1 Distribution schematic diagram of surface tilt (or horizontal displacement)

3.2.2 Calculation of surface curvature and horizontal deformation

In a similar way, according to Eq. (3), the curvature of point $A(x, y)$ along the direction φ can be expressed as Eq. (16).

$$K(\varphi)=\sum_{j=1}^{n}\iint_{D_j}\frac{-2\pi W_0}{r_j^4}\{1-\frac{\pi}{r_j^2}[(x-s)^2+(y-t)^2]\}\times \exp\left(-\pi\frac{(x-s)^2+(y-t)^2}{r_j^2}\right)\mathrm{d}s\mathrm{d}t-$$
$$\frac{1}{2}(2\cos^2\varphi-1)\times\sum_{j=1}^{m}\iint_{D_j}\frac{-4\pi^2W_0}{r_j^6}[(x-s)^2-(y-t)^2]\times \exp\left(-\pi\frac{(x-s)^2+(y-t)^2}{r_j^2}\right)\mathrm{d}s\mathrm{d}t-2\sin\varphi\cos\varphi\times$$
$$\sum_{j=1}^{n}\iint_{D_n}\frac{-4\pi^2W_0}{r_j^6}(x-s)(y-t)\times \exp\left(-\pi\frac{(x-s)^2+(y-t)^2}{r_j^2}\right)\mathrm{d}s\mathrm{d}t \tag{16}$$

Let

$$A=\sum_{j=1}^{n}\iint_{D_j}\frac{-2\pi W_0}{r_j^4}\{1-\frac{\pi}{r_j^2}[(x-s)^2+(y-t)^2]\}\times \exp\left(-\pi\frac{(x-s)^2+(y-t)^2}{r_j^2}\right)\mathrm{d}s\mathrm{d}t,$$

$$B=\frac{1}{2}\sum_{j=1}^{n}\iint_{D_j}\frac{-4\pi^2W_0}{r_j^6}[(x-s)^2-(y-t)^2]\times \exp\left(-\pi\frac{(x-s)^2+(y-t)^2}{r_j^2}\right)\mathrm{d}s\mathrm{d}t,$$

$$C=\sum_{j=1}^{n}\iint_{D_j}\frac{-4\pi^2W_0}{r_j^6}(x-s)(y-t)\times \exp\left(-\pi\frac{(x-s)^2+(y-t)^2}{r_j^2}\right)\mathrm{d}s\mathrm{d}t,$$

Then, Eq. (16) can be changed into:

$$K(\varphi)=A-B(2\cos^2\varphi-1)-2C\sin\varphi\cos\varphi=$$
$$A-B\cos(2\varphi)-C\sin(2\varphi)=$$
$$A-\sqrt{B^2+C^2}\left[\left(\frac{B}{\sqrt{B^2+C^2}}\cos 2\varphi+\frac{C}{\sqrt{B^2+C^2}}\sin 2\varphi\right)\right] \tag{17}$$

Angle β meets the requirement of Eqs. (18−19).

$$\cos\beta=\frac{B}{\sqrt{B^2+C^2}} \tag{18}$$

$$\sin\beta=\frac{C}{\sqrt{B^2+C^2}} \tag{19}$$

Then Eq. (17) can be expressed as:

$$K(\varphi)=A-\sqrt{B^2+C^2}\cos(2\varphi-\beta) \tag{20}$$

Let $\varphi\in[0, 2\pi]$, there are five situations of the distribution forms of curvature of point A.

Firstly, if $A>\sqrt{B^2+C^2}$, then $K(\varphi)>0$ in range $\varphi\in[0, 2\pi]$. In this case, the surface curvatures value of point A is a positive value in all direction, it ranges $[A-\sqrt{B^2+C^2}, A+\sqrt{B^2+C^2}]$, and the maximum value of curvature is $A+\sqrt{B^2+C^2}$. According to similarity, the horizontal displacement is a positive value, and point A subject to tensile deformation in all direction. Under the circumstances distribution of curvature (or horizontal displacement) is shown as Fig. 2(a).

Secondly, if $A<-\sqrt{B^2+C^2}$, then $K(\varphi)>0$ in range $\varphi\in[0, 2\pi]$. In this case, the surface curvatures value of point A is a negative value in all direction, it ranges $[A-\sqrt{B^2+C^2}, A+\sqrt{B^2+C^2}]$, and the maximum value of curvature is $A-\sqrt{B^2+C^2}$; it is a negative value. According to similarity, the horizontal displacement is a negative value, and point A subject to compression deformation in all direction. Under the circumstances distribution of curvature (or horizontal displacement) is shown as Fig. 2(b).

Thirdly, if $-\sqrt{B^2+C^2}<A<\sqrt{B^2+C^2}$, then the range of $K(\varphi)>0$ is $[A-\sqrt{B^2+C^2}, A+\sqrt{B^2+C^2}]$ when $\varphi\in[0, 2\pi]$. The surface curvature has two orthogonal principal directions, the curvature value are opposite sign along two main directions. There is a positive curvature value along a principle direction and a negative one along another. Similarity, the horizontal displacement of point A subjects to tensile deformation in one principle direction and compressive deformation in another one. Under the circumstances distribution of curvature (or horizontal displacement) is shown as Fig 2(c).

Fourthly, if $A=\sqrt{B^2+C^2}$, then $K(\varphi)>0$ in range $\varphi\in[0, 2\pi]$. In this case, the surface curvatures value of point A is a positive value in all direction, it ranges $[0, A+\sqrt{B^2+C^2}]$, and the maximum value of curvature is $A+\sqrt{B^2+C^2}$. Under the circumstances, the surface curvature value is $A+\sqrt{B^2+C^2}$ in a principle direction and the value is zero in another principle direction. According to similarity, the horizontal displacement is an opposite value. Point A subjects to compression deformation in all directions. Under the circumstances distribution of curvature (or horizontal displacement) is shown as Fig. 2(d).

Fifthly, if $A=-\sqrt{B^2+C^2}$, then $K(\varphi)>0$in range $\varphi\in[0, 2\pi]$. In this case, the surface curvatures value of point A is a negative value in all directions, it ranges $[A-\sqrt{B^2+C^2}, 0]$, and the maximum value of curvature is $A-\sqrt{B^2+C^2}$. Under the circumstances, the surface curvature value is $A-\sqrt{B^2+C^2}$ in a principle direction and the value is zero in another principle direction. According to similarity, the horizontal displacement is a negative value. Point A subjects to compression deformation in all directions. Under the circumstances distribution of curvature (or horizontal displacement) is shown as Fig. 2(e).

Any where in region of mining subsidence, distributions forms of curvature (or horizontal deformation) along $\varphi\in[0, 2\pi]$ can only appear one of five forms shown in Fig. 2.

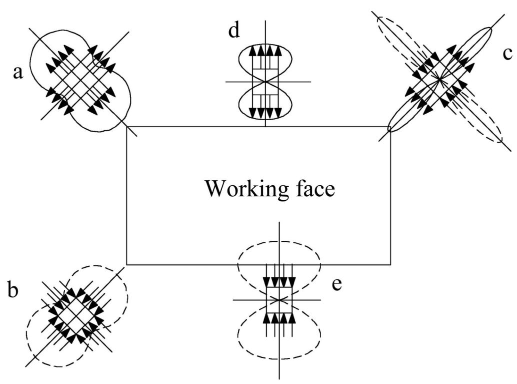

Fig. 2 Distribution schematic diagram of surface curvature (or horizontal deformation)

4 Development of mining subsidence prediction and analysis system

4.1 Composition and structure of system

The system was developed according to basic principles of probability integral method and maximum value calculation method based on the structure and modular design philosophy. Its overall implementation is a secondary development based on AUTOCAD and SURFER, which mining subsidence prediction part is based on AUTOCAD and mining subsidence analysis and visualization part based on the SURFER. The overall idea is to prepare basic data of mining subsidence prediction by entry mining information through data management section, file generation, database management; and then ground movement and deformation can be predicted by mining subsidence prediction section; at last, statistical analysis and visualization expression can be implemented by manipulating the kernel program of SURFER with data predicted. The flow chart of arbitrary shaped multiple working faces mining subsidence prediction and analysis system is shown in Fig. 3.

4.2 Implementation of arbitrary shaped multiple working faces mining subsidence prediction

Generally, arbitrary shaped working faces should be divided into multiple rectangular faces to calculate mining subsidence. Subdivision method is simple to implement, but it needs to modify the prediction parameters for small rectangular working faces divided, and calculation results is approximate for subdivision; and it increase the hardness to prepare the data. As known in Eqs. (1−5), for an arbitrary shaped mining area D, mining subsidence prediction can be implemented with a double integral. In order to obtain upper and lower limit of integral, mining region D should subdivide into number of triangles and probability integral method mining subsidence prediction can be implemented by double integral directly. Triangulation method can divide arbitrary shaped working faces accurately and avoid the defects of rectangle subdivision. Basic flow chart of mining subsidence prediction calculation is shown in Fig. 4.

4.3 Mining subsidence analysis using SURFER

The mining subsidence analysis system used Active X Automation technology and the program interface to customize the SURFER. SURFER can be used to draw the contour, paste diagrams, images and vector graphic easily, and also be used to three-dimension space analysis such as trend surface analysis, volume and area calculation, slope analysis, profile analysis et al. 60

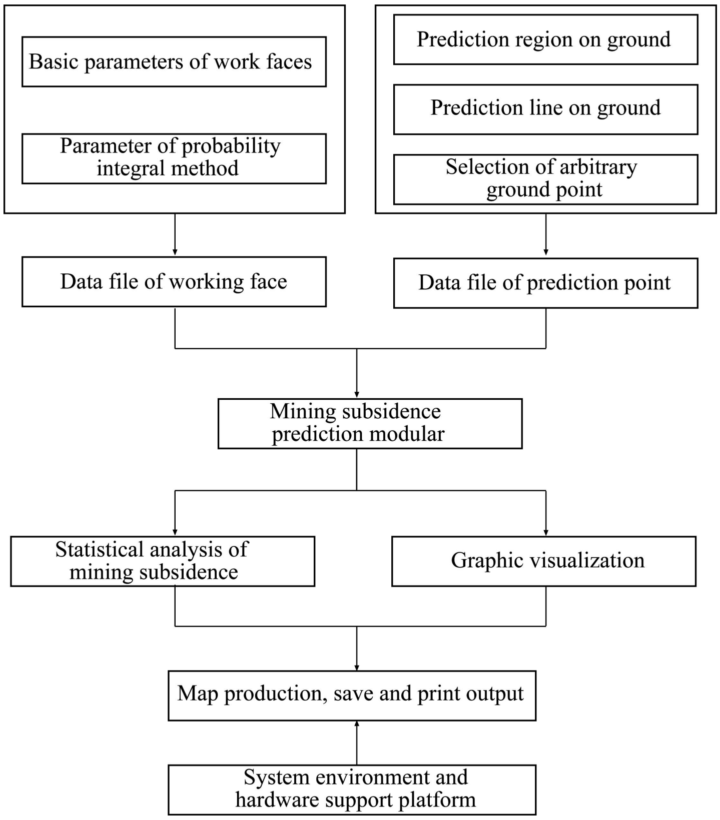

Fig. 3 General flow chart of arbitrary shape multiple working faces mining subsidence prediction and analysis system

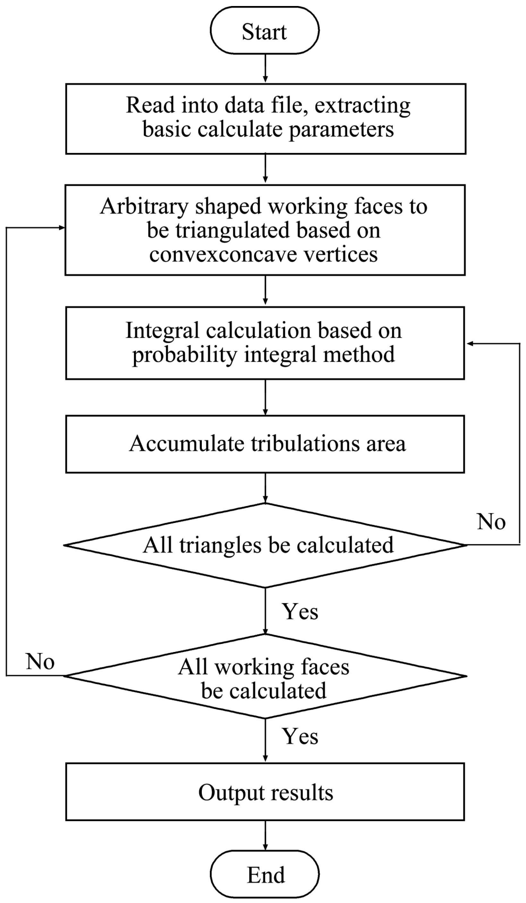

Fig. 4 Flow chart of mining subsidence prediction

different kinds of Active objects embedded in SURFER can be called by external applications, and almost all functions can be accomplished by customize development [11−15]. Surface movement and deformation calculated by mining subsidence module can be used to make variety maps and data analysis with kernel function in SURFER. Steps are as follows:

1) Three dimensional surface movement and deformation data should be got firstly by mining subsidence prediction module, point coordinate and deformation value are included.

2) SURFER connection established, and data predicted should be grid processed by SURFER kernel data processing function.

3) With expression function of SURFER graphic, various maps and data can be made, and do the overlay analysis with working faces.

4) Variety of statistical analysis and data processing can be done with SURFER data analysis function.

4.4 System functions and features

Compared with similar mining subsidence prediction system in China, the mining subsidence system has the following features.

1) Ground subsidence, tilt, curvature, horizontal displacement and horizontal deformation caused by multiple arbitrary shaped working faces can be calculated with the system; also the directions of

maximum deformation and its values can be got, it’s the main innovations in the development of this system.

2) Working faces data management section. The system can extract basic information of working faces in AUTOCAD; basic data can be acquired and managed by the system directly which improve the efficiency.

3) Establishment of mining subsidence parameters database management program. Mining subsidence data can be managed and used effectively with it.

4) Ground movement and deformation caused by arbitrary shaped multiple working faces can be predicted by the mining prediction system. Ground subsidence, tilt, curvature, horizontal displacement, horizontal deformation and its maximum values can be calculated by operations of the system. The prediction results can be output in the data files. Ground deformation caused by arbitrary shaped and arbitrary numbers of working faces can be got with the system.

5) Mining subsidence analysis system. The mining subsidence analysis system is a subprogram of mining subsidence prediction developed by secondly development with Active X Automation technology in SURFER. Mining subsidence data predicted can be processed to visualization expression, map production, and automation data analysis through the operation of the system; also base surface map of working faces, movement and deformation contour, profile, three dimensional surfaces, overlay chart and related analysis can be produced.

5 Application and discussion

5.1 Engineering application

In order to mine coal pillar resources under the villages in a coal mine in Xuzhou, China, two working faces No.7201 and No.7431 were planned to mine. Surfer above the working faces is flat, average elevation is 34−37 m, design length of No.7143 is 537−616 m, design width 105−135m, mining the 7th coal seam, average deep is 597 m, average thickness of coal seam is 7 m, seam dip angle is 0−12° and average angle is 6°. No.7201 working face is located in north of No.7143 face; design length is 454 m, design width 146.5−185.5 m, mining the 7th coal seam too, average mining depth is 520 m, average thickness of coal seam is 7 m, and average coal seam dip angle is 8°. Buildings in near villages would be damaged after two work faces mining. In order to know the ground movement and deformation after mining and provide a basis for mine decision making. Mining subsidence and ground deformation such as subsidence, tilt, curvature, horizontal displacement, horizontal deformation values along a specified direction also the maximum ground deformations were calculated by the mining subsidence prediction and analysis system described above. As space limited, only contour of maximum ground tilt and curvature caused by No.7201 and No.7431 work faces are shown in Fig. 5 and Fig. 6.

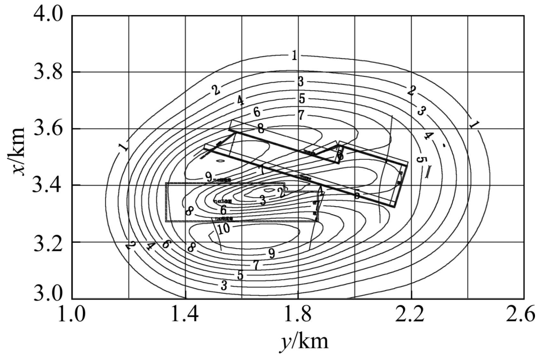

Fig. 5 Contour chart of maximum surface tilt (mm/m)

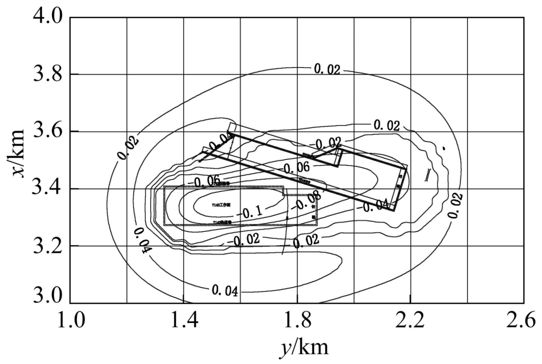

Fig. 6 Contour chart of maximum surface curvature (mm/m^2)

Maximum values and its direction of arbitrary point ground movement and deformation can be calculated accurately; Compare with traditional method, it analysis the ground deformation with the maximum values of all directions instead of along the specified direction, much more accurate building damage degree and damage range can be got with the new method above and it provides a much more accurate principle for ground movement and buildings damage analysis; the method has important practical significances on improve mining subsidence prediction analysis, protect the ground building and coal mine safety.

5.2 Discussion

Probability integral method is a most widely used method in China mining subsidence prediction. Non-rectangular working faces generally should be divided into rectangular or approximate rectangular ones traditionally; it involves issues such as coordinate transformation and small working faces correction and increases the complexity of calculation and reduces the calculation accuracy. On the other hand, for multiple work faces mining, it will unable to determine the maximum deformation direction and its value after complex coordinate transformations, which limits the analysis accuracy of probability integral method greatly.

Work faces profile errors can be reduced by using directly integral method to implement the probability integral method; mining subsidence prediction accuracy can be improved. All calculation is completed in the same coordinate with the directly integral method. It does not need coordinates transformations, and it reduces the complex of the calculation; maximum value of ground deformation and its direction can be determined with the method, and it can improves the accuracy of the mining subsidence prediction greatly.

6 Conclusions

1) With summary of problems in current mining subsidence prediction methods, the maximum ground deformation directions and its values are researched and its calculation methods are got based on probability integral method.

2) Ranges and distributions situation of arbitrary point ground movement and deformation along the direction $[0, 2\pi)$ are analyzed with rigorous mathematical derivation of probability integral method. It shows that arbitrary shaped multiple work faces mining, arbitrary point in the mining subsidence affecting area, have maximum tilt and horizontal displacement, the two maximum values are equal and opposite in direction; the maximum curvature and horizontal deformation occur in four directions perpendicular to each other, and there are five distribution forms of curvature and horizontal displacement in direction $[0, 2\pi)$.

3) Arbitrary shaped multiple work faces mining subsidence prediction and analysis system is developed. The system implements the probability integral method with direct integral method calculation, avoiding the errors of rectangular subdivision of non-rectangular, and improved the accuracy of mining subsidence prediction. Mining subsidence visualization, map production and data analysis visualization are implemented by tight coupling of VB and SURFER based on Active X technology. Engineering application shows that the system can calculate and analyze the maximum value of ground deformation; it has important practical significance to improve the accuracy of mining subsidence.

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