

QTPV Data Model and Algorithm and Its Application to Geological Exploration Engineering

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ABSTRACT 3D spatial data model and simulating are the core of 3D GIS can be adopted in different domains. A data model based on Quasi Tri Prism Volume (QTPV) has been proposed. QTPV definition and its special cases have been discussed. Using QTPV and its special cases, irregular natural geological bodies and regular subsurface engineering can be described efficiently. The proposed model is composed of five primitives and six objects. Data structures and topological relationship of the fives primitives and three objects describing stratigraphy are designed in detail. Some schemes are designed for the QTPV modelling of stratigraphy and subsurface engineering according to modelling data. The model manipulation method of QTPV cutting by an arbitrary plane is discussed. Using VC++ 6.0 programming language integrated with SQL database and OpenGL graphic library under windows environment, a system prototype 3DGeoM V has been developed. The experiment result shows that the QTPV model is feasible and efficient in modelling subsurface engineering.

KEY WORDS GIS; QTPV; data model; algorithms; visualization; subsurface engineering

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Introduction

3D spatial data model and modeling are the core of 3D GIS application in different domains. There are many 3D data models or data structures that had been investigated in the past years. For instance, Molenaar proposed 3D Format Data Structure (3D FDS) based on 2D topology data structure^[1], Pilout and CHEN^[2,3] have studied Tetrahedral Network (TEN) model, LI and SHI proposed hybrid data model called Octree TEN model^[4] and TIN-Octree model^[5], GONG proposed object oriented 3D data model which integrates raster and vector data structure^[6]. In urban 3D modeling, Zlatanova proposed a simplified spatial model (SSM)^[7], SUN proposed a 3D spatial data model based on surface triangled partition^[8], and so on. In

terms of geometry, all of 3D data models can be classified into the following three types: surface based (3D FDS, B Rep), volume based (CSG, TEN) and hybrids (Octree TEN, TIN-Octree). These models have their own features and suitability. Some scholars have analyzed and compared these models in terms of application domain, geometric and technical validity, efficiency of geometric algorithm, accuracy, and need for storage^[9-13].

In fact, many spatial objects could be represented only in 3D volume. The modeling method in 3D volume has been used more and more widely. The basic volumes in common use are hexahedron, four prism cone, tetrahedron, and tri prism. The geological bodies are complex. It is difficult to use regular hexahedron as the basic volume element and to represent boundary accurately. Tetrahedron is agile for representing

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complex geological bodies, but it will produce the huge data redundancy, and it is difficult for the algorithm to create a tetrahedron. In recent years, some scholars have investigated 3D data model based on tri prism volume. For example, ZHANG studied the normal tri prism volume in 3D stratum modeling, and discussed the data structure and cutting algorithm^[14]. GONG and QI introduced the irregular tri prism volume and discussed its data structures, topological relationship, but the modeling method and spatial manipulation^[15, 16]. Quasi tri prism volume (QTPV), compared with hexahedron, four prism cone and tetrahedron, is a smart volume and has some advantages in representing complex geological bodies.

1 QTPV data model

1.1 Quasi tri prism volume(QTPV)

Normal Tri Prism Volume (NTPV) is a volume element constructed by a triangle extended a distance along the vertical direction(see Fig. 1 (a)). Obviously, in the view of graph theory, an NTPV is an aggregation, which consists of vertices V , edges E , triangles T and side quadrilateral Q , i.e.

$$NTPV = \{V, E, T, Q\}$$

where

$$V = \{V_1, V_2, V_3, V_4, V_5, V_6\}$$

$$E = \{E_{12}, E_{23}, E_{21}, E_{45}, E_{56}, E_{64}, E_{14}, E_{25}, E_{36}\}$$

$$T = \{T_{123}, T_{456}\}$$

$$Q = \{Q_{1254}, Q_{2365}, Q_{3145}\}$$

and the constrained conditions

- ① $V_1(x, y)=V_4(x, y), V_2(x, y)=V_5(x, y), V_3(x, y)=V_6(x, y)$
- ② $E_{14} // E_{25} // E_{36}$
- ③ Q_{1254}, Q_{2365} and Q_{3145} are plane quadrilateral.

NTPV is a perfect volume and exists when the vertices distribution in regular location. In subsurface engineering, although the borehole is designed into vertical or with a special azimuth and inclination but the borehole center line does not always obey the design location because of the influence of rock pressure. That is to say, the

vertices which borehole cutting stratum interfaces are not in a vertical line and their horizontal coordinates of the vertices are different. When using these vertices to construct a tri prism volume, we cannot get NTPV but QTPV(see Fig. 1 (b)). QTPV has the same structure and topological relationship with NTPV, but it does not obey the constrained conditions. Obviously, being similar to tetrahedron, QTPV can be used as the basic volume element to design 3D spatial data model.

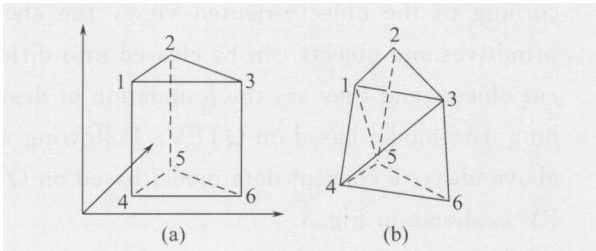


Fig. 1 Tri prism volume

In practical applications, vertices may be superposition and then there would be four types of QTPVs as shown in Fig. 2. Fig. 2(a) and Fig. 2(d) are tetrahedron, Fig. 2(b) is a four prism cone. It is obvious that no matter how complex a geological body is, it can be described by using a QTPV with different sizes and shapes. The extrusive advantage of QTPV is that only one data structure but not the hybrid data structure, such as Octree TEN, will be used to represent a geological body.

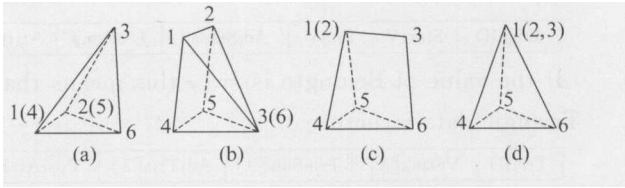


Fig. 2 The special cases of QTPV

1.2 Data model based on QTPV

The feature of the object oriented modeling (OOM) is that no matter how complex a spatial entity is, it can be described by an object. By use of the object identity, the relationships among objects can be created. A QTPV has five primitives, i.e. vertex, segment (edge, triangle side), triangle, side quadrilateral and QTPV.

They are the basic elements to construct elementary objects, which are point object, line object, surface object and body object. There are many types of spatial objects in subsurface engineering domain. For example, borehole is a line object which is composed of segments, interface or fault is a surface object which is composed of triangles or side quadrilateral (triangled), geological body inner is a body object and composed of QTPVs, gas rallying point and sample point are point objects and represented by a vertex. According to the object oriented view, the above primitives and objects can be classed into different objects and they are the foundation of designing data model based on QTPV. Following the above ideas, a concept data model based on QTPV is shown in Fig. 3.

1.3 Data structure

For the purpose of constructing 3D geological model with spatial location, topological relationship and attribute information, and of saving storage memory, more detail data structures of the primitives and elementary objects should be

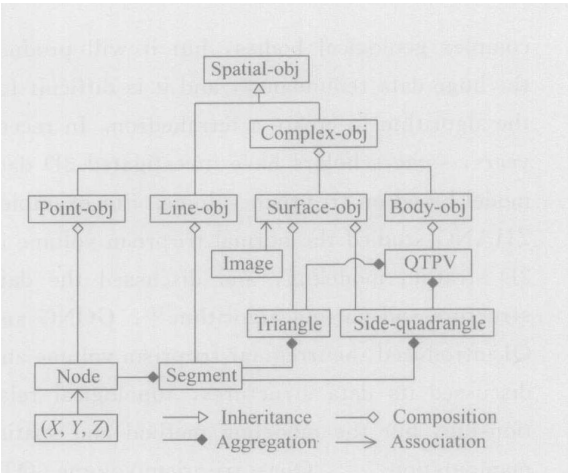


Fig. 3 Conceptual model based on QTPV

designed. The data structures include vertex, triangle side, edge, triangle, side quadrilateral, QTPV. Meanwhile, for the purpose of representation of 3D stratigraphy, bodies and their topological relationship, several data structures on TIN, interface (composed of TINs), geological body and image or texture should be designed. Here we only give six data structures definitions composed of a QTPV and three data structures formed a geological body.

Vertex data structure

VertexID	x	y	z	Attribute	IsBelong	Type	CutFlag
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“IsBelong” means what geological objects belong to; “Type” means the vertex is the original captured point or interpolation point.

Triangle side data structure

TriasideID	StartV	EndV	LeftTria	RightTria	UpSQquad	DownSQquad	Cutflag	CutCoord
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Edge data structure

EdgeID	StartV	EndV	AdjSQquad	IsBelong	Attribute	Cutflag	CutCoord
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If the value of Belongto is -1, this means that the edge length is zero and that it is a tine point.

Triangle data structure

TriasID	Vertex[3]	TriasSide[3]	AdjTria[3]	PosiAttr	PosiQTPV	NegaAttr	NegaQTPV	IsBelong
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Side quadrilateral data structure

SquadID	Vertex[4]	TriasSide[2]	Edge[2]	PosiQTPV	NegaQTPV	IsBelong	PartType
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QTPV data structure

QTPVID	Vertex[6]	Tria[2]	SQuad[3]	AdjPrism[5]	GeoObjType	IsBelong	CutFlag	CutMark[5]	PartitionCode
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TIN data structure

TINID	Type	TriaNum	Triangles	PosiGeoObj	NegaGeoObj	Attribute	IsBelong
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Stratigraphy or fault interface data structure

StratID	Type	MinBox	TINNum	TINs	PosiGeoObjNum	PosiGeoObjs	NegaGeoObjNum	NegaGeoObjs	Attribute	IsBelong
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Geological objects (stratigraphy, ore deposit, fault, folder, etc.) data structure

GeoObjID	GeoObjType	MinBox	StratIDs	QTPVs	AdjGeoObjs	BoundTINObjs	Attribute
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2 Algorithms of subsurface objects modelling

2.1 Stratigraphy modelling

With the different modeling data, stratigraphy modeling method can be classified into modeling using interpolation points of stratum interface and modeling using original borehole captured data.

1) Modeling using interpolation points of interface. By this modeling method NTPV will be constructed. The main process includes three steps. Firstly, to edit borehole data and to divide them into different layers, according to their lithology and height. Secondly, to carry on stratum interfaces curved face interpolation and build regular multi DEMs. These DEMs should have coincident frame of reference, for convenience of modeling. Lastly, to triangulate grids and to construct NTPVs according to corresponding two triangles located in adjacent stratum interfaces. If two interfaces are intersectant in a grid, then some special processes, such as calculating cross line, triangulating grid and constructing NTPVs, should be done (see Fig. 4).

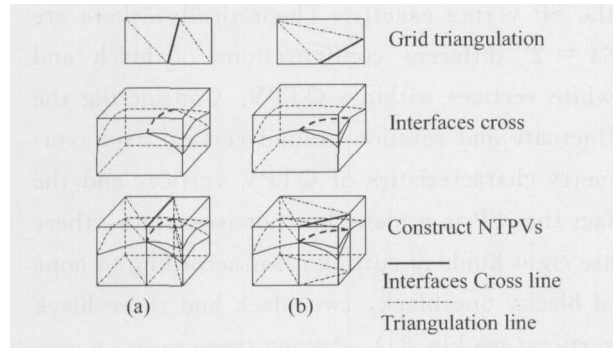


Fig. 4 Constructing QTPVs with interfaces crossed grid

2) Modeling using borehole captured data: In this case, the constructed model are QTPVs. This modeling is similar to Delaunay triangle network constructing. The latter is for constructing intersecting points belonging to the same interface into a TIN, while the former is for constructing a series of QTPVs between adjacent interfaces. Given the data structure of a borehole,

the curve point consists of 3D coordinates and an adjacent attribute code. The adjacent attribute code is the down adjacent geological body attribute of a point, and is numbered in increasing order from the earth's surface to the subsurface. The main steps in the modeling are as follows.

① Create a triangle (up triangle) by use of the methods of constructing a Delaunay TIN according to the borehole location points on the earth surface. This triangle is the up triangle of a QTPV, and the vertices of this triangle correspond to three boreholes.

② Expand a new triangle (down triangle) down along the three boreholes according to the adjacent attribute code of the up triangle points, as shown in Fig. 5. If their codes are the same, the new triangle points are the next points along the boreholes, as Fig. 5(a) shows. If their codes are different, in the borehole with a smaller code (e. g. *a*), the new triangle points are the next points along the boreholes. In the borehole with a larger code (e. g. *b* or *c*), the new triangle points will not change, as Fig. 5(b)–(d) shows.

③ Construct a QTPV according to the up triangle and down triangle, then change the down triangle into the up triangle.

④ Repeat steps ② and ③ until all the up triangle points are at the bottom of the three boreholes.

⑤ Expand the triangle along the triangle side on the earth's surface by the methods of constructing a Delaunay TIN. Repeat steps ② ④ and construct all of the QTPVs.

⑥ If all of the points are constructed into the triangles, stop the modeling process. Otherwise, go to step ⑤.

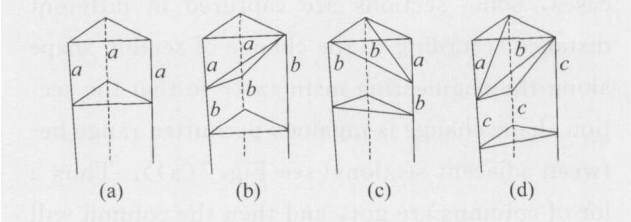


Fig. 5 Down expansion of QTPV

2.2 Deposit local modelling

Suppose that a stratigraphy model has been

constructed. There is a deposit *B* located in stratum *A*(see Fig. 6). In order to maintaining the constructed topological relationship of QTPVs model we should adopt local modelling method. How to insert deposit *B* into stratum *A*? Firstly, creating vertical lines passing through tine points (*a*, *b*, *c*, *d*), and the lines intersect with adjacent stratum interfaces and get some intersection points (*a'*, *a''*, *b'*, *b''*, ...)(see Fig. 6(a)). Secondly, local modelling should be conducted in stratum *A*. it includes two steps: triangulation and construction of QTPVs. After the local modelling, the topological relationship between the local model and the adjacent QTPVs should be processed. This process is divided into two aspects, i.e. flank relationship maintenance and fluctuate relationship maintenance.

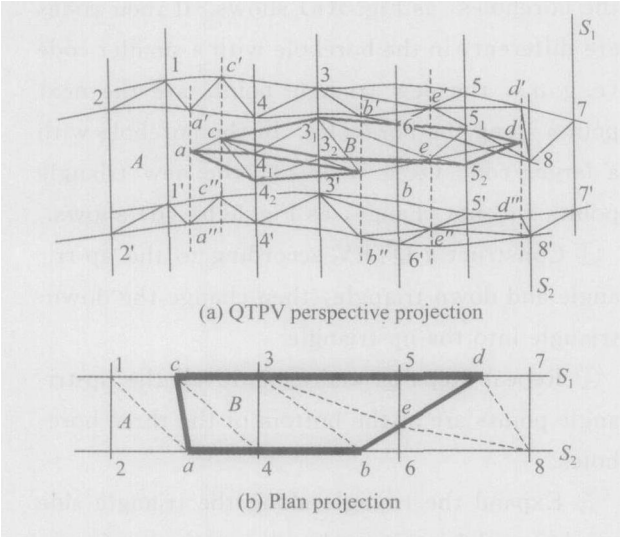


Fig. 6 Subsurface engineering constructed with QTPV

2.3 Subsurface engineering modelling

Subsurface engineering, such as silo, laneway, mining area, etc. always are regular. In these cases, some sections are captured in different distance according to the change of section shape along the engineering main axis, so that the section shape change is ingained permitted range between adjacent sections(see Fig. 7(a)). Thus a lot of columns are got, and then the column will be partitioned QTPVs. Different partitions should be adopted according to the section shape. For example, Fig. 6(b) is a circle laneway, adjacent sections have the same shape, so in

the circle section, take the centre of a circle as center point, construct a series of triangles every other definite central angle, and then construct QTPVs by connecting corresponding triangles in adjacent sections. Figs. 7(c)-(e) show different cases of constructing QTPVs on laneways.

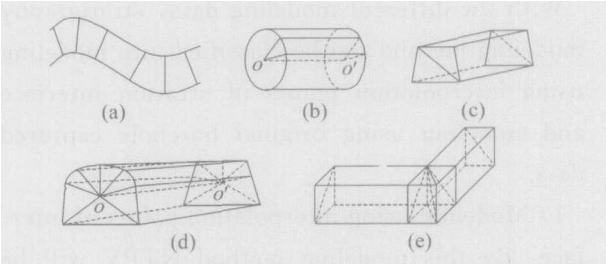


Fig. 7 Subsurface engineering construct QTPV

3 Algorithm of model cutting

Geological fence sections are a conventional method for geologist to understand the geological information. To extract data of a section from the geological model, one always cuts the model along an arbitrary plane. If using a section plane (SP) to cut a QTPV, many different situations will be had. The QTPV vertices can be classified into three kinds: black, white and triangle vertex. Black vertex means that it locates at the positive side of the SP, white vertex at the negative side and triangle vertex on the SP vertex exactly. Theoretically, there are $64=2^6$ different configurations of black and white vertices within a QTPV. Considering the fluctuate and rotation around vertical axis symmetry characteristics of QTPV vertices and the fact that SP is a plane but not isosurface, there are eight kinds of cutting cases according to none of black, one black, two black and three black vertices (see Fig. 8)). Among these cases, a special case that the side quadrilateral of QTPV may be convex or concave has been taken into account, i.e. two black vertices lying in the diagonal of convex or concave quadrilateral are treated separately (see Fig. 8 (e) and Fig. 8(f)). Because the side quadrilateral may not be a plane, the shade polygon vertices are points of SP intersect the sides (prim edge, triangle side) of a QTPV. In practical application, the points of SP intersecting the diago

nal of side quadrilateral should be calculated if we pay attention to a single QTPV.

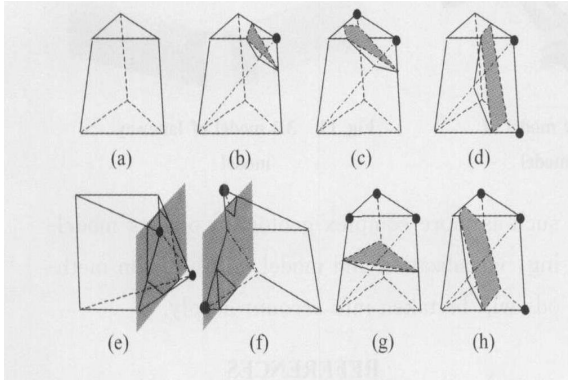


Fig. 8 General cutting cases

Generally speaking, the result of a plane cutting a 3D model based on QTPV is a profile. The processes of using an SP to cut the model and form a profile are as follows.

① To initialize a stack S . Use S to store the identity of a QTPV intersected with the SP. Initialize a queue Q . Use Q to store the triangles of the profile.

② To get a QTPV from the volume element list (VEL) and judge whether it intersects with the SP or not.

③ If the QTPV does not intersect with the SP, give the QTPV a process mark in the VEL. Find the next QTPV without a process mark. When such a QTPV is obtained, push it into stack S .

④ To pop a QTPV from stack S . Calculate the sub polygon formed by the SP that intersects with the QTPV according to the topologic relationship among the QTPV geometrical elements. Partition the sub polygon into triangles and input them into the queue Q . Give the QTPV a process mark in VEL. Find an adjacent QTPV that does not contain this mark and judge whether it intersects with the SP or not. If it does, then push it into stack S .

⑤ To repeat step ④ until stack S is empty and all of the QTPVs in the VEL have been marked "processed".

After the above processes a profile has been formed and it is consisted of the triangles in the queue Q .

4 Application to stratigraphy and geological exploration engineering

Based on the proposed QTPV model, modeling methods and the model cutting process, using VC⁺⁺ 6.0 program design language and integrating SQL database and OpenGL graphic library under windows environment, we have developed a system prototype named the 3D Geological Modeling and Visualization (3DGeoMV) system. 3DGeoMV includes the following functions: data input, data edit in 2D profile, stratigraphy and laneway QTPV 3D modeling based on the borehole data and section data of laneway, 3D fence model of stratigraphy created by using different arbitrary plane to cut the model, visualization of all kinds of models and results, lamp house control, model rotation and zoom, and so on.

Experimental data is composed of a set of real captured data of boreholes and a set of simulation data of laneway. Borehole data come from a geological exploration area in Inner Mongolia, China. There are 42 original boreholes and 5 strata. Because these strata are thin, for the purpose of increasing effect of vision, the height values of boreholes are multiplied by a factor more than 1.0. Meanwhile, an interlayer is added so as to validate modeling function of 3DGeoMV. For obtaining a smooth stratigraphy model, an interpolation process by use of curve fitting method has been done between two sparse boreholes in a profile. After interpolation there are 212 virtual (interpolation) and real boreholes in all. The wire frame graph representation about the stratigraphy model is shown in Fig. 9. Fig. 10 shows 3D fence model of stratigraphy model. Modelling result of a set of simulation laneway data is shown in Fig. 11.

5 Conclusions

Subsurfaces are in three dimensional space and need real 3D data model to represent. For the

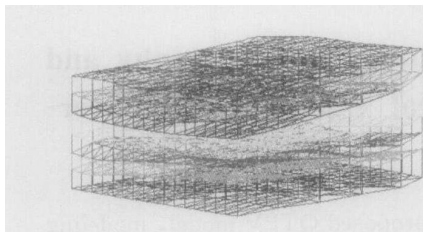


Fig. 9 Wire frame graph of stratigraphy model

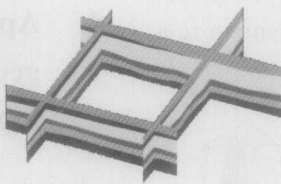


Fig. 10 3D fence model of stratigraphy model

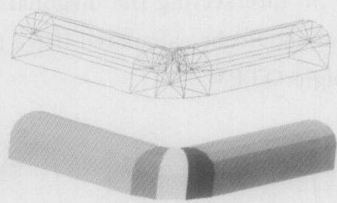


Fig. 11 3D model of laneway model

purpose of describing different subsurface objects many 3D data models and data structures have been investigated. Our experimental result shows that the proposed 3D data model based on QTPV are feasible and efficient for modeling irregular geological objects and regular subsurface engineering. On the basis of the above result, the following conclusions are drawn.

① 3D QTPV data model has the ability to model the real 3D objects with regular and irregular shape. Although it is a volume model, but we can also get the surface model of the modeled objects by designing a special algorithm. For example, seek all the triangles, which has the same positive negative attribute while the attribute of positive side and negative side are different for one triangle.

② The QTPV data structure not only overcome the strict data restriction, i. e. the captured points should be located on a regular 3D grid, but also overcome the disadvantages of TEN, such as huge data volume, complex topological relationship and complex modeling algorithm.

③ The complex geological objects could be described by use of only QTPV data structure but hybrid data structure. Thus it is convenient to database management.

④ Adding attribute structure on the vertices and attaching digitized borehole log to the edges of QTPV, we can get the inner attribute of geological objects at any position by linear or finite element interpolation methods. Thus the real 3D management of geological bodies can be achieved.

Our application cases are only stratigraphy modeling according to real borehole captured da

ta and simulated laneway data. Further works such as more complex geological objects modeling, visualization and model manipulation methods will be taken into account deeply.

REFERENCES

- 1 Molenaar M (1992) A topology for 3D vector maps. *ITC Journal*, (1): 25 33
- 2 Pilout M, Tempfli K, Molenaar M (1994) A tetrahedron based on 3D vector data model for geoinformation. In: Molenaar M, de Hoop S (eds). *Advanced Geographic Data Modeling*. Delft, The Netherlands: Netherlands Geodetic Commission. 129 140
- 3 Chen X Y, Doihara H, Nasu M (1995) A workstation for three dimensional spatial data research. In: Chen J ed. *Towards Three Dimensional, Temporal and Dynamic Spatial Data Modeling and Analysis*. Wuhan, China: LIESMARS. 42 51
- 4 Li D R, Li Q Q (1997) A study on hybrid data structure in 3D GIS. *Acta Geodatica et Cartographica Sinica*, 26 (2): 128 133 (in Chinese)
- 5 Shi W Z (1996) A hybrid model for 3D GIS. *Geoinformatics*, (1): 400 409
- 6 Gong J Y, Xia Z G (1997) An integrated data model in three dimensional GIS. *Journal of Wuhan Technical University of Surveying and Mapping*, 22 (1): 7 15 (in Chinese)
- 7 Zlatanova S (2000) 3D GIS for urban development: [Ph. D dissertation]. Netherlands: ITC.
- 8 Sun M, Chen J, Zhang X Z (2000) A 3D CM data model based on surface partition. *Acta Geodatica et Cartographica Sinica*, 29 (3): 257 265 (in Chinese)
- 9 Houlding S W (1994) 3D geoscience modeling computer techniques for geological characterization. New York: Springer Verlag.
- 10 Breuning M (1996) Integration of spatial information for geo information systems: lecture notes in earth sciences. Berlin: Springer.
- 11 Fritsch D (1996) Three dimensional geographic information system status and prospects. *The International*

- Archives of Photogrammetry and Remote Sensing, Vienna, Austria.
- 12 Cheng P G, Gong J Y (2001) Design of three dimensional spatial data model and its data structure in geological exploration engineering. *Acta Geodatica et Cartographica Sinica*, 30(1): 74-81 (in Chinese)
 - 13 Wu L X, Shi W Z, Gold C (2003) Spatial modeling technologies for 3D GIS and 3D GMS. *Geography and Geo Information Science*, 19(1): 5-11(in Chinese)
 - 14 Zhang Y, Bai S W (2001) An approach of 3D stratum modeling based on tri prism volume elements. *Journal of Image and Graphics*, 6 (3): 285-290 (in Chinese)
 - 15 Gong J Y, Cheng P G (2002) Study on 3D modeling and visualization in geological exploration engineering. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Xi'an.
 - 16 Qi A W, Wu L X, Li B et al. (2002) Analogic tri prism: a new 3D geological modeling methodology. *Journal of China Coal Society*, 27 (2): 158-163(in Chinese)

Notes to Contributors

Contributions are welcomed on one of the following subjects or in related areas:

- | | | |
|-------------|------------------|--------------------------|
| · GIS | · Geodynamic | · Physical geo surveying |
| · GPS | · Geo surveying | · Engineering surveying |
| · RS | · Photogrammetry | · Mapping apparatus |
| · Cartology | · Graphics | |

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