A parametric multi-level of detail modeling method for extra-long highway tunnel

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Abstract: Building information modeling (BIM) technology realizes the integration of multi-discipline fragment information and visual management and strongly supports tunnel dynamic design and digital construction. However, current BIM platforms, such as Revit, are difficult to establish and use in updating the tunnel model. To promote the application of BIM in tunnel design and construction, this paper illustrates a multi-level of detail (LOD) definition for tunnel structure and realizes the parameterized establishment of a fine model for mountain tunnels. Tunnel model units are decomposed into continuous, distributed, and special units based on spatial distribution characteristics, and each type of unit is modeled by a specific designed algorithm. Based on Dynamo, a visual modeling Revit plug-in, segmented tunnel models of different LODs are built and integrated together. Finally, by introducing progress information to the modeling algorithm, this paper realizes the dynamic update of the tunnel model. The method has been verified in practice in Laoying tunnel, Yunnan Province, successfully achieving the parameterized establishment of the detailed tunnel model of the extra-long tunnel in the mountainous area. The results show that this method meets the modeling requirements of highway tunnels and lays the foundation for BIM-based tunnel construction simulation, schedule optimization, and further application.

Keywords: Building Information Modeling, Parametric modeling, Extra-long mountain tunnel

1. Introduction
Building information modeling (BIM) realizes the integration and visualization of Architecture, Engineering and Construction (AEC) information and supports information sharing among various domains. However, tunnel engineering presents the characteristics of special structural form and uncertain and fickle geological conditions, which result in frequent construction changes [1]. The lack of basic model components, inefficient modeling method, low model reusability, high visualization requirements, and inconsistent application standards severely restrict the application BIM technology in the field of tunnel engineering [2].

The tunnel information model has achieved considerable development in construction simulation, construction schedule visualization, field management, quality control, risk monitoring, and warning [3]. However, given the wide variety of tunnel model components, large axis length, and irregular space distribution, tunnel modeling presents difficulty, and the details and accuracy of the tunnel model need to be improved. In the current parametric modeling method, the precise axis is mainly extracted by CAD or Civil3D[8-10], and a standard family model library per unit length is established
by distinguishing straight lines and curve segments[10, 11]. The family model library includes all kinds of basic tunnel model units (shotcrete, anchors, reinforcement mesh, etc.), and then using Revit secondary development, Dynamo, or array method[12], the unit model is accurately placed at a point to accomplish the tunnel model; several scholars[14,15] established the parameterized section unit model, which is controlled by the adaptive point, by clarifying the tunnel parametric parts (arch radius, side wall height, etc.) and parameter types (value, string, etc.) and imported the unit model into Unity3D or other modeling software to build the overall tunnel model.

However, several problems remain to be solved in the current parametric modeling method: 1) Artificially defined model unit length and division of the tunnel model to various parts lead to joint crack and spatial misalignment; model accuracy still needs to be improved to meet the requirements during the design and construction stage. 2) The automatic updating capability needs to be enhanced to reflect the frequent change in the site design and construction scheme. 3) The existing methods are difficult to use in coordinating the contradiction between the full-length model volume and high accuracy; the modeling method for the full-length long tunnel still needs to be studied.

To solve the above problems, based on the Revit and Dynamo visual programming, we accomplish a parametric model of a mountain-highway tunnel feasibility study, preliminary design, and construction phases by distinguishing the continuous, discrete, and special units of the tunnel model. By combining the construction schedule and design parameters, the automatic update method of model of construction phase is achieved. Through the application in Laoying long-length highway tunnel in Yunnan Province, the modeling method functions well for the visual disclosure of the design and construction information; it also promotes the development of BIM technology.

2. Parametric Multi-Level of Detail Modeling Method for Road Tunnel

2.1. Multi-LOD definition for tunnel model

Given the changeable geological conditions of tunnel engineering and the variability of the design and construction scheme, multi-LOD modeling rules are proposed, and they are conducive to improving the information level of rock tunnel engineering, standardizing the modeling, delivery, and application behavior of rock tunnel information models, and guiding the organization, storage, and exchange of models.

Multi-LOD technology is the definition of the content of model geometric information and minimum error. Based on the tunnel project construction progress, the tunnel model can be divided into three phases: feasibility study, preliminary design, and construction phases. Corresponding to the three phases, the tunnel model is divided into three LODs (LOD100, LOD200, and LOD300).

With the progress of the project phase, the model LOD degree increases. In addition, the component information is constantly superimposed and refined, and the carrying information depth, model accuracy, and delivery objects are constantly iterated to meet the requirements of visual design, model delivery, etc. In the feasibility study phase, the feasibility of the tunnel project plan, such as the optimal tunnel route scheme, is of concern. The information model mainly includes the tunnel spatial location and road route. In the preliminary design phase, the main support structure of the tunnel is designed based on the surrounding rock grade, which is classified in accordance with a survey report. The model is mainly composed of support structure, water prevention and drainage system, pavement structure, etc. In the construction phase, the model of the preliminary design phase is further refined. Designers mainly focus on the construction scheme, construction progress, etc. Considering the volume of the model, modeling efficiency, and engineering practice requirements, this paper defines the component content of the multi-LOD model (Table 1).

| Design phase          | LOD   | Information depth                                      | Main components                      | Delivery object       |
|-----------------------|-------|--------------------------------------------------------|---------------------------------------|-----------------------|
| Feasibility Study Phase| LOD 100 | Project Information Line Information Space Positioning | Spatial alignment Building limitation and interior contour | Main tunnel Inclined shaft |

Table 1. Regulations for multi-LOD Model
Preliminary Design Phase  LOD 200  Space Positioning  Material Information  Component geometry  Component Interrelation
Spatial alignment  Holdoor structure  Initial support*  Secondary support*  Water prevention and drainage system  Pavement 
Main tunnel  Inclined shaft  Emergency parking belt  Pedestrian crossing channel  Vehicle crossing channel  Wind room

Construction Phase  LOD 300  Detailed components  Material Information  Accurate positioning  Connector Details  Project Progress  Construction plan
Spatial alignment  Tunnel portal structure  Advance support  Initial support  Secondary support  Water prevention and drainage system  Pavement structure  Maintenance ditch 
Current construction section

* Initial and secondary linings in the preliminary design phase do not include the anchor rod, steel mesh, and steel arch frame.

2.2. Tunnel axis fitting
The axis of a tunnel is a spatial curve designed in separate horizontal and longitudinal forms. The axis information of the main tunnel, inclined shaft, wind room, and other structures are mostly expressed in CAD drawings in the form of horizontal and vertical curves. However, the corresponding relationship between the spatial coordinate and tunnel mileage cannot be reflected in the CAD drawings to support the precise positioning of structural components.
To obtain the coordinate information of each mileage of the tunnel axis, in this paper, we process the tunnel axis as a series of discrete points. To ensure the positioning accuracy of the axis, we set the straight line interval at 1 m and the curve section interval at 0.5 m. The tunnel axis is fitted by a high-order spline utilizing the coordinates of the discrete point.

2.3. Model decomposition and element establishment
Revit has advantages in component management and parametric modeling. Dynamo is a visual programming plug-in developed by Autodesk for Revit, and it can implement the modeling and editing of complex structures and expand the modeling capability of irregular models. In this paper, a parametric tunnel model is established by positioning, stretching, or placing the unit model in the Revit and Dynamo workspace. In addition, combining the parametric tunnel model with construction progress and change information drives the dynamic update of the model.
The tunnel structure consists of the tunnel body, tunnel portal, and auxiliary buildings. In accordance with the construction process of the tunnel, lining and pavement are continuously constructed. Steel frame, advance support, and anchor rods are mass produced in the factory and transported to the construction site for installation and splicing. The tunnel body is connected with the emergency parking belt, tunnel portal, wind room, and other auxiliary buildings to form a complete tunnel. Based on the construction characteristics, the tunnel model components are divided into three basic units: continuous, discrete, and special (Table 2).

Table 2. Classification of Basic Unit Model

| Classification | Subdivisional project | Component Form               |
|----------------|-----------------------|------------------------------|
| Continuous unit | Lining, Building Limitation, Shot Concrete, Inverted Arch, Pavement, Cable Ditch, Drainage Ditch and Drain pipe | Section profile |
| Discrete unit | Advance pipe, Anchor rod, Steel arch frame, Grille steel frame, Geotextile, Waterproof board, Transverse drainage pipe, Drain ditch cover plate, Mechanical and electrical equipment and Blocking wall | Complete Family model |
| Special unit | Wind room and Tunnel portal | Complete model |

1) Continuous units: The basic component of the continuous unit is the profile family model. The steps of the continuous establishment of the unit are as follows: First, a metric regular family model is created in Revit, and the model section profile is drawn with an elevation view based on the design drawing. Then, the dimension information, such as radius, angle, and others (Figure 2), are added to achieve the parametric size adjustment, finally completing the establishment of the basic section profile model. The continuous unit is stretched along the axis to avoid creating joint cracks fundamentally.

2) Discrete units: The basic component of the discrete unit is the complete family model, which contains materials, geometric relations, and key parameters. With steel arch as an example, first, in accordance with the design CAD figure, the lay-out path is drawn. Then, the parameterized I-steel section is stretched along with the path. Excess parts are cut off, material, dimension, and other attribute information are given, and the establishment of a steel arch family model is completed. Finally, the steel arch, locking foot pipe, longitudinal connection steel bar, connecting steel plate, slot steel, and bolts are joined to complete the I-steel arch frame (Figure 3).

3) Special units: Special units refer to the special structure models that cannot be established in batch through the algorithm, such as the wind room and tunnel portal. Given that the special units of each project are different, the complete model is mainly established by manual modeling method to improve the modeling efficiency.
2.4. Parametric modeling method
The LOD100 model of highway tunnel implements the description of the tunnel spatial positioning, which consists of the tunnel route, tunnel contour, tunnel boundary, and building limitation model. LOD100 model is modeled by continuous units. To establish the LOD100 model, first, we import the tunnel axis coordinate data and then fit the tunnel axis by the B-spline curve. Then, the dimension information (radius and thickness of tunnel contour) are endowed to the parametric continuous unit model, finally stretching the contour model along the full-length tunnel axis to establish the overall model.

In the preliminary design phase, the LOD200 model is further refined based on the LOD100 model, which can be used for system analysis and visualization. The LOD200 model consists of supporting structure, pavement structure, waterproofing, and drainage system. For continuous units, such as the initial spray concrete, the basic contour models are stretched along the axis to establish the geometric models, and the material and other parameter attributes are set. For the discrete units, such as anchor rod, grille arch frame, and steel arch frame, first, the basic unit family models, which include necessary basic attributes, are established in Revit. Then, the discrete unit models are placed in accordance with the design interval, distribution form, and placement points, which are calculated by space interpolation method. To ensure that the placed family model normal direction is consistent with the tunnel axis tangent direction, we obtain the angle between the tangent vector of the tunnel axis and the family model normal vector (Figure 5). In the design of tunnel engineering, lining structure is divided into different types based on the geological information, such as surrounding rock grade and geological environment. Therefore, along with the tunnel axis, segmented models are established based on the different lining types to avoid the joint cracks caused by the artificial definition of length of the unit model.

For the connection part of the emergency parking belt model and the crossing channel model, the outline entity of the main tunnel is modeled along the axis, and by corresponding the mileage information to the spatial coordinate point, the crossing channel and main tunnel models are accurately located and cut. Through the above steps, the connection part of the emergency parking belt model and the crossing channel model is established (Figure 6).
In the construction phase, the information of the construction procedure and schedule are extracted to lay the foundation for the dynamic update of the model. The LOD300 model consists of all structures e.g., anchor rod, steel mesh, and steel arch frame. The basic establishment method of LOD300 model is the combined construction procedure and construction schedule with the LOD200 model. Given that the LOD300 model contains all the structure, construction procedure, and schedule information, the tunnel model, which is nearby 200 m of the tunnel face is dynamically generated based on Dynamo to achieve a higher efficiency, and the LOD300 model updates constantly according to the actual construction information.

2.5. Model Splicing

Based on the above modeling method, the LOD200 model needs to be spliced. The data required for splicing the LOD200 model are the basic data and segmented model of the tunnel. The basic data include the mileage coordinates and mileage-lining mapping relations (Tables 3 and 4, respectively). The segment model of the main tunnel body established in accordance with the mileage-lining type table is positioned based on the coordinates and spliced by the emergency parking belt with the crossing channel, inclined well, wind room, and other structures. Then, the model of each tunnel line is completed by splicing. When the tunnel structure changes, the tunnel model can be re-built in real time by updating the family model parameters, such as size (e.g., anchor radius, anchor length, support radius, support thickness, etc.) and material.

| Table 3. Mileage Coordinates |
|-----------------------------|
| Data Name | Mileage | X   | Y   | Z   |
| example   | K0+000  | 1928.4 | 1120.8 | -25.2 |

| Table 4. Mileage-Lining Mapping Relations |
|------------------------------------------|
| DataName | Start Mileage | End Mileage | Lining Type |
| example  | K0+000        | K0+100      | SF5a        |

3. Implementation and Case Study

3.1. Establishment of information model of Laoying tunnel

Laoying tunnel is the control project of Bao-Lu (Baoshan-Lushui) Expressway in Yunnan Province. It is a detached ultra-deep buried tunnel with a length of over 11 km and maximum buried depth of 1255.01 m. Laoying tunnel has rich groundwater and complex geological conditions and cross five fault fracture zones. Thus, high construction risks and frequent changes of the design and construction plans are observed. Inclined shafts are present on the side of the tunnel as ventilation pipes. Laoying tunnel included nine lining types and three emergency parking belt sections. Referring to the mileage information in the design and construction, combining the existing axis information, the full-length of BIM model is established, and the visual integration and disclosure of the design and construction scheme is implemented.

According to the multi-LOD modeling rules, the Laoying tunnel information model is divided into three LODs (LOD100, LOD200, and LOD300), and the full-length model of different LODs is established in in accordance with the modeling methods mentioned above (Figure 7).
3.2. Dynamic update of tunnel model
Given the complexity of geological conditions, the construction scheme is frequently changed. Changes in the tunnel construction scheme are generally accompanied by a change in the tunnel lining type. Based on the Python script in Dynamo, tunnel lining types are associated with other (pavement structure, drainage system, anchor rod, steel frame, etc.) structures, and the mileage is mapped to the space coordinates by algorithm. When construction changes occur, it drives the automatic build up or dynamic update of the model, referring to the establishment method of LOD300 model. In the case of a design change, the predefined parameters of the basic unit can be quickly modified to implement the rapid update of the model, and it supports the visual disclosure of the design and construction change information.

The method can also be used for real-time management of the construction progress. Through the WebRequest node in Dynamo, the existing construction progress and construction scheme of Laoying tunnel can be obtained online. Furthermore, a tunnel information model integrates construction progress and excavation method is established in which construction progress and procedure of the tunnel face, initial lining, secondary lining, inverted arch, and other parts are independently modeled (Figure 8).
4. Discussion and Conclusion

Currently, obstacles still exist about the application of BIM technology in tunnel engineering, e.g., joint crack, spatial misalignment, low automatic updating capability, and the difficulty of balancing model accuracy and efficiency. To solve the above such problems, this paper proposes a parametric multi-LOD modeling method for extra-long highway tunnel based on the design and construction practice:

1) Multi-scale modeling rules are proposed to stipulate the accuracy and content of rock tunnel in different design stages to coordinate the contradiction between the full-length model volume and model accuracy of the growing tunnel.

2) According to the construction characteristics, the tunnel model components are divided into three basic types: continuous, discrete, and special. By integrating the construction procedure, the segment model that avoids joint crack and spatial misalignment is established.

3) Based on Revit and visual programming in Dynamo, a full-length parametric model of project feasibility phase and preliminary design phase are established. By integrating the real-time construction progress and parameters, the dynamic update method of the construction phase model is put forward.

The parametric modeling method and the definition of multi-LOD proposed in this article solves the problem of the model accuracy and dynamic update of the model in a certain extent, but the information depth and the degree of parameterization still need to be improved. The research of automatic modeling of tunnel engineering promotes the application of BIM technology in dynamic tunnel design and construction.

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