BIM-based Quantitative Assessment Method of Tunnel Collapse Risk in TBM Construction

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Abstract. Tunnel risk assessment plays an important role in tunnel design, construction and tunnel safety risk control. TBM method is more and more widely used because of its comprehensive advantages, especially in the diversion tunnel engineering. Because the geological conditions in the long tunnel are complex and changeable, TBM machines are extremely sensitive to the changing of geological conditions, various risks may occur during the TBM tunnel construction. But the risks are difficult to assess quantitatively. In this paper, an excavation model of diversion tunnel is established in ANSYS to analyze the deformation of surrounding rock, the instability probability of tunnel is obtained by Monte-Carlo method. Combined with BIM technology, the construction information model of TBM tunnel including personnel distribution, team cooperation, material transportation, structure layout and other engineering information is established. Based on combining surrounding rock information and TBM engineering information, the TBM tunnel is divided into several sections according to time and space by statistical method, the collapse risk of TBM tunnel during construction is quantitatively assessed by zoning to realize the visualization of risk class. The results can be used for TBM tunnel construction risk assessment, improving the efficiency of risk control.

Keywords: TBM tunnel, BIM, collapse, risk assessment

1. Introduction

Under the historical opportunity of the western development strategy and the implementation of the "Belt and Road" initiative, a large number of international cooperation in water conservancy and transportation projects have been put into construction, among which the diversion tunnel project is a key construction project of water conservancy projects. Compared with the traditional drilling and blasting method, TBM (Tunnel Boring Machine) construction method is widely used in the construction of long tunnels, it has the advantages of fast excavation speed, good construction quality, high construction safety, small disturbance of surrounding rock, environmental friendliness and low cost per unit length. However, the geological conditions of long tunnel are complex and changeable, so the number of risk accidents is increasing [1] and the collapse accident is one of the most serious accidents that cause casualties and economic losses [2]. Tunnel construction collapse risk involves many factors, the collapse mechanism is complex, so it is difficult to carry out dynamic collapse risk assessment.
Therefore, how to effectively carry out dynamic collapse risk assessment, there are still difficulties, information construction can solve the problem.

In risk assessment, Chen [3] proposed the "confidence index method" to assess the risk of tunnel construction stage; Shin [4] proposed the KTH-index to evaluate the collapse risk class of tunnel working face. However, this kind of assessment method is subjective and difficult to form a general consensus. In order to improve the accuracy of risk assessment, in-depth analysis of construction information, multiple information fusion [5], data mining [6], Bayesian network [7] are introduced into risk assessment, it is hoped that the coupling of large amounts of information can improve the accuracy of risk assessment. The research shows that there is a certain mapping relationship between the tunnel construction risk and the parameters in the construction information, but it is difficult to obtain a large amount of information. At present, through the modern information technology to establish the security risk management information system to solve the difficult problem of information acquisition. Information systems to preserve information and assess risk, researchers monitor and collect the information of construction processes in real time, in depth analysis and mining information, on the basis of making full use of information, research and development of monitoring and early warning analysis integrated information system[8-11].In summary, taking the establishment of tunnel information model as the goal of orientation, form information construction, dynamic risk assessment, the research on this method is still in its infancy.

Based on the concept of informatization, this paper takes a diversion tunnel project in Xinjiang province in China as the background, finite element method is used to analyze the deformation characteristics of surrounding rock and calculate the instability probability. According to the finite element simulation results, a quantitative risk assessment method is proposed. The information model of diversion tunnel construction is constructed by BIM (Building Information Model) technology, the tunnel risk assessment model is established by using statistical methods, the surrounding rock information and engineering information are combined for reasonable analysis, so as to provide reference for the risk assessment of TBM diversion tunnel construction collapse.

2. Tunnel information model
The information construction of TBM diversion tunnel is based on engineering data informatization, which is also the direction of future development. However, the current data informatization mainly focuses on the analysis and processing of data, the realization of engineering information construction is far from enough. The information construction of tunnel engineering is a dynamic process, requiring the information about surrounding rock, project scale and support methods in the construction process, besides, the information can directly reflect the changes of surrounding rock in tunnel construction. Therefore, the dynamic construction information model of diversion tunnel with combining three-dimensional structure and stratum is constructed through BIM technology to realize the informatization of engineering data, which can provide timely information about surrounding rock, equipment and personnel, achieve TBM diversion tunnel engineering informatization.

2.1. Modeling of TBM diversion tunnel
As shown in Figure 1, the BIM modeling of TBM diversion tunnel mainly contains three steps: (i) creating three-dimensional geometric model of tunnel, (ii) information storage (iii) combining geometric model and information to realize informatization and collaborative expression of three-dimensional model. The information storage is to input the spatial geometric information, engineering geological information and monitoring information into the three-dimensional geometric model.

2.1.1. Three-dimensional geometric model
Revit is the mainstream BIM software owing to its powerful three-dimensional drawing ability. Thus, it is adopted in this paper to construct the three-dimensional structure model and three-dimensional stratum model of TBM tunnel by using the plane information and geological information of the tunnel. (1) Structural model
With the powerful "Family" function in Revit, the core components of the tunnel model are created to form a family base by using the geometric information of tunnel structure extracted from the design.
plan. Then, the corresponding parts of the family base are combined to form a complete three-dimensional structure model of TBM tunnel, which is shown in Figure 2.

(2) Stratum model

According to the geological survey report, the geometric location data of the stratum boundary can be obtained by analysing the stratum drilling, stratum profile and other related data. After that, different strata interfaces are acquired through interpolation processing. Finally, the stratum model is constructed by stacking each layer in top-down order as shown in Figure 3.

![Figure 1. Modeling flow chart](image1)

![Figure 2. Structure model](image2)

![Figure 3. Stratum model](image3)

The completed three-dimensional structured stratum models of TBM tunnels are the preliminary BIM model, which need to be checked and revised repeatedly based on the practical engineering and experience to meet the actual project requirements [12].

2.1.2. Information storage

After establishing the BIM model, the component information is added on the basis of the engineering situation. Noticeably, the information attached to BIM model should be relatively important and concerned in practical engineering, and is helpful to understand TBM tunnel properties, such as...
surrounding rock state, personnel distribution, team cooperation, material transportation, structure layout, etc.

2.1.3. Information extraction
Data extraction of BIM model for TBM tunnel construction mainly includes two aspects: structural and stratum BIM model data. In the structural BIM model, the data on various aspects of tunnel structure can be quickly and accurately extracted. The schematic diagram of the extraction process is shown in Figure 4. Selecting any structure to directly obtain the relevant data of the structure, or double clicking the highlighted part to view the specific information of components. In the stratum BIM model, it is quickly and conveniently to understand the distribution of the stratum where the tunnel is located, including the information of stratum category and thickness.

The key to the data extraction process is to accurately obtain the engineering geology, hydrogeology and other relevant information according to the tunnel construction progress. In BIM model, the data of tunnel footage, stratum information and geological parameters during tunnel construction can be integrated to provide data support for numerical simulation and risk assessment.

Figure 4. Information extraction

3. Collapse risk assessment
In order to assess the collapse risk of TBM tunnel accurately, the surrounding rock state of tunnel and TBM construction state should be combined to analyze, the collapse risk should be assessed by interval, quantitative and multi index according to the characteristics of TBM tunnel. On the basis of obtaining risk data and information from TBM tunnel information model, the possibilities and possible consequences of tunnel collapse are described quantitatively, that is to establish risk probability model and loss model.

A calculation method based on the coupling of numerical simulations and Monte-Carlo principle was proposed to calculate the probability of tunnel collapse accident. The tunnel excavation model and data under different surrounding rock parameters are obtained by numerical simulation method, then collapse risk can be calculated by Monte-Carlo principle using the data. The risk class of TBM tunnel construction is assessed by risk consequence equivalent estimation method [13]. A risk assessment model of collapse during TBM tunnel construction, which is shown in Figure 5, is established based on TBM information model, coupling of numerical simulation and Monte-Carlo principle and consequent equivalent estimation.

The collapse risk class is determined by considering the probability and the consequences of collapse risk comprehensively. Firstly, the numerical model is established according to the parameter variables, which are analyzed according to the actual situation of the tunnel project, the deformation values of surrounding rock under different basic parameters are calculated by numerical simulation, the failure probability is calculated by Monte-Carlo method in probabilistic design system built in ANSYS. Then, according to the data provided by TBM tunnel information model, the risk consequence class of collapse is obtained by using the risk consequence equivalent estimation method. Finally, the TBM tunnel is
divided into construction area, support area and support completion area, the collapse risk class of different areas can be obtained according to the actual situation.

Figure 5. Construction risk assessment model

4. Engineering application

According to the severity of the collapse of a diversion tunnel in Xinjiang, China, a new method is used to evaluate the risk. The total length of the tunnel is about 283.393km, which is a super long underground tunnel. According to the construction section planning and construction scheme, the tunnel adopts 11 TBMs and drilling and blasting method. The main challenge in this construction project was the complexity of the geology. Stratum changes made the construction process extremely vulnerable to collapses. A 512m long tunnel is selected as the research tunnel in a diversion tunnel. The buried depth of the tunnel is 294m ~ 327m, the tunnel excavation diameter is 7.0m. The surrounding rock of the tunnel is mainly composed of Devonian tuffaceous sandstone, the rock mass is intact. However, the stability of the rock mass is poor at the secondary faults, in which the surrounding rock belongs to class IV ~ V.

The construction of the diversion tunnel is affected by many factors including design, environment and management. Construction design schemes, hydrogeological and geological conditions were collected to establish structural and geological BIM models, adding component information into models according to the actual situation.

4.1. Risk assessment of collapse during construction

4.1.1. Numerical model

Considering different surrounding rock parameters, ANSYS was used to simulate the whole section excavation process of the tunnel. The supporting structure is added while the stratum is excavated. The distance between the tunnel and the bottom boundary of the model is set to 35m. According to the buried depth of the tunnel, the weight of the upper part of the model is converted into a uniformly distributed load and applied to the upper boundary of the model. The distance in horizontal direction is limited to 10 times the tunnel excavation diameter. In the calculation process, the two-dimensional elastic-plastic nonlinear finite element method is adopted. The lining is set as elastic material, the surrounding rock is set as Drucker Prager material. The material parameters of each part shown in Table 1, are determined according to the numerical simulation results calculated in the tunnel information model and technical specifications for construction of highway tunnel [14]. The upper boundary of the model is set as free, the left and right boundaries are constrained in the horizontal direction, the upper boundary is constrained in the vertical direction. The schematic diagram of the model is shown in Figure 6.
4.1.2. Numerical simulation results and analysis

According to the parameters of different surrounding rock class, the surrounding rock deformation during tunnel excavation is simulated and the displacement is used to analyze the risk tendency of tunnel collapse accident. As shown in Figure 7, the displacement reaches the maximum value at the arch crown and reaches the minimum value at the arch bottom, the displacement decreases from the arch crown to the arch bottom.

The displacement of different regions of the tunnel under different surrounding rock class are shown in Figure 8.
Figure 8. Typical position displacement curve

The displacement increases with the changing of surrounding rock class from II to V. When the class of surrounding rock changes from III to IV, the deformation increases obviously because the tunnel passes through the fault fracture zone where the surrounding rock stability is poor. And with the increase of surrounding rock class, the order of displacement variation in different positions of tunnel is as follows: arch crown > arch shoulder > arch lumber > arch bottom. The displacement of arch crown and arch shoulder is the first to reach the allowable limit of displacement, the collapse accident is most likely to occur.

4.1.3. Risk assessment of collapse

Determining the allowable limit displacement of surrounding rock is the key to analyse the tunnel collapse risk. According to the actual engineering construction situation and code for design of road tunnel [15]. The allowable limit displacements of different surrounding rock classes are shown in Table 2. When the deformation of the surrounding rock exceeds the allowable limit value, accidents may occur, the accident probability is divided into five class, as shown in Table 3.

Table 2. Allowable limit displacement

| Surrounding rock | Allowable limit displacement(mm) |
|------------------|----------------------------------|
| V                | 120                              |
| IV               | 70                               |
| III              | 50                               |
| II               | 30                               |

Table 3. Accident probability class standard

| Probability range | Descriptive probability class |
|-------------------|------------------------------|
| >0.3              | Very likely                  |
| 0.03 to 0.3       | Likely                       |
| 0.003 to 0.03     | Occasional                   |
| 0.0003 to 0.003   | Unlikely                     |
| <0.0003           | Very unlikely                |

There are many factors influencing tunnel deformation. The elastic modulus \( E_1 \), poisson's ratio \( \mu \), cohesion \( c \), internal friction angle \( \varphi \) of surrounding rock, elastic modulus \( E_2 \), thickness \( t \) of lining
concrete, elastic modulus $E_3$ of bolt are selected. Each random variable obeys normal distribution, the average value and coefficient of variation of each random variable are shown in Table 4. According to the results of numerical simulation, considering the actual situation comprehensively, the hypercube technology of Monte-Carlo method in PDS module provided by ANSYS program is used. The most effective way to determine the sufficient cycles of Monte-Carlo simulation technology is to check the sample history curve and mean curve. When the number of cycles is sufficient, the mean curve will gradually converge and tend to be horizontal.

**Table 4. Statistical characteristics of random parameters**

| Material parameters | Statistical parameters | II | III | IV | V |
|---------------------|------------------------|----|-----|----|---|
|                     |                        | Average value | Coefficient of variation | Average value | Coefficient of variation | Average value | Coefficient of variation |
| Surrounding rock    | $E_1$(GPa)             | 19 | 0.2 | 11 | 0.2 | 2.3 | 0.2 | 1 | 0.2 |
|                     | $\mu$                  | 0.23 | 0.02 | 0.27 | 0.02 | 0.32 | 0.02 | 0.42 | 0.02 |
|                     | $c$(MPa)               | 1.9 | 0.32 | 1.5 | 0.32 | 0.5 | 0.32 | 0.1 | 0.32 |
|                     | $\phi$                | 42.9 | 0.2 | 35.4 | 0.2 | 25 | 0.2 | 20 | 0.2 |
| Lining structure    | $E_2$(GPa)            | 25.4 | 0.0853 | 25.4 | 0.0853 | 25.4 | 0.0853 | 25.4 | 0.0853 |
|                     | $H$ (m)               | 0.08 | 0.24 | 0.1 | 0.27 | 0.35 | 0.23 | 0.4 | 0.26 |
| Bolt                | $E_3$(GPa)            | 170 | 0.2 | 170 | 0.2 | 170 | 0.2 | 170 | 0.2 |

According to the selected variables, 500 Monte-Carlo simulation samples were carried out in ANSYS and the results were analysed and processed. Due to the space limitation, only the historical curve and mean value curve of the tunnel structure under the condition of class III surrounding rock are displayed, as shown in Figures 9-10.

**Figure 9. Simulation sample values result**  
**Figure 10. Mean values of samples result**

It can be found from Figure 9 that the random sample history fluctuates around the mean value in 500 samples. The amplitude is within the range of standard deviation and the sampling accuracy meets the requirements. As shown in Figure 10, with the increase of the number of cycles, the mean value and standard deviation of the displacement value gradually converge, which also demonstrates that the sampling accuracy of random input variables meets the requirements. According to ANSYS PDS technology, the failure probability $P$ under different surrounding rock conditions is calculated. The calculation results are shown in Table 5.

**Table 5. Probability calculation result**

| Surrounding rock | Failure probability (%) | Reliability (%) |
|------------------|-------------------------|-----------------|
| II               | 0.07                    | 99.93           |
| III              | 1.59                    | 98.41           |
| IV               | 2.03                    | 97.97           |
| V                | 2.97                    | 97.03           |

It can be seen from Table 5 that when tunnel construction passes through Class II, III, IV and V surrounding rock, the failure probability is 0.07%, 1.59%, 2.03% and 2.97% respectively. With the continuous improvement of surrounding rock class, the failure probability of tunnel structure increases gradually. Therefore, attention should be paid to the change of surrounding rock during construction,
especially in complex geological sections, to avoid instability and damage caused by unfavourable geological conditions during tunnel excavation, which can cause collapses in severe cases.

4.2. Estimation of risk consequence class

Combined with the principle of safety-oriented risk assessment and the actual situation of the project, the TBM diversion tunnel information model was analysed. Assuming that the accident consequence types are independent and linear, the risk consequence estimation model of diversion tunnel construction is established as follows:

\[
C = C_Z + C_R + C_G + C_H + C_S
\]

where \(C\) is overall risk consequence; \(C_Z\) is direct economic loss consequences; \(C_R\) is consequences of casualties; \(C_G\) is consequences of construction period loss; \(C_H\) is environmental damage consequences; \(C_S\) is social impact loss consequences.

To solve the problem of non-uniform measurement methods for construction period loss, social impact loss and environmental loss in consequence estimation of diversion tunnel construction safety risk, the consequence equivalent estimation method is used to evaluate the accident consequence class.

4.3. Collapse risk assessment

The risk of tunnel collapse is evaluated as follow:

Risk = Probability of collapse accident \times Severity class of accident consequence. The classification standard is shown in Table 8.

Table 6. Environmental and social impact equivalent value table

| Score | 18 | 13 | 9 | 5 | 3 |
|-------|----|----|---|---|---|
| Class | Catastrophic | Very severe | Severe | Moderate | Mild |

Table 7. Standard for the consequences

| Consequence equivalent | DC>20 | 13<DC<20 | 5<DC<13 | 1<DC<5 | DC<1 |
|-------------------------|-------|-----------|---------|--------|-------|
| Score                   | Catastrophic | Very severe | Severe | Moderate | Mild |
| Class                   | 5     | 4          | 3      | 2      | 1     |

According to the actual situation of the tunnel section KS90+100 ~ KS91+612, the surrounding rock of this section can be divided into three sections, as shown in Figure 11.

KS90+100~KS90+300: The section belongs to class II surrounding rock area with complete rock mass. According to Table 8 and the consequence equivalent calculation results, the collapse risk of this section is moderate;

KS90+300~ KS90+600: There are both class III and class IV surrounding rock in this section. According to the class IV surrounding rock with higher risk, the collapse risk of this section is high;

KS90+600~ KS90+612: This section is located in the secondary fracture zone, belonging to class V surrounding rock, the collapse risk is high.
### Table 8. Risk level standard

| Probability class | Consequences class |
|-------------------|--------------------|
|                   | Mild | Moderate | Severe | Very severe | Catastrophic |
| Very likely       | Hight | Hight | Very hight | Very hight | Very hight |
| Likely            | Medium | Hight | Hight | Very hight | Very hight |
| Occasional        | Medium | Medium | Hight | Hight | Very hight |
| Unlikely          | Low | Medium | Medium | Hight | Hight |
| Very unlikely     | Low | Low | Medium | Medium | Hight |

### Figure 11. Division of tunnel sections

#### 5. Conclusion

A method for TBM tunnel collapse risk assessment is proposed based on BIM technology, numerical simulation and Monte-Carlo principle, to assess the collapse risk of TBM tunnel under different surrounding rock classes during construction. According to the information provided by TBM model, the deformation of tunnel is analyzed by numerical simulation and the instability probability of tunnel is calculated by Monte-Carlo principle. The main conclusions are as follows:

1. BIM-based technology can provide complete equipment, construction and geological information, provide sufficient data support for construction risk assessment.
2. Based on the tunnel information model, numerical simulation can be used to quantify the probability of collapse and BIM model can be used to quantify the risk loss of different areas.
3. The method proposed in this paper has been applied to a diversion tunnel project in Xinjiang, China, its scientific nature and accuracy have been verified. The model and method will be further improved in the future.

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