Paper No. 34

ISMS 2016

3D geological modelling method based on hybrid data model

Xue-xi Chen [a,*], De-fu Che [b]

[a] Department of Safety, North China Institute of Science and Technology, Beijing, China, 101601
[b] Center for RS/GPS/GIS and Digital Mine, Northeastern University, Shenyang, Liaoning, China, 110004

ABSTRACT
Based on a comprehensive analysis of research findings using a 3D geological model made by predecessors, a new method using a hybrid data model is proposed to construct 3D geological models. This method takes borehole as its main modelling data source. The modelling process is comprised of the following steps: 1) generate the triangle irregular network (TIN) adhering to the Delaunay's law of ground surface according to borehole's collar data, 2) down the borehole extend each triangle of TIN into generalized tri-prism (GTP) with knowledge inference rule, 3) convert GTP model into tetrahedral network (TEN) model or boundary representation (B-reps) model according to a certain conversion algorithm. This mixed modelling method integrates the advantages of TIN, GTP, TEN and B-reps model. The model is not convenient for updating data dynamically, but makes it easy to construct 3D geological models, carry out visualization and spatial analysis, and extend the applicable scope of 3D geological models. Based on the constructed 3D geological model in Central Business District (CBD), Beijing, some engineering applications including arbitrary cutting, virtual excavation design, virtual wandering, and others are demonstrated. The flexibility and practicality of this modelling method is tested.
KEYWORDS: borehole data; 3D geological modelling; hybrid data model; knowledge inference rule; engineering application

1. INTRODUCTION

In recent years there has been an increased demand for simulating 3D geological information in mine, geology, environment, and geotechnical engineering. This has promoted research on 3D geological modelling and its application (Cao and Wang, 2004). Many scholars have put forward their respective 3D geological models, such as triangle irregular network (TIN) model (Lemon and Jones, 2003), boundary representation (B-reps) model (Wang, 2003; Cheng et al., 2004), tetrahedral network (TEN) model (Chen, 1995), tri-prism (TP) model (Gong et al. 2004; Zhang and Bai, 2001; Rui et al., 2004), and generalized tri-prism (GTP) model (Wu, 2004). Although TIN modelling is mainly used to describe the interface of geological bodies and is convenient to show and update data, it cannot describe the internal properties of geological mass. B-reps model records all the spatial data that constitutes a geological entity by complete vector structure and makes it easy to carry out spatial query and topology analysis, but it inconvenient for describing a geological entity accurately with a curved surface. TEN modelling has advantages in quick geometry shows and transformation and visualization for complex geological entities. However, it produces a great deal of redundant data when describing stratified geological bodies due to the complex construction algorithm. TP models and GTP models are easily to build and give consideration to both interface and internal properties. However, section visualization is more complicated, with a great number of deformation triangular prisms produced in the process of repeated free cutting.

Thus, a new method using a hybrid data model to construct 3D geological models is proposed to solve the problems discussed above. The first step is to generate ground surface TIN according to Delaunay's law based on borehole's collar data and to establish basic topology relationship among boreholes. The second step is to extend TIN triangle into GTP down the borehole with certain rules, to build the overall described model of the geological body. The third step is to convert GTP into TEN or B-reps via a corresponding conversion algorithm for visualization operation and spatial analysis. This mixed modelling method integrates the corresponding advantages of each model, such as convenient data updates for TIN, simple construction algorithm for GTP, convenient visualization operation for TEN, and spatial query for B-reps, making up for the defects of each single model.

2. 3D GEOLOGICAL MODEL BASED ON HYBRID DATA MODEL

*Corresponding author – email: xuexichen1210@163.com

2.1 3D Geological Model

The 3D geological model based on hybrid data model was designed for practical application, as is shown in Figure 1. This model includes such models as TIN, GTP, TEN, and B-reps and abstract geometry elements such as node, edge, arc, triangle, super-face, GTP, tetrahedron, and super-body. The component elements of B-reps such as node, arc, super-face, and super-body are called boundary geometry elements. These kinds of elements are mainly used to express topology relationships between geological entities. Node, edge, triangle, GTP, and tetrahedron are called volume geometry elements. Unlike boundary geometry elements, they are mainly used to express geometry topology structure change in the interior of geological entities. This model also defines constraints between geometry modelling elements that not only are the theoretical basis for spatial analysis, 3D visualization, and 3D query in 3D models, but also a guarantee of unity, correctness, and uniqueness for 3D geometry object reconstruction.

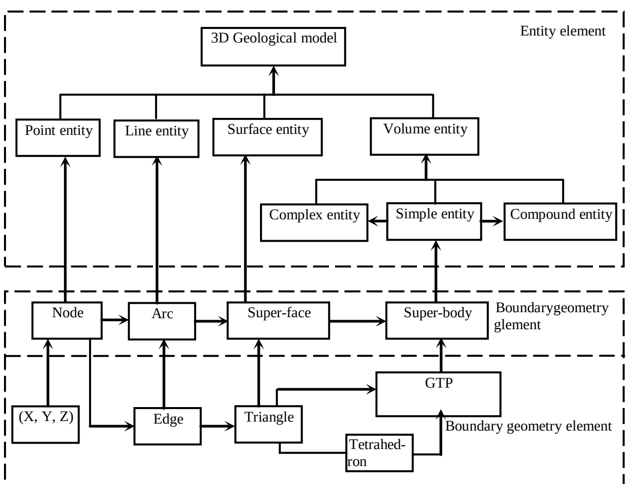

Figure 1: 3D geological model based on hybrid data model.

Geological entity is usually divided into the following: like point entity, line entity, surface entity, and volume entity. For volume entity, it can be divided further into three tapes: simple entity, complex entity, and compound entity. Complex entity is the combination of simple entities that belong to the same tape while compound entity is the gathering of simple entities affiliated to different types. Both complex entity and compound entity are defined by simple entity. Simple entity is defined by surface entity. Surface entity is defined by line entity. Line entity is defined by point entity. Obviously, this entity description method has a clear hierarchy and is convenient for organizational management.

2.2 Data Structure

According to object-oriented theory and methods, entity elements and geometry elements in Figure 1 can be designed to various object classes and be built to corresponding topology structures combined with a practical application. Their own member variables are thought of as data structure. In this paper only the main data structures of node, triangle, and GTP which have a close connection with modelling inference and algorithm efficiency are discussed.

Data structure of point:

```
class CBoreholePoint: public CObject   //point class
{long PointID;  // ID mark of point
char AttributeID;   //attribute mark
double x, y, z;  // x, y, z coordinate of point
int StratumNO;   //number of stratum
CString BoreholeNO; //number of borehole
CBoreholePoint*PrevPoint,*NextPoint;//previou-s point and next point in point chain
……}
```

Data structure of triangle:

```
class CTriangle: public CObject  //triangle class
{long TriangleID;  //ID mark of triangle
CTriEdge *Edge1, *Edge2, *Edge3; //three edges of triangle
CGtriprism *UpGtriprism, *DownGtriprism; // GTP of triangle up and down
CTriangle*PrevTriangle,*NextTriangle;//previou-s triangle and next triangle in triangle chain
……}
```

Data structure of the GTP:

```
Class CGtriprism: public CObject  // GTP class
{long GtriprismID; // ID mark of GTP
CTriangle *UpTriangle, *DownTriangle; // triangle at top and bottom of GTP
long TENDivNO; //code of sectioning the GTP into tetrahedron
……}
```

According to point data structure shown above, AttributeID is used to mark special points, such as the fault point. StratumNO is the code of stratum where the point is located. Its order increases progressively from ground surface to the lower. Attribute code of point is the lower adjacent stratum code. PrePoint and NextPoint are the previous point and the next point, respectively, on a point double linked list. On the one hand, point double linked lists are convenient for the retrieval of logical points of boreholes for extension. On the other hand, previous point and next point can be linked together when drawing under OpenGL driver, automatically solving deviation problems in a real situation. Therefore this double linked list helps improve modelling efficiency.

In data structure of triangle, PreTriangle and NextTriangle are the previous triangle and the next triangle on a triangle double linked list. Triangles whose three vertexes are subject to the same borehole number constitute of triangle double linked list. This double linked list efficiency can be improved when triangles extend into GTP along the borehole. In the data structure of GTP, TENDivNO is the section code. Based on this, it will section the GTP into tetrahedron by linking diagonals of quadrilateral at the side of GTP one by one.

3. 3D GEOLOGICAL MODELLING METHOD BASED ON HYBRID DATA MODEL

3.1 The Formation of Ground Surface TIN

The formation of ground surface TIN is the basis for mixed model construction. The process of regarding borehole's collar coordinates as data points and generating TIN according to Delaunay's law and establishing a basic topology relationship between boreholes is named the formation of ground surface TIN. The incremental insertion is one of the construction algorithms to generate Delaunay triangulation. The algorithm is suitable for ground surface modelling based on borehole data because of its simple principles. The basic steps are as follows (Wu et al., 1999). Firstly, define an initial polygon that contains all borehole data points. Secondly, construct an initial triangulation in the defined initial polygon, and then conduct iteration until all data are processed. The iteration should be as follows, to insert a P data point and to find the T triangle that contains P in the triangulation, then link P and the three vertexes of T to form a new triangle. Third, optimize triangulation using the Local Optimization Procedure (LOP) to meet Delaunay's law.

For fault ruptures above the ground, the constraint relationship between discrete points will be enhanced due to fault when constructing Delaunay triangulation at the orifice. It can be solved by viewing the fault line as a constraint and adopting an algorithm named constrained Delaunay triangulation. These kinds of algorithms mainly include constrain graph methods, divide-conquer algorithms, triangulation growth methods, encryption algorithms, and two-step methods. The diagonal exchanging algorithm that forcibly inserts constrained boundary is simpler, easier to realize, and is more practical than the other two-step methods (Li and Tan, 1999).

3.2 3D Geological Model Construction Method Based on the GTP

After the generation of TIN, the triangle can be extended down the borehole to form GTP. The main steps to form GTP are as follows.

1) Choose a triangle from TIN and set it to be the triangle of the first GTP.

2) As shown in Figure 2, a new triangle can be formed by extending three vertexes of previous triangles down the three boreholes according to stratum ID.

The stratum is formed in a sequence and always of different distribution map, which reflects ordinal relationship of abnormal stratums pinching out during geological formations. Besides, stratum can be broken and be constrained by the fault. Therefore, it is necessary to reflect this geologic structure rule when triangle extending down. In order to ensure correctness and uniqueness when reasoning the relationship mentioned above. The reasoning rules are as follows.

As shown in Figure 2(a), if none of three vertexes of the current extending triangle are the fault point, the next point of the corresponding borehole will be vertexes of a new triangle with the same code. As shown in Figure 2(b), once the code is different, vertex whose number is less than other's will be extended into a new triangle vertex along the corresponding borehole. Vertex whose number is bigger will be unchanged.

If the current extending triangle has one or two fault point(s) among the three vertexes, whether the attribute of next point of the rest of vertexes is the same as the attribute of fault point should be checked. If attribute is the same, fault point cannot be extended down regardless of number size until all the rest of the vertex extend down into the same attribute. Figure 2(c) shows that triangle 111 is extended down into triangle 221. The black circle dot represents fault point while the black triangle represents fault surface. Otherwise all vertexes can extend down based on number size. As is shown in Figure 2(c), triangle 222 extends down to form triangle 333.

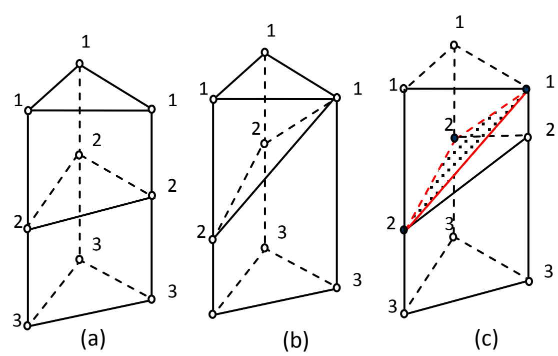

Figure 2: Down expanding rule of triangle.

In such situation as all current vertexes of the extending triangle are fault points, the way the triangle extends down to form a new triangle according to number size can be the same as the situation without any fault points. In Figure 2(c), triangle 221 is extended down to form triangle 222.

3) Construct GTP according to corresponding relationship between previous triangle and the next triangle on the triangle double linked list and borehole point list, then record reflected information and regard the next triangle as with the previous triangle.

4) Repeat step 2) and 3) until all vertexes of the previous triangle lie in the bottom of the borehole.

5) Repeat steps 1) to 4) until all TIN is traversed.

If there are new data about the borehole, only the local ground surface TIN should be modified and be extended down to generate new GTP. This method is convenient for dynamic modification. It can also automatically reason complex geological structures such as fault and pinch-out. This method has a simple construction algorithm.

3.3 Tetrahedron Generation and Boundary Conversion of GTP

After construction of the whole 3D geological model, it is necessary to transform the GTP model into a tetrahedron model or the B-reps model for visualization and engineering application analysis. The former is realized by the method named the smallest vertex identifier (Chen et al., 2004). Firstly, number each vertex of GTP uniformly for identification. This must meet the two following conditions. 1) The identification number is invariable and unique. 2) The identification numbers can be compared with each other. Secondly, the vertexes that have the smallest identification number are selected by comparing the identification numbers of four vertexes in each quadrangle at side of GTP, and then they are linked to the corresponding vertexes in the opposite face in order to finish tetrahedron division. To ensure that the geological body is described completely by GTP and to save memory space, it is not directly sectioned into a tetrahedron. Instead it will add tetrahedron division code to its data structure. Connection code of diagonal of the side face constitutes these codes in order, and each GTP element includes three mark bits, each of which has a corresponding connection way about the diagonal. Thus, tetrahedron division is finished by searching the identification number of GTP. This method has a certainty and is easy to program. What’s more, it does not need to store data of adjacent GTP elements for local operation. Only in this way, can a global unit be sectioned and compatible.

Boundary conversion is done through special data structure of GTP. According to topology relationship between GTPs, not only adjacent volume elements are easy to be found, but also boundary volume elements whose bottom triangle or side quadrangle is located in the boundary can be searched. For a boundary triangle, it will be added to a triangle-linked list expressed by an entity boundary. Boundary quadrangles should be sectioned into triangles by the smallest vertex identifier before being added to the linked list. The following are the procedures for boundary conversion. Firstly, initialize the triangle-linked list expressed by entity boundary to dynamically store s boundary triangle. Secondly, extract a GTP from the GTP linked list and search information as to adjacent volume elements according to the stored topology relationship among adjacent volume elements. If the top triangles or the bottom triangles are not the adjacent volume elements or the adjacent volume elements are of a different attribute, it will be added to the linked list. Side quadrangles in the same situation should be sectioned into two triangles by the smallest vertex identifier before being added to the linked list. Lastly, the second step should be repeated until the GTP linked list is fully processed.

Entity boundary expression not only contributes to analysis on spatial topology relationships between geological entities, but also simplifies visualization operations for those geological entities whose internal information is not needed.

4. ENGINEERING APPLICATION CASE

Based on modelling methods mentioned above, the 3D geological modelling system GeoMo^{3D} was developed by using VC^{++}6.0 and the 3D graphic drawing tool OpenGL. An engineering application experiment was carried out and combined with actual geological exploration data from the Beijing Central Business District. The studies area contained a total of 46 primitive boreholes. The stratum is divided into 10 layers, as is shown in Figure 3(a). Because a 3D geological model based on a hybrid data model can unify all surfaces of volume elements to be boundary triangles and can transform all volume elements into tetrahedrons, it is easier to perform normal analyses such as a random section plane or layer display. Above all, it is possible to conduct special visualization operations, such as virtual excavation and spatial query. Figure 3(b) is a fence diagram that is found by repeatedly sectioning the tetrahedron model. It clearly shows every internal detail of the geological model, which helps to learn the geological structure. As shown in Figure 3(c), by designing a virtual tunnel in the tetrahedron model and intersecting, we can observe the distribution situation of exposed geological structures after excavation. Figure 3(d) shows that we can study the spatial relationships between tunnel and stratum using the B-reps model. It can provide reference information for excavation design and influence analysis.

5. CONCLUSIONS

3D geological models can guide geological analysis in relevant application domains. This has practical value for project planning, excavation design, environmental impact analysis, and disaster prevention and reduction. Based on a comprehensive analysis of previous research findings related to 3D geological models, a new hybrid data model was proposed to construct a 3D geological model. It is not only convenient to dynamically update data, but also makes it easy to construct 3D geological models and to carry out visualization and spatial analysis. It automatically reasons complex geological structures such as faults and pinch-out, extending the applicable scope of 3D geological models. The successful development and application of the 3D geological modelling system GeoMo^{3D} demonstrates that this new modelling method has flexibility and practicability. There is further work to be done in order to better serve relevant application fields of geological engineering. For example, to improve the functions such as virtual design of geological bodies, attribute query and spatial analysis and inference are necessary.

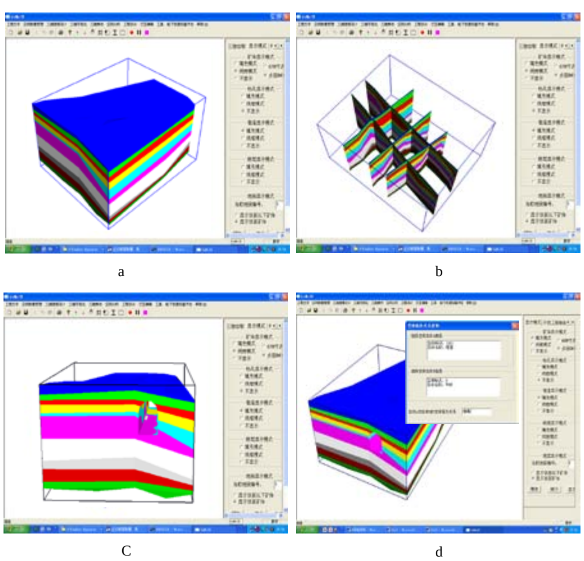

Figure 3: Application case of 3D geological modelling.

6. REFERENCES

Cao D Y, Wang Z G. (2004). Direct 3D-interation in 3D geological model visualization. Journal of China University of Mining and Technology. Volume 33, No. 4, pp. 384-387

Cheng P G, Liu S H, Wang W, et al. (2004). Study and application of a new 3D geological model construction method. Journal of Jilin University(Earth Science Edition). Volume 34, No. 2, pp. 309-313

Chen X Y. (1995). A workstation for three-dimensional spatial data research. In: The Fourth International Symposium of LIESMARS, Wuhan, pp. 42-51

Chen X. X, Wu L. X, Shi W. Z, et al. (2004). Diagonal generation by Smallest Vertex Identifier in GTP model. Geography and Geo-Information Science. Volume 20, No. 3, pp. 17-21

Gong J Y, Cheng P G, Wang Y D. (2004).Three-dimensional modeling and application in geological exploration engineering. Computers and Geosciences. Volume 30, No. 4, pp. 391-404.

Lemon A M, Jones N L. (2003). Building solid models from boreholes and user-defined cross-section. Computers and Geosciences. Volume 29, No. 3, pp. 547-555

Li L X, Tan J R. (1999). Multiple diagonal exchanging algorithm for inserting constrained boundary in constrained Delaunay triangulation. Chinese Journal of Computers. Volume 2, No. 10, pp. 1115-1118

Rui X P, Yang Y G, Xi Y T. (2004). Study on visualization of 3D stratum based on triangular prism. Journal of China University of Mining & Technology. Volume 33, No. 5, pp. 584-588

Wang C X. (2003). Study on geological modeling in 3D strata visualization. Chinese Journal of Rock Mechanics and Engineering. Volume 22, No. 10, pp. 1722-1726

Wu L X. (2004).Topological relations embodied in a generalized tri-prism(GTP) model for a 3D geoscience modeling system. Computers and Geosciences. Volume 30, No. 4, pp. 405-418

Wu X B, Wang S X, Xiao C S. (1999). A new study of Delaunay triangulation creation. Acta Geodaetica et Cartographica Sinica. Volume 28, No. 1, pp. 28-35

Zhang Y, Bai S W. (2001). An approach of 3D stratum modeling based on tri-prism volume elements. Journal of Image and Graphics. Volume 6, No. 3, pp. 285-290