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A 3D Multi-scale geology modeling method for tunnel engineering risk assessment

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ABSTRACT

A method for 3D multi-scale geology modeling is proposed for assessing tunnel engineering risk. Risk assessments have varying requirements at various different construction stages, therefore the proposed model can be modified for different scales. The regional scale 3D geological model, based on regional field surveys of geological boundary and attitude, is proposed for conducting preliminary evaluations with limited geological sampling data and the Hermite radial basis function (HRBF). The project scale geological model, based on updating and refining the regional scale model with dense drilling and geological prediction data, couples the geological body model for surrounding rock and the tunnel model. This project scale model is appropriate for performing pre-evaluations of tunnel construction. Once construction has begun, continuous rock structure surface information from the newly exposed tunnel face is incorporated into the outcrop scale geological model. It is based on a Monte-Carlo algorithm for conducting dynamic evaluations during construction. These modeling methods are applied to a case study, railway tunnel engineering of the Yuelongmen tunnel in China.

1. Introduction

Advancements in the construction scale of major infrastructure projects in transportation, water conservation, and hydropower have made China a world leader in tunnel construction. Construction in China has extended to western mountainous areas with complex topography and geology, and to karst regions. The excavation of high-risk deep tunnels frequently leads to geological disasters, such as inrushing water, collapse, and rock bursts. Geographic information system (GIS) technology, especially 3D GIS technology, can be rapidly employed to geological field applications (Jacobsen et al., 2011; Kessler et al., 2009; Mallet, 1992; Nigro et al., 2003; Scheck-Wenderoth and Lamarche, 2005; Wang et al., 2008). This development has brought new insights to risk assessment and tunnel management. However, to apply 3D GIS technology to tunnel engineering design and construction, regional geological models of the construction area, or local models for the area surrounding tunnels are necessary (Tacher et al., 2006). Comprehensive analyses, including excavation (Cai, 2008) and finite element (Taromi et al., 2015) analyses, can only be conducted based on geological models.

A visualized 3D geological model represents the spatial distribution of strata and discontinuities across three dimensions. This is a powerful and convenient tool for engineers to directly observe and analyze relationships between engineering structures and unfavorable geological conditions, such as fracture zones and weak interbeds. As a result, 3D geological modeling has attracted increasing attention from researchers in the engineering geology and geotechnical engineering disciplines (Xu et al., 2011). 3D geological modeling methods and visualization technologies have developed gradually in recent decades (Amorim et al., 2014; Houlding, 2012; Turner, 2006; Vollgger et al., 2015; Wellmann et al., 2010), and many researchers have contributed to studying correlative techniques. Many surface models have been used in geological models, including Coons surface (Zhou et al., 2016), NURBS surface (Piegl and Tiller, 2012; Zhong et al., 2008), DSI interpolation (Lévy and Mallet, 1999), and geostatistical interpolation (Liu et al., 2014). Based on these methods, modeling software has been developed, including GOCAD (Kaufmann and Martin, 2008; Mallet, 1992), Geomodeller (Calcagno et al., 2008), and Vulcan (Vulcan, 2014), which have been widely used for geological surveys (Kessler et al., 2009), geophysical inversions (He et al., 2014), mine 3D simulation (Vollgger et al., 2015), and water resource assessment (Hassen et al., 2016). These methods can simulate complex geological structures. However, when

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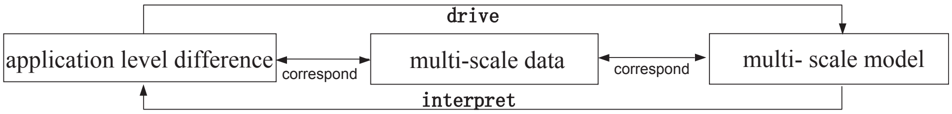

Fig. 1. The principle of application level difference-driven multi-scale partitions in engineering geological data.

constructing regional geological models with complex hierarchical and topological relationships, it has been difficult to satisfy the complex geometrical shapes of any one model and maintain consistency between models. For instance, when complex geometric shapes were guaranteed, model consistency was unsatisfactory. Conversely, when a method satisfies the consistency between models, the precision, effects, and agreement between models and original data are not satisfied (Smirnoff et al., 2008). Furthermore, these methods are primarily based on data acquired from drill-holes (Caumon et al., 2004; Lemon and Jones, 2003) or cross-sections (De Kemp, 1999; Lepage, 2002; Ming et al., 2010). However, tunnel engineering construction often conducted in complex geological terrain; as such, borehole or section data are difficult to obtain. Therefore, the demands of tunnel engineering applications are difficult to satisfy using single scale geological modeling methods. However, with continuous excavation and application of advanced geological forecast technology during construction, new data can be acquired.

Tunnel risk assessment and management are essential steps in the complete life cycle of construction; Zhang et al., 2011 and Xu et al., 2011 proposed a three-stage risk assessment and management method, which included a preliminary evaluation, pre-evaluation, and dynamic evaluation at the prospecting stage, design stage, and construction stage, respectively. 3D geological scale modeling provides additional information due to variations in the target geological body at different risk assessment stages. On the basis of an engineering example, we propose a novel multi-scale modeling method combined with 3D GIS technology.

2. The principle of tunnel engineering geological data across multiple scales for applications in risk assessment

Scale is an important characteristic of spatial data. Geological scale is defined on the basis of two aspects: geological factors on a space with relative sizes and degree of conceptual abstraction. At different scales, geological elements likely exhibit different spatial forms, structures, and details. The elements of spatial morphology at different abstraction levels should form a multi-scale expression of geological elements and satisfy different levels and requirements of user-space modeling and analysis applications (Zhang et al., 2010).

In the life cycle of a tunnel, the pre-survey planning stage needs to fully encompass and analyze the geological state and distribution of potential disaster sources in pre-selected areas of the tunnel. Therefore, studying the regional geological environment caused by tunnel construction is a necessary primary element of the preliminary evaluation. Using preliminary field geological survey data, we can construct a macroscopic 3D geological model of the tunnel engineering area, carry out a preliminary evaluation of geological environment conditions, and form a feasibility report for tunnel construction. In the design phase, detailed tunnel design planning initially determines the construction method. Through drilling, geophysical surveys, and other technical means, a 3D geological model is established in the planning stage, which can be updated and refined locally. Based on an updated and detailed 3D geological model, the risk of geological disaster in a designed tunnel line is pre-evaluated. In the construction phase, accurately understanding current excavation is the next step in the construction requiring pre-judgment and coordination arrangements. During tunnel construction, the continuous excavation of tunnels and application of various advanced geological prediction methods will continue to produce new data, such as the location and numbers of joints and cracks. This data can be applied to build a more detailed 3D geological model that meets the needs of dynamic risk assessment during the construction period, and determine the technical support program to guide construction. These three described stages are different in terms of cognition and conceptual character; the first stage is "the demonstration of tunnel planning feasibility," the second stage is "the concrete design of the tunnel line," and the third stage is "the implementation of the tunnel excavation and support scheme." The three stages and their application requirements drive the data needs, multiple levels of acquisition, and multi-scale geological models, as shown in Fig. 1. In this study, the geological model is divided into three spatial scales: regional, tunnel project, and outcrop. The regional scale refers to the tunnel engineering area and extends a few kilometers to tens of kilometers to the surrounding area and encompasses the terrain surface, regional faults, geologic formations, and lithology information. The tunnel project scale refers to the scope of the tunnel engineering area, focusing on the areas of tunnel construction. The main research objects are bedrock surfaces, rock interfaces, tectonic surfaces, geological surfaces, lens body, stratigraphic units, folds, caves, and exploration objects, i.e., drilling, flat copper, exploration pits, and trenches. The outcrop scale refers to joint and fissure data obtained from newly excavated tunnel faces.

Based on the multi-scale definitions and characteristics of risk assessment at different stages of the tunnel engineering life cycle, this study proposes a conceptual multi-scale 3D geological model for tunnel engineering. External factors include different scale survey data of the tunnel engineering area; these are used to establish a multi-resolution integrated 3D geological model that represents the 3D multi-scale geological data. This model can meet the different requirements of geological risk assessment during different stages of the tunnel project life cycle. For practical applications, the multi-scale expression is the basis for multi-scale geological problem analyses because the data demands can span a range of resolution needs. Geological problem analyses are generally based on a certain spatial scale and level, i.e., geological phenomena and processes are usually dependent on scale. In essence, multi-scale 3D geological modeling uses geological survey data with different precisions to establish multi-level of detail(LOD) features, which can meet the needs of multi-level analyses of geological tunnel engineering.

3. Regional scale modeling for preliminary evaluation

In the planning phase of a tunnel engineering project, the 3D geological model of the tunnel engineering area, referred to as the regional model, should be used to study the stability of the tunnel area and regional geological environmental problems. This is a preliminary evaluation of the tunnel project risk, which provides a reference for studying tunnel feasibility.

Geological survey data, such as geological plans, geological section maps, and cross-section tunnel designs, are often drawn in the CAD datum. The natural forms of surface geological outcrops are shown as geological boundaries (closed polygons). Data indicate geological space extending in a downward direction. However, geological models cannot be simply built by extending geological boundaries to connect contours; this would not meet topological consistency requirements and regularity edges of a regional geological model.

As 3D geological modeling methods have progressed, some novel modeling methods have been proposed based on geological survey data, including potential-field interpolation, and stochastic and uncertainty methods. Regional 3D geological models (Calcagno et al., 2008), as well as fundamental structures have been simulated using these methods,