Overview of Three-dimensional Geological Modeling Technology

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Abstract

In the 21st century, with the development of computer technology, the threedimensional geological modeling technology as the persistent pursuit of geologists has had continuous breakthroughs. At present, relatively sophisticated threedimensional modeling software and applications have already come into existence. This paper studies the origin, the technical methods and the software’s current research situation of threedimensional geological modeling comprehensively, which aims at providing reference for colleagues.

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1. Origin of three-dimensional geological modeling

In the late 1980s, with the gradual development and growth of computer graphics application, visualization in science has become a newly arisen research direction. This had promoted information visualization into the research frontier of geoscientific field in the 1990s, which is called three-dimensional geological modeling. Since the concept of three-dimensional geologic modeling concept was proposed by Simon W. Houlding from Canada, the three-dimensional visualization about geological structure had attracted more and more national attention. Canada put forward the requirement of “vertical geological mapping” in 1989, Australia initiated three-dimensional research programs that aimed at obtaining deep earth information in 1990, in order to promote the development of three-dimensional geological modeling. The adoption of three-dimensional visualization technology on geological information processing mainly refers to the performance of constructed mathematical model in three-dimensional form by combining computer graphics technology after the mathematical model in accordance with geological characteristics was established by appropriate data types and data structure, and this description for geological body is much more realistic.

2. Three-dimensional mathematical modeling and visualization method

Conventional three-dimensional modeling process includes two aspects, conventional mathematical modeling process and visual data modeling process. In the three-dimensional modeling process of geological structure, the “spatial form and structure factors” of geological structure need to be considered, so that researchers can analyze and study geological structure more accurately and intuitively. The obtained three-dimensional visualization model would present the true form and characteristics of geological structure, and also reflect the spatial relationships among geological structure elements clearly. Finally, the research of geological structure can be well quantified by combining three-dimensional GIS’s analysis function and information processing capability to space.

Three-dimensional mathematical modeling methods include the TIN surface model, the 3D regular network model, the tetrahedron model and the integration model.

2.1. TIN surface model

TIN (Triangular Irregular Networks) method is to construct geological model by using irregular triangular facets, broadly speaking, any constructing method of geological model that based on triangular facets can be called TIN surface model. This method aims at finding the link among the randomly distributed control points, and then choosing a relatively reasonable way to link up these points, in order to construct a triangle network with complete function and good-looking form. TIN surface model is a surface-based descriptive method, it has much smaller data amount and computation than the body-based descriptive method. For different geological body objects, the description of geological body can be adjusted by adding or reducing the control points. The spatial pattern of geological surface can be represented more accurate and authentic by adding the control points, and the work load of local characteristics description can be reduced without affecting the overall spatial pattern by reducing the control points. Delaunay triangulation is the most commonly used method in the TIN surface method, although X, Y and Z coordinates must be provided in the three-dimensional point that usually need to be described, the Delaunay triangulation is carried out in two-dimensional space of X and Y, and the Z coordinate is only used while the forming of a triangle. Therefore, the application of TIN surface method has some limitations, and it cannot be directly used to describe complex geological body.
2.2. Three-dimensional regular network model

Three-dimensional regular network method is the extension of 2D regular network method in three-dimensional space, and it is a relatively simple method in three-dimensional modeling. This method divides the study space of geological body into several regular networks, and these regular networks are used to describe the corresponding geological body. The most obvious feature of three-dimensional network method is simpleness, simple data structure and algorithms with simple operation can be constructed in allusion to the space which is divided according to certain rules. But this method also has its own shortcomings, and the huge workload of data sets and calculation is the main shortcoming.

2.3. Tetrahedron model

Tetrahedron method can be seen as an extension of 2.5-D TIN surface method in three-dimensional space. In a three-dimensional space, three points can form a triangular plane, and multiple triangular planes can form both external and internal surface of geological body. Similarly, four points can form a tetrahedron, and multiple tetrahedrons can form geological solid. Polyhedron is the smallest unit in the constitution of geological body’s natural shape, tetrahedron method is one of the polyhedron methods, this method belongs to body description method, and tetrahedron is the smallest unit of body elements. In the tetrahedron method, geological body with any shapes can be divided into a number of irregular tetrahedrons, and their topological relations and the space form they constructed need to be described in the data structure of tetrahedron method. The vertex of each tetrahedron is a control point, and each edge of tetrahedron is a control line. The connection between points and lines in the surface space of geological body represents the morphology and geological properties of geological body. Tetrahedron method can describe the surface morphology of geological body, and at the same time it can describe the internal structure and characteristics of geological body by adopting body function interpolation.

2.4. Visualization of three-dimensional geoscience model

Visualization is an additive factor in two-dimensional geological model, whereas visualization effects are important considerations in the mathematical modeling of three-dimensional geoscience. Visualization of geological model could provide various presentation modes for the analysis of geological structure, there are mainly five modes which are listed as following.

1) Three-dimensional landscape mode. This mode observes the surface of three-dimensional geological body model from different directions, angles and distances, light, surface texture and other three-dimensional effects can be added to enhance the sense of reality of the model. However, this approach also has its limitation, which is only the surface of the model can be seen.

2) Three-dimensional landscape mode of uncovering cap rock. This approach can be seen as a variation of three-dimensional landscape mode, which adds one more item to the original basis. It assumes that the interface of overlying geological formation can be seen by uncovering the cap rock on the geological body.

3) Perspective three-dimensional landscape mode. This approach can be seen as a variation of the three-dimensional landscape mode of uncovering cap rock, and more descriptions about the internal ecological interface are added by this mode. It assumes that the internal ecological interface can be seen by penetrating some parts of geological body.

4) Isoline projection mode. This mode is similar to the deposit elevation isoline map or seismic exploration horizon structure map, and the following method is its principle, the intersecting line or contour line of the structure index plane’s interface vertically projects on horizontal plane to form an isoline map. This is an
important way to present three-dimensional model by using traditional two-dimensional mode. Geological engineers could have a good command of the space morphology of geological interface by adopting the contour map of the geological body interface.

(5) Section mode. This mode is similar to the profile map in traditional geological work, to present the internal structure of three-dimensional model by using two-dimensional approach. This mode assumes that the geological morphology construction of the horizontal and vertical section inside the model can be observed on the cutting plane of the geological model. Since this two-dimensional section can be easily modified and quantified, the internal structure of geological model can be vividly presented by adopting parallel cutting mode to the model.

3. Present research situation of three-dimensional geological modeling method

Three-dimensional geological modeling method is the focus of current researches, there are many types of modeling methods, and the classification is also very complex. This paper describes the modeling methods according to the following classifications on the basis of the summary of current modeling approaches.

3.1. Classification by modeling scale

Macro-modeling and micro-modeling are distinguished according to the differences of modeling scale. Macro-modeling mainly studies the regional characteristics of the geological object; micro-modeling mainly studies the micro characteristics of rocks, minerals and some other geological bodies. The main data sources of macro-modeling are drill hole, profile and geological plane maps, etc.; the main data sources of micro-modeling are rock sections, photographs, the three-dimensional point cloud that attained directly from instruments, etc.

3.2. Classification by the disposal of geological body’s internal property

Structure modeling and property modeling are distinguished according to the different disposal analyses of geological body’s internal property.

Structure modeling mainly presents the geometric shape and geological properties of geological body and also the spatial relationship between them, which could provide services for various engineering designs, and the internal property of geological body is supposed to be a uniform one. Property modeling is the presentation of the non-uniform property inside geological body, geological body includes the parameters that can reflect formation properties like porosity, permeability, oil saturation and reflection speed of seismic wave and so on. Constructing property modeling for these parameters can provide services with relatively great economic value for the practical application.

3.3. Classification by the data model that is adopted

These methods can be divided into surface-based modeling method, body-based modeling method, and the modeling method that based on the mixture of surface and body according to different spatial data models that the modeling adopted. Synthesizing the existing researches, these can be further divided into section modeling method, surface modeling method, block modeling method, frame modeling method, entity modeling method and so on.

Section modeling method is to connect the adjacent sections to form a three-dimensional geological body. Surface modeling method usually achieves the model construction by adding multi-layer DEM repeatedly.
Block modeling method is to present geological objects on the basis of three-dimensional networks. Frame modeling method can be used to describe the ore body in any shapes, but sometimes the surface need to be modified and the geological block need to be separated in order to deal with the interpolation of geological surface. Entity modeling method can facilitate the volume calculation and reserve estimate.

3.4. Classification by the differences of realization methods

Three-dimensional spatial interpolation, geometric modeling, and alternant modeling are distinguished according to the different specific realization methods. Three-dimensional spatial interpolation refers to the data from limited known samples, and the proper value from a certain mathematical formula area. For the geological body with simple geological structure and no complex boundary constraints, spatial interpolation is very effective; but for the geological body with complex structure and sparse geological samples, some additional treatments are needed. Geometric modeling focused on the construction of geological body’s geometric shape rather than the technology it used. Alternant modeling refers to the users manually edit the outline of geological body according to their own geological knowledge and experience in the three-dimensional environment. It lays particular emphasis on the user participation in the modeling process, this mainly due to the high complexity of geological body and the non-uniqueness of geological solving.

3.5. Classification by the data source of modeling

The commonly used geological data includes drilling data, profile data and so on. The modeling methods that based on profile data, discrete points, drilling data, multi-source data, etc. are distinguished according to the different data sources the modeling adopted. The following paper will review and summarize the commonly used modeling approaches that are adopted in modeling.

(1) Modeling method based on drilling data
(2) Modeling method based on profile data
(3) Modeling method based on multi-source data

3.6. Classification by the driving mode of modeling

Modeling method based on knowledge driving and modeling method based on data driving are distinguished according to the different driving modes of modeling.

Modeling method based on knowledge driving is based on artificial intelligence, geological semantic is used to define the grammar rules of geology, and these rules are used to describe different geological events and the correlation between these events, and then this correlation is used to restrict the construction of geological model.

This method requires no overlap of geological events in the same modeling area, and this method cannot be used in the area with frequent tectonic movement. The advantages of the modeling method based on knowledge driving are listed as following: 1) knowledge of geological expert can be integrated in the modeling process to improve the construction accuracy of the model; 2) the evolution process of geological events can be shown by diagrams to facilitate the editing and correcting work of modeling staff. And the disadvantages are: 1) the regional division of modeling is difficult; 2) the constraints to geological events are too harsh; 3) the method can only be used to construct geological interface currently, the construction of block has not yet been realized. Because of its technical difficulty and harsh modeling condition, the practical utilization of this method is very rare, and it is not the main modeling method.
None of the current modeling methods can completely satisfy all the needs of the modeling with different types of data, all of the methods have more or less problems. The most typical problem is that the adopted modeling method is usually only suitable for limited data types. For example, the section modeling method provides good support to the profile data without overlap, but it is not suitable for the profile data with network-shaped distribution. However, the data of different types will definitely be used if you want to fully and reasonably present the different properties of geological body in reality, and it is the same even only to present the spatial, chemical or physical properties of the same geological body. Therefore, in the establishment of geological body model, a specific and reasonable geological body modal can be achieved by integrating the advantage that different types of data present different properties of geological body. In the design of three-dimensional geological body model, multi-source geological data can be combined to comprehensively construct geological body model.

Two of the above methods can be comprehensively used to describe geological body, in order to better construct the model of geological body. Li Qingquan and some others had proposed the integration method of octree and tetrahedron, the integration method of TIN and CSG and the integration method of vector and raster. For example, if the integration method of TIN surface method and three-dimensional regular grid method is adopted in the construction of three-dimensional geological model, the specific steps are as following: Firstly, establishing research space, and then constructing a corresponding three-dimensional regular grid; Secondly, constructing the TIN surface of the selected geological body; finally, transforming the generated TIN surface to the corresponding three-dimensional regular grid, and then a link between TIN surface and three-dimensional regular grid is created.

4. Present research situation of three-dimensional geological modeling software

With the increasing advance of science, a technique called “Volume Visualization” is proposed in the aspect of three-dimensional visualization. This technique is to describe the integral characteristics of geological body by adopting the metamodel of three-dimensional volume, rather than manually divide the geological body into point, line and plane models. This technique has been widely used at home and abroad. The GM (Geoscience Modeling) in the gocad software developed by France Nacy University, the AVS system developed by American Advanced Visual System Company and the LYNX system developed by Canadian LYNX Geosystems Company all provide the modeling function of three-dimensional geological body. In China, Wu Lixin, Hu Jinxing, etc. put forward the technical difficulties of volume visualization technique in three-dimensional geological modeling and the overall framework of the volume visualization in urban geological model, and also research the display algorithm and vision model; Liu Xiuqiu discussed about the volume visualization technique in urban geological model, and Zhu Liangfeng made a further improvement; Zhang Yu, Bai Shiwei, etc. detailedly studied the application of the volume element based on tri-prism volume in three-dimensional geological modeling; Yu Wanrui, etc. mainly studied the application of volume visualization system in the aspect of geophysical exploration data; Huang Wenjing, etc. mainly studied how to conduct three-dimensional reconstruction of geological data field by using volume rendering method.

Comparing with foreign countries, the start of domestic three-dimensional geological modeling and visualization software system is relatively late, but it still has made some developments and achievements.

1) In 1996, Geophysics Institute of Chinese Academy of Sciences cooperated with Shengli Petroleum Administration Bureau on the key project “Research on three-dimensional modeling and graphical display of geological body” of National Natural Sciences Foundation, and began the study of gocad.

2) Changchun University of Technology developed a three-dimensional GIS system “GeoTransGIS” on the TITAN GIS of Apollo company, which is mainly used to establish the structural model of lithosphere and dispose three-dimensional information.
3) The RDMS that was developed by University of Petroleum Development and the SLGRAPH that was developed cooperatively by Nanjing University and Shengli Oil Field are mainly used in the visualization disposal of oil exploration data.
4) The GeoView that was developed by China University of Geosciences can realize realistic three-dimensional geo-information management, computational analysis and evaluation decision support.
5) The TrapDEM that was developed by China Petroleum Exploration and Development Research Institute can recover the movement history of geological body by using three-dimensional tectonic evolution.
6) The Lzheng geographic information system that was developed by Beijing Lzheng Software Design Research Institute is relatively mature software, and it is mainly used to conduct three-dimensional geological modeling.
7) In 2002, Beijing Oriental Titan Corporation and Guangdong Provincial Institute of Geological Survey developed the three-dimensional modeling software TITAN T3M cooperatively, based on Titan’s original product “three-dimensional modeling software above and below ground”, this software is added some new features, which are mainly about the applications of geological structure modeling.
8) In recent years, Wuhan Zhongdi Digital Technology Company has made some achievements on the development of three-dimensional geological software system. In addition to the development of mature fundamental GIS platform “MAPGIS”, they also constructed three-dimensional modeling platform MapGIS TDE based on the MAPGIS, launched a series of software systems that aimed at specific industry area like mining and so on, and these systems has been applied into some actual projects which had achieved good effects.

Some of these software systems are general visualization systems, while the others are exclusive visualization system in geological field, which involve three-dimensional visualization in seismic exploration, three-dimensional geological modeling, deposit simulation, mining assessment, design and planning, production management and so on, and most of them possess the versions based on various platforms.

With the help of existing software, the issue of how and to what extent can the three-dimensional geological modeling solve the practical production problems is explored. On the other hand, problems can be discovered through the application research, which will facilitate the improvement of three-dimensional geological simulation theory and methods and the development of software.

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