Analysis on Security Risks in Tunnel Construction Based on the Fault Tree Analysis

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Abstract: Since tunnel engineering, as a kind of underground construction, has huge security risks, it is very important to evaluate the safety risk of tunnel construction stage. It cannot only provide basis for risk control but ensure construction safety. Taking Qingpingchuan tunnel as an example, the WBS-RBS method is employed to identify the construction risk of the tunnel and the identified risk sources are used to analyzed qualitatively and quantitatively with fault tree theory. Finally, we can conclude that the critical factor affecting the collapse of Qingpingchuan tunnel is the instability of surrounding rock, and that the secondary critical factor lies in the inconsistence of the soil quality with the survey documents, low effect of waterproof and drainage facilities, weak strength of pre reinforcement, excessive steps of excavation cycle, unqualified support construction, inaccurate advanced geological prediction, etc.

1. Introduction
Tunnel engineering belongs to underground construction, with large investment, long construction period, adverse construction environment, complex and changeable geological conditions, and difficulties in controlling construction security. In recent years, with the increasing of expressway mileage, the number of tunnels and the proportion of mileage increase, especially the proportion of super long tunnels. The construction risk of super long tunnel is higher than that of ordinary tunnel, so it has more uncontrollable factors. As a result, it is necessary to put forward a reliable risk assessment method for tunnel construction before construction, identify severe hazard sources and take effective avoidance measures to ensure the safety of tunnel construction.

In-depth researches on risk management of tunnel construction has been done both domestically and abroad. Aliahmadi et al. (2010) [1] proposed a method named intelligent expert decision making by combining game theory and fuzzy analytic hierarchy process, and applied the method to specific tunnel projects. Meanwhile, this method is suitable for all stages of tunnel engineering. Zhu Zengyao and Wang Longxiang et al. (2017) [2], taking Dengzhou-Wanhua section tunnel of Foshan Metro Line 2 as the research object, identified the specific risk source through risk identification, obtained the risk level through expert scoring, evaluated the importance of risk source by AHP, and put forward reasonable risk control measures accordingly. Liu Jie et al. (2015) [3] established a weight solution model of G314 Gongger tunnel risk grade evaluation index by using fuzzy analytic hierarchy process theory, and established Gongger tunnel construction risk assessment model combined with improved set pair analysis method, which solved the problems of mutual isolation of tunnel construction risk evaluation
index factors and difficulty in quantifying evaluation results in previous evaluation methods. Xu Dongqiang et al. (2018) \cite{4} established a large deformation security evaluation index system for highway tunnels by using Analytic Hierarchy Process (AHP), calculated the weight of each risk factor, and then introduced the weight into the data envelopment method to rank the risk levels of each decision-making unit by moving the maximum risk curve. However, from the existing research at home and abroad, the main methods of risk assessment are Analytic Hierarchy Process (AHP) and expert scoring method. The biggest drawback lies in the establishment of evaluation indicators and the construction of judgment matrix of AHP have strong subjective human factors, and lack of objective data, especially when the number of experts and scholars is insufficient and there are too many evaluation indicators, the evaluation results will exist in a big deviation.

In this paper, WBS-RBS is used to identify the risk of tunnel body according to the construction process, and the identified risk sources are analyzed qualitatively and quantitatively by the fault tree analysis. In this way, the evaluation method based on the construction process avoids subjectivity and has a higher degree of coincidence with the actual risk.

2. Theory and Method

2.1 Special Risk Assessment Ideas for Tunnel Security
Firstly, the top events of tunnel construction security are determined through investigation; secondly, on the basis of being familiar with tunnel construction methods, work breakdown structure (WBS) and risk decomposition structure (RBS) are carried out for the tunnel according to the tunnel construction process, and the results of WBS and RBS are coupled to complete the source survey of top event analysis. Thirdly, through qualitative and quantitative analysis of the fault tree, the sensitive factors of the top event of tunnel excavation are obtained. According to the order of sensitivity, the influence factors of the top event are determined.

2.2 Fault Tree Analysis Method
Fault Tree Analysis (FTA) is a method to determine the most disallowed event in the system as the top event, analyze the causes of the top event layer by layer, establish the fault tree, simplify the analysis, then carry out qualitative analysis and quantitative analysis, and finally put forward the system accident analysis and suggestions.

2.2.1 Overview
Fault Tree Analysis (FTA), also known as fault tree analysis, is a kind of fault reason analysis layer by layer through logical reasoning. The analysis results of each layer and the logical relationship between them are represented by corresponding graphic symbols, forming several tree shapes, which are called fault tree analysis \cite{5}. The terms and basic logical relations of fault tree analysis are as follows:

1. Top Event: it refers to the event that cannot be allowed to occur in the system, which is placed at the top of the fault tree as the root of the fault tree.
2. Bottom Event: it refers to the input event of fault tree, which is located at the bottom of fault tree and can be divided into basic event and non-basic event.
3. Intermediate Event: located in the middle of the fault tree, it is not only the input event of the upper level event, but also the output event of the lower level event.
4. And Gate: in the And Gate structure, the output event of and gate occurs only when all input events occur.
5. Or Gate: in the Or Gate structure, when any input event occurs, the output event occurs.

2.2.2 Qualitative Analysis on Fault Tree
The qualitative analysis on fault tree is mainly to determine which combination of bottom events will lead to the occurrence of top events. The cut set refers to the combination of several bottom events in the fault tree. Only when all the bottom events occur in the combination, the top event of fault tree will
occur. In case a bottom event is removed randomly from a cut set, the cut set is the most important small cut set. In qualitative analysis on fault tree, downward method is usually used to solve the minimum cut set of fault tree, and then quantitative analysis can be carried out.

The idea of solving the minimum cut set of system fault tree by the downward method is as follows: starting from the top event, proceed according to the following steps from top to bottom. First, replace the upper level event with a lower level event. Secondly, judge the logical relationship between the lower level events. If it is an and gate, each and gate input event will be listed horizontally in the table; if it is an Or Gate, each or gate event will be listed vertically in the table. So, we get a cut set. In this way, it is gradually pushed forward until all the bottom events of the fault tree are converted.

2.2.3 Fault Tree Quantitative Analysis

The probability of each bottom event in the fault tree is unknown, and the probability of the minimum cut set formed by the combination of the bottom events is also unknown. In order to solve the above problems, the fault tree must be quantitatively analyzed. The main contents of quantitative analysis include: calculating the probability of fault occurrence at the top of fault tree and calculating the critical importance of each bottom event of fault tree.

(1) Occurrence Probability of Top Event of the System

In case the fault tree of a system has minimum cut sets of n named \(K_1, K_2, \ldots, K_n\), the top event probability of the fault tree can be expressed by formula (1)

\[
Q(T) = q(k_1 + k_2 + \ldots + k_n) = \sum_{i=1}^{n} q(k_i) - \sum_{i<j}^{n} q(k_i k_j) + \sum_{i<j<k}^{n} q(k_i k_j k_k) + \ldots + (-1)^{n-1} q(k_1 k_2 \ldots k_n)
\]

(2) Critical Importance

The critical importance of the bottom event, the ratio of the probability change rate of the basic unit of the system and the probability change rate of the top event caused by it can be expressed by formula (2).

\[
I_i^{Cr}(t) = \lim_{\Delta Q_i(t) \to 0} \frac{\Delta g(Q(t))}{g(Q(t))} \frac{\partial g(Q(t))}{\partial Q_i(t)} = \frac{Q_i(t)}{g(Q(t))} \frac{\partial g(Q(t))}{\partial Q_i(t)} = I_i^{Pr}(t)
\]

3. Engineering Application

3.1 Project Overview

Qingpingchuan tunnel is a construction period control project of civil engineering section 6 of Suiyan expressway. The starting and ending mileage is ZK84+052~ZK86+244 (right line K84+061~K86+241), and the line length is 2192m on the left and 2180m on the right. The surrounding rock is grade V loess, the longitudinal and transverse cutting depth of the gully is very large, and the erosion is relatively strong, accompanied by serious soil and water loss. The climate in this area is semi-arid, with strong water evaporation and less precipitation, but the time period is relatively concentrated. This natural condition is not conducive to the recharge of groundwater by atmospheric precipitation. Therefore, the surface water is easy to discharge, and the hidden danger of groundwater is small, which will not cause great difficulty to the construction.

3.2 Determining Top Events

Top event refers to the event that cannot be allowed to occur in the system. It is placed at the top of the fault tree as the root of the fault tree. The surrounding rock bearing capacity of Qingpingchuan tunnel is weak, the length of the tunnel is large, and it is accompanied with serious soil erosion. Based on the study of the construction scheme, the on-site technical management personnel, front-line operation personnel and tunnel experts are interviewed. It is generally believed that the most impermissible event
in the construction process of Qingpingchuan tunnel is cave collapse. Thus, in this paper, it is determined that the tree top event of Qingpingchuan tunnel construction safety risk accident is cave collapse.

3.3 Cause Analysis of Qingpingchuan Tunnel Construction Security Risk Top Event Based on WBS-RBS

3.3.1 WBS-RBS Decomposition Structure of Qingpingchuan Tunnel Construction
In order to deeply analyze the causes of the top event, this paper first decomposes the work structure of Qingpingchuan tunnel according to the construction process. The qingpingchuan tunnel project is divided into five major structures: portal excavation and portal reinforcement construction, tunnel pre support and pre reinforcement and initial support construction, tunnel body excavation and excavation construction, tunnel waterproof and drainage construction and tunnel secondary lining construction. After each structure continues to be decomposed, Fig.1 of the work breakdown structure (WBS) of qingpingchuan tunnel is obtained; Then the risk structure is decomposed from the perspective of management. The tunnel construction risk is divided into four parts: human, technology, environment and management. The human factor is included in the management factors, and each risk structure is decomposed into Fig.2. Finally, the risk source of each sub project is analyzed, and the coupling matrix is established to comprehensively investigate the causes of the top event.
3.3.2 Risk Source Survey of Tunnel Body Construction

The “process” layer obtained from the decomposition of Fig.1 is used as the column vector in the risk coupling matrix, and the “basic risk source” obtained from the decomposition of Fig.2 is used as the row vector in the risk coupling matrix. Whether there is such risk should be considered according to each process and all basic risks. If there is no such risk source in the process, it can be shown by “0”; otherwise, shown by “1”. The risk coupling matrix is shown in Tab.1.

Through coupling effect, the risk events or factors represented by each “1” in the table are obtained: W12R311, W13R311 surrounding rock stability is poor; W12R31 soil quality does not conform to the survey documents; W12R12, W13R312 groundwater or heavy rainfall, W13R14, W12R23 waterproof and drainage facilities are not effective; W12R311 portal has bias pressure; W13R22 slope is too steep; W14R23 excavation...
scheme does not match with geological conditions; W12R15, W13R15 are too high excavation, too steep slope; W14R24 monitoring frequency is not enough, miss the best support opportunity; W14R15 support quality is not qualified; W14R22 support design parameters are unreasonable; W14R14 steel pipe and steel arch frame strength is insufficient; W22R24 advanced geological forecast is not accurate; W22R311 special geology; W23R21 soil quality is inconsistent with the survey documents; W22R312, W3R313 groundwater or heavy rainfall; W4R22, W4R23 waterproof and drainage facilities effect The results show that: the cross-section size of W13R22 tunnel is not reasonable; W12R15, W13R15 cycle interval is too large; W22R24 deformation monitoring frequency is too low, missing the best support opportunity; W31R15, W32R15, W33R15, W33R15, W33R15, W31R15, W13R15, W13R15, W13R15, W13R24, W22R24, W22R24, W22R24. The construction quality of W14R15 anchor rod, steel mesh, steel support and shotcrete is unqualified; W31R14, W32R14, W33R14, W34R14 reinforcement, steel pipe and concrete strength are insufficient; W22R14 fails to find out the cause of collapse and blindly resume construction.

3.4 Establishment of Fault Tree

The surrounding rock of Qingpingchuan tunnel is grade V loess with loose soil and weak self-stability. In order to ensure security and avoid cave collapse, the observation points and frequency should be increased, and the data analysis and feedback should be done to realize the dynamic construction scheme adjustment. Since the collapse risk is vary from different location and span size of the tunnel body, three construction methods with different security levels are adopted in turn. The tunnel entrance section is prone to collapse, so the unilateral wall heading method with strong support capacity is adopted; the safest annular excavation method is adopted for the tunnel body section; the clear width of the emergency parking zone in the tunnel is larger than that in other places, and the double wall heading method is adopted.

The main objective factors leading to tunnel collapse include failure of advanced geological prediction, decline of self-stability of surrounding rock, improper excavation, support failure and ineffective protection of suspension construction. The fault tree of cave collapse top event is obtained by layer by layer analysis of various factors, as shown in Fig.3

![Fault Tree of Tunnel Collapse](image)

**Fig.3 fault tree of tunnel collapse top event**

3.5 Qualitative Analysis

Qualitative analysis is to analyze which events or combinations of events will lead to the occurrence of top events, that is to find the minimum cut set of top events. In the following section, the minimum cut set method is used in Section 3.
According to Tab.2, the final cut set of cave collapse is as follows:

\[
\{W_{22R24}\};\{W_{22R311}\};\{W_{22R21}\};\{W_{22R312},W_{4R22},W_{4R23}\};\{W_{3R312},W_{4R22},W_{4R23}\};\{W_{22R314}\};\{W_{31R14}\};\{W_{22R23}\};\{W_{22R15}\};\{W_{3R23}\};\{W_{3R15}\};\{W_{3R14}\};\{W_{22R14}\}.
\]

After sorting out, the minimum cut set of cave collapse is obtained as follows:

\[
\{W_{22R24}\};\{W_{22R311}\};\{W_{22R21}\};\{W_{22R312},W_{4R22},W_{4R23}\};\{W_{31R14}\};\{W_{22R314}\};\{W_{22R23}\};\{W_{22R15}\};\{W_{3R23}\};\{W_{3R15}\};\{W_{3R14}\};\{W_{22R14}\}.
\]

Based on the above analysis, there are 13 basic events that can lead to cave collapse, namely: inaccurate geological forecast in advance; instability of surrounding rock; inconsistency of soil quality with the survey documents; groundwater or heavy rainfall; low effect of waterproof and drainage facilities; affection of the blasting of other projects; weak strength pre reinforcement; inconsistency of excavation scheme with the geological conditions; excessive steps of excavation cycle; unreasonable support design parameters; unqualified support construction; weak strength of steel bar, steel pipe and concrete; and blind resumption of work.

### 3.6 Quantitative Analysis

Through qualitative analysis, it is clear which combination of the bottom events in the fault tree will lead to the occurrence of the top event, but the probability of the top event occurrence and the contribution of each basic event to the top event are largely unknown. This requires quantitative analysis. Firstly, the probability of occurrence of basic events is obtained by expert scoring method. The statistics of the results are shown in Tab.3.

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#### Tab.3 probability statistics of basic collapse events

| minimal cut set | basic events | implication | occurrence (%) |
|----------------|--------------|-------------|----------------|
| k1             | W_{22R24}    | inaccurate geological forecast in advance | 5 |
| k2             | W_{22R311}   | instability of surrounding rock           | 50 |
According to the probability of top event in Formula (1) for probability statistics of basic collapse events in Tab. 3, the probability of top event can be obtained as 0.7667.

The probability of cave collapse in top event is as follows:

$F_S = Q(T_2) = q(k_1 + k_2 + \cdots + k_{13})$

$= \sum_{i=1}^{13} q(k_i) - \sum_{i<j}^{13} q(k_i k_j) + \sum_{i<j<s}^{13} q(k_i k_j k_s) + \cdots$

$+ (-1)^{13-1} q(k_1 k_2 \cdots k_{13})$

$= 0.7667$ (3)

The risk sensitivity of the basic event when the top event is cave collapse can be calculated by substituting the obtained accident probability $F_S = Q(T_2)$ and basic event probability Tab.3 into the risk sensitivity evaluation Formula (2).

| Basic Event Code | Basic Event Meaning | Basic Event Risk Sensitivity |
|------------------|---------------------|----------------------------|
| W22R24           | inaccurate geological prediction | 0.0160                     |
| W22R311          | poor stability of surrounding rock | 0.3044                     |
| W22R21           | inconsistence of soil quality with the survey documents | 0.0338                     |
| W22R312, W4R22, W4R23 | groundwater or heavy rainfall | 0.0160                     |
| W22R23           | low effect of waterproof and drainage facilities | 0.0338                     |
| W22R314          | blasting impact of other projects | 0.0031                     |
| W3R14            | weak strength of pre reinforcement | 0.0338                     |
| W22R23           | inconsistence of excavation scheme with the geological conditions | 0.0160                     |
| W22R15           | excessive steps of excavation cycle | 0.0338                     |
| W3R15            | unqualified support design parameters | 0.0338                     |
| W22R14           | blind resumption of work | 1                           |
3.7 Ranking of Sensitive Factors

Based on the references of many fault tree and expert interviews, this paper selects the factors whose sensitivity is more than 0.1 as the critical factor, the sensitivity between 0.01 and 0.1 is the secondary critical factor, and the sensitivity less than 0.01 is the non-critical factor [6]. The order of basic events according to the sensitivity is shown in Tab.5.

| Basic Event Code | Basic Event Meaning                                      | Basic Event Risk Sensitivity | Types of Risk Factors   |
|------------------|--------------------------------------------------------|------------------------------|-------------------------|
| $W_{3R_{15}}$    | unqualified of support construction                     | 0.0338                      |                          |
| $W_{3R_{14}}$    | weak strength of support pipe material                  | 0.0031                      |                          |
| $W_{22R_{14}}$   | blind resumption of work                                | 0.0031                      |                          |

4. Conclusion

Through the qualitative and quantitative analysis on WBS-RBS risk source identification and fault tree analysis, the following conclusions can be obtained.

(1) The critical factors affecting tunnel collapse can be finally identified as the instability of the surrounding rock;

(2) The secondary-critical factors are: inconsistence of soil quality with the survey documents; groundwater or heavy rainfall; low effect of waterproof and drainage facilities; affection of the blasting of other projects; weak strength pre reinforcement; inconsistence of excavation scheme with the geological conditions; excessive steps of excavation cycle; unreasonable support design parameters;

(3) The non-critical factors are: affection of the blasting of other projects, weak strength of support
pipe material and blind resumption of work.

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