Complex 3D geological modeling based on digital twin

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Abstract. With the development of digital twin and multi-source data fusion technologies, objectively and accurately reflecting the complexity of geological structures has been the key to the development of geological modeling. Therefore, a complex 3D geological modeling method based on digital twin is proposed. Integrating multi-source data, the method realized 3D modeling of geological body containing complex structures through potential-field interpolation based on cokriging algorithm. Combined with real-time sampling data such as geological sketch of palm surface and advanced geological prediction obtained during the construction process, the 3D geological model was locally corrected to achieve a realistic approximation of the newly revealed geological conditions. The results show that the digital twin geological model can reasonably and effectively use multi-source and multi-scale geological information to truly reflect the 3D spatial characteristics of complex geological structures. It also reflects the refined process of geological model before and after the engineering construction, and provides effective safety guarantee for the tunnel and underground space engineering in the construction and operation stages.

1. Introduction

As one of the important research elements of engineering geology digitization, the early methods of 3D geological modeling focus on the similarity of external form, while neglecting or incompletely accounting for the internal characteristics. This point poses a significant impediment to understanding the underground geological phenomena deeply. Where accurate understanding of the internal conditions of geological body has been recognized as vitally important for engineering construction, improving the refinement of geological model is pivotal.

In order to develop a geological model that can realistically represent the characteristics of geological body, it is important to make full use of massive, multi-source, multi-dimensional, and dynamic complex spatial geological data [1]. Borehole data can determine the stratigraphic division and form a series of stratigraphic surfaces by interpolating the original data points of the same stratigraphic surface, which is mostly suitable for layered geological body modeling [2,3]. However, the amount of direct sampling data available is limited. It is difficult to reconstruct complex geological phenomena such as faults. Section data not only contains real geological information, but also contains the experience of geological experts. The complex geological model can be represented with the formation surface by constructing curved surface [4,5]. However, the amount of effective data from a single data source is limited, so it is hard to reflect the geological characteristics in detail. Therefore, in
recent years, the comprehensive utilization of multi-source data has gradually become the research trend of 3D geological modeling [6,7]. The integration of multi-source information from various ways can more truly reflect the 3D space characteristics of geological body and improve the accuracy of the model. However, due to the difficulty of data integration, there is no complete method system at present. Most of the existing researches only involve the integration of two kinds of data sources. Here, we aim to integrate topographic surface map, section data and borehole data to realize 3D modeling of geological body containing complex structures.

In recent years, digital twin technology has been widely and highly concerned. As an important means to realize the interaction and integration between the physical world and the information world, it can create virtual models of physical objects in a digital way, and reflect the life cycle process of physical objects [8]. At present, the research of digital twin technology mainly focuses on (i) fault prediction and health management of complex equipment [9-11], (ii) product development, manufacturing and service [12,13], (iii) smart city construction [14,15]. However, the research in the field of engineering geology is rarely involved. Based on the characteristics of engineering geology, according to the five dimensional model [13], the complex 3D geological modeling problem is standardized into a digital twin problem. Taking tunnel engineering as an example, this paper focuses on the modeling method of 3D geological model at different stages of the life cycle. In order to reflect the change process of the geological model with the excavation, combined with the real-time geological sketch and advanced geological prediction data obtained during the construction process, the 3D geological model is locally modified to realize the real approximation of the newly exposed geological conditions.

2. Geological modeling with digital twin guidance

The concept of digital twin was first proposed to describe product manufacturing and real-time virtual presentation. Generally speaking, there are three dimensions: physical, virtual, and connection parts. With the deepening of the research on digital twin, a five dimensional structure model has been proposed, and has been widely recognized and applied [13]. Because the conceptual model is a general reference architecture, which can be applied to different application objects in different fields. The geological modeling problem is standardized as a digital twin problem based on this model (Figure 1).

2.1. Physical entity (PE) - geological body

Geological body exist objectively. Because engineering geology is closely related to engineering construction, the study of geological body usually needs to consider three stages: survey and design stage, construction and excavation stage, operation and maintenance stage. With the gradual progress of each stage, more and more geological information is exposed, so as to more fully understand and grasp the morphological characteristics and change process of geological body.

2.2. Virtual entity (VE) - 3D geological model

Geological model is a faithful digital mirror image of physical entity (geological body), which integrates geometry, physics, behaviour and regulation.

2.2.1. Geometry model (Gv). It describes the spatial distribution characteristics of geological structure, i.e. the structural model. According to the spatial geometric features of geological body, it can be classified into layered and non-layered entity. Layered entity occupies most of the earth's surface, which is the research object of this paper. When building a regional model with complex geological structure, two main problems are generally solved: the expression of spatial geometry of geological body and the description of geometric relationship. The construction of geological structure model with high accuracy is the key of 3D geological modeling, and it is also the focus of this paper.
Figure 1. Five-dimensional conceptual model for geological modeling based on digital twin.

2.2.2. *Physics model* ($P_v$). It describes the physical attribute parameters inside the geological body, i.e. the attribute model. Usually, the attribute model is built on the basis of 3D geological structure model, and the corresponding relationship between them is established. It can provide physical and mechanical parameters of surrounding rock such as elastic modulus, poisson ratio, cohesion and internal friction angle for later mechanical analysis.

2.2.3. *Behaviour model* ($B_v$). With the progress of engineering construction, a large number of geological data continue to appear. In order to further improve the accuracy and authenticity of the geological model, the spatial geometry of the geological model is modified by using the data of different stages and scales. In addition, many physical and mechanical parameters in the geological body have the law of variation with time and space caused by construction. With the help of real-time monitoring data, the spatial-temporal model of the distribution characteristics of surrounding rock attribute parameters is established to analyze and predict the mechanical state of the changing tunnel excavation system.

2.2.4. *Regulation model* ($R_v$). It includes the laws and rules of geology, the experience based on implicit knowledge, and the relevant standards in geological field. These rules make the geological model have the ability of real-time judgment, evaluation, optimization and prediction. Besides integrating the existing knowledge to build regulation model, we can also use machine learning algorithm mining to generate new rules.

2.3. *Service System* ($S_s$)
Based on geological body and geological model, it provides intelligent operation, accurate control and reliable operation and maintenance services. It mainly includes two parts:

2.3.1. *Function Service* ($F_s$). It is used to support the operation and implementation of internal functions of digital twin. For example: a series of operation and management functions for geological
model; data management services for digital twin data; interface and data transmission services for connection.

2.3.2. Business Service (B). It is used to meet the needs of customers and businesses in different fields. For example: data upload, data view and operation guidance services for construction site staff; numerical simulation, dynamic simulation services for professional and technical personnel; risk assessment, prediction and analysis services for management decision-makers.

2.4. Digital Twin Data (DD)
Digital twin data is updated and optimized with the generation of real-time data, including the following five parts. ( i ) Geological body data: elevation data, geological section data and borehole data obtained through geological exploration; palm surface information and advanced geological prediction obtained in the process of engineering construction, ( ii ) Geological model data: relevant data reflecting the spatial geometric shape and physical attribute parameters of geological body; relevant data driving behaviour model and regulation model, (iii) Service system data: algorithm and data related to service function. ( iv ) Related knowledge in geological field: geological rules, expert experience knowledge, theoretical algorithm, etc. ( v ) Derived data: derived data obtained after preprocessing, classification, conversion, association, integration, fusion and other related operations.

2.5. Connection (CN)
The above four parts are connected in pairs to ensure the real-time and effective transmission of data, so as to ensure the consistency between the parts.

3. Complex 3D geological modeling method

3.1. Geological data
Due to the complex geological conditions and geological processes, there are great differences in various technical survey methods. Therefore, the geological raw data has the characteristics of huge quantity, variety and complex structure, which greatly hinders the progress of 3D geological modeling research. In order to make a variety of geological information available, reliable for the modeling system, the applicability, difference and discreteness of the data should be fully considered, and the multi-source geological data should be effectively coupled.

3.1.1. Topographic surface map. It reflects information such as geographic location, surface fluctuation, and elevation data. The elevation data can be extracted by ArcGIS to generate a 3D topographic surface. The topographic surface is essential, which defines the upper limit of the 3D geology model. The ‘geology map’ for modeling area is created from the intersection of this topographic surface and the (mathematical) 3D model.

3.1.2. Section data. It reflects the stratum contact relations and geological structure characteristics. As the closest reflection of the real geological situation, the section data contains not only real geological information, but also the experience of geological experts. When building a 3D model of geological formations, a typical method is creating sections and defining or interpreting the geology within those section views.

3.1.3. Borehole data. Traditional modeling methods often use spatial interpolation of discrete borehole data to obtain continuous surface data. However, due to factors such as the cost of acquiring borehole data and the natural environment of the survey area, the amount of borehole data acquired is often limited. Thus, with its reliability and accuracy, the generated model can be directly or indirectly corrected.
3.2. Potential-field interpolation method based on cokriging algorithm

Potential-field theory can be used to create a single geological interface or a series of approximately parallel geological interfaces \( l_k = 1, 2, \ldots \). The essence is to simplify and generalize the geological environment by using a potential-field, which can be considered as a scalar function \( T(p) \) located at any point \( p = (x, y, z) \) in 3D space. Any geological interface can correspond to an equipotential surface, i.e., a series of points \( p \) located on the surface satisfying \( T(p) = t_k \), where \( t_k \) is the unknown potential field value. That is, the formation can be equivalently considered to be surrounded by two continuous geologic interfaces \( l_k \) and \( l_k' \). The potential values of the point \( p \) are \( t_k \) and \( t_k' \).

![Figure 2](Image)

**Figure 2.** Principle of the potential-field interpolation method [16]. (a) Red and blue points denote contact location of two formations respectively; arrows denote orientation data. (b) Geological formation simulated with the potential-field method. Red and blue curves represent the reference equivalents of the simulated geological contact interfaces. The black curves represent the selected potential field equivalents.

Two types of data are required to construct \( T(p) \): (i) contact location data (3D points located on the geological interfaces \( l_k, l_k' \), \( \ldots \)), (ii) orientation data (3D unit vectors belonging to the orientation field and polarised along younging direction.)

Since the potential values at the sampling points \( p_0, p_1, \ldots, p_m \) located on the same geological interface are unknown, these data can be considered as \( m \) increments \( T(p_{\alpha}) - T(p_{\beta}), \ \alpha = 1, \ldots, m \), and each increment is equal to zero. The orientation data at the point \( p_\beta \) can be expressed in the form of partial derivative \( \partial T(p_\beta) / \partial u_\beta \), where \( u_\beta \) denotes three coordinate axes \( x, y, z \). The \( p_\alpha \) must be located on the geological interfaces, and the \( p_\beta \) can be located anywhere. The potential increment at any point \( p \) can be estimated by cokriging algorithm as follows:

\[
T(p) - T(p_0) = \sum_{\alpha=1}^{M} \mu_{\alpha} (T(p_{\alpha}) - T(p_0)) + \sum_{\beta=1}^{N} \nu_{\beta} \frac{\partial T}{\partial u_\beta} (p_\beta)
\]

Where, the weights \( \mu_\alpha \) and \( \nu_\beta \) are functions of \( p \) (and \( p_0 \)), determined by the cokriging system; \( M \) denotes the total number of increment; \( N \) denotes the total number of \( \partial T(p_\beta) / \partial u_\beta \).

4. Case analysis

4.1. 3D geological model construction

Taking a tunnel project in Guangzhou as an example, the geomorphic unit of the tunnel belongs to weathering and erosion hilly landform. The stratum in the tunnel site is relatively simple, and the
bedrock in some sections is exposed on the surface, which is mainly distributed with quaternary eluvium. The bedrock is granite intrusion of late Yanshan period, and the lithology is monzonitic granite. There is a fault fracture zone near the middle of the tunnel. According to the survey results of engineering geological drilling, the lithology of the tunnel site is as follows:

| Stratigraphic sequence | Contact relationship | Formation                                      | Symbol |
|------------------------|----------------------|------------------------------------------------|--------|
| Fault sequence         | Erode                | Fault                                          | F      |
| Top cover              | Onlap                | Quaternary residual slope deposit              | Q₄d+el|
| Bottom cover           | Onlap                | Quaternary alluvium and diluvium               | Q₄d+pl|
| Fully-Strongly weathered granite | Onlap            | Fully weathered monzonitic granite            | γ₅2(3) |
| Weakly-Slightly weathered granite | Onlap            | Weakly weathered monzonitic granite          |        |
|                        |                      | Slightly weathered monzonitic granite         |        |

Digital elevation model (DEM) is established by using topographic surface map, to generate a 3D topographic surface. The contact location data and orientation data on the stratigraphic interface are obtained by discretizing the section information. Combined with the outcrop data in the topographic surface map, the potential-field interpolation is carried out, and the preliminary 3D geological model is obtained (Figure 3).

![Figure 3. View of the 3D geological model. (a) Spatial distribution of geological section and surface direction data. (b) Preliminary solid geological model.](image)

4.2. 3D geological model calibration
Figure 4 shows the inconsistency between the preliminary geological model and the borehole data at the exit of right line of tunnel. The spatial position of the contact point on the stratum interface within 50m around the borehole is adjusted. The potential-field interpolation is carried out again based on the corrected point position data. The stratum surface obtained from the section information is relatively smooth (Figure 4a), because the survey data usually reflect the macro trend of the internal structure of the geological body. So it is difficult to obtain the local variation characteristics. The corrected stratum interface has a certain degree of local distortion and inversion, which shows the real spatial distribution law of stratum. Compared with the preliminary 3D geological model (Figure 3b), the exposure of slightly weathered granite and the distribution range of weakly and strongly weathered granite in the upper left part of the corrected model (Figure 5) have changed.
Figure 4. Geological model modification based on borehole 5th at the exit of right line of tunnel. (a) Preliminary geological section. (b) Section after borehole correction.

Figure 5. Final complex 3D geological model.

4.3. Local modification of geological model based on palm surface information
The palm surface information obtained during tunnel excavation can be regarded as small-scale section information. Therefore, according to the existing palm surface data, combined with the relevant experience and knowledge of geological engineers, 30 local sections are added near the tunnel entrance and exit. The contact location data and orientation data obtained by discretizing the line shape information of the palm surface are added to the corresponding potential-field for interpolation. In the initial regional geological model without local correction, the strata change gently near the tunnel entrance (Figure 6a). After the correction, the geological irregularity, singularity and serious structural variability within 50m around the tunnel have been reflected (Figure 6b).
5. Conclusion

Based on the five dimensional model in digital twin, this paper proposes a complex 3D geological modeling method. This method can make full use of the limited geological exploration data, geological expert experience and construction excavation information. Through potential-field interpolation based on cokriging algorithm, the prediction and approximation of the real geological environment were realized. The final geological model clearly and intuitively shows the 3D space characteristics of the complex geological body, reflecting the refined process before and after the engineering construction. The final results were consistent with the known actual geological conditions. Subsequent research work will focus on optimizing the interpolation algorithm, especially the spatial random field functions and structure functions with geological significance, in order to obtain geological models with higher accuracy. In addition, the 3D geological modeling work guided by digital twin will surround some aspects of virtual model, dynamic update, and data interaction.

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