

# A Stratigraphic Modeling Method based on Borehole Data

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## Abstract

The complexity of stratigraphic architecture makes the geological modeling over-reliance on labor, this means more time-consuming and inefficiency. It is a difficult problem in using only borehole data in engineering survey for computerized automatic modeling to quickly establish the stratigraphic model. We joined connectivity criteria, as well as virtual drilling method, using an improved "layer-cake" method to create a stratigraphic model based on borehole data automatically. This method has the ability to deal with the formation lens, tip off, erosion and other phenomena of stratum effectively. We can make stratigraphy model based on the interpolated multi-layer of TIN data structure. This approach has been applied in engineering geological modeling of some regions in Nanjing, China.

**Keywords:** Borehole data; stratigraphic modeling ; 3D modeling; automatic identification.

## 1. Introduction

The main concern of stratigraphic modeling software is the underground space information. GIS software usually concern a plane or on the XY coordinates of a single-valued attribute, geological modeling software is to express the properties in the entire three-dimensional space. The most important work in 3D geological modeling process is to determine the various strata interface. With the continuous development of computer technology especially the technology of computer graphics, the using rate of computers in three-dimensional geological modeling and geological visualization is increasing. The demand for Real-time display and expression of geological information is also growing strongly. How to perform the geological conditions in three-dimensional graphics and describe the complex structure between stratum or in a single stratum, and provide intuitive, accurate geological information, has already been a hot research in recent years.

Stratum refers to the general term formed in a geological time due to sedimentation and magma activities. It consists primarily of shallow metamorphic rocks, sedimentary rocks and volcanic sedimentary rocks, or a certain deterioration of them. The formations may be the consolidation of rock, or no consolidation of sediments.

Generally speaking, the interface between stratum is divided according to the lithology, fossils, mineral composition, chemical composition and physical properties. The stratigraphic sequence is generally in accordance with the order of age, a stratum which has a latter formation is upper than the stratum which have former formations.

Stratigraphic data acquisition has a variety of ways as borehole, adit, acoustic method and electromagnetic method. Borehole method is the most widely used in current projects. According to the rock cores obtained by boreholes, you can easily and more intuitively identifying the stratigraphic sequence. Therefore, borehole data is the most important source of data for geological modeling software. Geological modeling software's main function is explaining the borehole data and other original survey data to continuous stratigraphic information and store them in computer with a specific data structure, using computer graphics to perform. Due to the cost and environmental constraints, the distance between two adjacent holes is generally quite long. After borehole data is obtained, the interpretation work is generally completed by artificial experience. This work usually first connect the discrete borehole stratum together to form a full profile map, several parallel and intersected profile map can basically describe the geological conditions in a region. Most geological modeling software is manually drawn on the basis of artificial drawn profile maps and to make them digitized, interpolated to form a three-dimensional stratigraphy model. The over-reliance on manual identification hampered the effectiveness of the modeling.

In recent years, many scholars have studied on automatic construction method of 3D geological modeling algorithms and stratigraphic modeling software. Zhong Denghua et.al [1,2] proposed a complex geological modeling based on NURBS, Zhu Liangfeng et.al [3] proposed a method based on borehole data to establish the model of sedimentary stratum. Caumon et.al[4] based on the surface structure to make 3D geological model. Lemon et.al[5] established a geological model based on the cross-section profile map of the borehole data. Royse [6] and Guyonnet-Benaize et.al[7] studied on specific area to establish the geological model.

Turner [8] summarized “layer-cake” geological modeling method. Now it seems that due to the complexity of the stratigraphy, the algorithms lack of artificial work are difficult to guarantee in all cases to restore the true stratigraphic situation, they can only be focused on some particular cases. This paper aims to let the computer simulate the behavior of artificial, identify and determine the various formation of stratum, to achieve a automatic modeling without human interaction, and as much as possible to restore the true geological conditions.

## 2 Dispose borehole data

### 2.1 Discrete borehole segments

As the most important source of data, borehole data is usually drawn after the end of the project detailed exploration and saved as DWG format with AutoCAD software. Borehole data in DWG files first need to convert to specific file format recognized by 3D modeling software. In this paper we use XML format. So a specific ARX program is developed to extract borehole data to XML format designed for three-dimensional modeling software.

For every single stratum, its elevation is continuous. There is an upper interface and a lower interface for every stratum, and the upper interface has a higher elevation than the lower interface at the same xy coordinate. As shown in Fig.1, every borehole can be discretized into segments.

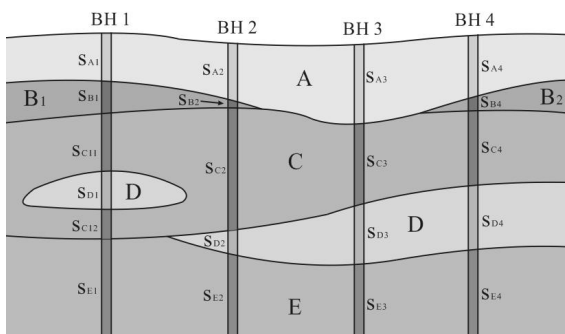


Fig.1 Stratum interfaces in a profile map

The geological body segments in each borehole discretization, is saved by the linked list structure. These geological bodies each expression meaning of a stratigraphic bottom elevation and thickness at the XY coordinates. When all boreholes have been read, the establishment of geological samples is complete. The geological body samples are classified, as shown in Fig.2. use these geological body samples in different XY coordinates to predict the entire stratigraphic distribution in space.

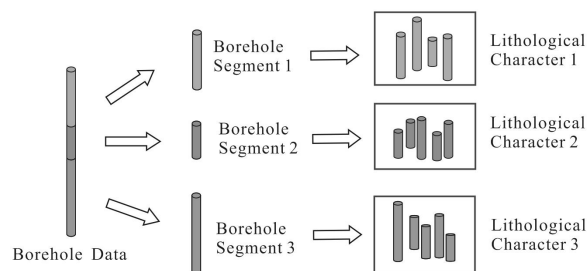


Fig.2 Geological body sample segments

### 2.2 Flat-connectivity

According to borehole data statistics, using stratum B in Fig.1 for example. The borehole segments which belong to stratum B is classified. But not all of these segments are fully connected, stratum B may be cut off at somewhere. So we should make a criteria for the determination the connectivity of Stratum B in XOY plane.

As shown in Fig.3, for each of different stratum (stratum B, for example), the establishment of a number of connectivity strata parts is as follows:

1. Create borehole DTIN. The node with color means this borehole contains segment of stratum B, the node without color means not contain.
2. Start from one of the colored nodes, marked “1”, find the segments connect node “1” and other colored nodes. These connected and colored nodes are marked “2”.
3. Find the segments connect nodes marked “2” and other colored nodes, mark these connected nodes with “3”, circulate this step until no more new colored nodes are newly connected. As shown in Fig.3, nodes marked 1 to 6 are original data of stratum B.

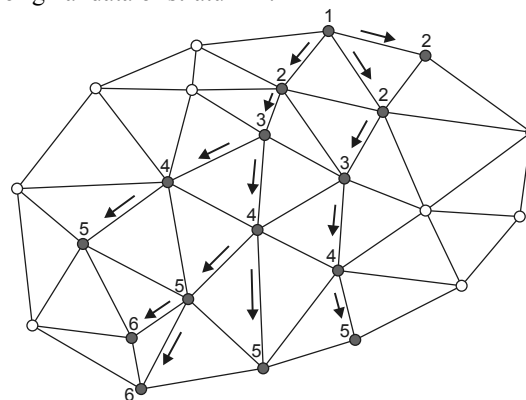


Fig.3 Plane connectivity diagram

### 2.3 Add virtual boreholes

Due to stratigraphic complexity, pinchout often occurs in stratum. If compare two adjacent borehole and find that a

stratum exist in one borehole and disappear in the other, the stratum must be pinched out at some site between the two boreholes. In order to improve interpolation precision, we could process borehole data in advance before modeling. We add virtual boreholes in order to solve this problems.

As shown in Fig.4, number BH1 ~ BH4 are initial boreholes, compare BH2 with BH3 to find that the stratum C disappears in BH2, while compare the adjacent BH3 and BH4 to find stratum E disappears in BH4. We add virtual drilling BH5 to the midpoint of the segment connecting BH2 and BH3, stratum C in BH5 has a thickness of 0, other stratum in BH5 can be obtained by interpolate the boreholes nearby. Similarly, we add BH6 at the midpoint of BH3 and BH4, the thickness of stratum E is 0. In calculating stratigraphic model, the virtual boreholes as BH5 and BH6 is also seen as original boreholes.

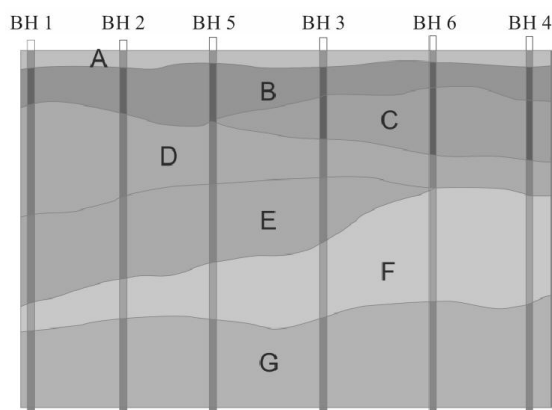


Fig.4 Add virtual boreholes according to the stratum

### 3 Stratigraphic data structure based on the multi-storey triangular network

According to computer graphics and graphics-based works, any 3D objects eventually need to be converted into a series of triangular mosaic structure. In three-dimensional geological modeling software, the stratigraphy models are actually transformed into space triangles for rendering. Therefore, we directly use multilayer triangular network data structure to store the information of geological body, not only the data structure is simple, but also the calculation is more convenient.

#### 3.1 Create a primary TIN structure according to surface points

With respect to the density of the borehole, the density of the surface data points is more detailed. Each of the stratum TIN triangulation network is actually projection of

primary TIN in this stratum. Looking down from just above the XOY plane, the stratum's TIN triangulations are complete coincidence. Therefore, we need to create only one primary TIN using surface data and extend downward. If surface data points are too few and the density is too low that makes the triangle number of TIN is not enough. We can interpolate some surface points to solve this problem.

#### 3.2 Delaunay triangulation algorithm

Delaunay triangulation algorithm is needed for establishing DTIN structure. As the the primary TIN is the two dimensional subdivision of DTIN in XOY plane, 2D Delaunay algorithm can be suitable. Many scholars have researched on Delaunay triangulation algorithm. Lawson [9] proposed a incremental insertion method, Deviller [10] raised an ear-elimination method, in addition, the divide-and-conquer method .etc. Divide-and-conquer method takes the lowest running time, but more complicated data structures and algorithms. This paper use divide-and-conquer algorithm to establish DTIN mesh structure.

### 4 Construction of stratigraphy model

After the determination of primary TIN, each stratum can be constructed by elevation interpolation using XY coordinates of primary TIN's nodes. We should make sure that the number of points is enough to meet the modeling needs. So when the interpolation is complete, we can get the triangular meshes to build geological models directly.

#### 4.1 Spatial interpolation techniques

In study of complex natural phenomena and solve engineering problems, we often use observed values to estimate values elsewhere, this is usually called spatial estimation. In general, a geological or geophysical attribute value in space has a certain degree of continuous and correlative distribution. Variables in space have better correlation when the error range of the observations and estimated numbers is smaller. On the basis of assuming the correlation of space variable exists, using the known variables to predict unknown variables, called spatial interpolation techniques.

Commonly-used spatial interpolation techniques have fitting function interpolation method, inverse distance weighted method, Bezier surface interpolation method, B-spline surface interpolation method and Kriging interpolation method .etc.

### 4.2 Kriging interpolation algorithm

We use Kriging interpolation method for interpolation. It was first proposed by South African mining engineer Krige.D.G to estimate the gold grade. The basic idea is: "According to the location of the sample space and different correlation levels between samples, give each sample different weights, use weighted moving average to estimated center blocks' average grade. In recent years, Kriging interpolation methods have a wide range of applications in the field of geological mapping and spatial data interpolation [11].

In this paper, the elevation of each stratum interface is interpolated by Kriging method. According to the principle of Kriging method, it is assumed that under the premise of the second-order stationary of random variable, the

estimated point value  $Z^*(x_0) = \sum_{i=1}^n \lambda_i Z(x_i)$ . Where are the values of the values of observation points.

### 4.3 Cut out stratum after interpolation

After interpolated by original data as  $H_{top}(i)$  and  $H_{bottom}(i)$  in boreholes, every stratum is divided into two DTIN triangulation interfaces which called the upper interface and the lower interface, their vertices are called  $Z_{top}(k)$  and  $Z_{bottom}(k)$ . Traversal each vertex in DTIN and check out whether the corresponding  $Z_{top}(k) \geq Z_{bottom}(k)$ . If  $Z_{top}(k) < Z_{bottom}(k)$  appears, it shows that the stratum in area of vertex k has a negative thickness. This do not conform to the actual situation, the stratum is not exist in this area actually and should be cut from DTIN triangulation. As shown in Fig.5, stratum C is a intercalary stratum between stratum A and B, the dotted lines are the upper and lower interfaces calculated by Kriging algorithm which have negative thickness parts, these parts should be cut.

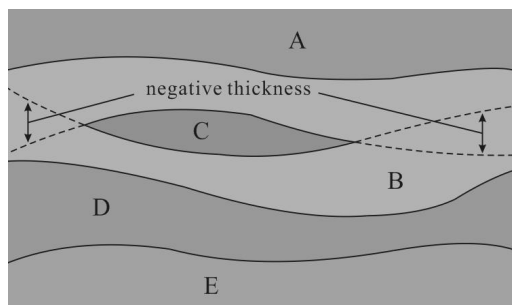


Fig.5 Cutting when stratigraphic thickness is negative

When DTIN triangulation of each stratum is established, adjustment is also needed to avoid intersection between

different stratum. If there has an intersection between border upon stratum, it must be an error. In most cases, newer stratum erode the older ones. So we can classify the stratum by their ages, then take cut operations. As shown in Fig.6, stratum A erodes B and C, so some parts of stratum B and C must be cut.

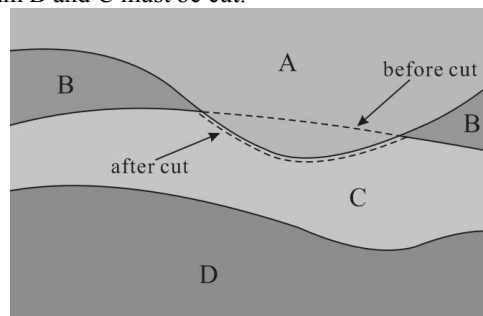


Fig.6 Cutting when stratigraphic erosion occur

## 5 application and conclusion

We represented an automatic stratigraphic modeling procedure that based on borehole data and without any artificial participation, determine the connectivity of boreholes through computer automatically, interpolation and generate each stratum's DTIN triangulation to make solid models. We use virtual boreholes to locate the pinch-out boundary, connect borehole segments in horizontal view to identify the rough shape of each stratum. Then using Kriging algorithm for stratigraphic interpolation, to build three-dimensional stratigraphic model quickly. In practical application, we developed a web application using ActionScript3.0 and Java, the application is applied to build the three-dimensional stratigraphic model in metro construction in Nanjing, Jiangsu, China. The stratigraphic model is shown in Fig.7, Fig.8 and Fig.9.

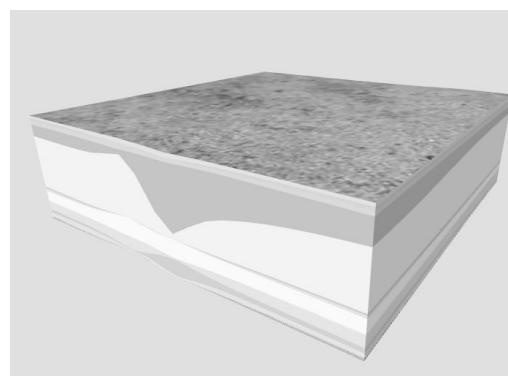


Fig.7 Geological entity model

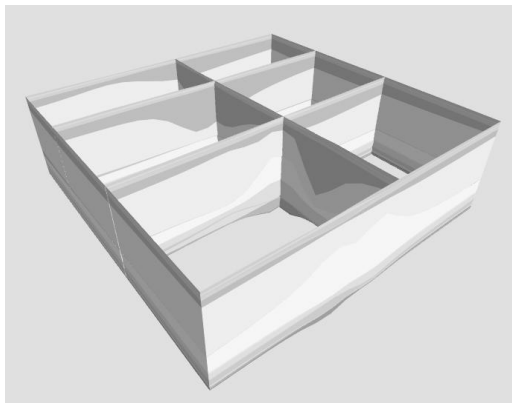


Fig.8 Geological cross section model I

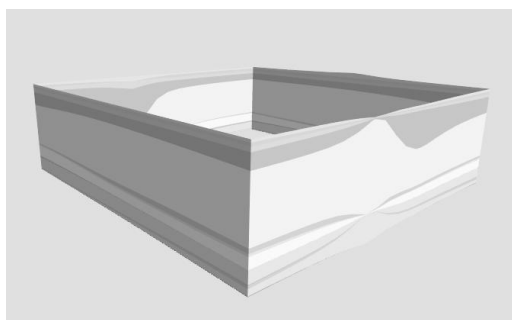


Fig.9 Geological cross section model II

The stratigraphic modeling method in this paper can create three-dimensional model that contain some complex geological structure as lens, pinch out and so on. This method cannot deal with some extreme situation as fold and fault because of their unpredictability. The modeling of fold and fault is a difficulty of computer automatic modeling. In the future research, there are several problems to be study and improvement as how to use artificial intelligence and simulate the artificial experience for more complicated and accurate geological judgement.

## References

- [1] Zhong D H, Li M C, Song L G, Wang G. Enhanced NURBS modeling and visualization for large 3D geoenvironmental applications: An example from the Jinping first-level hydropower engineering project, China[J]. *Computers & Geosciences*. 2006, 32(9): 1270-1282.
- [2] Zhong D H, Li M C, Wang G, Liu D H. Visualization analysis of complex geologic body with NURBS modeling[J]. *Journal of Computer-aided Design & Computer Graphics*. 2005(2):284-290 (in Chinese).
- [3] Zhu L F, Zhang C J, Li M J, Pan X, Sun J Z. Building 3D solid models of sedimentary stratigraphic systems from borehole data: An automatic method and case studies[J]. *Engineering Geology*. 2012, 127(0): 1-13.
- [4] Caumon G, Collon-Drouaillet P, Le Carlier De Veslud C, Viseur S, Sausse J. Surface-Based 3D Modeling of

- Geological Structures*[J]. *Mathematical Geosciences*. 2009, 41(8): 927.
- [5] Lemon A M, Jones N L. Building solid models from boreholes and user-defined cross-sections[J]. *Computers & Geosciences*. 2003, 29(5): 547-555.
- [6] Royse K, Rutter H, Entwisle D. Property attribution of 3D geological models in the Thames Gateway, London: new ways of visualising geoscientific information[J]. *Bulletin of Engineering Geology and the Environment*. 2009, 68(1): 1.
- [7] Guyonnet-Benaize C, Lamarche J, Masse J, Villeneuve M, Viseur S. 3D structural modelling of small-deformations in poly-phase faults pattern. Application to the Mid-Cretaceous Durance uplift, Provence (SE France)[J]. *Journal of Geodynamics*. 2010, 50(2): 81-93.
- [8] Turner A. Challenges and trends for geological modelling and visualisation[J]. *Bulletin of Engineering Geology and the Environment*. 2006, 65(2): 109.
- [9] Lawson C L. Software for C surface interpolation [A]. RICE JR. *Mathematical Software*[C]. New York: Academic Press, 1977.161- 194.
- [10] Devillers O. On deletion in Delaunay triangulations[A]. 15th Annual ACM Symposium on Computational Geometry[C]. 1999. 181- 188 .
- [11] Fedorov V V. Kriging and other estimators of spatial field characteristics (with special reference to environmental studies)[J]. *Atmospheric Environment* (1967). 1989, 23(1): 175-184.