Integration Method of Three-dimensional Complex Tunnel Network Model

Zhi-hua Zhang, En-ke Hou, and Xiao-xia Luo

Abstract— **In recent years, "Digital Mine" has been an important research direction in the field of geology and mineral resources. In particular, three-dimensional network modeling of mine tunnel with its spatial analysis is an important research perspective. It is significant research direction on theoretical study of "digital mine", mineral resources exploration, mining decision-making management, mine production and mine safety etc. In order to seamlessly integrate the models of simple tunnel and intersected complicate tunnel, directed double nodes approach and midpoint interpolation approach were proposed; In order to solve the problem that the two corresponding half-tunnels will crack at sharp turning, the uniform height approach on section arch was proposed. Using Windows XP as the platform, MS Visual C++6.0 as development tools and OpenGL graphics package as the graphic processing display tools, the experimental system of three-dimensional tunnel network model was designed and developed. Using real mining data, the experimental system was tested. It is shown that the proposed method is the practical and effective.**

Index Terms—**Digital Mine, Tunnel, Modeling, Three Dimensions.**

I. Introduction

In the digital era, the traditional mining engineering experiences the tremendous development. Tunnels are the channels through which the mineral products are transported from workface to ground. They also can be used to ventilate fresh air and deliver workers. For the whole mine, tunnels are key parts to mine projects. Thus they are a significant part of 3D tunnel modeling on DM field. Many researchers have paid a lot of efforts in modeling 3D tunnels. Yang et al. (2004) utilize cylinder to represent 3D tunnel and the auxiliary function to build 3D tunnels [1]. However the disadvantage is that this method cannot handle the situation when the tunnels intersect, and cannot guarantee the inner connectivity of 3D tunnels. Therefore, the approach is rigid and inflexible. Chen et al. (2004) directly used quasi tri-prism volume (QTPV) to simulate the underground tunnel [2]. They choose QTPV since it is a potential 3D spatial data model. QTPV can not only establish internal geological structure, but also create topological relations among the geological entities. It is suitable for modeling geological exploration engineering. Although it is a potential three-dimensional data model, it cannot guarantee connectivity within the tunnels and the intersection among tunnels. Wei et al. (2005) expressed 3D tunnel model by using 3D facial model (framework) [3]. They divided the arch of tunnel into 8 segments (the arch is half circle, the step length is P/8.0). After the section data obtained, the whole tunnel was described. TIN (Triangulated Irregular Network) were utilized to deal with intersection of tunnels, it will increase the data storage and the difficulties of 3D modeling. It is difficult to be applied in the modeling of complex tunnel network. Zhang H.M et al. (2007) utilize the Bezier curves to simulate 3D tunnel [4]. They decompose the 3D tunnel into roof, bottom, and two profiles. The bottom and two profiles were approximated by using polygons, which can easily be generated by OpenGL. The arch roof was fitted by Bezier curves. Sun et al. (2007) proposed the approach that the tunnel was simulated by constraint triangulations [5]. They also addressed the issue of intersection. However, for complex tunnel network, it would increase the difficulty of modeling. Based on framework model, Wang (2005) deeply studied arch section, and subdivided the arch into 15 parts [6]. Based on these parts, they developed the intuitionistic model. It cannot be applied to model different types of tunnel sections. Moreover, many researchers have studied the modeling of tunnel, but they didn't take tunnel's intersection into consideration [7-12].

Although beneficial explorations for 3D tunnel modeling were researched by many scholars, there are many problems existed in 3D tunnel modeling, such as intersection modeling of tunnel, spatial analysis and query of 3D tunnel, etc. 3D mining softwares of overseas were lack of the processing and shown about intersection modeling of 3D tunnel, such as Surpac. According to these shortcomings, we have proposed some modeling methods to solve the problem of muti-intersection of tunnels; meanwhile, the complex tunnel would be constructed easily.

II. Subdivision of Tunnel Network Model

The basic idea of subdivision: skeleton model of Tunnel network, which is expressed by nodes and centerlines (such as Fig.1 shows), can be used to subdivide complex tunnel network into simple-tunnels and complex-tunnels. Those subdivided tunnels were built respectively, three-dimensional tunnel network model were integrated by those simple-tunnels and complex-tunnels. Namely, the skeleton of intersection is collection, named PART-TWO, which is set of complex-tunnels, the rests can be looked as other collection, namely PART-ONE, which is composed of

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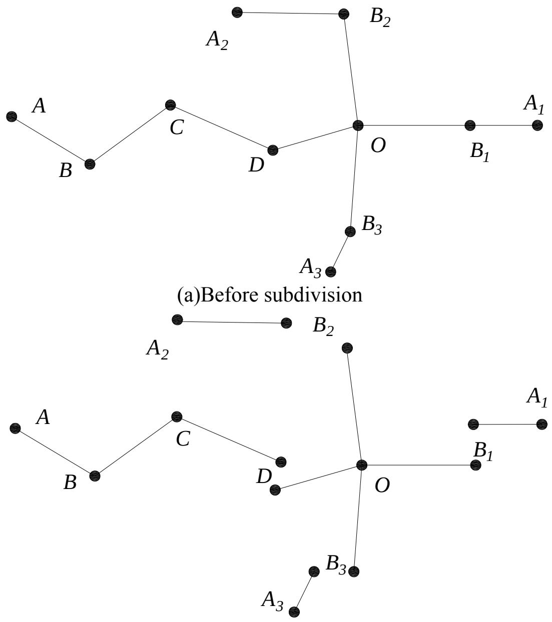
the single-tunnels. Then, the whole tunnel network can be combined of PART-ONE and PART-TWO [13-15].



(a)Before subdivision

(b)After subdivision

Fig. 1. Skeleton model of tunnel network

The concrete division process: As for intersected part, the intersected node is look as center, which can extend to each branch tunnel. The nodes, which are adjacent to intersected node, are classified as node set of PART-TWO. The centerline set consists of the lines which are composed of the intersected node and its adjacent node. As to single-tunnel, its node set is made up of all the nodes on the single-tunnel, including the node which is adjacent to intersected node. As shown in Fig.1, we will take Fig.1 (a) for example, it is a cross intersection, *A, B, C, D*, A_1, B_1, A_2, B_2, A_3, B_3, *O* are nodes, *O* is intersection node (center node), according to the principle of division, there are *D*, B_1, B_2, B_3 neighboring with *O*, so the node set of PART-TWO is $\{D, B_1, B_2, B_3, O\}$, link set is $\{DO, B_1O, B_2O, B_3O\}$. The node set of PART-ONE is $\{\{A, B, C, D\}, \{A_1, B_1\}, \{A_2, B_2\}, \{A_3, B_3\}\}$, and its link set is $\{\{AB, BC, CD\}, \{A_1B_1\}, \{A_2B_2\}, \{A_3B_3\}\}$. As shown in Fig.1 (b), there are four mutual independent single tunnels which construct the PART-ONE. The divided principle of trifurcate tunnel and multi-intersections tunnel is the same as cross-section tunnel. If there are *n* points adjacent with intersection node, the node set of PART-TWO has *n*+1 nodes, and its link set has *n* centerlines.

The advantage of this subdivision: (1) the tunnel network is simplified, so that the structure of tunnel network is clarity. (2) As for modeling of PART-ONE, we adopt wireframe to build. (3) In the order of PART-ONE modeling, as long as several single tunnels are separate complete. During the modeling, it needs not to consider the modeling order. For example, there are three single tunnels: a, b, c. a can be modeled first, b or c can be modeled first too. For a single-tunnel, if the modeling sequence of nodes is A→B→C, then the sequence C→B→A is also possible. (4) There are many intersection parts in PART-TWO, every part is individual on the aspect of modeling, regardless of the orders.

According to Fig.1 (b), the tunnel network is subdivided into PART-ONE and PART-TWO, the basic information of two parts are shown in Table I and Table II.

TABLE I: BASIC ELEMENTS OF PART-ONE

Tunnel line	Arcs	nodes
ABCD	AB, BC, CD	A, B, C, D
A_2B_2	A_2B_2	A_2, B_2
A_1B_1	A_1B_1	A_1, B_1
A_3B_3	A_3B_3	A_3, B_3

TABLE II: BASIC ELEMENTS OF PART-TWO

Tunnel line	Arcs	nodes
DOB_2	DO, OB_2	D, O, B_2
B_2OB_1	B_2O, OB_1	B_2O, OB_1
B_1OB_3	B_1O, OB_3	B_1O, OB_3
B_3OD	B_3O, OD	B_3O, OD

III. THE INTEGRATION OF MODELS

As mine tunnel network is crisscross and more complex, it is difficult to build the whole three-dimensional network model. So, we need to subdivide the complex tunnel network in order to construct three-dimensional tunnel model easily. No matter what the tunnel network is more complex, it can be split in terms of intersected node. There are three tunnel branches in intersected node at least ($n \geq 3$, n represents single tunnel branches).

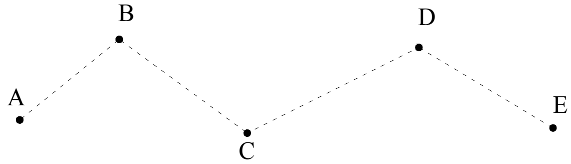
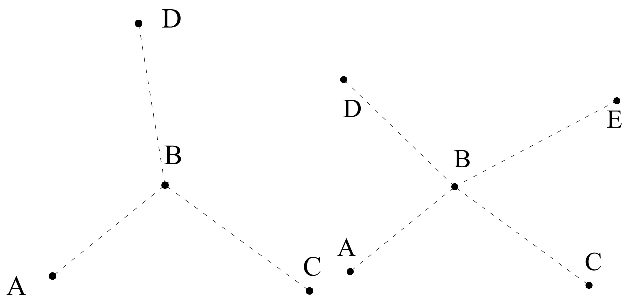
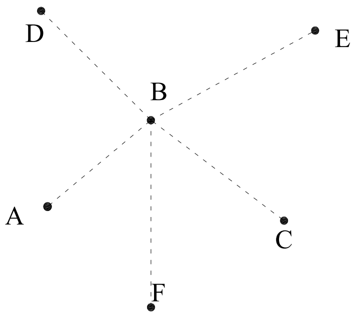


Fig. 2. Skeleton model of single-tunnel (PART-ONE)

As Fig.2 shown, there is skeleton information of single-tunnels in PART-ONE, PART-TWO contains the skeleton information of complex-tunnels, includes intersection among tunnels (Fig.3). Commonly, there are three types in intersection tunnels: intersection of three tunnels (Fig.3a), intersection of four tunnels (Fig.3b), intersection of n-tunnels (n>=5, Fig.3c). No matter what the types are, there is integration between PART-ONE and PART-TWO, then it is the necessary problem to be solved that is realized seamless integration between PART-ONE and PART-TWO. We will discuss the different situations in the following part.



(a) Trifurcate tunnel (b) Cross tunnel



(c) Five-fork tunnel

Fig. 3. Skeleton models of complex-tunnels (PART-TWO)

We will describe the integration modeling methods between single-tunnel and complex-tunnel in detail. For the integrated modeling between single-tunnel and complex-tunnel, we will discuss the example which seamless integration model is build between the trigeminal shaped tunnel (complex-tunnel) and single-tunnel. As shown in Fig.4, the dotted line *AB* is centerline of single-tunnel, it belongs to type of PART-ONE. The dotted line *AO*, *CO*, *DO* represent the center lines in three branches of trigeminal shaped tunnel, *O* is crossing node. It is type of PART-TWO. In Fig.4, the solid line is the side line of tunnel, assuming the position calculated in the figure, and if it is not processed, the case will appear as shown in Fig.5.that means the node A_{12} and A_{22}, A_{11} and A_{21} can not overlap in two-dimensional environment. So the completion of three-dimensional tunnel is not continuous overall. Therefore, the paper proposes two solution methods, namely the method of mid-point interpolation and directed method of two-node.

A. Midpoint Interpolation Method

Midpoint interpolation: According to analytic geometry, a number of points on a same straight line have the same azimuth. That is the slope of line, if we know the three-dimensional coordinates of two points, the three-dimensional coordinates of mid-point can be obtained after calculation. Then, two points and mid-point are in the same straight line, it ensures that their position will not change.

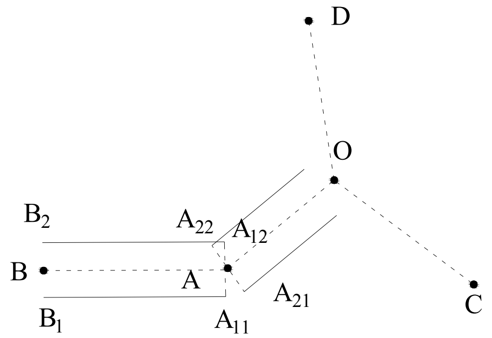


Fig. 5. Discontinuous composed model of tunnels

The specific processing steps are as follows:

Step1: Obtain the three-dimensional coordinates of every tunnel's center line.

Step2: Subdivide the whole tunnel network, get the skeleton information of PART-ONE and PART-TWO.

$$\begin{cases} x_m = (x_1 + x_2)/2 \\ y_m = (y_1 + y_2)/2 \\ z_m = (z_1 + z_2)/2 \end{cases} \tag{1}$$

Step3: If the node to be inserted is in the PART-ONE, that is chosen in arc which connects the PART-ONE and PART-TWO. On the assumption that this arc is Arc1, the two nodes are N1(x1, y1 , z1) and N2(x2, y2, z2), the mid-point Nm can be solved by using (1). Therefore, the arc is bisection, the part which is adjacent to PART-ONE is also belong to PART-ONE, the other half belongs to PART-TWO, the models of PART-ONE and PART-TWO which are constructed would organically connect. Because of the same direction, the models are combined together seamless. As shown in Fig.6(a), before interpolation, the dotted line is boundary of PART-ONE and PART-TWO, after interpolation, the arc N_1N_2 is split, N_m is mid-point of arc N_1N_2, the dotted line(split line) has changed, that is the spilt line moves to N_m, the arc N_1N_m belong to PART-ONE, N_mN_2 belong to PART-TWO, as illustrated in Fig.6(b). After partition, the tunnel model to be built would be integrated seamlessly.

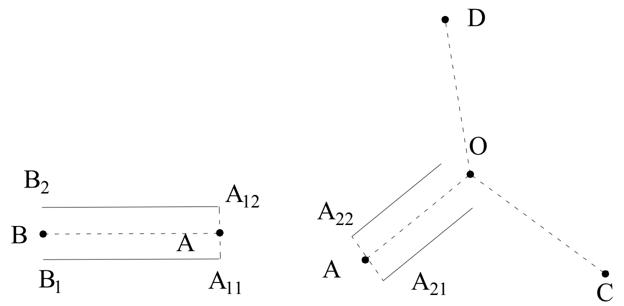
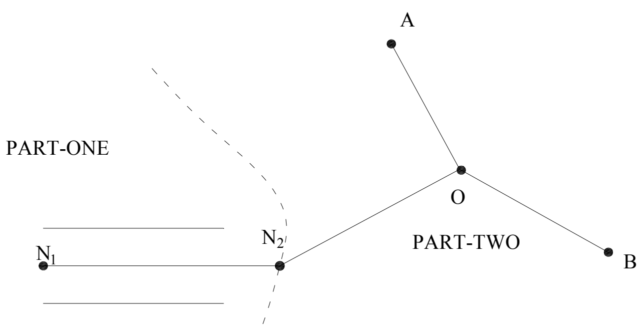
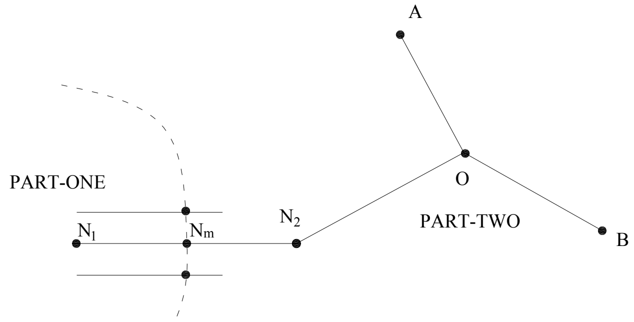


Fig. 4. Models after subdivision



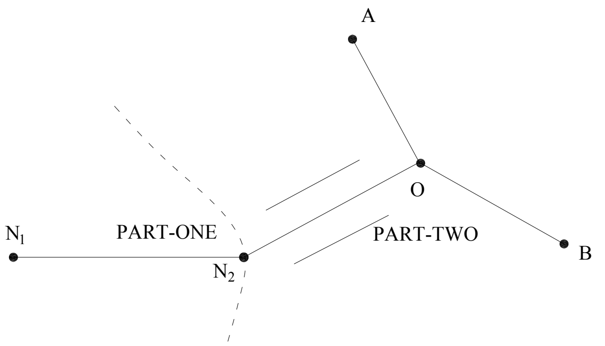
(a) Before interpolation



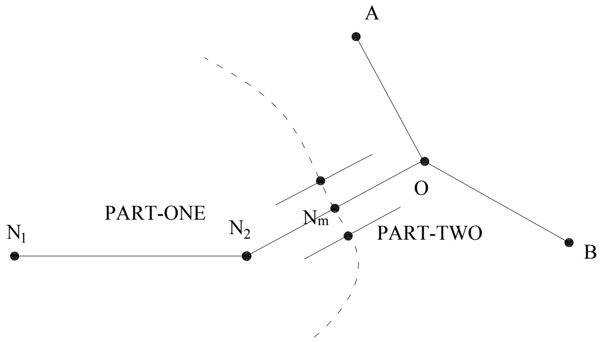
(b) After interpolation

Fig. 6. Interpolation of first case

Another situation is to spilt the arc, which is within PART-TWO, connects with PART-ONE. Assumed that the arc has two nodes, which are *O* (the intersected node) and N_2, as Fig 7(a) shows. We can still use the (1) to calculate the three-dimensional coordinates of N_m. It is different from above case that the arc can be subdivided into two new arcs within PART-TWO, one is N_2N_m which is classified to PART-ONE, the other is N_mO which is still belong to PART-TWO, as shown in Fig.7(b). The three-dimensional coordinates of N_m can be solved by using (1). N_m is the tail node of tunnel line $N_1N_2N_m$, N_m is also a node of arc ON_m in trigeminal-shaped tunnel.



(a) Before interpolation



(b) After interpolation

Fig. 7. Interpolation of second case

As shown in Fig.7(a), before interpolation, the dotted line separates PART-ONE and PART-TWO, After interpolation, the arc N_2O is spilt, N_m is mid-point of N_2O, the dotted line(the spilt line) moves to N_m, N_2N_m is classified to PART-ONE, N_mO belongs to PART-TWO (Fig.7(b)), After partition, the tunnel model built would be integrated seamlessly.

B. Directed Method of Double Nodes

Directed method of double nodes: the principle of this method is similar to the mid-point interpolation method, two nodes can fix a straight line, the direction doesn't change, it doesn't require interpolation, we can use the known nodes to solve. Firstly, the intersected node in PART-TWO can be used to direct, it can calculate the coordinates of inflection points and corresponding points (N_{r1}, N_{l1}) in connection between PART-ONE and PART-TWO. Then, the node within PART-ONE, which is adjacent to PART-TWO, can be utilized to direct the branch of PART-TWO. it can calculate the coordinates of inflection points and corresponding points (N_{r2}, N_{l2}) in connection between PART-ONE and PART-TWO. Thirdly, in theory, N_{r1}=N_{r2}, N_{l1}=N_{l2}, it would achieve the model integration of PART-ONE and PART-TWO. The specific calculation steps are as follows:

Step1: The tunnel network is divided into PART-ONE and PART-TWO.

Step2: While it deals with PART-ONE, it need to add a node in the tail node of PART-ONE, this node is intersection node of PART-TWO. In PART-TWO, every branch of PART-TWO also requires to add a new tail node which is adjacent to connected node in PART-ONE.

Step3: In during of concrete computation, these nodes stored again are only involved in directional terms, they don't reflect in the actual three-dimensional modeling. Formula is as follows (2), k_1 represents the slope of *BC*, the coordinate of C_{L1} is (x_{L1}，y_{L1}), k_2 represents the slope of *CO*, the coordinate of C_{L2} is (x_{L2}，y_{L2}), the coordinate of C_{R1} is (x_{R1}，y_{R1}), the coordinate of C_{R2} is (x_{R2}，y_{R2}). In terms of (2), the coordinates of $C_L(x_L,y_L)$ and $C_R(x_R,y_R)$ will be obtained.

$$\begin{cases} y_{LC} = y_{L1} + k_1(x_{LC} - x_{L1}) \\ y_{LC} = y_{L2} + k_2(x_{LC} - x_{L2}) \\ y_{RC} = y_{R1} + k_1(x_{RC} - x_{R1}) \\ y_{RC} = y_{R2} + k_2(x_{RC} - x_{R2}) \end{cases} \tag{2}$$

Fig.8 is schematic diagram before node orientation, dotted line subdivides the PART-ONE and PART-TWO, *ED*, *DC*, *CO*, *AO*, *BO* is center line of tunnel, C_{L1} and C_{R1} are two sides points which the node C is corresponding to in the PART-ONE, C_{L2} and C_{R2} are two sides points which the node *C* is corresponding to in the PART-TWO. These side nodes can be obtained by using (2). From Fig.8, if we don't use the directed method of double nodes, the side lines of PART-ONE and PART-TWO can crack or overlap each other after integration, as shown in Fig.8.

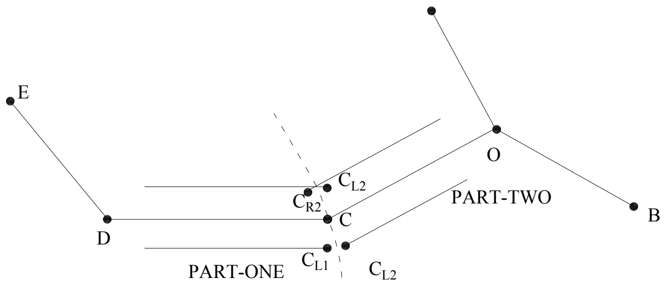


Fig.8. Diagram before node orientation

In Fig.9, for modeling of PART-ONE, the node *O*, which belongs to PART-TWO, will be used to calculate as an orientation node. Then, the coordinates of C_R and C_L will be received.

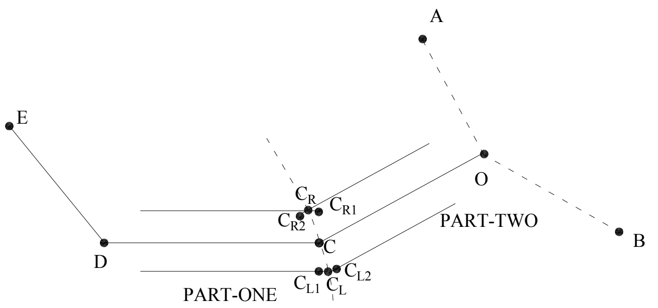


Fig. 9. Directed method of double nodes in PART-ONE

In Fig.10, as modeling of PART-TWO, the node *D*, which belongs to PART-ONE, will be used to calculate as an orientation node. Then, the coordinates of C_R and C_L will be received. It is known by comparing Fig.9 with Fig.10 that the two parts of C_R and C_L should have same values. According to directed method of double nodes, the tunnel model built would be integrated seamlessly.

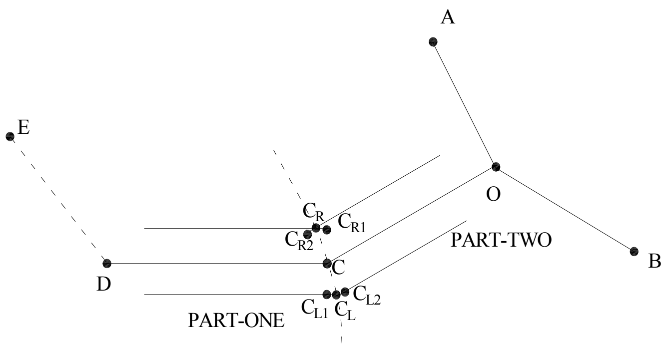


Fig. 10. Directed method of double nodes in PART-TWO

C. Approach to Avoid Cracking: Uniform Height Method On The Arch

As it will occur to sharp turn in the intersection of tunnels, so that the elevation value was calculated distortion, the half-tunnel model can be higher or lower on the arch, it will make two corresponding half-tunnels not merge, i.e. cracking phenomenon will generate. In order to prevent this case happening, the paper puts forward the uniform height method, and it is an effective method to modify the arch data.

Arch uniform height method: there are discrete points which possess same type or locate in the same sequence on the arch, the height from discrete point to tunnel floor locks to a constant, this method can limit the height of discrete point from floor, rather than limit the elevation value. When the tunnel appears sharp turn, it will lead to the elevation out of actual seriously.

Fig.11 is a diagram of arch uniform height method. According to the idea of symmetric modeling, take the right half section for example, we will obtain five discrete points after 5 deciles (a discrete point every 18 degrees), such as R_2, R_3 in the figure. If there is a sharp turn, the span of C_1R_0 will become large on the arch, the points' coordinates of *x* and *y* is correct, but the elevation values become large. It will result in distortion section, and make the two corresponding half-tunnel model cracking. In accordance with the uniform height method, take R_1 for instance, the elevation of discrete point on the arch can be calculated by using (3).

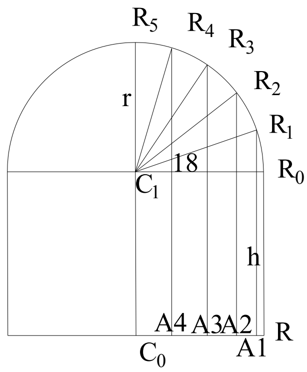


Fig.11. Diagram of uniform height method

$$z_{Ri} = z_{C0} + h + r \times \sin(i \times \pi / 10) \quad i = 1, ..., 5 \tag{3}$$

In the (3), Z_{c0} is elevation of C_0, *h* is height of RR_0, *r* is the radius of arch.

In order to avoid change of *r* in the tunnel intersection and turning, the value of *r* will be set as constant. During the modeling, *r* is a constant, because *h* is a constant too, (3) can be transforming into (4).

$$z_{Ri} = z_{C0} + Const\_i \quad i = 1, ..., 5 \tag{4}$$

Const_i is a height which the distance is from i^{th} discrete point to floor on the arch, in any section, the discrete points, which locate in the same place of different arches, have identical height, namely *Const_i*. So, the heights from discrete points to floor are constant, for example, on section *A*, distance from discrete point located in R_3 to floor is *const_3*, meanwhile, on section *B*, distance from discrete point lie in R_3 to floor is also *const_3*.

In any section, the discrete points locate in R_1, the height *const_1* is a constant, similarly, when the discrete point lies in R_2, the *const_2* is a constant. It is the main idea of uniform height method. After amendment, the *x* and *y* coordinates of discrete points can't be changed, their elevations can be computed by using (4). Thus, the cracking problem is solved in the sharp turn of tunnel intersection.

It is worth noting that the uniform height method applies only the tunnel section of same type in the field of tunnel 3D modeling. For instance, assuming that tunnel network exists just arch section, the uniform height method can be used to calculate the elevation of discrete points on the arch; if it has both arch tunnel and trapezoidal tunnel, we can use two different types of uniform height, one is utilized to compute the arch section, the other is used to determine the trapezoidal section of tunnel.

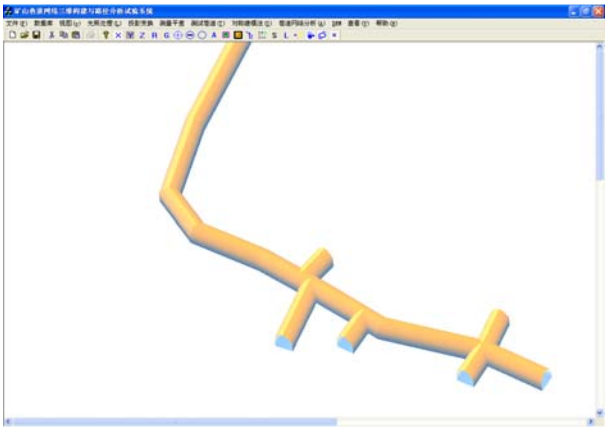
IV. Conclusion

The modeling steps of tunnel network are following:

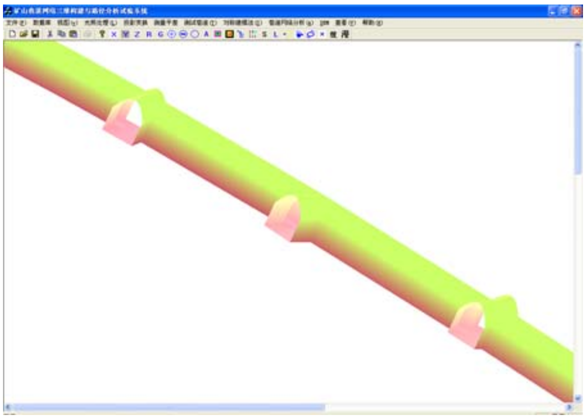
Step1: The whole skeleton model of tunnel network is subdivided into PART-ONE (composed of single-tunnels) and PART-TWO (constituted by complex-tunnels).

Step2: The models of PART-ONE and PART-TWO would be constructed respectively.

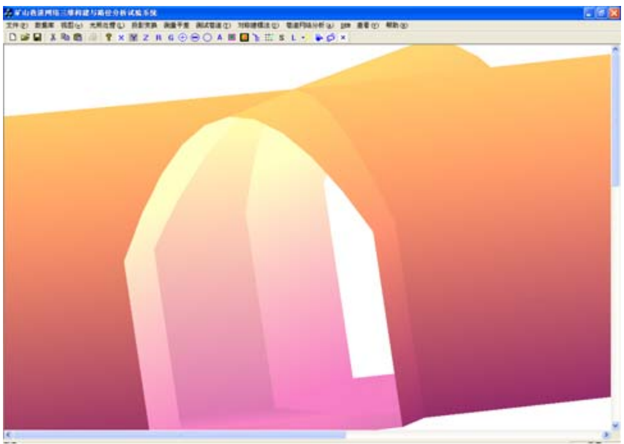
Step3: The 3D tunnel network model would be build by integrating the PART-ONE and PART-TWO. The tunnel models constructed by using above modeling methods are showing in Fig12. Fig.12 (a), Fig.12 (b) and Fig.12(c) are 3D models from different views. Fig.12 (d) is wireframe model of the part tunnel network.



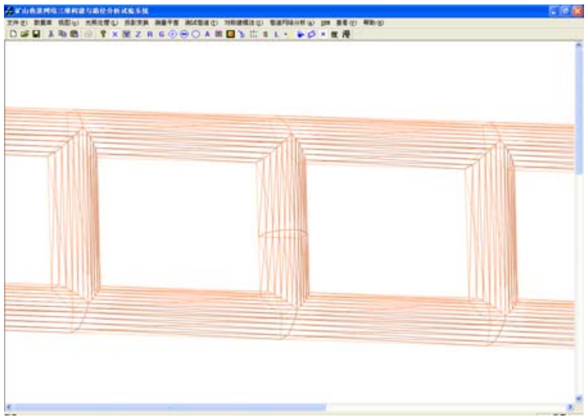
(a)3D tunnel



(b) 3D tunnel model (from different views)



(c) 3D tunnel model after zoom in



(d) 3D wireframe model

Fig. 12. 3D tunnel network model

We utilize Windows XP as the platform, MS Visual C++6.0 as development tools, and use OpenGL graphics package for the graphic processing function display tools, the experimental system of three-dimensional tunnel network modeling was designed and developed according to above mentioned methods (midpoint interpolation method, directed method of double nodes, arch uniform height method). Actual mining data are as instance, the experimental system has been tested, and it is shown that the paper verifies the practicality and effectiveness of research. The next work is that we will do more time for spatial analysis on the basis of 3D tunnel network model. It will give the make-decision for the mine production and mine safety.

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