Investigation on Collapse Risk of Subsea Tunnel Based on Data Mining: A Collapse Risk Recognition Model

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Abstract. Due to the special geological conditions, the collapse of the subsea tunnel occurs frequently. To control the collapse risk of the subsea tunnel, this paper selected seven indicators including over-span ratio, buried depth, groundwater condition, rock mass integrity, rock mass grade, support method and construction level. The weight of the seven indicators is calculated by entropy method, among the results, the support method has the highest weight, and the construction level has the lowest weight. Finally, the evaluation model is established to evaluate the collapse risk of the subsea tunnel engineering in China, and the results obtained via the evaluation model are basically consistent with the excavation situation. The proposed evaluation model is demonstrated as an innovative method for the collapse risk evaluation of the subsea tunnel engineering.

1. Introduction

The subsea tunnels have developed rapidly due to the advantages of saving time, protecting the environment and reducing the impact on the land. Despite this fact, due to complex geological conditions and construction factors, collapse accidents in subsea tunnels occur frequently. Generally speaking, subsea tunnels have higher investment costs and higher construction risks than mountain tunnels [1]. Once the collapse accident occurs in the subsea tunnels, the consequences will be unimaginable [2]. Hence, it is of considerable significance to investigate the collapse risk of the subsea tunnel using an appropriate method. Scholars have performed many types of research for a long time. The current research methods mainly include theoretical research, numerical simulation and model experiments [3, 4]. Considering the seepage law of groundwater, Ji et al. established a mathematical model to reduce the deformation of the rock around the tunnel and the settlement of the ground [5]. Once the collapse accident occurs in the subsea tunnels, the consequences will be unimaginable [2]. Hence, it is of considerable significance to investigate the collapse risk of the subsea tunnel using an appropriate method. Scholars have performed many types of research for a long time. The current research methods mainly include theoretical research, numerical simulation and model experiments [3, 4]. Considering the seepage law of groundwater, Ji et al. established a mathematical model to reduce the deformation of the rock around the tunnel and the settlement of the ground [5]. Zhang et al. introduced a typical grouting method, and then elaborated the site-specific grouting techniques employed in the Xiang'an subsea tunnel [6]. Xue et al. analyzed the mechanism of mud inrush from extensional faults, shear faults and compressive faults based on the cusp catastrophe model, and built the potential function for the risk of water or mud inrush [7]. Shin et al. investigated the hydraulic effects on the fractured zones of the subsea tunnel by using numerical simulation and model tests [8]. Theoretical analysis ignored comprehensive analysis of the special geological conditions and failed to make effective use of actual data. The calculation process of the numerical simulation is too simple to simulate the construction process, and the data obtained by numerical
simulation have a poor correlation with the engineering parameters. The model experiment is costly and the test period is long. Therefore, an efficient and low-cost method is now urgently needed.

The subsea tunnel collapse is a multi-factor nonlinear problem, and is affected by subjective factors and objective factors. Therefore, this paper aims to examine the main factors influencing collapse risk of the subsea tunnel and evaluate the tunnel collapse risk. Based on the characteristics and the collapse mechanism of the subsea tunnel engineering, this paper selected seven factors affecting the subsea tunnel collapse risk, i.e. over-span ratio, buried depth, rock mass integrity, rock mass grade, groundwater condition, support method and construction level. The sensitivity of the seven indicators to the collapse risk is obtained by entropy weight method. An extension model for evaluating the subsea tunnel collapse risk is established. Finally, the extension model is used to evaluate the collapse risk of five sections of subsea tunnel engineering in China. The results indicate that the collapse risk grade obtained via the extension model is basically consistent with the actual situation. Moreover, the collapse risk evaluation model realizes a multi-criteria evaluation of the subsea tunnel collapse risk and provides a practical guide for the construction of similar engineering.

2. Method

2.1. Entropy weight method

According to the information theory, the entropy $E$ represents the amount of information contained in the decision indicator. Generally speaking, the smaller the $E$ of the indicator, the greater the variability degree of the indicator, the more important the role it can play in the decision-making process, which means the higher weight it has. Using the entropy weight method to calculate the objective weight mainly includes the following steps [9].

2.1.1. Data normalization. Assume there are $m$ indicators in the decision-making process, each indicator has $n$ sets of data samples. For the positive indicator $x^+$, the larger the index is the higher collapse risk the tunnel will be. Eq (1) is used to normalize the indicator $x^+$. The negative indicator $x^-$, the larger the index is, the lower collapse risk the tunnel will be, Eq (2) is used to normalize the indicator $x^-$. 

$$v_{ij} = \frac{x^+_j - \text{min}(x^+_j)}{\text{max}(x^+_j) - \text{min}(x^+_j)} \quad (1)$$

$$v_{ij} = \frac{\text{max}(x^-_j) - x^-_j}{\text{max}(x^-_j) - \text{min}(x^-_j)} \quad (2)$$

Where $x_{ij}$ is the $i_{th}$ value of the index $j$, the $v_{ij}$ represents the normalized value.

2.1.2. Entropy definition. On the basis of obtaining the normalization data, the entropy $E_i$ of the indicator $i$ can be defined according to Eq.(3). In Eq.(3), $K=1/\ln n$. Since $v_{ij}$ is the $j_{th}$ actual value corresponding to the indicator $i$ and $m$ represent the count of the indicators, the case that $f_{ij}=0$ does not exist.

$$f_{ij} = v_{ij} / \sum_{j=1}^{n} v_{ij}$$

$$H_i = -K \sum_{j=1}^{n} f_{ij} \ln f_{ij} \quad (3)$$
2.1.3. Calculate the objective weight. Finally, on the basis of defining the entropy $E$ of the evaluation indicator, the entropy weight vector $w_i (w_1, w_2, w_3, \ldots, w_m)$ of the indicator is defined according to Eq. (4).

$$w_i = \frac{1-H_i}{m-H_i}$$ (4)

In Eq. (4), $0 \leq w_i \leq 1$, $\sum_{i=1}^{m} w_i = 1$.

2.2. Extension model
At present, the extension theory has been widely used in engineering construction, industrial safety, economic analysis and mathematical research. The calculation process for using the extension theory to comprehensively evaluate the collapse risk of the subsea tunnel is as following steps [10].

2.2.1. Matter element matrix. In a decision-making process, $F$ represents the target attributes, $g_j$ is the value of the corresponding characteristic indicator $p_j$. The decision-making process can be expressed as Eq. (5).

$$R = \begin{bmatrix} F & p_1 & g_1 \\ p_2 & g_2 \\ \vdots & \vdots \\ p_n & g_n \end{bmatrix} = \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_n \end{bmatrix}$$ (5)

2.2.2. Classical field. Assume that $R_0$ represents the collapse risk grade, and the influencing indicator set of the subsea tunnel collapse risk is $p_j$ ($p_1, p_2, \ldots, p_n$). The classical field is established in Eq. (6).

$$R_{0t} = \begin{bmatrix} F_{0t} & p_1 & < a_{0t1}, b_{0t1} > \\ p_2 & < a_{0t2}, b_{0t2} > \\ \vdots & \vdots \\ p_n & < a_{0tn}, b_{0tn} > \end{bmatrix}$$ (6)

where $R_{0t}$ represents the collapse risk grade is $t$, $p_j$ is the $j_{th}$ influencing factor for collapse risk. $<a_{0tj}, b_{0tj}>$ is the value range about risk grade $t$.

2.2.3. Controlled field.

$$R_p = \begin{bmatrix} F_p & p_1 & < a_{p1}, b_{p1} > \\ p_2 & < a_{p2}, b_{p2} > \\ \vdots & \vdots \\ p_n & < a_{pn}, b_{pn} > \end{bmatrix}$$ (7)
As seen in Eq.(7), $p_j$ represents the $j_{th}$ factor of the target attribute $R_p$. The largest value range of the index $p_j$ is $<a_{pj}, b_{pj}>$. $R_p=\{F_p, p, g\}$ is called the controlled field.

2.2.4. Comprehensive correlation degree. According to Eq.(8), the collapse risk grade correlation degree of the $j_{th}$ factor to collapse risk grade $t$ is obtained.

$$k_{jt} = \begin{cases} \frac{-\rho(g_{jt}, g_{0jt})}{g_{0jt}} & g_{jt} \in g_{0jt} \\ \frac{\rho(g_{jt}, g_{0jt}) - \rho(g_{jt}, g_{pt})}{\rho(g_{jt}, g_{pt})} & g_{jt} \not\in g_{0jt} \end{cases}$$

In Eq.(8), the function $\rho(g_{jt}, g_{0jt})$ and $\rho(g_{jt}, g_{pt})$ are calculated by Eq.(9).

$$\begin{align*}
\rho(g_{jt}, g_{0jt}) &= |g_{jt} - \frac{1}{2}(a_{0jt} + b_{0jt})| - \frac{1}{2}(b_{0jt} - a_{0jt}) \\
\rho(g_{jt}, g_{pt}) &= |g_{jt} - \frac{1}{2}(a_{pt} + b_{pt})| - \frac{1}{2}(b_{pt} - a_{pt})
\end{align*}$$

On the basis of obtaining the single index correlation degree, the comprehensive correlation degree is calculated by Eq.(10).

$$k_{jt}(F_j) = \sum_{j=1}^{n} w_j k_{ij}(g_{jt})$$

Where $w_j$ is the weight of the $j_{th}$ indicator, and $\sum_{j=1}^{n} w_j = 1$. Correlation degree is the crucial criterion for determining the collapse risk grade of the tunnel. The greater the correlation degree, the greater the degree to which the index is approach to the corresponding collapse risk grade. If $k_{0jt}(F_j) = \max\{k_{jt}(F_j)_{t=1,2,...,n}\}$, the collapse risk grade of $F_j$ is $t$.

3. Engineering application

The subsea tunnel engineering project is located in Fujian province, China. The subsea connects Haicang District with the Xiamen area. The total length of this tunnel is 7.79km. The lowest elevation of the subsea tunnel is 70.3m below sea level. The thickness of overlying rock mass is about 40m in the sea area, and the depth of tunnel in the land section is about 20–60m.
The subsea tunnel has complex geological conditions, including weathering troughs and fault fracture zone. During construction, the geological prediction system is carried out to provide construction guidance for engineering safety, including seismic wave detection and infrared water detecting (Figures 1a and 1b). Taking this engineering as a case study. The collapse risk evaluation system was established as follows.

3.1. Extension model for grading the collapse risk of the subsea tunnel

According to the engineering characteristics and the collapse risk mechanism of the subsea tunnel engineering, seven influencing factors of tunnel collapse risk were selected. Among them, the subjective factors include support method $M$ and construction level $C$. The objective factors are the over-span ratio $e$, buried depth $h$, surrounding rock integrity $k_v$, surrounding rock grade $T$, groundwater condition $w$. The over-span ratio $e$ and the buried depth $h$ are important factors for determining the collapse risk of the subsea tunnel. $e$ is the ratio of the tunnel diameter $C$ to the thickness of the tunnel overlying rock $D$, i.e. $e=C/D$. Generally speaking, the larger the buried depth of the tunnel, the higher the self-weight of the surrounding rock above the tunnel, thus the higher the collapse risk during tunnel construction. The surrounding rock grade can directly reflect the stability of surrounding rock and is an essential indicator for the tunnel collapse risk evaluation as well. The buried depth $h$, over-span ratio $e$ and surrounding rock grade $T$ can be obtained from the geological exploration data.

The surrounding rock integrity is an important indicator reflecting the collapse risk grade of the tunnel, and can be expressed by the integrity coefficient $k_v$, i.e. $k_v=(V_p/V_s)^2$. Among them, $V_p$ is the longitudinal wave velocity of the rock mass, and can be obtained from the Tunnel Seismic Prediction (Figure 1b). $V_s$ represents the transverse wave velocity of the rock, which can be obtained from the laboratory tests. Generally speaking, the larger the surrounding rock integrity coefficient, the higher the surrounding rock stability, and the lower collapse risk of the surrounding rock.

Due to the complex distribution of the groundwater in the subsea tunnels, the groundwater condition is an essential factor in investigating the tunnel collapse risk (Figure 1f). In this paper, the groundwater content of the surrounding rock obtained by infrared water detecting (Figure 1a) on-site is selected as an evaluation index of groundwater condition. Subjective factors are important indicators for maintaining the stability of the subsea tunnel. When the objective collapse risk indicators are abnormal, the subjective collapse risk indicators i.e. support method and construction level, are utilized to reduce the collapse risk of the subsea tunnel. The supporting method of this engineering mainly includes the primary support, secondary lining, secondary lining and invert, secondary lining.

Figure 1. (a) Infrared water detecting, (b) Field detection-TSP203, (c) Curtain grouting, (d) Construction recording, (e) Pre-grouting, (f) Water flow on-site.
and pre-grouting (Figure. 1e), secondary lining and curtain grouting (Figure. 1c). Moreover, the quantitative standards for construction level mainly include the frequency of tunnel monitoring, timeliness of tunnel seismic prediction and construction experience of the subsea tunnel.

According to the extension theory, the collapse risk was divided into five grades: extremely high (I), high (II), medium (III), low (IV) and micro (V). Correspondingly, the value ranges of the indexes were divided into equal intervals in Table 1, which constituted the collapse risk grading standards. Moreover, on the basis of the experts' suggestions in related fields, the descriptions of the collapse risk of different grades are listed in Table 2.

| Table 1. Grading standards of the indexes for collapse risk. |
|-------------------------------------------------------------|
| **Index** | **Collapse risk grading standards for the subsea tunnel** |
|           | Extremely high (I) | High (II) | Medium (III) | Low (IV) | Micro (V) |
| $e$       | 2.0–3.0           | 1.5–2.0   | 1.0–1.5      | 0.5–1.0  | 0–0.5     |
| $h$ (m)   | 45–60             | 30–45     | 20–30        | 10–20    | 0–10      |
| $w$       | 0.8–1.0           | 0.6–0.8   | 0.4–0.6      | 0.2–0.4  | 0–0.2     |
| $k_v$     | 0–0.2             | 0.2–0.4   | 0.4–0.6      | 0.6–0.8  | 0.8–1.0   |
| $T$       | 1.0(V)            | 0.8(IV)   | 0.6(III)     | 0.4(II)  | 0.2(I)    |
| $M$       | $0.2(M_1)$        | $0.4(M_2)$| $0.6(M_3)$  | $0.8(M_4)$| $1.0(M_5)$|
| $C$       | 0–0.2             | 0.2–0.4   | 0.4–0.6      | 0.6–0.8  | 0.8–1.0   |

Note: $e$-Over span ratio. $h$-Buried depth. $w$-Groundwater condition. $k_v$-Rock mass integrity. $T$-Grade of the rock mass. $M_1$-Primary support, $M_2$-Secondary lining, $M_3$-Secondary lining and invert, $M_4$-Secondary lining and pre-grouting, $M_5$-Secondary lining and curtain grouting. $C$-Construction level.

| Table 2. The description of the collapse risk grade. |
|---------------------------------------------------|
| **Collapse risk grade**                          | **The description of the grade** |
| Extremely high (Grade 1)                         | The collapse risk of the subsea tunnel is extremely high. The cumulative deformation of the tunnel is more than 60mm per day. The tunnel collapsed, and the volume of the tunnel collapse exceeded 20m$^3$. |
| High (Grade 2)                                   | The collapse risk of the subsea tunnel is high. The cumulative deformation of the tunnel may reach to 45–60mm per day. The amount of water inflow may reach 900m$^3$/d. There may be cracks in the support structure. It is necessary to change the support method. |
| Medium (Grade 3)                                 | The collapse risk of the subsea tunnel is medium. The cumulative deformation of the tunnel may reach 30–45mm per day, which is under the normal range. The amount of water inflow may reach to 600–800m$^3$/d. |
| Low (Grade 4)                                    | The collapse risk of the subsea tunnel is low. The cumulative deformation of the tunnel may reach to 20–30mm per day. The amount of water inflow is 300–600m$^3$/d. |
| Micro (Grade 5)                                  | The collapse risk of the subsea tunnel is micro. The cumulative deformation of the tunnel is less than 20mm per day. It is not necessary to change the construction or support method. |

3.2. Weight calculation
The entropy weight method analyzes the variability degree of each index in the process of weight calculation. Therefore the learning samples of the index are essential. According to the on-site
construction recording (Figure. 1d) and geological exploration data, the actual data of the collapse risk indexes are obtained and listed in Table 3.

**Table 3.** Learning data sample.

| No. | e   | h (m) | w  | k_v | T  | M  | C   |
|-----|-----|-------|----|-----|----|----|-----|
| 1   | 2.30| 15.8  | 0.6| 0.38| 0.5| 0.4| 0.85|
| 2   | 2.30| 16.4  | 0.6| 0.38| 0.5| 0.4| 0.9 |
| 3   | 1.75| 20.1  | 0.7| 0.44| 0.5| 0.4| 0.65|
| 4   | 1.26| 22.5  | 0.6| 0.32| 0.6| 0.6| 0.7 |
| 5   | 1.31| 28.6  | 0.5| 0.35| 0.7| 0.8| 0.8 |
| 6   | 1.38| 30.0  | 0.5| 0.58| 0.7| 0.8| 0.8 |
| 7   | 1.38| 30.5  | 0.4| 0.58| 0.7| 0.8| 0.75|
| 8   | 1.10| 32.0  | 0.4| 0.58| 0.6| 0.6| 0.65|
| 9   | 1.13| 33.8  | 0.3| 0.46| 0.6| 0.6| 0.85|
| 10  | 0.90| 34.5  | 0.4| 0.46| 0.7| 0.8| 0.8 |
| 11  | 0.95| 34.8  | 0.6| 0.46| 0.7| 0.8| 0.55|
| 12  | 0.82| 35.6  | 0.8| 0.46| 1.0| 0.2| 0.75|
| 13  | 0.79| 37.0  | 0.7| 0.61| 1.0| 0.2| 0.75|
| 14  | 0.88| 37.0  | 0.4| 0.61| 0.8| 0.6| 0.9 |
| 15  | 0.88| 37.5  | 0.7| 0.61| 0.8| 0.6| 0.95|

The objective weight of the evaluation indexes is obtained according to Eqs.(1)-(4), results can be seen in Table 4.

**Table 4.** Weight of the index.

| Index | e   | h (m) | w  | k_v | T  | M  | C   |
|-------|-----|-------|----|-----|----|----|-----|
| H_j  | 0.9765 | 0.9880 | 0.9875 | 0.9922 | 0.9913 | 0.9736 | 0.9966 |
| Weight | 0.249 | 0.127 | 0.133 | 0.082 | 0.092 | 0.28 | 0.037 |

3.3. Evaluation results

The engineering application is a crucial way to verify the feasibility of the investigation method and can optimize the evaluation model. Based on actual construction data, five sets sample data of the tunnel sections were selected for collapse risk evaluation (Eq.(11)).

\[
Q_{7x5} = \begin{bmatrix}
1.33 & 1.25 & 1.15 & 1.90 & 2.11 & \text{Over-span ratio} \\
26.8 & 19.4 & 45.0 & 55.0 & 34.0 & \text{Buried depth} \\
0.60 & 0.40 & 0.40 & 0.85 & 0.80 & \text{Groundwater condition} \\
0.80 & 0.80 & 0.20 & 0.40 & 0.50 & \text{Rock mass integrity} \\
0.40 & 0.60 & 0.60 & 0.70 & 0.80 & \text{Rock mass grade} \\
0.60 & 0.60 & 0.20 & 0.20 & 0.20 & \text{Support method} \\
0.85 & 0.75 & 0.90 & 0.60 & 0.60 & \text{Construction level} \\
\end{bmatrix}
\]

Based on the extension theory, the evaluation results are obtained according to Eqs.(5)~(10) in Table 5.
Table 5. Comprehensive evaluation results.

| Samples | Correlation degree of the collapse risk grade | Evaluation grade | Actual grade |
|---------|---------------------------------------------|------------------|--------------|
|         | $k_i$ | $k_{II}$ | $k_{III}$ | $k_{IV}$ | $k_V$ |           |             |
| 1       | 0     | 0.2077  | 0.4755   | 0.5875   | 1.0000 | V         | IV          |
| 2       | 0     | 0.2019  | 0.5014   | 0.6482   | 1.0000 | V         | V           |
| 3       | 0.2628| 0.4576  | 0.0964   | 0        | 1.0000 | V         | IV          |
| 4       | 0.8018| 1.0000  | 0.1269   | 0        | 0.9622 | II        | II–III      |
| 5       | 0.8128| 1.0000  | 0.2399   | 0        | 0.9929 | II        | II          |

Finally, the actual grade and the evaluation results obtained via the collapse risk evaluation model are listed in Table 5. Table 5 shows that the evaluation results of the evaluation model are basically consistent with the actual situation.

4. Conclusion
Support method and construction level are subjective factors affecting the collapse risk of the subsea tunnel. Over-span ratio, buried depth, groundwater condition, surrounding rock integrity and surrounding rock grade are the objective factors. In this paper, the entropy weight method is used to calculate the objective weight of the seven indexes, in which the support method has the highest weight, the over-span ratio has the second-highest weight, and weight of the construction level is the lowest. The calculation results indicate that the support method plays an indispensable role in the construction safety of the subsea tunnel. Therefore, it is extremely crucial to guarantee the construction quality of the support structure during construction. This paper established an extension model for evaluating the collapse risk of the subsea tunnel and successfully applied it to a subsea tunnel engineering in China. The evaluation results of the five construction sections showed that the evaluation results obtained via the extension model are basically consistent with the actual excavation situation. Moreover, we can expand the number of engineering data to conduct a more comprehensive database of the subsea tunnel. Thus, the collapse risk grading system of the subsea tunnel can be standardized by engineering applications.

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