Karst development characteristics and collapse risk assessment along Shaoxing metro line 1

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Abstract. Urban subway construction in karst areas can be seriously threatened by geological disasters, which impact the safety of subway construction and operation. Given the effects of geological conditions and human engineering activities, it is necessary to comprehensively analyze the influence of various factors and then evaluate the risk of karst collapse. With the section between Yanghe road station and Jianhu town station of Shaoxing metro line 1 as an example, crosshole seismic wave computed tomography (CT) was employed to prospect the geometric characteristics and spatial distribution of karst caves. Based on the survey results, ten influencing factors were selected as evaluation indexes for karst collapse susceptibility. Then, an assessment system was established, and each index was quantitatively rated through three grades. The analytical hierarchy process was used to determine the weight of these indexes, and the fuzzy transform principle and maximum membership degree principle were applied to quantitatively and comprehensively evaluate the collapse risk level in the study area. Results showed that karst cave development mainly occurred in the bedrock surface under 11 m. The caves were mostly 2–5 m high, and most of them were filled. Approximately 70% of the studied section had a moderate or high risk of karst collapse. As the subway passes through the karst area, appropriate measures should be implemented for the different risk sections to ensure the safety of construction and operation.

1. Introduction

In recent years, with the rapid development of urban rail transit engineering in China, an increasing number of cities have started to accelerate the construction of subways. In the construction process, a variety of complex geological conditions are often encountered, such as soil softness, soil expansion, and soil and karst collapse [1]. Karst problems are particularly prominent. Wuhan, Nanjing, Changsha, Guangzhou, Shenzhen, Nanning, Guiyang, and other cities have experienced serious karst geological disasters in the process of tunnel construction [2]. Generally, subway tunnels need to pass through shallow bedrock and an overlying sand layer during construction. Karst caves and cracks in the bedrock cause leakage of the overlying soil layer in the crossing area and then lead to the collapse and large deformation of the surrounding rock, which seriously affect the construction safety and stability of the tunnel engineering. Therefore, the possibility of karst leakage and collapse should be evaluated by studying the development characteristics and properties of karsts in engineering areas. Such
assessment is important for ensuring the safety of engineering construction and reducing and controlling major disasters.

To prevent and control karst geological disasters in urban subways, extensive studies have been conducted on the detection method, collapse risk assessment, and disposal measures of karsts. With regard to investigation techniques for karst terrains, different site exploration and testing techniques have been developed to identify the occurrence characteristics of karst structures, such as borehole tests, tunnel seismic prediction (TSP), ground-penetrating radar (GPR), and crosshole seismic wave computed tomography (CT). For example, Pesendorfer and Loew [13] performed a systematically cored borehole exploration (about 10,000 m) with open-hole and packer tests in karstified and fractured limestones. Based on the high-resolution transient pressure records of these tests, they obtained standard formation properties and diagnostic information, including the type, orientation, and dimension, of permeable structures. Sun et al. [4] presented several TSP forecasting examples of a highway tunnel in a karst zone. They summarized the concrete reflection of caves and underground rivers in TSP and established a judgment rule for caves and underground rivers. Alimoradi et al. [5] and Asadollahi and Foroozan [6] performed similar application studies associated with TSP. Al-fares et al. [7] tested the performance of GPR in a karst environment. The results indicated that GPR is suitable for the analysis of near-surface (<30 m in depth) karst structures, especially those with rare and discontinuous clayey coating or soil that absorbs and attenuates the radar. Duan et al. [8] explored the viability of crosshole seismic CT techniques for effectively detecting caves in the foundation of karst terrains. The results proved that crosshole seismic CT is particularly well adapted to the detection of deeply buried karst caves (>30 m in depth) because it can provide a detailed view of the subsurface. However, as each detection method has restricted conditions and shortcomings, an appropriate investigation technique should be selected in combination with information about the geological and engineering conditions of each study area [9].

Collapse risk assessment and disposal measures of karsts have been drawing equal attention. Choi et al. [10] presented a formalized procedure and associated tools to assess the risks of an underground construction project in Korea. Based on the fuzzy analytic hierarchy process, Chen et al. [11] established a risk assessment model of tunnel collapse and successfully applied it to the Qingshangang Tunnel. To quantitatively evaluate the risk of an urban karst collapse disaster, Wu et al. investigated the geological conditions of Xuzhou in detail. Eight disaster-causing factors, such as the degree of karst development, coating conditions, and hydrodynamic conditions, were selected to evaluate the vulnerability of karst collapse in the study area by means of tomographic analysis and fuzzy comprehensive evaluation. A regional map showing Xuzhou’s susceptibility to karst collapse was developed [12]. According to a comprehensive analysis of the influencing factors of karst collapse along the Xuzhou subway, He et al. [13] established a fuzzy comprehensive evaluation model of karst collapse stability using ModelBuilder in ArcGIS. The subway line was divided into four different risk levels, and the karst collapse stability along the line was predicted under the conditions of current and increasing mining. Li and Wu [14] proposed a multi-factor comprehensive risk assessment method for karst tunnels. The assessment method was applied to the risk assessment of the Yichang-Wanzhou Railway Dazhiping Tunnel, and the assessment results agreed well with the site construction conditions. Taking the karst area of Guangzhou as an example, Cui et al. [15] established a set of construction procedures for the treatment of karst caves, including field investigations, judgments, treatments, and effect inspections. Treatment standards, materials, construction steps, and effect inspection methods for the treatment of karst caves were proposed and successfully applied to the construction of Guangzhou’s metro shield tunnel.

However, most of the above studies are regional rule summaries, and their conclusions are not widely applicable. If their results were applied to a specific project, the results will not be targeted enough due to differences in the geological and engineering conditions. In the present study, a comprehensive method is proposed for assessing the karst collapse risk of a subway construction project in Shaoxing, China. The comprehensive method consists of two parts. (1) Initial karst detection is performed via crosshole seismic wave CT to obtain the development characteristics of the karst in
the study area, and the results are then used as a part of evaluation indexes for karst collapse susceptibility. (2) The karst collapse risk is systematically evaluated based on the area’s geological and engineering conditions by combining fuzzy evaluation and the analytical hierarchy process. This comprehensive method can make the assessment of karst collapse risk more efficient, and it can provide a reliable reference for the construction of similar projects in the karst development area.

2. Geological survey of study area

The fourth section of Shaoxing urban rail transit line 1 includes four underground stations and three interval tunnels. The four stations are the Fenghuang, Yushan, and Yanghe road stations and Jianhu town station. The three interval tunnels are from Fenghuang road station to Yushan road station, Yushan road station to Yanghe road station, and Yanghe road station to Jianhu town station. The scope of this study is the interval between Yanghe road station and Jianhu town station, with a starting mileage of YK43+789.980 and an ending mileage of YK44+754.494. The total length is 964.5 m. Two parallel subway tunnels are arranged along the subway line, and the shield tunneling method is adopted. The section of the tunneling is circular, with an external diameter of 6.7 m, and the depth of the floor is 18–20 m.

The landform of the site is slightly flat and a lacustrine sedimentary plain. The existing floor elevation is approximately 5.50–6.93 m. The terrain gradually rises from north to south, and the underlying bedrock becomes deeper and shallower from north to south. The site topography is favorable for the accumulation and concentration of groundwater. The Quaternary overburden in the study area is mainly composed of a soil layer, a viscous soil layer, and clayey soil gravel with a thickness of 17.7–25.4 m. The underlying basement lithology is dominated by limestone of the middle Cambrian Yangliugang Formation (∈2y). Due to the influence of structures and folds, there are many pores and fissures in the rock. Moreover, this site is in southern China, which has rich dissolution capacity and controllable groundwater. The measured level of the karst water at the site is 2.6 m, and it is also under pressure. The fault structure is developed, the tectonic movement is dominated by oscillatory lifting movement, and karst caves are developed both horizontally and vertically.

3. Karst development characteristics in study area

3.1. Karst exploration method

The main types of karst in this area are karst caves and dissolution gaps, and the karst is mainly in the bedrock. Because the intensity of the underground water level is higher, the karst in the bedrock is filled with fluid-soft plastic silty clay mixed with crushed stone, which is characterized by low resistance (high conductivity), low wave velocity, and a high electromagnetic attenuation coefficient. Theoretically, geophysical methods, such as GPR, transient electromagnetic methods, and high-density electric methods, can be used to detect karst. However, there is strong electromagnetic interference, stray current interference, and vibration interference in urban areas. Therefore, the crosshole seismic wave CT method was finally adopted in this work, and the development location, size, and nature of crosshole karst and earthen caves were determined with a comprehensive analysis of drilling data in the early stage.

A Geode96 shallow seismograph was used for the crosshole seismic wave CT detection. Three rows of detection holes were arranged along the tunnel direction on both sides and in the middle of the tunnel. The longitudinal hole spacing was 15 m, the middle row of the detection holes had a staggered arrangement, and the detection holes on both sides were arranged in a triangle. A total of 189 detection holes and 438 groups of elastic wave CT profiles were arranged. The CT inversion results of the typical interpore seismic waves in this region are shown in Figure 1. As shown in Figure 1a, the low-speed zone of the upper overburden is clearly demarcated from the relatively high-speed zone of the underlying bedrock. There is no low-speed zone and no karst cave development in the moderately weathered bedrock. Figure 1b shows that, when karst caves develop between the detected sections, the overall seismic waves show a decrease in velocity. The depth of the bedrock surface is 22.9–32.3 m,
and the corresponding elastic wave velocity is on the contour line of 2600 m/s. The velocity of the intact limestone below the bedrock is 3500–5000 m/s, and the karst cave wave velocity is 2000–3200 m/s. The light blue range in Figure 1b delineates the karst development near hole Z30; the development range is concentrated near the depth of 32.8–44.3 m, and it tends to spread to the left. A verification hole was arranged 5.5 m to the left of hole Z30, revealing a mud-filled karst cave at a depth of 34–38 m, moderately weathered bedrock at a depth of 38–38.9 m, and mud-filled karst caves at a depth of 38.9–41.2 m. The verification results agree with the range of velocity anomalies delineated by the elastic wave CT.

![Figure 1](image-url)

**Figure 1** Cloud map of interpore seismic wave CT inversion results for (a) nonkarst and (b) karst caves.

### 3.2. Morphology and scale of karst
The detection results show that the karst development types in the study area are mainly caves and gaps, the thickness of the overburden is 17.7–25.4 m, and the karst in this area is covered karst. As shown in Figure 2, an analysis of 438 groups of elastic wave CT inversion images shows 524 karst cave anomalies. The karst cave height is 0.2–15.8 m, the average cave height is 2.5 m, and 225 karst caves (42.94% of the total) are shorter than 2 m. There are 225 caves (42.94%) with heights of 2–5 m. There are 69 abnormal bodies (13.17%) with heights of 5–10 m. Six of the karst caves (1.15%) are taller than 10 m high.

![Figure 2](image-url)

**Figure 2** Height distribution map of karst caves, detected by elastic wave CT.

### 3.3. Vertical distribution characteristics of karst
The distribution of the karst caves was studied by examining the burial depth of the karst cave roofs under the bedrock surface. The distribution of the karst cave heights, identified by elastic wave CT, is shown in Figure 3. As shown in the figure, more than 30% of the karst caves uncovered by the survey are within 4.0 m below the bedrock surface, 50% are within 6.0 m below the bedrock surface, and more than 80% of the anomalies are within 11.0 m below the bedrock surface. However, only 24 karst caves with burial depths greater than 15.0 m were found, which account for only 4.57% of the total number of karst caves. The above statistical results show that the karsts developed in this area are more shallow and less deep.

![Figure 3 Distribution of karst cave roof distance from bedrock surface, determined by elastic wave CT.](image)

3.4. Lateral distribution characteristics of karst

The statistics of the linear karst rate (the percentage of karst cave footage to the total footage of solvable rock) of the buried depth below the bedrock surface are shown in Figure 4. The linear karst rate is relatively large at 1–6 m below the bedrock surface, with a maximum value of 31.92% at 2 m. It is relatively stable at 7–13 m, between 8.76% and 13.37%. The karstification rate gradually decreases from 14 m below the bedrock level to 4.66% at 18 m.

![Figure 4 Statistics of linear karst rate of buried depth line under bedrock surface.](image)

3.5. Filling characteristics of karst

According to the filling conditions of the karst caves, the karst caves exposed by the borehole were classified as fully filled, semifilled, and unfilled. There are 154 fully filled karst caves (59.69% of the total number of karst caves) and 99 unfilled karst caves (38.37%). The average buried depth is 3.62 m below the surface of the moderately weathered bedrock. There are 5 semifilled karst caves (1.94%),
and the average burial depth under the surface of the moderately weathered bedrock is 6.97 m. The overall burial depths of the fully filled and semifilled karst caves are small, and the burial depth of the unfilled caves is large; these findings generally show the “filled top, unfilled bottom” feature of karst development. The fillings are mainly mud (the drill pipe sinks slowly), gravel containing silty clay, and clay with crushed stone. The properties of the filling materials are highly different and generally poor.

Figure 5 Statistical map of buried depth of karst caves with and without filling under bedrock.

4. Risk assessment of karst collapse

The risk of karst collapse in the study area was assessed using a fuzzy comprehensive evaluation method based on the analytic hierarchy process. First, the risk factor and evaluation sets of the evaluation object were established based on the fuzzy comprehensive evaluation method. Then, the weight values of each evaluation factor were determined by the analytic hierarchy process. Finally, appropriate fuzzy operators were used for comprehensive evaluation.

4.1. Determination of index system and establishment of evaluation model

There are three basic criteria for the formation of karst collapse. The first is the existence of soluble rock, which is the space of dissolution (karst cave or soil cave). Second, caprock with a certain thickness is overlaid. Finally, the sloughing force is greater than the antisloughing force, and the sloughing force mainly includes water and air force produced by water flow, dead weight of rock and soil, and engineering activities [16]. Therefore, based on the analysis of the geological conditions of the karst engineering along the subway line in Shaoxing City, four kinds of influencing factors, namely, hydrogeological conditions, overburden conditions, karst conditions, and human engineering activities, were selected to establish the evaluation index system of karst collapse susceptibility. That is, evaluation indexes $U = \{U_1, U_2, U_3, U_4\} = \{\text{hydrogeological conditions, overburden conditions, karst conditions, human engineering activities}\}$. The hydrogeological conditions can be decomposed into the distance between the pore water level and the bedrock surface and the difference between the pore water level and the karst water level. The overburden conditions can be decomposed into the structure, properties, and thickness of the soil layer. The karst conditions can be divided into the borehole exposure karst rate (the percentage of boreholes exposed to karst caves against the total number of exploratory boreholes), degree of karst filling, and karst cave size. The human engineering activities can be divided into the tunnel depth and the distance between the cave and the tunnel. The evaluation index system of karst collapse susceptibility along the subway line in Shaoxing is shown in Figure 6.
4.2. Determination of evaluation index weight

The factors affecting the occurrence of karst disasters are highly complex. The weights of the different risk levels were determined, and the degree of the influence of each factor on the occurrence of karst collapse disasters was identified. The analytic hierarchy process was combined with expert scoring to determine the relative weight of each factor [17]. As shown in Table 1, the hierarchical structure model (1–9 scale method) was used to compare any two evaluation indexes item by item, their relative importance was determined by referring to expert opinion, and corresponding scores were specified to obtain the judgment matrix and weight values of the evaluation indexes [18].

Table 1. Quantified value of importance.

| Scale (assignment) | Implication                                                                 |
|--------------------|-----------------------------------------------------------------------------|
| 1                  | \((u_i \text{ and } u_j \text{ are equally important})\)                    |
| 3                  | \((u_i \text{ is slightly more important than } u_j)\)                       |
| 5                  | \((u_i \text{ is significantly more important than } u_j)\)                 |
| 7                  | \((u_i \text{ is more important than } u_j)\)                              |
| 9                  | \((u_i \text{ is more important than } u_j)\)                              |
| 2, 4, 6, 8         | (The intermediate value of any two adjacent criteria above, such as “2”, is between equally important and slightly important.) |
| Reciprocal         | (The judgment value of \(u_i\) compared with \(u_j\) is \(a_{ij}\), and the judgment value of \(u_j\) compared with \(u_i\) is \(a_{ji}=1/a_{ij}\).) |

Through a comparison of the relative importance of each evaluation index, the discriminant matrix of the criterion and subcriterion layers was obtained as follows.
\[ A \sim B = \begin{pmatrix} 1 & 2 & 2 & 4 \\ 1/2 & 1 & 1 & 2 \\ 1/2 & 1 & 1 & 2 \\ 1/4 & 1/2 & 1/2 & 1 \end{pmatrix} \] (1)

\[ B_1 \sim C = \begin{pmatrix} 1 & 2 \\ 1/2 & 1 \end{pmatrix} \] (2)

\[ B_2 \sim C = \begin{pmatrix} 1 & 1 & 2 \\ 1/2 & 1/2 & 1 \end{pmatrix} \] (3)

\[ B_3 \sim C = \begin{pmatrix} 1 & 5 & 1 \\ 1/5 & 1 & 1/5 \\ 1 & 5 & 1 \end{pmatrix} \] (4)

\[ B_4 \sim C = \begin{pmatrix} 1 & 2 \\ 1/2 & 1 \end{pmatrix} \] (5)

On the basis of the discriminant matrix of the above criterion and subcriterion layers, the final weight of each evaluation index on the target layer can be obtained by multiplying the weight of the subcriterion layer on the criterion layer and the weight of the criterion layer on the target layer. The calculation results are shown in Table 2.

**Table 2. Weight of evaluation factors of susceptibility to karst collapse.**

| Criterion layer               | Weight | Subcriterion layer                                           | Weight |
|-------------------------------|--------|--------------------------------------------------------------|--------|
| Hydrogeological conditions    | 0.444  | Distance between pore water level and bedrock surface       | 0.67   |
|                               |        | Difference between pore water level and karst water level   | 0.33   |
|                               |        | Soil layer structure                                        | 0.4    |
| Overburden conditions         | 0.222  | Soil layer property                                         | 0.4    |
|                               |        | Soil layer thickness                                        | 0.2    |
|                               |        | Borehole exposure karst rate                                 | 0.455  |
| Karst conditions              | 0.222  | Degree of karst filling                                     | 0.09   |
|                               |        | Karst cave size                                             | 0.455  |
| Human engineering activities  | 0.112  | Tunnel depth                                                | 0.667  |
|                               |        | Distance between cave and tunnel                             | 0.333  |

**4.3. Grading and quantification of evaluation index**

The evaluation index was divided into several intervals according to the risk degree. The greater the degree of risk, the higher the general level. The significance of index classification is that it is more conducive to the determination of membership. The evaluation indexes of the formation conditions of
karst ground collapse along the Shaoxing subway were analyzed, and the indexes were classified and evaluated. The three indexes were used to classify the karst ground collapse. The quantitative values were 3, 2, and 1. The larger the value, the more prone the area is to collapse. The classification and quantification of the hazard evaluation indexes of karst collapse are shown in Table 3.

**Table 3.** Classification and quantification of hazard evaluation index of karst collapse.

| Evaluation index | Code | Level and value |
|------------------|------|----------------|
| **B1 Hydrogeological conditions** | | |
| Distance between pore water level and bedrock surface/m | C1 | >40 | 10–40 | <10 |
| Difference between pore water level and karst water level/m | C2 | <2 | 2–16 | >16 |
| Soil layer structure | C3 | Unitary | Binary | Multivariate |
| Soil layer property | C4 | Clayey soil | Wind-sand shale | Sandy soil |
| Soil layer thickness/m | C5 | >20 | 10–20 | <10 |
| **B2 Overburden conditions** | | |
| Borehole exposure karst rate/% | C6 | <30 | 30–60 | >60 |
| **B3 Karst conditions** | | |
| Degree of karst filling | C7 | Fully filled | Semifilled | Unfilled |
| Karst cave size/m | C8 | <5 | 5–10 | >10 |
| **B4 Human engineering activities** | | |
| Tunnel depth/m | C9 | >20 | 10–20 | <10 |
| Distance between the cave and the tunnel/m | C10 | >30 | 8–30 | <8 |

### 4.4. Fuzzy comprehensive evaluation

According to fuzzy theory, the membership degree of the actual values of each evaluation index to the risk level of each karst disaster is expressed by the membership degree $u(x)$, and the degree of membership needs to be represented by the membership function. The indexes are mostly distributed in a straight line according to the establishment principle and method of the membership function and through the statistical analysis of the distribution characteristics of each index data. The calculation formula is as follows:

$$u_i(x) = \begin{cases} 1 & \text{if } x \leq C_{ij} \\ \frac{(C_{ij} - x)}{(C_{ij} - C_{ij})} & \text{if } C_{ij} < x < C_{ij} \\ 0 & \text{if } x \geq C_{ij} \end{cases}$$

(6)
\[
R_{(U1)} = \begin{pmatrix}
0, 0.7, 0.3 \\
0, 0.9, 0.1
\end{pmatrix},
R_{(U2)} = \begin{pmatrix}
1, 0, 0 \\
1, 0, 0 \\
0, 0, 7, 0.3
\end{pmatrix},
R_{(U3)} = \begin{pmatrix}
0, 0, 9, 1 \\
0, 1, 0 \\
0, 0, 1
\end{pmatrix},
R_{(U4)} = \begin{pmatrix}
0, 0, 4, 0.6 \\
0, 0, 1
\end{pmatrix}.
\]

Then, the fuzzy first-level transformation is implemented.

\[
B_{(U1)} = A_1 \cdot R_{(U1)} = (0.67, 0.33) \begin{pmatrix}
0, 0, 7, 0.3 \\
0, 0, 9, 0.1
\end{pmatrix} = (0.766, 0.234)
\]

\[
B_{(U2)} = A_2 \cdot R_{(U2)} = (0.4, 0.4, 0.2) \begin{pmatrix}
1, 0, 0 \\
1, 0, 0 \\
0, 0, 7, 0.3
\end{pmatrix} = (0.8, 0.14, 0.06)
\]

\[
B_{(U3)} = A_3 \cdot R_{(U3)} = (0.455, 0.09, 0.455) \begin{pmatrix}
0, 0, 9, 0.1
\end{pmatrix} = (0.0, 0.5, 0.5)
\]

\[
B_{(U4)} = A_4 \cdot R_{(U4)} = (0.667, 0.333) \begin{pmatrix}
0, 0, 4, 0.6 \\
0, 0, 1
\end{pmatrix} = (0, 0.267, 0.733)
\]

Thus, the second-level fuzzy relation matrix is obtained as follows:
Finally, the second-level fuzzy transformation is conducted. 

\[
B = A^* R = \begin{bmatrix}
0 & 0.766 & 0.234 \\
0.8 & 0.14 & 0.06 \\
0 & 0.5 & 0.5 \\
0 & 0.267 & 0.733
\end{bmatrix}
\begin{bmatrix}
0, 0.766, 0.234 \\
0.8, 0.14, 0.06 \\
0, 0.5, 0.5 \\
0, 0.267, 0.733
\end{bmatrix} = \begin{bmatrix}
0.178, 0.512, 0.310
\end{bmatrix}
\] (12)

On the basis of the principle of the maximum degree of membership, the karst ground collapse risk of the YK44+051–YK44+080 section (between Yanghe road station and Jianhu town station) is classified as level II, which indicates a moderate risk of karst collapse. The karst collapse risk of the other evaluation units of the Yang-Jian tunnel interval of the Shaoxing subway can be obtained by using the above method, and the evaluation results are presented in Table 4. The assessment results show a high risk of karst collapse at sections YK44+127–YK44+317 and YK44+436–YK44+479. The risk of karst collapse at sections YK43+904–YK43+950 and YK44+051–YK44+080 is moderate. As the areas with moderate–high risk of karst collapse account for approximately 71.43% of all the tunnel intervals, it is necessary to implement specific measures for the different risk sections when the subway passes through the karst area to ensure the safety of the subway tunnel during construction and operation.

Table 4. Evaluation results of karst collapse risk.

| Section          | Membership degree | Risk of karst collapse |
|------------------|-------------------|------------------------|
| YK43+904–YK43+950| (0.264, 0.558, 0.178) | Moderate               |
| YK43+976–YK44+008| (0.551, 0.137, 0.312) | Low                    |
| YK44+051–YK44+080| (0.178, 0.512, 0.310) | Moderate               |
| YK44+127–YK44+317| (0.155, 0.344, 0.501) | High                   |
| YK44+332–YK44+376| (0.398, 0.320, 0.282) | Low                    |
| YK44+436–YK44+479| (0.411, 0.107, 0.482) | High                   |
Figure 7 Risk zonation assessment map of karst collapse of tunnel interval between Yanghe road station and Jianhu town station.

5. Conclusions
(1) The karst geology of the fourth section of Shaoxing metro line 1 is distributed in the interval between the Yanghe road station and Jianhu town station, and the karst caves are mainly developed in the range of 11 m below the bedrock surface, accounting for approximately 80% of the total anomalies. The number of karst caves decreases with increasing depth, and the karst development is “more shallow and less deep”.
(2) The karst in the study area is covered karst, the heights of the karst caves are 0.2–15.8 m, and karst caves with heights of 2–5 m account for 42.94% of all karst caves. The filling form is mainly fully filled. Generally, shallow karst caves are mostly fully or half-filled, and those with large burial depths are mostly unfilled.
(3) Karst collapse is closely related to hydrogeological conditions, overburden conditions, karst conditions, human engineering activities, and other engineering geological factors, and an evaluation index system of the risk of karst collapse was established. The analytic hierarchy process was used to determine the weight of each index, and a fuzzy comprehensive evaluation method was used to quantitatively and comprehensively evaluate the risk of karst collapse in the process of subway construction. According to the evaluation results on the risk of karst collapse in each section, approximately 70% of the studied section has a moderate or high risk of karst collapse, whereas the rest has low risk. As the subway passes through the karst area, specific measures should be taken for the different risk sections to ensure the safety of construction and operation.

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