

# 3D SPATIAL DATA MODEL BASED ON QUASI TRI-PRISM VOLUME AND ITS APPLICATION IN SUBSURFACE ENGINEERING

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## Commission IV, WG IV/1

**KEYWORDS:** GIS, Modeling, Data Structures, Method, System, Visualization, Engineering, Application

### ABSTRACT:

3D spatial data model and modelling are the core of 3D GIS theory and applications. For this reason, a data model based on Quasi Tri-Prism Volume (QTPV) has been presented in this paper. The QTPV definition and its special cases due to vertices of QTPV may be superposition have been considered. The proposed model is composed of five primitives and six objects. The primitives consist of vertex, segment (edge, triangle side), triangle, side quadrilateral, and QTPV, and the objects consist of point, line, face, solid, complex, and spatial object. Their data structures and topology describing stratigraphy are designed and implemented in detail. Some modelling methods are designed for the purposes of the QTPV modelling of stratigraphy and subsurface engineering according to the modelling data. The model manipulation for the QTPV cutting using an arbitrary plane is discussed. We implemented a system prototype, called 3DGeoMV, using VC++6.0 programming language integrated with SQL database and OpenGL graphic library under the windows environment. The real data from the boreholes, which located at a geological exploration area in China's Inner Mongolia, is used to verify the developed model and the developed system prototype. The experiment result demonstrates that the QTPV model is feasible and efficient for applications in the subsurface engineering. With applications of the presented QTPV, irregular natural geological bodies and/or regular subsurface engineering can be represented efficiently.

## 1. INTRODUCTION

3D spatial data model and modeling are the core of 3D GIS theory and applications in different domains. Many 3D data models or data structures have been investigated in the past years. For instance, Molenaar proposed a 3D Format Data Structure (3D FDS) based on 2D topological data structure (Molenaar, 1992). Pilout (1993) and Chen (1995) have researched Tetrahedral Network (TEN) model. Li and Shi proposed hybrid data model known as Octree-TEN model (Li, 1997) and TIN-Octree model (Shi, 1996), Gong (1997) proposed an object-oriented 3D data model integrated raster and vector data structure. In urban 3D model area, Zlatanova (2000) proposed a Simplified Spatial Model (SSM), and Sun (2000) proposed a 3D spatial data model based on surface triangular partition. From a geometric point of view, these 3D data models can be classified into the following three categories: 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 (Houlding, 1994; Breuning, 1996; Fritsch, 1996; Cheng and Gong, 2001; Wu et al., 2003).

In fact, many spatial objects could only be represented by 3D volume. The modeling method based on 3D volume has become widely and increasingly. The basic volumes in common use are hexahedron, four-prism cone, tetrahedron, and tri-prism. However, the geological bodies are complex. It is difficult to apply regular hexahedron as a basic volume element to represent boundary accurately. Tetrahedron is agility in

representing complex geological bodies, but it will cause the huge data redundancy, and the algorithm of creating tetrahedron is more difficult and is under researching. In the recent years, some scholars have investigated 3D data model based on tri-prism volume. For examples, Zhang (2000) has made research about the normal tri-prism volume in 3D stratum modeling, and discussed the data structure and cutting algorithm. Gong (2002) and Qi (2002) introduced the irregular tri-prism volume and discussed its data structures and topological relationship, but the modeling method and spatial manipulation have not further been investigated. Quasi Tri-Prism Volume (QTPV) is a smart volume and has some advantages in representing complex geological bodies compared to hexahedron, four-prism cone and tetrahedron.

This paper presents QTPV data model, its manipulation, and its application in subsurface engineering. In Section 2, the QTPV data model and its data structure are designed. In Section 3, some modelling methods are proposed for the purpose of QTPV modelling of stratigraphy and subsurface engineering according to the modelling data. In Section 4, an algorithm of model cutting is presented. Applications of the QTPV model in stratigraphy and laneway are given in Section 5. Finally, conclusions are given in Section 6.

## 2. QUASI TRI-PRISM VOLUME DATA MODEL

### 2.1 Quasi-Tri-Prism Volume

Normal Tri-Prism Volume (NTPV) is a volumetric element constructed by a triangle extending a distance along the vertical direction, shown in Figure 1a. Obviously, in the view of the

graphic theory, a NTPV is an aggregate consisting of vertices  $V$ , edges  $E$ , triangles  $T$  and side-quadrilateral  $Q$ , i.e.,

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

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 located in regular situation. For a subsurface engineering, although the borehole is designed with a vertical direction or with a special azimuth and inclination, the borehole central line does not always obey the designed location because of the influence of rock pressure. That means that the vertices, which borehole cutting stratigraphy interfaces, are not in a vertical line and their horizontal coordinates of the vertices are different. With application of these vertices to construct Tri-Prism Volume, we cannot obtain the NTPV, rather than Quasi-Tri-Prism Volume (QTPV) (Figure 1b). QTPV has the same structure and topology with NTPV, but QTPV does not comply with the constrained conditions of NTPV. Obviously, being similar to tetrahedron, QTPV can be used as a basic volumetric element to design a 3D spatial data model.

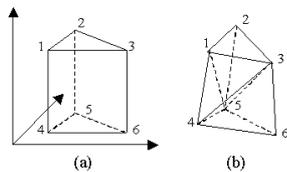


Figure 1. Tri-prism volume

In practical application, vertices may be superposition and QTPV may be one of the four special cases. As illustrated in Figure 2, (a) and (d) are tetrahedrons, (b) is four-prism cone. It is obvious that no matter how complex a geological body, the body can be described using QTPVs 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, can be used to represent a geological body.

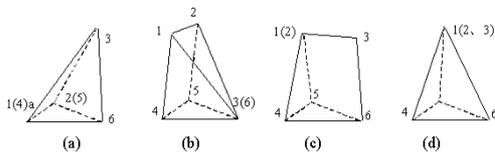


Figure 2. The special cases of QTPV

Vertex data structure

VertexID	x	y	Z	Attribute	IsBelong	Type	CutFlag
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“IsBelong” refers to the geological objects the vertex belongs to; “Type” refers to the vertex of either an original sample point or interpolation point.

## 2.2 Data model based on QTPV

Object-oriented technology is widely used in computer society. The characteristic of Object-Oriented Modeling (OOM) is that no matter how complex a spatial entity, it can be described by an object. Using object identities the relationship among objects can be created. A QTPV has five primitives: Vertex, segment (edge, triangle side), triangle, side quadrilateral, and QTPV. They are basic elements to construct primary objects, which are point, line, surface and body. There are many types of spatial objects in subsurface engineering domain. For example, borehole is a line object composed of segments; an interface or fault is a surface object composed of triangles or side quadrilateral (triangled); the inner of a geological body is a body object and composed of QTPVs; gas rallying point or sample point of ore deposit is point object and represented by a vertex. According to the principle of the object-oriented data model, the above primitives and objects are the foundations of designing a data model based on QTPV. Based on the above idea, a conceptual data model based on QTPV is depicted in Figure 3.

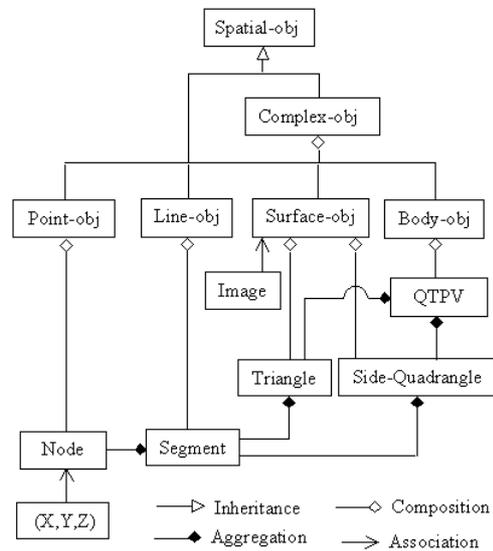


Figure 3. Conceptual model based on QTPV

## 2.3 Data Structure Design

In order to construct a 3D geological model with spatial location, topological relationship and attribute information, and of saving storage memory, more detailed data structures of the primitives and elementary objects should be considered. The data structures include vertex, side of a triangle, edge, triangle, side-quadrilateral and QTPV. On the other hand, in order to represent 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 the definitions of six data structures composed of a QTPV and three other data structures composed of geological objects are provided as the follows:

Triangle side data structure

TriaSideID	StartV	EndV	LeftTria	RightTria	UpSQuad	DownSQuad	Cutflag	CutCoord
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Edge data structure

EdgeID	StartV	EndV	AdjSQuad	IsBelong	Attribute	Cutflag	CutCoord
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If the value of IsBelong is -1, the edge length will be is zero so it will be a tine point.

Triangle data structure

TriaID	Vertex[3]	TriaSide [3]	AdjTria[3]	PosiAttr	PosiQTPV	NegaAttr	NegaQTPV	IsBelong
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Side quadrilateral data structure

SQuadID	Vertex[4]	TriaSide[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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### 3. MODELING OF SUBSURFACE OBJECTS

#### 3.1 Stratigraphy Modelling

With the differences of modeling data, stratigraphy modeling method can be classified into: modeling using interpolation points of startigraphy interface and modeling using original borehole's captured data. They are discussed as follows.

**3.1.1 Modeling Using Interpolation Points of Interface:** This modeling method constructs NTPV. The main process includes three steps. First, borehole data are compiled and divided into different layers according to their lithology and height. Second, stratigraphy interfaces are carried out curved face interpolation and thus, regular multi-DEMs are built. These DEMs should have coincident frames of references so as for the convenience of later modeling. Finally, grid triangulation should be made to be regular and consequently NTPVs are constructed with corresponding two triangles located in adjacent stratigraphy interfaces. If the interfaces are crossed in a grid, then some special processes, such as calculation of cross line, and grid triangulation and construction of NTPVs, should be done, referred to Figure 4.

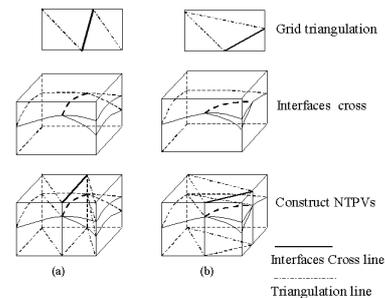


Figure 4. Constructing of QTPVs by interfaces crossed grid

**3.1.2 Modeling Using Borehole Captured Data:** In this case, the constructed model is QTPVs. This modeling is similar to Delaunay triangle network. The latter is for constructing intersecting points belonged to the same interface into a TIN, while the former is for constructing a series of QTPVs between adjacent interfaces. Let the data structure of a borehole 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 are as follows:

- (1) Create a triangle (up-triangle) using 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 codes of the up-triangle points. As shown in Figure 5, if their codes are the same, the new triangle points are the next points along the boreholes (see Figure 5a). If their codes are different, in the borehole with a smaller code (for example a in Figure 5), the new triangle points are the next points along the boreholes. In the borehole with a large code (for example b or c in Figure 5), the new triangle points will not change, as illustrated in Figure 5b-5d.
- (3) Construct a QTPV according to the up-triangle and down-triangle, and 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's side on the earth's surface by using 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 triangle, stop the modeling process; otherwise, go back to step (5).

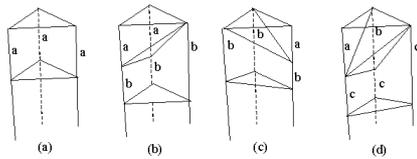


Figure 5. The down-expansion of QTPV

### 3.2 Deposit Local Modelling

Suppose that a stratigraphy model has been constructed. There is a deposit B located in stratigraphy A (Figure 6). In order to maintain the constructed topological relationship of QTPVs model, we should adopt local modelling method. How do we insert the deposit B into the stratigraphy A? Firstly, vertical lines are created to pass through points (a, b, c, d), and the lines are crossed with adjacent stratigraphy interfaces into some intersection points (a', a'', b', b'',...) (Figure 6a). Secondly, local model should be conducted in the stratigraphy A performing the two steps of triangulation (Figure 6b) and construction of QTPVs. After the local modelling finished, the topological relationship between the local model and the adjacent QTPVs should be handled. This process is divided into two aspects: flank relationship maintenance and fluctuate relationship maintenance.

### 3.3 Subsurface Engineering Modelling

Subsurface engineering, such as silo, laneway, mine, etc. always are regular. In these cases, some cross sections are captured in different distance according to the changes of section shape along the engineering main axis, so as to the section shape change be in permitted range between adjacent sections (Figure 7a), thus a lot of columns are obtained, then partition the column into QTPVs. Different partition methods should be adopted according to the section shapes. For example, Figure 6b illustrates a circle laneway, adjacent sections have the same

shape, in the circle section, the center of a circle is taken as center point, a series of triangles is constructed for every other definite central angle, and then QTPVs is constructed by connecting corresponding triangles in adjacent sections. Figure 7c, 7d and 7e show the different cases of constructing QTPVs on laneways.

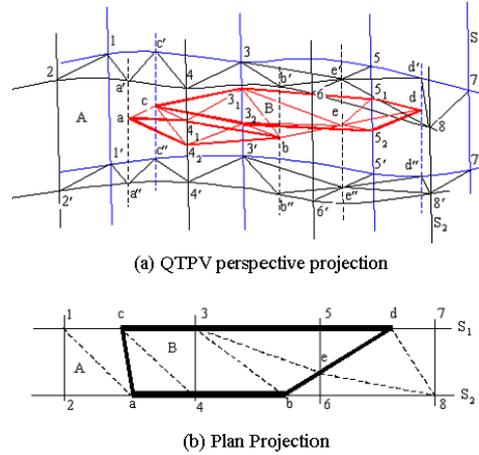


Figure 6. Subsurface Engineering construct QTPV

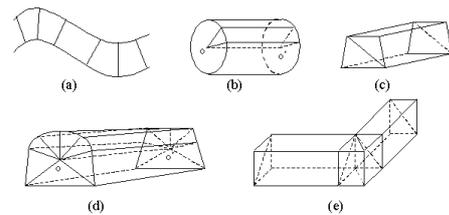


Figure 7. Subsurface Engineering construct QTPV

## 4. QTPV MODEL CUTTING PROCESS

Geological fence sections are a conventional method for geologists 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 a Section Plane (SP) is employed to cut a QTPV, many different results will be led. The QTPV vertices can be classed into three kinds: black, white and triangle vertex. Black vertex locates at the positive side of the SP, white vertex locates at the negative side and triangle vertex is on the SP exactly. Theoretically, there are  $64 = 2^6$  different configurations of black and white vertices considerably within a QTPV. Considering the fluctuation and rotation around vertically axial symmetric characteristics of QTPV vertices and the fact that SP is a plane rather than an isosurface, there are eight kinds of cutting cases according to the number of black vertices, shown in Figure 8. Among these cases, a special case, in which the side-quadrilateral of QTPV may be convex or concave, has been taken into account, i.e. two black vertices lied on the diagonal of convex or concave quadrilateral are treated separately, in Figure 8e and 8f. Because the side quadrilateral may not be a plane, the shade polygon vertices are points of SP intersect the sides (prism edge, triangle side) of a QTPV. In practice application, the points of SP intersect the diagonal of side-quadrilateral should be calculated if we pay attention to a single QTPV.

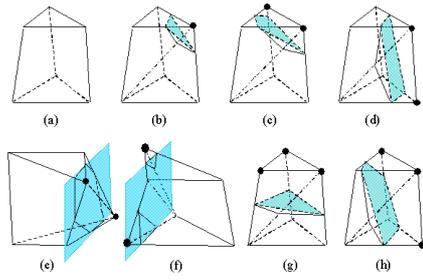


Figure 8. General cutting cases

Generally speaking, based on QTPV, the result of a plane cutting a 3D model is a profile. The follows show the processes of using a SP cut-away the model and formed a profile:

- (1) Initialize a stack S, and use S to store the identity of a QTPV intersected with the SP, initialize a queue Q, and use Q to store the triangles of the profile.
- (2) Get a QTPV from the Volume Element List (VEL) and evaluate whether it intersects with the SP.
- (3) If the QTPV does not intersect with the SP, a process mark is given to the QTPV in the VEL and the next QTPV without a process mark is the required to be found. When one QTPV is obtained, it is pushed into stack S.
- (4) 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 evaluate judge whether it intersects with the SP. If it does, then push it into stack S.
- (5) Repeat step 4 until stack S is empty and all of the QTPVs in the VEL are marked with the word "processed".

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

### 5. QTPV MODEL APPLICATION IN STRATIGRAPHY AND SUBSURFACE ENGINEERING

Based on the proposed QTPV model, the modeling methods and the model cutting process, we use VC++6.0 language, SQL database, and OpenGL graphic library under windows environment to implement a system prototype, named '3D Geological Modeling and Visualization (3DGeoMV) system'. The functions of this prototype includes: data input, data edition in 2D profiles, stratigraphy and laneway QTPV 3D modeling according to the borehole data and section data of laneway, 3D fence models of stratigraphy created by using different arbitrary planes cutting the model, visualization of all kinds of models and results, lamp-house control, model rotation and zoom, etc.

Experimental data is composed of a set of real data of boreholes and a set of simulation data of laneway. The borehole data are from a geological exploration area in the Inner Mongolia, China. There are 42 original boreholes and 5 stratums. Since the stratigraphies are thin, for the purpose of increasing the viewing effects, 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. To obtain a smooth

stratigraphy model, an interpolation process has been done between two sparse boreholes in a profile by using curve fitting method. After interpolation 212 virtual (interpolation) and real boreholes are obtained in all. The wire-frame graph representation of the stratigraphy model is illustrated in Figure 9. Visualization of 3D stratigraphy model is shown in Figure 10 and the cut 3D stratigraphy model is shown in Figure 11. Figure 12 shows 3D fence model of the stratigraphy model. Modelling results of a set of simulation laneway data are shown in Figure 13.

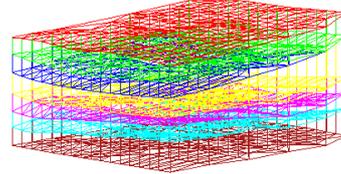


Figure 9. Wire-frame graph of stratigraphy model

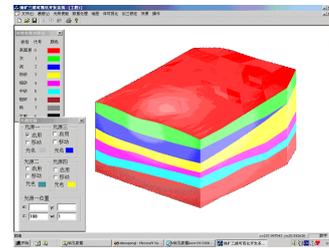


Figure 10. Visualization of 3D stratigraphy model

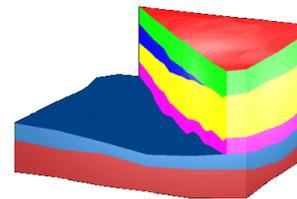


Figure 11. Visualization of the cut 3D stratigraphy model

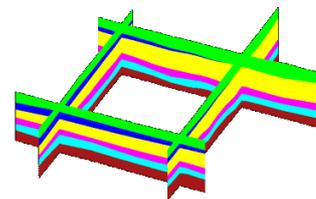


Figure 12. 3D fence model of stratigraphy model

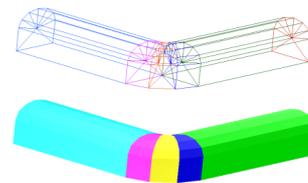


Figure 13. 3D model of laneway model

## 6. CONCLUSION

The subsurface engineering is truly three-dimensional and is required a real 3D data model. For the purpose of describing different subsurface objects, many 3D data models and data structures have been investigated. Our experimental results demonstrated that the proposed 3D data model based on QTPV is feasible and efficient in modeling irregular geological objects and regular subsurface engineering. The following conclusions can be drawn:

- (1) The developed 3D QTPV data model has the ability of modeling regular and irregular 3D objects. Although it is a volumetric model, but we can also get the surface model of the modeled objects by designing a special algorithm. For example, for the purpose of obtaining a stratigraphy interface, we should seek all the triangles which have the same positive-negative attribute while the attribute of positive side and negative side are different for one triangle.
- (2) The QTPV data structure could 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 modeling algorithm complex.
- (3) The complex geological objects could be described by using only QTPV data structure while hybrid data structure does not need. Thus it is convenient for database management.
- (4) When 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 using linear or finite element interpolation methods. Thus the real 3D management of geological bodies can be achieved.

Our applicable cases are only stratigraphy modeling according to real borehole captured data and simulated laneway data. The further works are taking into account for more complex geological objects and consummate modeling, visualization and model manipulation methods.

## ACKNOWLEDGEMENTS

The research is financially supported by the Hong Kong Polytechnic University ASD research fund under contract number of No. 1.34.A222 and the Open Research Fund Program of LIESMARS under the contract number of No. WKL (01) 0302.

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