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A new 3D geological modeling method based on the division of spatial units by using intersected geological sections

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Abstract. Based on the intersected geological sections, this paper puts forward a kind of 3D geological modeling method based on the division of spatial units. On the basis of self-governing thought, the method divides the complex overall regional into some single cells, and then to construct 3D geological model within each cell. After all the cells' model have been completed, all the models within the cells are merged to form the final overall model in the modeling area. Compared with the modeling method based on approximate parallel section data, this method can effectively overcome the disadvantages of only can choosing a single direction (horizontal or vertical). this method can meet the requirements of large area of 3D geological modeling in city. The proposed method is applied to quaternary 3D geological modeling for one city in china. Intuitive 3D geological model is established, based on the model built, the related analysis and geological evaluation work on the model can be carried out.

Keywords. Spatial units, intersected cross-section, cells.

1. Introduction

The three-dimensional geological modeling method based on the approximately parallel sections is to establish correspondence between the contours of sections, then connect these contours with the triangular patches, and finally block both ends of the section to construct geological mass model. In addition, the topological relation of the three-dimensional geological model is also established [1-8]. This method has some limitations in the practical applications, for there are many crossing sections. Therefore, in this method, only the transverse sections or longitudinal sections could be used to construct the three-dimensional geological model, which means that the opposite type fails to be utilized. Consequently, the geological information contained in them also fails to be used [9]. Therefore, it is necessary to study a new modeling method for the intersected geological sections.

Zhang Baoyi [9] proposed a multi-constrained three-dimensional geological modeling technology based on arbitrary section and divides the intersected sections into two types, the connected sections and constrained sections. Dominated by the former one, they regard the constrained sections, hierarchical data of the drilling holes, contour and surface and topography data as the constraints to construct a more reasonable geological interface model [9]; Qu Honggang et al [10] put forward a modeling method based on the intersected folded section, and used the intersected section composed of multiple sections in different directions to improve the correspondence between geological boundary of sections. As these geological boundaries in different directions are connected together naturally, the human-computer interaction is often used to solve these problems in most conventional methods. Although these methods have provided useful references for the modeling of intersected sections, they are in the initial exploration phase, and cannot be fully applied to the complex geological conditions. Besides, there are few literatures at home and abroad. Therefore, in-depth researches are required in the future.

Based on the data of intersected sections, this paper adopted the thought of “self-governing” to divide the modeling space into a plurality of cells and then separately modeled for each cell. In this process, the public interface of the geological block should be generated only once and be shared by the upper and bottom geological blocks, which could ensure the geometric and topological consistence of the model.

2. The general idea of modeling

The general idea of modeling based on intersected sections is shown as follows: first, ensure the consistency of the formation classification and formation elevation of the intersected sections at the intersection. Then, divide the intersected sections spatial consistency into multiple cells (each cell consists of part of the section lines and section areas of multiple sections). Construct geological interface and form block model within each cell. Finally, merge all the blocks within each cell to form the geological model with the formation as a unit. The general modeling flow chart is shown in Figure 1.

2.1 Intersected-sectional consistency processing

The consistency of the intersected section data means ①the consistency of attribute information of formations classification ②the equal elevation of formation classification boundaries of intersected sections at the intersection. However, in the actual situation, due to some human factors of the uncertain mapping accuracy, users could only try to ensure the consistency of the former one, but it is difficult to achieve the consistency of the latter one. The authors have made detailed explanation of the test and calibration methods to achieve the spatial consistency of the intersected sections, so herein they won’t be described again, as is shown in literature [11].

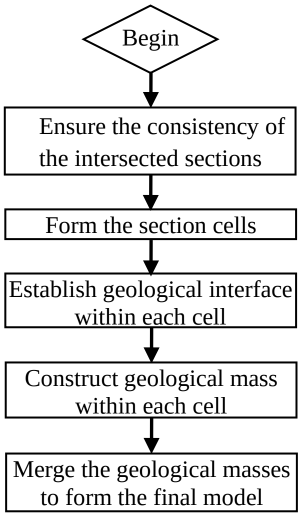


Figure 1. Modeling flow chart

2.2 Division of spatial cells

As the section is perpendicular to plane *xoy*, each section is composed of multiple drilling holes. Connect their orifice coordinates and map them to plane *xoy* to form a two-dimensional broken line. Multiple broken lines divide the two-dimensional space into multiple closed areas. The mature two-dimensional closed polygon generation algorithm of GIS software could be used to achieve the division of cells of the three-dimensional intersected sections. The process is shown as follows:

(1) Map the broken line connected by the drilling holes of each section to plane *xoy* to form multiple intersected two-dimensional broken lines.

(2) Based on the multiple two-dimensional broken lines, the mature polygon generation algorithm of two-dimensional GIS software is used to generate a plurality of two-dimensional polygons. For any polygon R, find the corresponding broken lines and then the section P_i (i = 0, 1, 2, $\cdots$) corresponding to them.

(3) For each broken line of polygon R, obtain two intersection points at both ends and set as J_{i1} and J_{i2}, and they are corresponding to section P_i.

(4) In the three-dimensional space, find the three-dimensional section line and section area from section P_i, which are located between J_{i1} and J_{i2}, and add them to the current cell.

(5) Repeat steps (3) and (4) for other broken lines of the current polygon and their corresponding sections, so all the section lines and areas in the current cell could be found out.

Repeat set (2)-(5) to form all the cells.

2.3 Construction of geological model within the cell

The construction of geological model within the cell can be divided into two steps:① the construction of the geological interface within the cell;② the construction of the geological mass based on the geological interface (each mass is an closed and hollow model composed of a number of geological interfaces).

The construction of geological interface is the core and difficult point of the construction of geological model, which will be elaborated in chapter 3.

After the geological interfaces within the cell are completed, they are not formed real masses although they are geometrically closed. Therefore, the aim to construct geological masses is to convert them into closed masses based on the incidence relation between them, finally achieving the conversion from surface modeling to mass modeling. Jun [12] adopted the right-hand maximum angle rule to achieve the automatic construction of rock mass model based on the characteristics of the mass model. However, in this algorithm, the geological interface of rock is a three-dimensional plane, while in this paper, it is curved space composed of triangulation. Therefore, this algorithm cannot be applied to this paper. On this basis, Chen Guoliang proposed an improved algorithm to construct geological masses automatically, which could achieve the construction of any kind of complex model rapidly and effectively. The detailed information can be found in literature [13].

2.4 The merger of geological mass

After the construction of geological mass within a single cell, each one of them has certain formation properties (like the same age, the same lithofacies, the same lithology), and finally all the geological masses in cells with the same formation properties are merged to form a geological mass model with formation as the unit. During the process, it is necessary to remove the public geological interface between two adjacent cells (these geological interfaces are cross-sectional polygons on a profile) for ensuring the consistency of the simplification and topology of the model. Specific steps are shown as follows:

(1) For any given formation encoding C, locate the set of masses with formation encoding of C from all the cells- $\boldsymbol{B} = \{b_1, b_2, \ b_i, \cdots, b_n\}$.

(2) Put masses within B into circulation, and aggregate the included geological interfaces into $\boldsymbol{S} = \{s_1, s_2, s_i, \cdots, s_n\}$.

(3) Collect statistics of geological interfaces in S, and if there is $s_i = s_j$ (herein refers to the equal of ID of the two interfaces), then s_i and s_j will not participate in the construction of the geological mass of the formation.

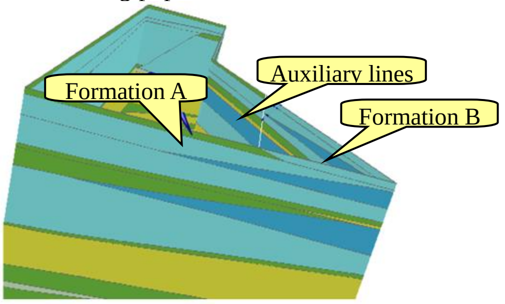
(4) Remove all the overlapped interfaces in S to form $\boldsymbol{S}'$. Create a new geological mass NB, add all the geological interfaces of $\boldsymbol{S}'$ to NB, and then the construction of NB, the geological mass with formation encoding of C, is completed.

(5) Adopt the above steps for all formations within the modeling area, and then the construction of all geological masses with formations as the unit is completed.

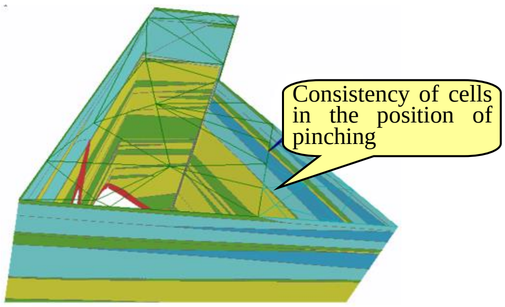
As the geological interfaces of geological masses are referenced by different masses during the construction process (whether it is the construction within a single cell or the merger of the geological mass), adjacent geological masses in the vertical direction reference the same geological interface and the constructed geological masses possess full topology consistency.

3. Construction of geological interface within the cell

After all the cells are located, the smallest unit of modeling is the individual cell, and coming next is to use a series of closed hatching within individual cell to establish geological interface. In the modeling process, it is capable of choosing the top contour line of each formation for the construction. If the formation is continuous, it is easy to find out a circle of closed contours of the current formation and then use a closed boundary line of the circle to conduct constrained Delaunay triangulation to construct top interface of formations. However, geological phenomena are, in fact, very complex. Many formations are not continuous in spatial distribution. Complex situations like pinching, penetrating, branching and spiral usually appear, leading to the discontinuity and openness of the section line of the current formation, namely the missing of the boundary line of formations. For this purpose, the modeling method must be able to deal with these cases effectively. One of the most straightforward ideas is to build the missing boundary out in advance and then select the closed border to construct the network. Based on this idea, this paper describes how to build the missing boundary in a variety of complex geological conditions. In this paper, the built missing boundary line is referred to the auxiliary line, and an auxiliary line may belong to part of the closed border of multiple geological interfaces. These lines need to be constrained in the triangulation process, and in so doing, these created geological interfaces will be consistent in geometry and topology in the current auxiliary line. Figure 2 shows the addition of auxiliary lines for simple pinching and network construction, but the actual model is more complex than this. Construction methods of geological interfaces for different complex geological phenomenon will be separately narrated in the following paper.



(a) Adding auxiliary lines



(b) Consistency of the left and right cells in the position of auxiliary lines

Figure 2. Adding auxiliary lines and constraint triangulation

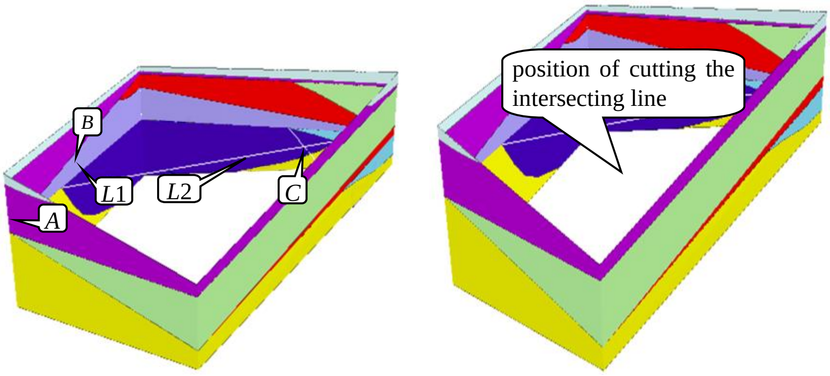
3.1 Pinching of formations

Pinching is one of the most common geological phenomena for formations. When it happens, first determine the common pinching border of the two pinching formations by adding the auxiliary line, and then automatically build formation interface based on these boundary lines. It is usually very easy to add auxiliary lines for simple pinching of formations, but because of the complexity of pinching of formations, it often needs to cut off multiple pinching lines and then build each geological interface. If the top formation associated with auxiliary lines has two identical formation attributes, then the two lines need to cut off each other, and the elevation of the cut segment in the cutting position can be re-calculated by taking the average. Figure 3 (a) shows that auxiliary line *L*1 and *L*2 do not intersect in the three dimensional space. If they are not processed by intersecting and cutting, a gap will exist between the top geological interface of the latter constructed formation *B* and formation *C*. Because auxiliary line *L*1 belongs to top formation *A* and *B* and auxiliary line *L*2 belongs to top formation *A*, *B*, and C, the two lines have two identical associated formations

A and *B*. Therefore, we must cut off *L*1 and *L*2. *L*1 and *L*2 enjoy consistent elevation in the cutting position after being cut and form four segments, as is shown in Figure 3 (b).

3.2 Branching of formations

Branching is reflected in the cross-section as a continuous formation polygon with bifurcation conducting in two directions in a particular position. It is generally accompanied by pinching, and the end position of branching is usually the position of pinching. As stratigraphic polygons in the cross-section are not independent, when bifurcation appears in one formation it may also come into being in another formation in the position of the bifurcation, as is shown in Figure 4 (b).



(a) The original two auxiliary lines (white lines in the chart)

(b) Auxiliary lines after being cut (white lines in the chart)

Figure 3. Cutting auxiliary lines

Ideas for solving bifurcation of formations are that first divide the formation polygon with branching in form into multiple non-branching polygons by adding auxiliary lines, then add auxiliary lines for each non-branching polygon according to the method used in 3.1 to build formation interface. Figure 4 shows the processing steps of branching of formations.

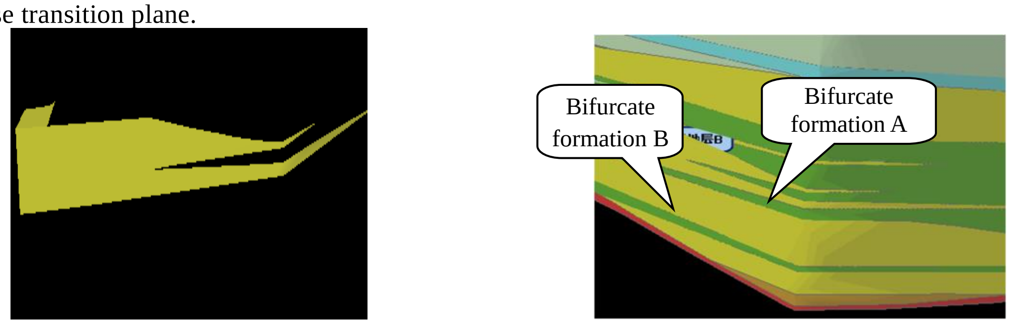
The above analysis indicates that the essence of this approach lies in dividing two formations with branching into two non-branching formations and the use of pinching formation treatments on each non-branching formation to build geological interfaces.

3.3 Spiral of formations

Spiral of formations is reflected in the cross-section as the spiral distribution of a continuous formation polygon in space. As is shown in Figure 5 (a), the solution is to divide it into simple continuous formations. Specifically, divide the polygons of formations with spiral into multiple non-spiral polygons by adding auxiliary lines, and finally conduct the top and bottom dimension for each non-spiral polygon. Based on this idea, Figure 5 shows steps for constructing a spiral formation. It can be seen from it that the polygon of spiral formation is divided into three non-spiral formation polygons.

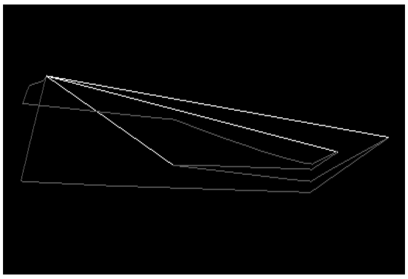
3.4 Faults and phase transition

When faults or phase transition exist in a cell, it must be the first priority to build the fault plane and the phase transition plane and then build other geological interfaces within the constraints of these interfaces. In building constraint interface, first determine the boundary of constraint plane by adding auxiliary lines and then build the constraint plane through the boundary polygons. Figure 6 shows the phase change phenomenon and the sample of building phase transition plane.

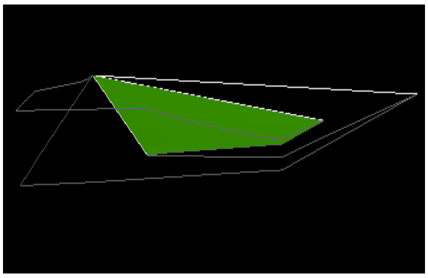


(a) Branching formation

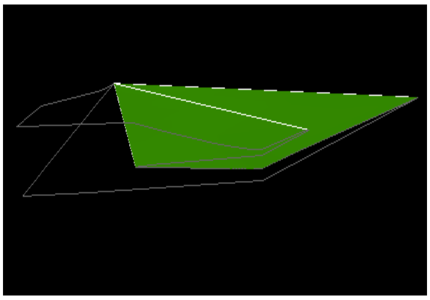
(b) Connection of two bifurcate formations



(c) Addition of auxiliary lines (highlighted white lines)



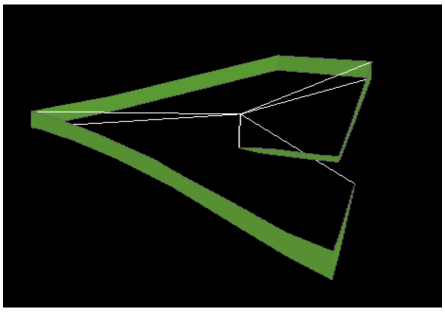
(d) Formation plane in the top bifurcation



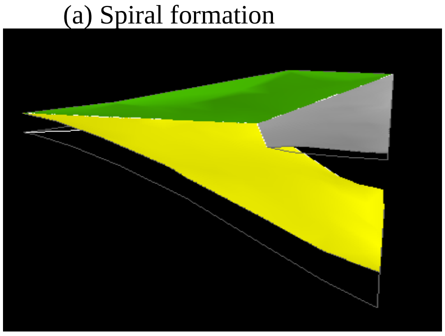
(e) Formation plane in the bottom bifurcation

Figure 4. Processing of branching of formations

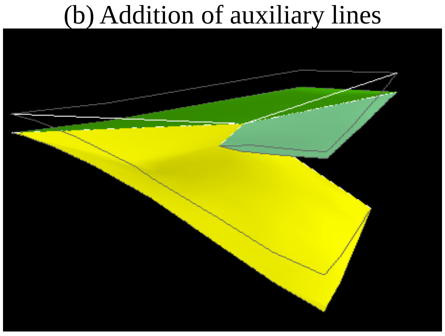
(a) Spiral formation



(b) Addition of auxiliary lines

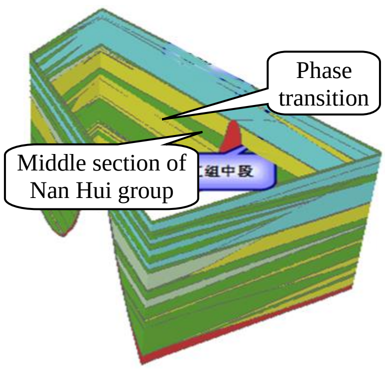


(c) Top spiral plane

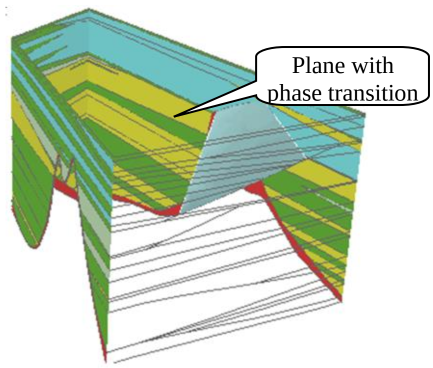


(d) Bottom spiral plane

Figure 5. Processing of spiral of formations



(a) phase transition of formations



(b) Construction of planes with phase transition

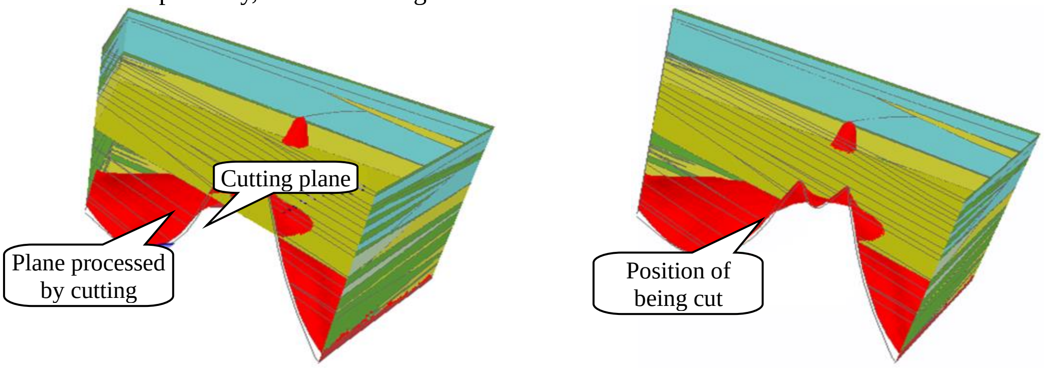
Figure 6. Processing of formations with phase transition

3.5 Formation penetration

The constructed formation interfaces might intersect with each other in the space. For example, the bedrock in the Quaternary geology penetrates other formations, although it is also a pitching, the process to add auxiliary lines will be very complex. Therefore, this paper adopted the following steps: first, construct the initial geological interfaces, then conduct interacting cutting for them and select some sub-surfaces. The specific steps are shown as follows: first, build penetrating formation interface by penetrating the closed boundaries of formation interfaces and then construct other penetrated formation interfaces with the same approach (auxiliary lines may also be needed in the process of constructing the penetrating and penetrated formation interfaces, but they are not their pitchout boundaries), and then conduct interacting cutting for them. In this way, the penetrated formation interface is divided into several sub-surfaces, and those above the penetrating formation interface should be retained, while those below it will be ignored. Meanwhile, the penetrating formation interface is also divided into multiple sub-surfaces which could be used as the penetrating formation interface of the next cutting. The core to process formation penetration lies in the cutting algorithm of spatial triangulation, as shown in the previous literature [14]. Figure 7 indicates examples of processing formation penetration.

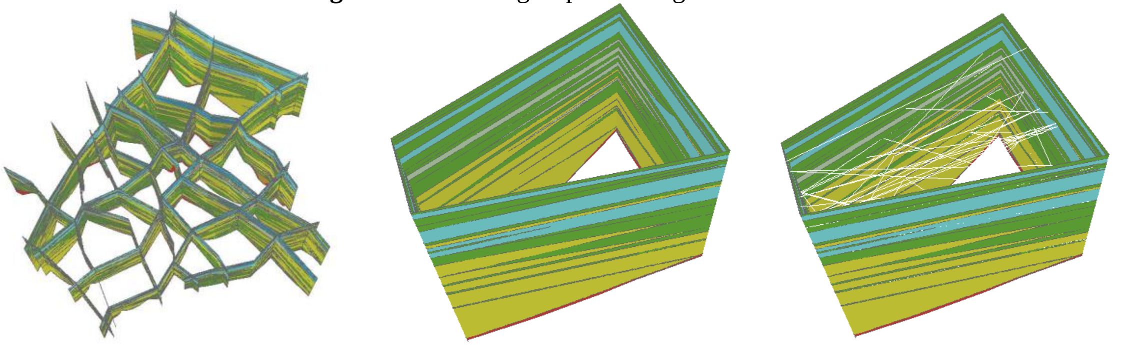
4. Case study—Quaternary geological modeling

The Quaternary geology in a city is the slow settlement area with clastic sediments of clay and sand and the stacking thickness of 200-300 m, which shows distinct rhythm characteristics from top to bottom. The modeling method proposed in this paper was carried out. In this process, more than 560 Quaternary drilling holes were used to build 15 Quaternary geological sections across the city. Based on these three-dimensional geological sections, this city was divided into 28 cells which were modeled respectively, as shown in Figure 8.

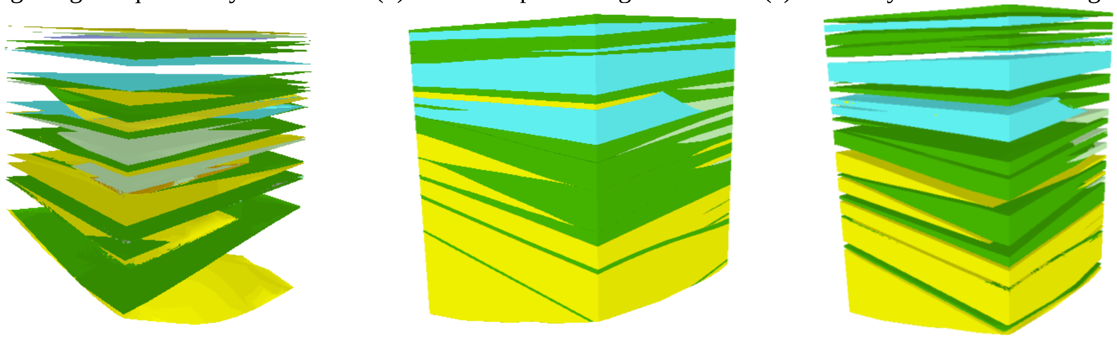


(a) Formation plane before being cut (b) Formation plane after being cut

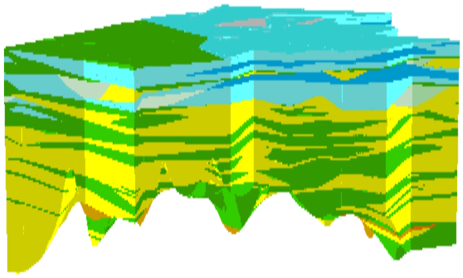
Figure 7. Processing of penetrating of formations



(a) 15 geological quaternary sections (b) sketch map of a single cell (c) Auxiliary lines within a single cell



(d) Geological interfaces within a single cell (e) Geological mass within a single cell (f) Explosive display of masses within a single cell



(g) Formation masses in all cells
Figure 8. Quaternary modeling of a certain city

5. Conclusion

Based on the data of intersected sections, this paper proposed to utilize the thought of “self-governing” to build the model. In the process of constructing geological interfaces, different ideas and methods were put forward based on the complex geological conditions. Besides, examples were used to demonstrate the effectiveness. However, there are still some problems to be solved in the further study.

1) It is not easy to achieve interactive modeling methods, especially when the geological conditions are complex. Therefore, how to explore the hidden geological laws of the data and achieve efficient model building is the key point of the further study.

2) To make the model more artistic, the auxiliary lines should be expressed by the curved segments rather than the straight segments. Therefore, how to express auxiliary lines with curved segments should be studied in the future.

References

[1] Keppel E. Approximating of complex surfaces by triangulation of contour lines[J]. IBM Journal of Research and Development, 1975, 19(1): 2~11.

[2] Meyres D, Skinner S, Sloan K. Surfaces from contours[J]. ACM Transactions on Graphics, 1992, 11(3): 228~258.

[3] Herbert M J, Jones C B. Contour correspondence for serial section reconstruction: complex scenarios in palaeontology[J]. Computers & Geosciences, 2001, (4): 427~440.

[4] Fuch S H, Kedem ZM, Uselton S P. Optimal surface reconstruction from planar contours[J]. Communications of the ACM, 1977, 20(10): 693~702.

[5] Schumaker L L .Reconstructing 3D objects from surfaces[C]//Ppdahmen W, Gasca M, Micchelli C A: Computation of Curves & Surfaces. Netherlands: Kluwer Academic Publishers, 1989: 275~309.

[6] Muller H, Klingert A. Surface interpolation from cross sections[C]//Pphagen H, Muller H, Nielson G M: Focus on Scientific Visualization. Berlin: Springer-Verlag, 1993: 139~189.

[7] Tipper J C. The study of geological objects in three dimensions by the computerized reconstruction of serial sections[J]. Geology, 1976, 84(4): 476~484.

[8] Qu Hong-gang, Pan Mao, Wang Yong, et al. Three- dimensional geological modeling from topological cross-sections[J]. Acta Scientiarum Naturalium Uni- versitatis Pekinensis, 2006, 42(6): 717~723.

[9] Zhang Baoyi. Research on the multi-constrained three-dimensional geological modeling technology based on section [D]. China University of Geosciences (Wuhan), 2007.

[10] Qu Hong-gang, Pan Mao, Ming Jing, et al. An efficient method for high-precision 3D geological modeling from intersected folded cross-sections[J]. Acta Scientiarum Naturalium Universitatis Pekinensis, 2008, 44(6): 915~920.

[11] Chen Guo-liang, Zhu Liang-feng, Liu Xiu-guo. An approach for checking and adjusting the consistency of intersected cross-sections in 3D geological structure modeling[J]. Journal of Xinyang Normal University (Natural Science Edition), 2009, 22(3): 248~251.

[12] Lu J. Systematic identification of polyhedral rock blocks with arbitrary joints and faults[J]. Computers and Geotechnics, 2002, 29(1): 49~72.

[13] Chen Guo-liang, Zhu Liang-feng, Liu Xiu-guo. Technology and method for building 3D geological fault structure model[J]. Journal of Xinyang Normal University (Natural Science Edition), 2007, 20(2): 248~251.

[14] Chen Guo-liang, Liu Xiu-guo, Shang Jian-ga, et al. Incision analysis technology and method for 3D geological structure model[J]. Computer Engineering, 2007, 33(20): 184~186.