Mining Subsidence Prediction Based on 3D Stratigraphic Model and Visualization

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Abstract. 3D phenomenon involved in mining subsidence was Classified, summarized and aggregated, established the hierarchical structure that describing the geologic phenomena and engineering phenomena of stratum structure. Proposed a 3D stratigraphic model that mixed Multi-DEM with Tetrahedral Network. The model uses Multi-DEM to build layered surface of the earth's surface and geology, and uses TEN to makeup inter layer geological mass. This is in favor of exactly expressing the surface information, and it is benefit to engineers and technicians to check the geological condition in the stratum, also it provides detailed geological mining conditions for the mining subsidence prediction research and accurately establishes prediction model. Engineering sample shows that the predicted results of the system is more close to the measured values.

Keywords: mining subsidence prediction; 3D stratigraphic model; DEMs-TEN model; 3D visualization.

1 Introduction

Coal which is the main energy in China plays an important role in the development of the national economy. However, coal mining resources causes a lot of problems such as leading to the movement and deformation of surface, destroying the buildings and other facilities on the surface, and bringing about the collapse and damage of land. The paper aims to build the 3D stratigraphic model and the visualization algorithm model which take into consideration the relevant geological mining conditions such as overburden strata structure and mining methods, and explore the approaches of combination of the 3D geological modeling and the subsidence prediction theory according to the 3D stratigraphic modeling and the visualization technology. So it provides analysis technology for the subtle study of movement and deformation of surface.Although many scholars in geography, mapping, compute science and other areas carried out a lot of studies on the theory and method of 3D GMS and made a lot of creative achievements,such as Simon W. Houlding [1],Dennis J. Burford [2], Cyril Galera [3],Hengxing Lan [4],Alex Smirnoff [5],Andrew Crooks [6],and so on. but this work is still in the theoretical research stage as a whole. So far, a whole 3D GMS hasn't been developed in the world. It makes the value of 3D original data in mining

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geology, petroleum geology, meteorology, ocean and many other fields not used fully and restricts severely the effective expression and visualization process of 3D space information. In addition, there are similar problems in the mining subsidence field. Therefore, it is very necessary to further study on the subject that GMS and the 3D visualization technology are used in mining subsidence prediction.

2 Mining Subsidence Prediction Model

The Random Medium Theory is brought in mining subsidence calculation by Polish scholar Lee's Wanny in the 1950s, and then developed into Probability Integral Method by Chinese academician Baochen Liu, Guohua Liao and so on, and be widely used in China's coal mining subsidence prediction area. This method takes the moving process of rock strata and surface caused by mining as a random process, and takes the rock strata as the particle body of random medium, the probability distribution model of the upper particle body movement caused by the particle body in the bottom fell out .

In Fig.1, shows prediction model of the arbitrary point's movement and deformation on the surface. The paper will take the model as the foundation to establish a 3D stratigraphic model that suitable for mining subsidence prediction. Suppose the calculation mining width of the mining alignment as l_1, the calculation mining width of the mining inclination as l_2, the sinking value W_A of point A will be the maximum subsidence value multiplied by volume that surrounded by the standard normal function curved surface of point A and the mining area.

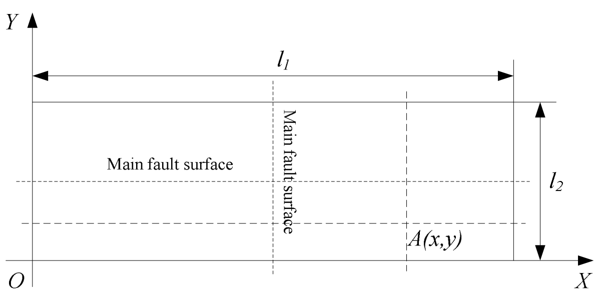

Fig. 1. Movement prediction of arbitrary point

Now take the lower left of the mining area as the coordinate origin, according to the sinking prediction formula on the limited mining main profile, the following kinds of formula founded:

(1) Sinking:

$$W(x,y) = W_{\max} \times \left\{ \Phi\left(\frac{3x}{R_0}\right) - \Phi\left[\frac{3(x-l_1)}{R_0}\right] \right\} \times \left\{ \Phi\left(\frac{3y}{R_0}\right) - \Phi\left[\frac{3(y-l_2)}{R_0}\right] \right\} = W_{\max} C_x \times C_y \tag{1}$$

(2) Inclination along the direction φ:

$$i(x,y,\phi)=\frac{\partial W(x,y)}{\partial \phi}=\frac{1}{W_{\max}}\left[i^0(x)W^0(y)\cos\phi+W^0(x)i^0(y)\sin\phi\right] \tag{2}$$

(3) Curvature along the direction φ:

$$K(x,y,\phi)=\frac{\partial}{\partial \phi}i(x,y,\phi)=\frac{1}{W_{\max}}\left[K^0(x)W^0(y)\cos^2\phi+W^0(x)K^0(y)\sin^2\phi+i^0(x)i^0(y)\sin 2\phi\right] \tag{3}$$

(4) Horizontal movement along the direction φ:

$$U(x,y,\phi)=bri(x,y,\phi)=\frac{1}{W_{\max}}\left[U^0(x)W^0(y)\cos\phi+U^0(y)W^0(x)\sin\phi\right] \tag{4}$$

(5) Horizontal deformation along the direction φ:

$$\begin{aligned}\varepsilon(x,y,\phi)&=brK(x,y,\phi)\\&=\frac{1}{W_{\max}}\left\{\varepsilon^0(x)W^0(y)\cos^2\phi+\varepsilon^0(y)W^0(x)\sin^2\phi+\left[U^0(x)i^0(y)+U^0(y)i^0(x)\right]\sin\phi\cos\phi\right\}\end{aligned} \tag{5}$$

The above model takes random medium theory as a foundation, and deduced a prediction model which takes the standard normal distribution as the sinking probability density function. The model calculates easily, and has definite geometrical and physical significance of this model's parameters; also it can do field measurement, and establish corresponding engineering calculation model for the development of 3D visualization system of mining subsidence prediction.

3 3D Stratigraphic Model

3.1 Modeling Process of 3D Stratum

Currently there are many technical methods for stratigraphic information detection, but the most direct and the most widely used method to obtain stratigraphic information is drilling method. According to the arrangement position of rock strata demarcation point in stratum borehole data, can determine the sequence of the stratum. And can treat the Multi-DEM by litho logy in cross-classification processing, thus can form 3D stratigraphic framework, which divided by elements of litho logy in 3D space. Also can introduce special body object (such as TEN objects and so on) to rich stratum content, last form complete meaning of 3D stratigraphic model.

The 3D stratigraphic model based on Multi-DEM is according to drill hole sampling points of subsidence prediction area, and establish DEM of the stratum boundary surface or the boundary surface of ore body and surrounding rock strata's from the earth's surface to underground in proper order, then form 3D stratigraphic model after separately suturing the DEM that adjacent and belong to the same stratum or ore body. In order to modeling, according to the stratum sequence, number the stratum that revealed by drill hole information within the research area, and the top layer is rock strata I, the following is rock strata II, rock strata III…, the modeling process is as follows:

(1) Borehole data pretreatment. Select some points in the research area to carry drilling sampling, due to the stratum existing wedge out phenomenon, so the rock strata's number in drill hole sampling is very different. As shown in Fig.2, according to the standard rock strata sequence, for the missing rock strata in some drill holes, we insert virtual layers which thickness is 0 in the drill hole, and after the pre-treatment making every drill hole have the same rock strata sequence and the same number of layers.

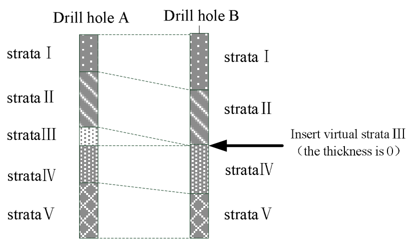

Fig. 2. Diagram of borehole data pre-processing

(2) Insert virtual drill hole in the four angular points of drill hole bounding box in the research area. Drill hole is mainly distributed inside in the research area, if the stratum modeling is carried by the original drill hole, will obtain an irregular 3D digital stratum, and this will be inconvenient to the following study of the stratum, therefore it needs outward expansion to form the bounding box. For this moment, need to insert virtual drill hole in the four angular points of the irregular 3D digital stratum bounding box.

(3) Build standard triangulation network of rock strata surface. According to the plane coordinate (x, y) of drill hole point for every rock strata surface, use plane Delaunay Triangulation Algorithm to build standard triangulation network of every rock strata surface, and use different colors or textures to express rock strata surface.

(4) Generate 3D stratigraphic framework model. Because of every drill hole has the same rock strata sequence, so start form the discrete points in the standard triangulation network of rock strata surface, and use the 3D constraint tetrahedron algorithm to build TEN from top to bottom. So this can establish the whole 3D digital stratum.

(5) The visualization of TEN. Use different colors or textures to express different attribute of rock strata.

3.2 The Mixed Data Model Based on Multi-DEM and TEN

The mixed data model based on Multi-DEM and TEN (the following called as DEMs-TEN model), DEMs consists of some adjacent triangles, so its basic geometrical element is triangle. TEN includes basic geometrical elements as follows: vertex, line segment (such as tetrahedron edge, triangle edge), triangle, tetrahedron and so on. Use object-oriented ideas, and abstract the stratum entity to the following four basic elements: vertex, line segment, triangle, tetrahedron and so on. In Fig.3, shows the DEMs-TEN model based on UML.

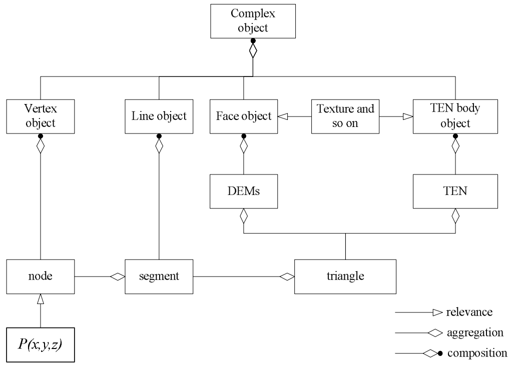

Fig. 3. DEMs-TEN hybrid model based on UML

From the stratum attribute perspective, drill hole is the line object that comprised by many line segments; adjacent triangles in the same layer face comprise a stratum surface object; under the restriction of the two neighbouring layers' surface, the TEN's Vexel that connected with each other comprises a whole geological object; the node can be used to describe a punctual object, that is the intersection between drill hole and rock strata surface; different space objects in certain space range can comprise a complex geological object. Fig.3 shows the corresponding relation between geometrical element and entity object.

3.3 Mixed Modeling Process and Related Algorithm of DEMs-TEN

In section 3.2, abstracted the borehole data to scattered point source information and designed the data structure of the scattered point source information, and on the base of this, provide reconstruction for the DEM of every stratum surface, then form the basic framework of 3D stratum. Using 3D constraint Delaunay TEN to create network on the adjacent stratum surface, and to reach the purpose of stitching the adjacent stratum surface, and then get the 3D model of the whole stratum.

Suppose the data set of one stratum surface's scattered points is $S_1=\{V_i \mid V_i \in R^3, i=1,2,3,\ldots\}$, its adjacent stratum surface's scattered points data set is $S_2=\{V_j \mid V_j \in R^3, j=1,2,3,\ldots\}$. Carry Delaunay triangulations on S_1 to form a triangle set, and use adjlink pointer *P* to indicate the triangle set, and use the algorithm provided in literature[7,8] to achieve the Delaunay triangulation.

The following, will use recursion partition method to generate TEN of constraint surface. In order to describe conveniently, the paper designs data fields dissection algorithm *Partition_Subdivision()* and tetrahedral set generation algorithms *Create TEN()*. The algorithms are as follows:

Algorithm 1: TEN generation algorithms of constraint stratum surface *Partition_ Subdivision.*

Algorithm ideas: Make use of the splitting plane Ω which perpendicular to *X* axis to divide the given data fields space into two approximately equal half-space Φ_1 and Φ_2, and divide the stratum surface triangle set *P* into three parts: the triangle adjlink

P_x which intersect Ω, the triangle adjlink P_l which in the left of Ω, the triangle adjlink P_r which in the right of Ω; for the triangle in the P_x ,can call the tetrahedral set constructed function *CreateTEN()* separately in half-space; if P_l and P_r is not null, recursive call *Partition_ Subdivision()* separately in the two half-space Φ_1 and Φ_2. The algorithm steps are as follows:

STEP 1: set the triangle storage adjlink pointer P_x,P_l,P_r null;

STEP 2: use plane Ω to divide the point set into three point sets, separately is: $S_{2\text{-}0}\in\Omega$, $S_{2\text{-}1}\in\Phi_1$, $S_{2\text{-}2}\in\Phi_2$;

STEP 3: make the initial boundary triangles and the generated triangles in the process of new tetrahedron generation according to the different position that intersect Ω, in the left of Ω, in the right of Ω, and make P divide into three triangle adjlink sets, and separately assign to P_x, P_l, P_r;

STEP 4: call the tetrahedral set constructed function *CreateTEN ()* for every triangle t in P_x; add the other triangles except the triangle t of new generated tetrahedron to P_x, and update the value of the splitting planeΩ;

STEP 5: if P_l is not null, then recursive call the *Partition _ Subdivision(*Φ_1,P_l*)*;

STEP 6: if P_r is not null, then recursive call the *Partition _ Subdivision(*Φ_2,P_r*)*;

Algorithm 2: the generation algorithms of tetrahedral set *CreateTEN ()*

In order to describe conveniently, appoint the data structure that the algorithm referred to as follows:

(1) the three vertexes' index *VertexID* of triangle that comprised TEN have counter clockwise arrangement;

(2) the four vertexes *ABCP* of TEN are arranged as follows: △*ABC* is one of TEN's faces, the △*ABC* has the counter clockwise arrangement from vertex *P*, *P* is the vertex that the thumb pointed according to the right hand rule, then called *P* is over the face where the △*ABC* is, or, called *P* is under the face where the △*ABC* is, shown in Fig.4.

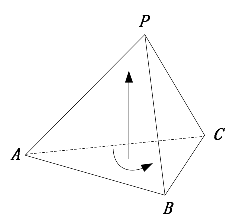

Fig. 4. Tetrahedron schematic diagram

Supposing $P(x, y, z)$ is a spatial arbitrary point, given the space coordinate of △*ABC* are respectively: $A(x_1, y_1, z_1)$, $B(x_2, y_2, z_2)$, $C(x_3, y_3, z_3)$, the space position relationship of point *P* and △*ABC* is obtained by the formula (6) below:

$$V = \begin{vmatrix} x & y & z & 1 \\ x_1 & y_1 & z_1 & 1 \\ x_2 & y_2 & z_2 & 1 \\ x_3 & y_3 & z_3 & 1 \end{vmatrix} \tag{6}$$

(1) If *V = 0*, said *P (x, y, z)* is included in the face where the △*ABC* is.

(2) If *V = 0*, said *P (x, y, z)* is above the face where the △*ABC* is.

(3) If *V = 0*, said *P (x, y, z)* is below the plane where the △*ABC* is.

In order to construct a Delaunay tetrahedron on the basis of the given △*ABC*, and the Delaunay tetrahedron has on overlap or cross with the current tetrahedral set and constraint surface triangle, the essence is to seek another vertex suited to △*ABC*. If written *T* (△*ABC*, *P*) for the generated Delaunay tetrahedron, the vertex *P* should meet the following conditions:

(1) *P* is above the face of the △*ABC;*

(2) The generated *T(△ABC,P)* is Delaunay tetrahedron, that is the external ball of *T(△ABC,P)* does not contain any other vertex; the algorithm to judge whether the other vertex *V* in the external ball of *T(△ABC,P)* can refer to literature[9].

(3) While generating *T(△ABC,P)*, recording the other vertex(set *O* point) which in the same external spherical with this tetrahedron, record it in the linked list *Vertex_link*, after *T(△ABC,P)* successfully built, continue to look for the appropriate points in linked list *Vertex_link* for the new triangle to generate Delaunay tetrahedron, the generation process shown in Fig.5.

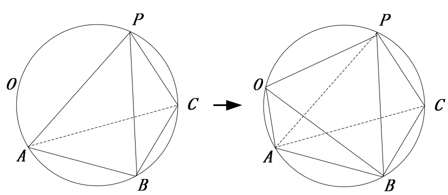

Fig. 5. New TEN generation process

4 Sample Analysis

Based on the ideas, *3D Subsidence* is developed which is used to predict mining subsidence and visualization. In order to analyze and validate the *3D Subsidence* system, the following method will be used to calculate mining Subsidence. That is: using the current probability integral method and *3D Subsidence* to calculate the mining subsidence respectively, then compare with the measured sinking value. A coal mine 3252 surface observation station is located up of the coal mine 3252 working face, the geologic structure of this place is complicated, the coal bed is mono clinal structure, the mean obliquity of the coal rake is 24 degrees, the coal bed is sandy shale and grey-white medium-grained sandstone, and the hardness is from 6 to 7.5 degrees, overlying rock strata is fine sandstone 11.8m, medium-grained sandstone 5m, sandstone 9.4m, sandy shale 27.2m, alluvium 15-20m; The parameter of the 3252 earth's surface observation station is in table 1, *3D Subsidence* system also uses the predicted parameter values in table 1.

Table 1. Parameter table of probability integration method

parameter	value	unit
Mining coal rake mean obliquity α	24	(^{0})
Mining effects spread degree θ	70	(^{0})
Mining depth of the working face uphill H_1	103	(m)
Mining depth of the working face downhill H_2	42	(m)
Level projection length of the working face l	230	(m)
Level projection length of tilt direction of the working face L	123	(m)
Shifting distance of the inflexion besides open-off cut S_1	-3.4	(m)
Shifting distance of inflexion besides stopping mining line S_2	1.9	(m)
…	…	…

Establish a rectangular coordinate system to take coordinate transformation for the point that has not compute. Take the crossover point O' of left border and lower boundary of working face level projection as base point, x'-axis and y'-axis are parallel to uphill downhill of the coal rake. The coordinate of arbitrary point $A(x',y')$ can be obtained from the rectangular coordinate computing, the coordinate of the points that have not computed that need in the earth surface moving should be $A(x,y)$ after inflexion translation, then :

$$\begin{aligned} &l = l' + S_1 + S_2 \\ &x = x' + S_1 \\ &y = y' + H_1 ctg\theta + \frac{S_4}{\sin\theta}\sin(\alpha+\theta) \\ &L = L' + H_2 ctg\theta + \frac{S_3}{\sin\theta}\sin(\alpha+\theta) + H_1 ctg\theta + \frac{S_4}{\sin\theta}\sin(\alpha+\theta) \end{aligned} \quad (7)$$

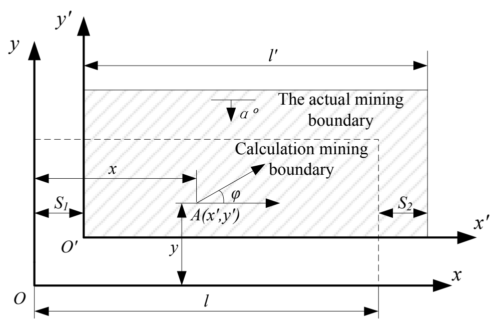

Fig. 6. Establishment and transformation of coordinate system

Compare the earth surface sinking value computed by probability integral and 3D Subsidence system with measured value obtained by observation station, and the comparison condition shows in Fig.7. W_C-measured observed value; W_J- the sinking value computed by probability integral; W_M- the sinking value computed by the system.

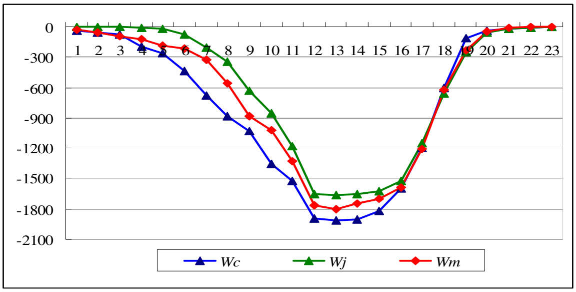

Fig. 7. Results comparison chart

It can be seen from Fig.7 that the prediction of the system owns more degree of accuracy and is more close to measured value. Because it considered the coal rake and overburden structure, what could be better to choose expected parameters, and it considered the distribution form of the coal rake in the 3D stratigraphic modeling, and fitting better with measured value.

The screen shot of the 3252 working face subsidence stratum modeling and 3D visualization simulation results by *3D Subsidence* system is shown in Fig.8, (a),(c) are 3D stratum effect drawing in different viewing angle,(b),(d) are the 3D stratum effect drawing with remote sensing corresponding (a),(c).

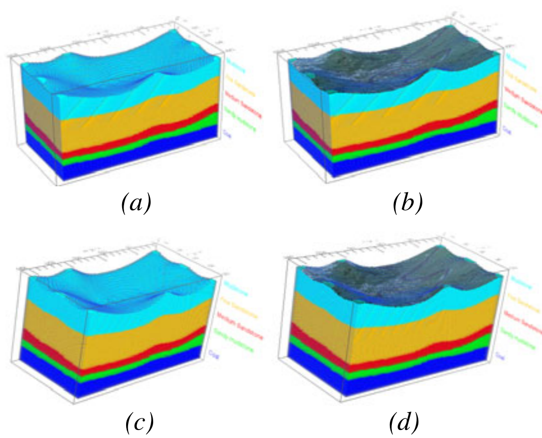

Fig. 8. Three-dimensional visualization of mining subsidence effect picture

5 Conclusions

(1) It takes 3D stratum model and mining subsidence prediction model together for the first time, then technical staff can obtain the mining subsidence prediction model that meet the actual engineering directly from 3D stratum modeling, and improve the accuracy of mining subsidence prediction by the reasonable expected parameter that chosen from the interactive modeling process. (2) We make a classification,

summarize, accumulation to the 3D geology phenomena by the object-oriented method, put forward Multi-DEMs and mixed tetrahedron grid 3D stratum model, the model uses multi-DEMs to structure the stratum's surface and layer geology surfaces, and uses TEN to structure inter layer geologic mass with the accurate express of face object. (3) It carry out the mining subsidence prediction 3D visualization system *3D Subsidence*. The system supports to the true 3D display of mining subsidence, meanwhile, it integrates 2D and 3D information together, further enriched and developed the methods and means of mining subsidence field.

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