comprehensive weight - set pair analysis theory for heritage buildings adjacent to metro construction

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Abstract: With the rapid development of urban rail transit systems, the safety of nearby heritage buildings and historic sites is threatened. To better protect these heritage buildings and sites, it is crucial to be able to rapidly and accurately evaluate these threats, especially when a rail project has a potential impact upon numerous heritage buildings and sites in an old city. Based on set pair analysis (SPA) theory, this paper presents a risk assessment model to assess the safety of heritage buildings adjacent to metro construction. First, the risk level of adjacent heritage buildings is graded. Second, this study establishes an assessment index system comprising 16 single indexes among four categories related to heritage building, metro, soil, and management, and determines the threshold for the level of corresponding risk for each evaluation factor. To improve the reliability of the index weighting, a linear weighting method is adopted, which comprehensively considers subjective weights calculated by the analytic hierarchy process and objective weights calculated by the clustering weight method. Finally, the proposed SPA model is verified by using it to assess the structural safety risk of a heritage building adjacent to the Zhengzhou Metro Line Three. By extracting the field measured data at different survey points on the metro line, the risk levels of the heritage building in the shield tunneling process are evaluated, and the results verify the feasibility of the SPA model. The proposed SPA method can provide decision-making support for controlling risk on similar projects.

Keywords: Set pair analysis theory; Risk assessment; Heritage buildings; Shield tunneling; Risk control

1. Introduction

Large underground rail transit systems have been recently built in several Chinese cities in order to avoid traffic congestion and problems lined to it [1, 2]. Such underground rail development can dramatically affect the surrounding urban environment [3]: shield tunneling can easily release the stress of surrounding rocks above the roof, produce soil loss, and cause nearby ground settlement, road surface cracking, excessive building deformation, and so on [4]. Heritage buildings are irreplaceable and have especially important historic, artistic, and scientific value; so, the threats to the safety of adjacent heritage buildings due to metro construction must not be ignored [5]. For example, on September 23, 2009, in Tianjin, Metro Line Three was seriously flooded during construction, and this caused many cracks from the
foundation up to the roof of the adjacent historic DD Hotel. The greatest crack was 70 cm wide, and there was a partial collapse on the northwest side of the hotel [6]. Underground rail transit construction threatens the structural integrity of adjacent heritage buildings not only in China, but throughout the world [7]. For example, the Historical Archives in Cologne (Germany) collapsed due to metro construction; on March 3, 2009, many cracks appeared in the external wall of the building, which quickly spread to the roof and triggered the collapse of the archives [8]. Nevertheless, underground rail transit projects are being vigorously promoted in big cities, and thus, it is important for engineers to be able to evaluate the risks of shield construction on the safety of adjacent heritage buildings [9]. Many research works have investigated the impact of underground rail transit construction upon adjacent buildings. The main research methods include finite element analysis (FEA) [10-12], empirical analysis (EA) [9, 13], Bayesian networks (BNs) [14, 15], information fusion (IF) [4, 16], extended cloud model (ECM) [17], and the chromatography multiply assessment method (CMAM) [6, 18]. All the above research methods have some advantages, and some disadvantages. For example, FEA is not only a multi-parameter and dynamic analysis method, but it can also be used for repeated simulation calculations of various working conditions with high accuracy and visualization. The method has been widely used to study the influence of tunnel environments. However, the modeling process of this method is complex, requiring a highly professional background and theoretical approach on the part of relevant users, and the time cost cannot be ignored. Especially when a metro line is built in the old part of a city, and there are many heritage buildings near the line that require an assessment of the impact of metro construction on structural safety, this method is deemed to be time-consuming and expensive. EA needs to obtain prior examples and experiences through statistical analysis of a large number of actual engineering monitoring data, so as to provide theoretical guidance for engineering, so that the results of this method can get as close as possible to the real engineering practice. Yet, this method is only applicable to similar engineering constructions in similar environmental conditions; so, its popularity and application have certain limitations. BNs is based on probabilistic reasoning, which can solve the problems of uncertainty and incompleteness, but it has high complexity and high computational demands, and its analytical quality depends on whether there is a sufficient amount of reliable prior data samples. IF is based on the Dempster–Shafer evidence theory, which can fuse a variety of data, and it is more intuitive than BNs. However, there is no solid theoretical support for the synthesis rules, so its rationality and effectiveness are controversial. ECM can be used to evaluate the impact of metro tunnel shield construction in a simple,
quick, and convenient way, but it is easy to lose important information in the calculation process. In CMAM, images are overlaid according to a chromatic principle by means of Photoshop or ArcGIS technology platform. The operation is simple and the method gives intuitive, vivid, and concise images, but the interaction between the metro tunnel and heritage building factors, as well as the contribution of soil factor and management factor, is not considered, and it is only applicable to the evaluation of metro lines during the planning stage. In general, most of the available methods have certain limitations. This study attempts to explore from a new angle a more convenient and efficient method to evaluate heritage buildings under the impact of nearby metro tunnel shield construction, avoiding unnecessary complex numerical simulations of many of the lower risk buildings, and provide a basis for decision-makers to determine risk levels and protection measures for structural safety. It is of practical significance to create a thorough construction plan and ensure the structural safety of heritage buildings during metro construction using shield tunneling.

This study presents such a method, using factors related to heritage buildings, metro construction, soil conditions, and construction management as evaluation index factors, by using mathematical tools to build the safety assessment model, based upon set pair analysis (SPA). It simply and rapidly evaluates the risk to adjacent heritage buildings under the influence of metro shield tunneling construction. Moreover, when shield tunneling is used during the metro construction process, relevant risks can be controlled in real time by updating the data for each evaluation parameter, thus providing feedback for the adjustment and optimization of the construction plan.

### 2. Safety risk assessment model

#### 2.1 Basic SPA theory

The SPA theory was first introduced in 1989 by Zhao Keqin as a new kind of systems analysis method that focuses on the study of certainty and uncertainty in a given system [19]. In this system, “identity”, “opposition”, and “difference” are used to describe the relationships between objects: identity and opposition represent two aspects of certainty, whereas difference represents uncertainty. Identity, opposition, and difference are interrelated and influence and restrict each other, and they transform each other under certain conditions [20]. The three can be indicated with the correlation degree shown in Eq. (1), thus transforming the dialectical understanding of uncertainty into a mathematical operation.
\[ \mu(w) = \frac{S}{N} + \frac{F}{N} i + \frac{P}{N} j = a + bi + cj \]  

(1)

where, \( N \) is the total number of features with the set pair \( H = (A, B) \) (assumption sets \( A, B \)), which describes identity, opposition, and difference; \( S \) represents the common features, \( P \) represents opposite features, \( F \) represents features that are neither common nor contrary, and \( N = S + F + P \). The ratios, \( S/N \), \( F/N \), and \( P/N \) are, respectively, called the identity degree, difference degree, and conflict degree of sets \( A \) and \( B \). For convenience, let \( a = S/N \), \( b = F/N \), and \( c = P/N \), with the values of \( a \), \( b \), and \( c \) satisfying the condition \( a + b + c = 1 \). The coefficients of the difference degree and conflict degree are \( i \) and \( j \), respectively, with \( i \in [-1, +1] \) and \( j = -1 \). When \( i = 1 \), the uncertainty is converted into an identity degree; when \( i = -1 \), the uncertainty is converted into a conflict degree; and when \( i \in (-1, +1) \), there is a mixed degree of identity and opposition.

### 2.2 Establishing the hierarchy model

#### 2.2.1 Standard grades of risk

According to the relevant standard specification [21] and existing literature [16, 17][22], combining safety control measures and protection requirements of heritage buildings, the structural safety of adjacent heritage buildings under the influence of metro construction can be classified into five levels: I (safe), II (low risk), III (medium risk), IV (high risk) and V (extreme risk). Table 1 lists the relationships among risk levels, effects, and safety control measures of heritage buildings.

| Level | Risk  | Effects                                      | Safety control measures                                                                 |
|-------|-------|----------------------------------------------|---------------------------------------------------------------------------------------|
| I     | Safe  | Basically intact, no effect                  | No essential strengthening measures required.                                         |
| II    | Low risk | Slight effect: building’s outdoor floor has a few slight cracks (width <0.05 mm), without non-uniform settlement; non-structural components have slight cracks (width < 0.05 mm); the main structure of the building has no visible cracks, lateral displacement occurs at the top of the structure (<H/700). | Take essential pre-reinforcement measures during construction; strengthen monitoring of surface subsidence and building displacement. |
| III   | Medium risk | Medium effect: building outdoor floor has some cracks (0.05-0.30 mm), without non-uniform settlement; non-structural components have some cracks (0.05-0.30 mm); the main structure of the building has a few slight cracks (width < 0.05 mm); lateral displacement (H/700 ~ H/600). | Take essential pre-reinforcement measures during construction; strengthen monitoring of surface subsidence and building displacement; conduct trend analysis weekly for building damage caused by tunneling. |
| IV    | High risk | Large effect: building outdoor floor has many cracks (0.30-0.50 mm), with slight non-uniform settlement; non-structural components have many cracks (0.3-0.5 mm); the main structure of the building has many cracks (0.05-0.25 mm), lateral displacement (H/600 ~ H/500). | Take essential pre-reinforcement measures during construction; strengthen monitoring and feedback of surface subsidence and building displacement; conduct field tests to guide the adjustment of parameters during construction; invite experts to analyze weekly the trend for building damage caused by tunneling. |
| V     | Extreme | Severe effect: building outdoor floor has many Conclude field tests and strengthening analyses; |                                                                                                                                 |

Table 1 Relationships among risk levels, effects, and safety control measures
risk cracks (width >0.50 mm), with significant non-uniform settlement; non-structural components have many cracks (width >0.5 mm); the main structure of the building has many cracks (width >0.25 mm), lateral displacement (> H/500).

optimize the construction plan according to parametric analysis and expert opinions; strengthen monitoring and feedback of surface subsidence and building displacement; invite experts to analyze weekly the trend for building damage caused by tunneling, and make a contingency plan; after construction, repeat safety assessment.

2.2.2 Selection of evaluation factors

The main reason that metro construction affects the structural safety of heritage building is the loss of soil above the pipeline caused by shield tunneling construction. This leads to uneven settlement of the site in the area where the heritage buildings are located, thus threatening the structural safety of these buildings [22]. The impact that metro construction has on the structure of heritage buildings is divided into three main factors: building, soil, and metro tunnel. In addition, construction management is indispensable. Effective safety management can control risks in a timely manner and ensure the safety of the construction site and surrounding environment [23]. Therefore, the evaluation factors are mainly derived from four sources: heritage building, metro construction, soil, and management:

(1) Heritage building factors($b_1$): the importance degree($c_1$) of the heritage building consists of protection level, historic value, scientific value and artistic value [24]. The higher the degree of importance, the greater is the loss due to disaster, and therefore, greater are the security implications. The ability of heritage buildings to resist the influence of the external environment is also important for the safety of heritage buildings; such capability comprises the geometric character($c_2$), structure type ($c_3$) and deterioration degree($c_4$), as they are all related to the structural reliability parameters [21, 25].

(2) Metro construction factors($b_2$): The distance from the metro construction to a heritage building is an important factor affecting the safety of these buildings [22, 26], and it includes namely, cover depth ($c_5$ the vertical distance from the tunnel roof to the ground [27]); and horizontal distance($c_6$). According to R. Peck, the land subsidence is caused by the loss of soil, with the soil loss showing a positive correlation relationship to the section size ($c_7$) [28]. The advancing speed ($c_8$) has a significant effect on land subsidence [29].

(3) Soil factors($b_3$): Soil is the medium for the interaction between a building and the metro, and it is a direct factor affecting the safety of heritage building [16]. Friction angle($c_9$), compression modulus($c_{10}$), Poisson's ratio($c_{11}$), and cohesion are the main parameters that describe the engineering geological characteristics [30]. X. Li et al. pointed out that Poisson's ratio was the most sensitive to surface subsidence and the cohesion was the least sensitive [31]; and Y. Zhang et al. also pointed out that cohesion was the least sensitive [32], so cohesion was not selected. Soil loss rate ($c_{12}$) is the soil loss per unit of soil excavation area.
The larger the loss rate, the greater is the soil loss per unit area, the more significant is the ground subsidence, and the greater is the impact on the heritage buildings [33].

(4) Management factors ($b_4$): Construction management is a dynamic process that organically combines people, materials, machinery, law, and the environment at the construction site [34]. High-frequency and high-precision monitoring measurement ($c_{13}$), a perfect management system ($c_{14}$), an ideal contingency plan ($c_{15}$), and a professional monitoring engineer ($c_{16}$) are the key factors to ensure construction safety.

The influence of metro construction using shield tunneling upon the safety of adjacent heritage buildings can be evaluated by considering several indexes. With reference to the above analysis, this study selected the 16 indexes listed in Table 2 as our evaluation indexes, from among four categories: heritage buildings factors, metro construction factors, soil factors, and management factors.

| Table 2 Safety risk evaluation index system of heritage buildings |
|---------------------------------------------------------------|
| **Target (O)** | **Criteria (B)** | **Index (C)** |
| Safety risk of heritage buildings | Heritage building factors ($b_1$) | Importance degree $c_1$ (score) |
| | | Geometric character $c_2$ (score) |
| | | Structure type $c_3$ (score) |
| | | Deterioration degree $c_4$ (score) |
| | Metro construction factors ($b_2$) | Cover depth $c_5$ (m) |
| | | Horizontal distance $c_6$ (m) |
| | | Section size $c_7$ (m) |
| | | Advancing speed $c_8$ (mm/min) |
| | Soil factors ($b_3$) | Friction angle $c_9$ ($^\circ$) |
| | | Compression modulus $c_{10}$ (MPa) |
| | | Poisson’s ratio $c_{11}$ |
| | | Soil loss ratio $c_{12}$ (%) |
| | Management factors ($b_4$) | Monitoring measurements $c_{13}$ (score) |
| | | Management system $c_{14}$ (score) |
| | | Contingency plan $c_{15}$ (score) |
| | | Monitoring engineer $c_{16}$ (score) |

2.2.3 Grade division standard of evaluation factors

The proposed safety risk evaluation index system for adjacent heritage buildings under the influence of metro construction using shield tunneling thus comprises both objective evaluation factors (construction and soil) and subjective evaluation factors (building and management). Each factor has a certain contribution to the ultimate risk level and it is, therefore, necessary to analyze the intervals of the evaluation factors. Objective factors are measured by actual values on a real project, while subjective factors are measured by the judgments of relevant experts using a 100-mark system (0-100) [16]. There is fuzziness in the determination of the grade interval of those factors. Combining with engineering practices and
theoretical analysis, the reasonable intervals for each factor are recognized. The evaluation criteria are shown in Tables 3 and 4.

Since there are different attribute categories for the indexes, and the unit for each index is different, the indexes are not easy to analyze; accordingly, each index is normalized to allow comparison.

\[
c_{i1}' = \frac{c_i - \min(c_i)}{\max(c_i) - \min(c_i)} \quad (2)
\]

\[
c_{i2}' = \frac{\max(c_i) - c_i}{\max(c_i) - \min(c_i)} \quad (3)
\]

where \(c_{i1}'\) is a “the smaller the better” index (negative index), \(c_{i2}'\) is a “the bigger the better” index (positive index), \(\max(c_i)\) is the maximum value of the \(i\)th index, and \(\min(c_i)\) is the minimum value of the \(i\)th index.

The values of each index in Tables 3 and 4 are normalized according to Eqs. (2) and (3), and the normalized results are listed in Table 5.

**Table 3** Evaluation criteria for each objective index

| Evaluation factor | Attribute category | I       | II      | III     | IV      | V       |
|-------------------|--------------------|---------|---------|---------|---------|---------|
| \(c_5\)           | Positive index     | >32     | 24~32   | 16~24   | 8~16    | <8      |
| \(c_6\)           | Positive index     | >32     | 24~32   | 16~24   | 8~16    | <8      |
| \(c_7\)           | Negative index     | <4      | 4~8     | 8~12    | 12~16   | >16     |
| \(c_8\)           | Negative index     | <20     | 20~40   | 40~60   | 60~80   | >80     |
| \(c_9\)           | Positive index     | >20     | 15~20   | 10~15   | 5~10    | <5      |
| \(c_{10}\)        | Positive index     | >16     | 12~16   | 8~12    | 4~8     | <4      |
| \(c_{11}\)        | Positive index     | >0.4    | 0.3~0.4 | 0.2~0.3 | 0.1~0.2 | <0.1    |
| \(c_{12}\)        | Negative index     | <0.5    | 0.5~1.0 | 1.0~1.5 | 1.5~2.0 | >2.0    |

**Table 4** Evaluation criteria of each subjective index

| Evaluation factor | Attribute category | I       | II      | III     | IV      | V       |
|-------------------|--------------------|---------|---------|---------|---------|---------|
| \(c_1\)           | Negative index     | Ungraded immovable cultural relics; very low historic value; very low artistic value; very low scientific value | 0~20     | 20~40   | 40~60   | 60~80   | 80~100  |
| \(c_2\)           | Positive index     | County cultural relic protection unit; low historic value; low artistic value; low scientific value | 80~100   | 60~80   | 40~60   | 20~40   | 80~100  |
| \(c_3\)           | Positive index     | Municipal cultural relic protection unit; general historic value; general artistic value; general scientific value | Height <5 m, length–width ratio 1.0~1.5, length–height ratio >5.0, height–width ratio <0.5 | 0.5~1.0 | 0.5~1.0 | 1.0~1.5 | 0.5~1.0 | 0~20    |
|                   |                    | reinforced concrete structure, pile foundation | Height 5~10 m, length–width ratio 1.5~2.5, length–height ratio 3.0~5.0, height–width ratio <0.5 | 0.5~1.0 | 0.5~1.0 | 1.0~1.5 | 0.5~1.0 | 0.2~2.5 |
|                   |                    | Frame/bent structure, reinforced concrete foundation | Height 10~15 m, length–width ratio 2.5~3.5, length–height ratio 3.0~5.0, height–width ratio <0.5 | 0.5~1.0 | 0.5~1.0 | 1.0~1.5 | 0.5~1.0 | 0.2~2.5 |
|                   |                    | Concrete structure, reinforced concrete/plain concrete foundation | Height >25 m, length–width ratio >4.5, length–height ratio <0.5, height–width ratio >4.5 | 0.5~1.0 | 0.5~1.0 | 1.0~1.5 | 0.5~1.0 | 0.2~2.5 |
|                   |                    | Brick/stone mix structure, brick mix/rubble base | Height >25 m, length–width ratio >4.5, length–height ratio <0.5, height–width ratio >4.5 | 0.5~1.0 | 0.5~1.0 | 1.0~1.5 | 0.5~1.0 | 0.2~2.5 |
|                   |                    | Wooden structure, no foundation or unknown | Height >25 m, length–width ratio >4.5, length–height ratio <0.5, height–width ratio >4.5 | 0.5~1.0 | 0.5~1.0 | 1.0~1.5 | 0.5~1.0 | 0.2~2.5 |
reflects the contribution of specific index data. In the present work, subjective and objective weights can be divided into subjective weights and objective weights. The subjective weight reflects the amount of willingness on the part of the decision-maker, while the objective weight reflects the contribution of specific index data. In the present work, subjective and objective weights are determined by expert evaluation. The evaluation criteria are shown in Table 5:

| Evaluation factor | Attribute category | I   | II  | III | IV  | V   |
|-------------------|--------------------|-----|-----|-----|-----|-----|
| \( c_1 \)         | -                  | 0.00–0.20 | 0.20–0.40 | 0.40–0.60 | 0.60–0.80 | 0.80–1.00 |
| \( c_2 \)         | +                  | 0.00–0.20 | 0.20–0.40 | 0.40–0.60 | 0.60–0.80 | 0.80–1.00 |
| \( c_3 \)         | +                  | 0.00–0.20 | 0.20–0.40 | 0.40–0.60 | 0.60–0.80 | 0.80–1.00 |
| \( c_4 \)         | -                  | 0.00–0.20 | 0.20–0.40 | 0.40–0.60 | 0.60–0.80 | 0.80–1.00 |
| \( c_5 \)         | +                  | 0.00–0.20 | 0.20–0.40 | 0.40–0.60 | 0.60–0.80 | 0.80–1.00 |
| \( c_6 \)         | +                  | 0.00–0.20 | 0.20–0.40 | 0.40–0.60 | 0.60–0.80 | 0.80–1.00 |
| \( c_7 \)         | -                  | 0.00–0.20 | 0.20–0.40 | 0.40–0.60 | 0.60–0.80 | 0.80–1.00 |
| \( c_8 \)         | -                  | 0.00–0.20 | 0.20–0.40 | 0.40–0.60 | 0.60–0.80 | 0.80–1.00 |
| \( c_9 \)         | +                  | 0.00–0.33 | 0.33–0.50 | 0.50–0.67 | 0.67–0.83 | 0.83–1.00 |
| \( c_{10} \)      | +                  | 0.00–0.20 | 0.20–0.40 | 0.40–0.60 | 0.60–0.80 | 0.80–1.00 |
| \( c_{11} \)      | +                  | 0.00–0.20 | 0.20–0.40 | 0.40–0.60 | 0.60–0.80 | 0.80–1.00 |
| \( c_{12} \)      | -                  | 0.00–0.17 | 0.17–0.3 | 0.33–0.50 | 0.50–0.67 | 0.67–1.00 |
| \( c_{13} \)      | +                  | 0.00–0.20 | 0.20–0.40 | 0.40–0.60 | 0.60–0.80 | 0.80–1.00 |
| \( c_{14} \)      | +                  | 0.00–0.20 | 0.20–0.40 | 0.40–0.60 | 0.60–0.80 | 0.80–1.00 |
| \( c_{15} \)      | +                  | 0.00–0.20 | 0.20–0.40 | 0.40–0.60 | 0.60–0.80 | 0.80–1.00 |
| \( c_{16} \)      | +                  | 0.00–0.20 | 0.20–0.40 | 0.40–0.60 | 0.60–0.80 | 0.80–1.00 |

2.3 Determination of index weight

Weights can be divided into subjective weights and objective weights. The subjective weight reflects the amount of willingness on the part of the decision-maker, and the objective weight reflects the contribution of specific index data. In the present work, subjective and objective weights are determined by expert evaluation. The evaluation criteria are shown in Table 5:
weights were obtained using the analytic hierarchy process (AHP) and the clustering weight method (CWM), respectively, and this study adopted a linear weighting method to determine the weight of each factor, which is helpful to improve the reliability of the evaluation results.

2.3.1 The AHP approach

The AHP decomposes elements related to evaluation problems into a target layer, criterion layer, index layer, and other layers. It is a multi-level weight analysis method that integrates people’s subjective judgments and is a concise systematic analysis and evaluation method combining qualitative and quantitative analyses [35]. The AHP theory itself is very mature, so this paper will not elaborate on it; specific steps are explained in the relevant literature [36, 37]. It is worth noting that consistency testing of the results should be carried out; if this testing passes, the eigenvector can be used as the weight vector; if not, the judgment matrix needs to be reconstructed until it can pass the consistency test.

2.3.2 The CWM approach

In the CWM approach, the clustering weight is usually calculated by means of a simple threshold method. However, this method neglects differences in the ranges of each index’s standard value [38]. Therefore, this study uses a revised CWM in which the weight of each index at the different levels is determined by considering not only the measured value of the samples but also the standard value of the evaluation index at each level. The specific steps are as follows:

Step 1: Construct the original decision matrix as follows.

\[
R = (x_{ij})_{nm} \quad (i = 1,2,\ldots,n; j = 1,2,\ldots,m)
\]  

where \( x_{ij} \) is the upper threshold of the \( i \)th index at the \( j \)th level.

Step 2: Calculate the weight distribution of each index as follows.

\[
\frac{x_{ij}}{\sum_{j=1}^{m} x_{ij}} \quad (i = 1,2,\ldots,n; j = 1,2,\ldots,m)
\]  

\[
\frac{x_{ij}^0}{x_{ij}^r} \quad (i = 1,2,\ldots,n; j = 1,2,\ldots,m)
\]

where \( y_{ij} \) is the weight distribution of each index, and \( x_{ij}^0 \) is the normalized evaluation value of the actual sample.
Step 3: Calculate the clustering weight.

\[
Z_i = \frac{\sum_{j=1}^{m} y'_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{m} y'_{ij}} \quad (7)
\]

where \( Z_i \) is the clustering weight of the \( i \)th index.

### 2.3.3 Comprehensive weight

The comprehensive weight can be calculated by referring to Eq. (8).

\[
w'_i = a \times w_i + (1 - a) \times Z_i, \quad a \in [0,1] \quad (8)
\]

where \( w_i \) is the AHP weight, \( Z_i \) is the CWM weight, and \( a \) is a weight coefficient that varies for different projects.

### 2.4 Determination of SPA correlation degree

The core of the SPA evaluation method is to determine correlation degree, and the key to determine correlation degree is the coefficient of the difference degree. The SPA method, which is different from the Set Membership method, is a wide-domain functional structure whose use can fully improve the information utilization rate and ensure the credibility of the comprehensive results [39]. As listed in Table 1, the following five correlation-degree functions, \( \mu_i(j) \), were constructed for the safety risk evaluation index for adjacent heritage buildings influenced by shield tunneling construction, for the degree-of-correlation models of levels I–V, as shown in Eqs. (9)–(13).

\[
\mu_i(1) = \begin{cases} 
1 - \frac{1}{2(x_i - s_{i(1)})} & x_i \in [0, s_{i(1)}] \\
-1 & x_i \in (s_{i(1)}, s_{i(2)}) \\
\frac{2x_i}{s_{i(1)} - s_{i(2)}} & x_i \in (s_{i(2)}, s_{i(3)}) \\
-1 & x_i \in (s_{i(3)}, s_{i(5)}) 
\end{cases} \quad (9)
\]

\[
\mu_i(2) = \begin{cases} 
1 & x_i \in [s_{i(1)}, s_{i(2)}] \\
-1 + \frac{2x_i}{s_{i(1)}} & x_i \in [0, s_{i(1)}] \\
\frac{2(x_i - s_{i(2)})}{s_{i(3)} - s_{i(2)}} & x_i \in (s_{i(2)}, s_{i(3)}) \\
-1 & x_i \in (s_{i(3)}, s_{i(5)}) 
\end{cases} \quad (10)
\]

\[
\mu_i(3) = \begin{cases} 
-1 + \frac{1}{2(x_i - s_{i(1)})} & x_i \in (s_{i(2)}, s_{i(3)}) \\
1 - \frac{2(x_i - s_{i(3)})}{s_{i(4)} - s_{i(3)}} & x_i \in (s_{i(3)}, s_{i(4)}) \\
-1 & x_i \in [0, s_{i(1)}], \text{ or } x_i \in (s_{i(4)}, s_{i(5)}) 
\end{cases} \quad (11)
\]
\[
\mu_i(4) = \begin{cases} 
-1 + \frac{1}{2(x_i - s_{i(l)})} & x_i \in s_{i(l)}, s_{i(l+1)} \\
1 - \frac{2(x_i - s_{i(l)})}{(s_{i(l+1)} - s_{i(l)})} & x_i \in \left(s_{i(l)}, s_{i(l+1)}\right) \\
-1 & x_i \in [0, s_{i(l)}] 
\end{cases} 
\]

\[
\mu_i(5) = \begin{cases} 
-1 + \frac{1}{2(x_i - s_{i(l)})} & x_i \in \left(s_{i(l)}, s_{i(l+1)}\right) \\
1 - \frac{2(x_i - s_{i(l)})}{(s_{i(l+1)} - s_{i(l)})} & x_i \in \left(s_{i(l+1)}, s_{i(l+2)}\right) \\
-1 & x_i \in [0, s_{i(l+1)}] 
\end{cases} 
\]

In Eqs. (9)–(13), \(\mu_i(1)\) through \(\mu_i(5)\) are the degrees of correlation of each index \(i\) for the five assessment levels, with \(i = 1, 2, 3, \ldots, 16\); \(s_{i(1)}\) through \(s_{i(5)}\) are the upper thresholds for the respective levels I–V in the normalized safety risk evaluation criteria, and \(s_{i(1)} \neq s_{i(2)} \neq s_{i(3)} \neq s_{i(4)} \neq s_{i(5)}\); \(x_i\) are the normalized measured values of the \(i\)th index. By substituting the measured values of each index into the above models, the correlation degree of each evaluation level can be obtained.

The SPA method is applied herein essentially to formulate each safety risk index (sample value) and grading criteria as a set pair, as well as to calculate the correlation degree between the safety risk index and each evaluation level.

Then, Eq. (14) is used to calculate the average degree of correlation.

\[
\mu_j = \sum_{i=1}^{n} w_i \mu_i(j) 
\]

where \(\mu_j\) is the average correlation degree of the safety risk index on the \(j\)th evaluation level; and \(w_i\) is the comprehensive weight of each safety risk index.

If \(\mu_k = \max\{\mu_j\}, k = 1, 2, \ldots, m\), the safety risk assessment result of the sample can be identified at the \(k\)th level.

### 3. Case study verification

A heritage building is located at 27 Square in the old town of Zhengzhou in Henan Province. Built in 1971, the building is a cultural monument comprising hexagonal conjoined twin towers, and it has a reinforced concrete structure with a height of 63 meters in 14 layers. The base has three layers with a surrounding white marble fence, the tower has 11 layers, and a hexagonal bell tower 2.7 meters in diameter stands at the top of the tower (Fig. 1). The foundation is a 1500-mm-thick raft foundation, under which lies 200 mm of plain concrete and 800 mm of thick sand cushion. It was declared by the State Council of the People’s Republic of China to be a part of the National Key Cultural Relic Protection Unit in 2006.
The tunnel of the Zhengzhou Metro Line Three (ZMLT) runs alongside the heritage building. The horizontal distance between the tunnel edge and the building is only 3 m, and the vertical distance is 20.5 m; the spatial relationship is illustrated in Fig. 2.

Fig.1 External façade of the heritage building

Fig.2 Spatial relationships between tunnel and building: (a) profile; (b) plan

3.1 Data acquisition

During the propulsion process for the ZMLT shield construction at the side of the heritage building, the values of each objective evaluation index were obtained by means of field detection of geological conditions and tunnel design depths at different horizontal distances. The values of each subjective evaluation index were obtained according to the scores given by the domain experts on the heritage building and management factors. Table 6 lists the values of each evaluation index. Table 7 lists the corresponding values as normalized using Eqs. (2) and (3).

Table 6 Values of 16 evaluation indexes

| Index | \( c_1 \) | \( c_2 \) | \( c_3 \) | \( c_4 \) | \( c_5 \) | \( c_6 \) | \( c_7 \) | \( c_8 \) | \( c_9 \) | \( c_{10} \) | \( c_{11} \) | \( c_{12} \) | \( c_{13} \) | \( c_{14} \) | \( c_{15} \) | \( c_{16} \) |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| -25 m | 83     | 25     | 78     | 23     | 20.9   | 25     | 6.2    | -      | 19     | 4.6    | 0.33   | 1.06   | 81     | 92     | 63     | 51     |
| -20 m | 83     | 25     | 78     | 23     | 20.82  | 20     | 6.2    | -      | 18     | 5.4    | 0.29   | 1.13   | 81     | 92     | 63     | 51     |
| -15 m | 83     | 25     | 78     | 23     | 20.77  | 15     | 6.2    | -      | 19     | 5.7    | 0.34   | 1.02   | 81     | 92     | 63     | 51     |
| -10 m | 83     | 25     | 78     | 23     | 20.68  | 10     | 6.2    | -      | 17     | 5.8    | 0.31   | 1.21   | 81     | 92     | 63     | 51     |
| -6 m  | 83     | 25     | 78     | 23     | 20.57  | 6      | 6.2    | -      | 18     | 6.3    | 0.28   | 1.27   | 81     | 92     | 63     | 51     |
| 3 m   | 83     | 25     | 78     | 23     | 20.5   | 3      | 6.2    | -      | 19     | 5.1    | 0.26   | 1.31   | 81     | 92     | 63     | 51     |
| 6 m   | 83     | 25     | 78     | 23     | 20.42  | 6      | 6.2    | -      | 18     | 6.1    | 0.28   | 1.28   | 81     | 92     | 63     | 51     |
| 10 m  | 83     | 25     | 78     | 23     | 20.3   | 10     | 6.2    | -      | 17     | 5.7    | 0.3    | 1.38   | 81     | 92     | 63     | 51     |
| 15 m  | 83     | 25     | 78     | 23     | 20.23  | 15     | 6.2    | -      | 18     | 4.2    | 0.32   | 1.21   | 81     | 92     | 63     | 51     |
| 20 m  | 83     | 25     | 78     | 23     | 20.18  | 20     | 6.2    | -      | 18     | 5.5    | 0.29   | 1.54   | 81     | 92     | 63     | 51     |
| 25 m  | 83     | 25     | 78     | 23     | 20.1   | 25     | 6.2    | -      | 19     | 4.5    | 0.34   | 1.10   | 81     | 92     | 63     | 51     |

Table 7 Values of 16 normalized evaluation indexes

| Index | \( c_1 \) | \( c_2 \) | \( c_3 \) | \( c_4 \) | \( c_5 \) | \( c_6 \) | \( c_7 \) | \( c_8 \) | \( c_9 \) | \( c_{10} \) | \( c_{11} \) | \( c_{12} \) | \( c_{13} \) | \( c_{14} \) | \( c_{15} \) | \( c_{16} \) |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| -25 m | 0.03   | 0.75   | 0.22   | 0.23   | 0.48   | 0.38   | 0.31   | -      | 0.37   | 0.77   | 0.34   | 0.35   | 0.19   | 0.06   | 0.37   | 0.49   |
| -20 m | 0.03   | 0.75   | 0.22   | 0.23   | 0.48   | 0.50   | 0.31   | -      | 0.40   | 0.73   | 0.42   | 0.38   | 0.19   | 0.08   | 0.37   | 0.49   |
| -15 m | 0.03   | 0.75   | 0.22   | 0.23   | 0.48   | 0.63   | 0.31   | -      | 0.37   | 0.72   | 0.32   | 0.34   | 0.19   | 0.08   | 0.37   | 0.49   |
| -10 m | 0.03   | 0.75   | 0.22   | 0.23   | 0.48   | 0.75   | 0.31   | -      | 0.43   | 0.71   | 0.38   | 0.40   | 0.19   | 0.08   | 0.37   | 0.49   |
| -6 m  | 0.03   | 0.75   | 0.22   | 0.23   | 0.49   | 0.85   | 0.31   | -      | 0.40   | 0.69   | 0.44   | 0.42   | 0.19   | 0.08   | 0.37   | 0.49   |
| 3 m   | 0.03   | 0.75   | 0.22   | 0.23   | 0.49   | 0.93   | 0.31   | -      | 0.37   | 0.75   | 0.48   | 0.44   | 0.19   | 0.08   | 0.37   | 0.49   |
| 6 m   | 0.03   | 0.75   | 0.22   | 0.23   | 0.49   | 0.85   | 0.31   | -      | 0.40   | 0.70   | 0.44   | 0.43   | 0.19   | 0.08   | 0.37   | 0.49   |
| 10 m  | 0.03   | 0.75   | 0.22   | 0.23   | 0.49   | 0.75   | 0.31   | -      | 0.43   | 0.72   | 0.40   | 0.39   | 0.19   | 0.08   | 0.37   | 0.49   |
| 15 m  | 0.03   | 0.75   | 0.22   | 0.23   | 0.49   | 0.63   | 0.31   | -      | 0.40   | 0.79   | 0.36   | 0.37   | 0.19   | 0.08   | 0.37   | 0.49   |
| 20 m  | 0.03   | 0.75   | 0.22   | 0.23   | 0.50   | 0.50   | 0.31   | -      | 0.40   | 0.73   | 0.42   | 0.38   | 0.19   | 0.08   | 0.37   | 0.49   |
3.2 Correlation calculation

Taking the measured data set as an example, the nearest horizontal distance between the tunnel and the building was set as 3 m, and the advancing speed for the shield machine was tentatively set at 40 mm/min. The calculation process was then undertaken as follows:

3.2.1 Weights calculation

According to the established hierarchical structure model, combined with experience in engineering practice, a method based on a scale of 1–9 was adopted to construct the judgment matrixes of the criterion and the index layers, included as Tables 8 and 9. The CWM decision matrix thus constructed is included as Table 10.

Table 8. Judgment matrix of criterion layer

|   | b₁ | b₂ | b₃ | b₄ |
|---|----|----|----|----|
| b₁ | 1  | 1/3| 1  | 1/2|
| b₂ | 3  | 1  | 2  | 1  |
| b₃ | 1  | 1/2| 1  | 2  |
| b₄ | 2  | 1  | 1/2| 1  |

Table 9. Judgment matrixes of index layer

|   | c₁ | c₂ | c₃ | c₄ | b₂ | c₅ | c₆ | c₇ | c₈ | b₃ | c₉ | c₁₀ | c₁₁ | c₁₂ | b₄ | c₁₃ | c₁₄ | c₁₅ | c₁₆ |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| c₁ | 1  | 5  | 3  | 1/3| c₅ | 1  | 1/2| 3  | 1/2| c₆ | 2  | 1  | 3  | 1  | c₇ | 1/3| 1/3| 1  | 1/2|
| c₂ | 1/5| 1  | 1/4| 1/7| c₈ | 2  | 1  | 2  | 1  | c₉ | 3  | 1  | 2  | 1/2| c₁₀| 1/3| 1/2| 1  | 1/5|
| c₃ | 1/3| 4  | 1  | 1/5| c₁₁| 2  | 1/2| 1  | 1  | c₁₂| 5  | 2  | 3  | 1  | c₁₂| 1/3| 1/2| 1  | 1/3|

Table 10. Decision matrix of CWM

| x₁₂ | c₁ | c₂ | c₃ | c₄ | c₅ | c₆ | c₇ | c₈ | c₉ | c₁₀| c₁₁| c₁₂| c₁₃| c₁₄| c₁₅| c₁₆ |
|-----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| I   | 0.20| 0.20| 0.20| 0.20| 0.20| 0.20| 0.33| 0.20| 0.20| 0.17| 0.20| 0.20| 0.20| 0.20| 0.20| 0.20|
| II  | 0.40| 0.40| 0.40| 0.40| 0.40| 0.40| 0.50| 0.40| 0.40| 0.33| 0.40| 0.40| 0.40| 0.40| 0.40| 0.40|
| III | 0.60| 0.60| 0.60| 0.60| 0.60| 0.60| 0.67| 0.60| 0.60| 0.50| 0.60| 0.60| 0.60| 0.60| 0.60| 0.60|
| IV  | 0.80| 0.80| 0.80| 0.80| 0.80| 0.80| 0.83| 0.80| 0.80| 0.67| 0.80| 0.80| 0.80| 0.80| 0.80| 0.80|
| V   | 1.00| 1.00| 1.00| 1.00| 1.00| 1.00| 1.00| 1.00| 1.00| 1.00| 1.00| 1.00| 1.00| 1.00| 1.00| 1.00|

Using MATLAB, the AHP weight matrix was calculated to be $W = [0.0389 \ 0.0077 \ 0.0191 \ 0.0838 \ 0.0781 \ 0.1267 \ 0.0407 \ 0.1168 \ 0.0219 \ 0.0675 \ 0.0389 \ 0.1198 \ 0.0347 \ 0.1095 \ 0.0775 \ 0.0185]^T$. Using Eqs. (4) – (7) in MATLAB, the CWM weight matrix was calculated to be $Z$
Using Eq. (8), \( a \) is 0.3 in this project after repeated calculations, the comprehensive weight matrix was calculated to be \( W' = [0.0915 \ 0.0745 \ 0.0269 \ 0.0473 \ 0.0703 \ 0.1270 \ 0.0420 \ 0.0735 \ 0.0364 \ 0.0919 \ 0.0578 \ 0.0801 \ 0.0287 \ 0.0405 \ 0.0588 \ 0.0527]^T \).

### 3.2.2 Correlation degree calculation

According to Eqs. (9) – (13), the correlation degree of each evaluation factor with each level was calculated as shown in Table 11.

Using Eq. (14) and the comprehensive weight matrix, the average correlation degree \( \mu_j \) \((j = 1,2, \ldots, 5)\) of the safety risk assessment level for the heritage building was calculated as shown in Table 12.

### Table 11. Correlation degree of each evaluation factor with each level

| Evaluation | I   | II  | III | IV  | V   |
|------------|-----|-----|-----|-----|-----|
| \( c_1 \)  | -1  | -1  | -1  | 0.7 | 1   |
| \( c_2 \)  | -1  | -1  | -0.5| 1   | 0.5 |
| \( c_3 \)  | 0.8 | 1   | -0.8| -1  | -1  |
| \( c_4 \)  | 0.7 | 1   | -0.7| -1  | -1  |
| \( c_5 \)  | -1  | 0.125| 1   | -0.125| -1 |
| \( c_6 \)  | -1  | -1  | -1  | -0.25| 1   |
| \( c_7 \)  | -0.1| 1   | 0.1 | -1  | -1  |
| \( c_8 \)  | -1  | 1   | 1   | -1  | -1  |
| \( c_9 \)  | 0.6 | 1   | -0.6| -1  | -1  |
| \( c_{10} \)| -1  | -1  | -0.45| 1   | 0.45|
| \( c_{11} \)| -1  | 0.2 | 1   | -0.2| -1  |
| \( c_{12} \)| -1  | -0.24| 1   | 0.24| -1  |
| \( c_{13} \)| 1   | 0.9 | -1  | -1  | -1  |
| \( c_{14} \)| 1   | -0.2| -1  | -1  | -1  |
| \( c_{15} \)| -0.7| 1   | 0.7 | -1  | -1  |
| \( c_{16} \)| -1  | 0.1 | 1   | -0.1| -1  |

### Table 12. Average correlation degree of each risk assessment level

| Level | I   | II  | III | IV  | V   |
|-------|-----|-----|-----|-----|-----|
| \( \mu_j \)| -0.6190 | -0.0758 | -0.0629 | -0.1619 | -0.3181 |

### 3.2.3 Determination of risk level

According to Eq. \( \mu_k = \max \{\mu_j\} \), \( \mu_k = \mu_3 \), which represents the safety risk assessment level for the heritage building at Level III in the present case for 3 m distance and 40 mm/min speed. Namely, the structural safety impact upon the heritage building is at Level III when the shield tunneling machine advances 3 m away from the nearest point of the building at a speed of 40 mm/min. Thus, decision-makers would need to take essential pre-reinforcement
measures during construction, strengthen monitoring of the surface subsidence and building displacement, and conduct weekly trend analyses for building damage caused by the tunneling.

4. Results and discussion

During the propulsion process for the shield tunneling construction of the ZMLT, the risk level for the safety impact of a heritage building corresponding to different locations and different advancing speeds are summarized in Table 13.

Table 13. Summary sheet of the evaluation results

| $c_8$ | 20  | 25  | 30  | 35  | 40  | 45  | 50  | 55  | 60  | 65  | 70  | 75  | 80  | 85  | 90  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| -25m  | II  | II  | II  | II  | II  | II  | II  | II  | II  | II  | II  | II  | II  | II  | II  |
| -20m  | II  | II  | II  | III | III | III | III | III | III | III | III | III | III | III | II  |
| -15m  | II  | II  | II  | III | III | III | III | III | III | III | III | III | III | III | III |
| -10m  | II  | II  | II  | III | III | III | III | III | III | IV  | IV  | IV  | IV  | IV  | IV  |
| -6m   | II  | II  | II  | III | III | III | III | III | IV  | IV  | IV  | IV  | IV  | IV  | IV  |
| 3m    | II  | II  | II  | III | III | III | IV  | IV  | IV  | IV  | IV  | IV  | IV  | IV  | IV  |
| 6m    | II  | II  | II  | III | III | IV  | IV  | IV  | IV  | IV  | IV  | IV  | IV  | IV  | IV  |
| 10m   | II  | II  | II  | III | III | IV  | IV  | IV  | IV  | IV  | IV  | IV  | IV  | IV  | IV  |
| 15m   | II  | II  | II  | III | III | IV  | IV  | IV  | IV  | IV  | IV  | IV  | IV  | IV  | IV  |
| 20m   | II  | II  | II  | III | III | IV  | IV  | IV  | IV  | IV  | IV  | IV  | IV  | IV  | IV  |
| 25m   | II  | II  | II  | III | III | IV  | IV  | IV  | IV  | IV  | IV  | IV  | IV  | IV  | IV  |

From Table 13, the following results can be obtained:

(1) When the advancing speed ($c_8$) of the shield machine is in the low speed range (20–35 mm/min), the position of the shield machine relative to the heritage building (horizontal distance $c_6$) has no significant impact upon structural safety, and the risk assessment level is II.

(2) When $c_6$ is constant, with increase of $c_8$, the structural safety risk to the heritage building becomes more serious.

(3) When $c_6$ is diverse, with changes to $c_8$, the structural safety risk could be the same; for example, the risk assessment level is IV for all of the following cases: $c_6 = 3$ m, $c_8 = 55$ mm/min; $c_6 = \pm 6$ m, $c_8 = 60$ mm/min; $c_6 = \pm 10$ m, $c_8 = 65$ mm/min; and $c_6 = -15$ m, $c_8 = 75$ mm/min.

(4) When $c_6 = -15$ m and $c_6 = 15$ m, $c_8$ no longer has exactly the same influence on the structural safety, and its effect differs from that for other symmetrically horizontal distances.
to the heritage building. The main reason is the obvious difference in geological conditions at ±15 m.

(5) When  $c_6 = 25$ m, $c_8$ has little influence on structural safety; the levels are all II. This finding is consistent with relevant standard requirements [40], namely, that when a metro structure or pipeline runs alongside an existing structure, the monitoring range is generally within 30 m of both sides of the metro structure and the pipeline.

The SPA evaluation method is conducted before the construction, with the decision-makers implementing the corresponding safety control measures according to the evaluation results. If the risk assessment results show Level-I and Level-II risks, according to the classification requirements of Table 1, the necessary engineering measures do not need to be taken before construction. Otherwise, engineering measures should be taken to control the higher level of risk.

In the actual construction of this project, the normal advancing speed of the shield machine is 60 mm/min. Table 13 shows that metro shield construction has a very high impact on the structural safety of heritage buildings at this speed. To reduce the impact on the structure of this building while also optimizing the metro construction schedule, when  $c_6<6$ m, the speed should not exceed 50 mm/min, when  $c_6 = 6–15$ m, the speed should not exceed 60 mm/min; when  $c_6>15$ m, the shield construction could be carried out at the normal advancing speed of 60 mm/min. Furthermore, additional pre-reinforcement measures are required before construction, such as installing 29-m-length $\Phi 800@1000$ mm isolation piles between the building and the metro tunnel, thereby forming an isolation curtain to limit deformation of the soil mass behind the piles [41]. During construction, the monitoring of surface subsidence and building displacement should be strengthened. The layout of on-site monitoring points is shown in Fig. 3. The shield cutter head moved into the 30 m scope of the building on April 15, 2019, and the shield tail moved away from the 30 m scope on April 29, 2019. The monitoring data for the surface subsidence are shown in Fig. 4(a), and building displacement data are shown in Fig. 4(b). The monitoring results show that the surface subsidence is 4.87 – 4.79 mm, the maximum differential settlement of the building is 1.89 mm, and the gradient $\approx 0.13\%$, conforming to the relevant control standards [21, 42]. After the construction, no visible cracks or uneven settlement occurred on the outdoor floor of the building (see Fig. 5(a)), no visible cracks appeared in the main structure (see Fig. 5(b)), a few slight cracks appeared in the non-structural components (see Fig. 5(c)), and a door tilted slightly (see Fig. 5(d)).
The above analysis shows that the evaluation results are in line with objective reality, and that risk control can be effectively carried out by taking protective measures and controlling the related parameters.

Fig.3 Layout of the monitoring points

Fig.4 Monitoring data curve: (a) surface subsidence; (b) building displacement

Fig.5 Damage to different parts: (a) outdoor floor; (b) main structure; (c) non-structural components; (d) door

5. Conclusions

This study have established a safety risk assessment model of the influence of metro construction on adjacent heritage buildings. The model is based upon the SPA theory and uses 16 single indexes as evaluation factors, namely, importance degree, geometric character, structure type, deterioration degree, cover depth, horizontal distance, section size, advancing speed, friction angle, compression modulus, Poisson's ratio, soil loss ratio, monitoring measurements, management system, contingency plan, and monitoring engineer. The model has been applied in practice by analyzing a heritage building in Zhengzhou, and the main conclusions are as follows.

(1) The SPA-based safety risk assessment model greatly improves the information utilization rate and guarantees the credibility of the evaluation results. Therefore, the method is suitable for multi-level and multi-objective complex decision systems.

(2) In general, when metro lines go through old cities, a large number of heritage buildings are affected. Commonly used numerical simulation methods have high precision and the workload is large if every building is included in the calculations. The SPA method can be used to conduct the evaluation of buildings one by one. It is not only very simple but also easy to operate using computer programs, making it more efficient. For buildings with higher risk level, numerical simulation is used to calculate the specific stress concentration area, and targeted protective measures can be implemented.

(3) A calculation example herein shows that the evaluation results are in line with objective reality. According to the dynamic changes to the risk levels of heritage buildings in the process of metro shield tunneling, this method can be used to control risk by slowing the advancing speed of the shield machine as appropriate, thereby improving the construction plan. The SPA method can effectively guide similar projects and is worth popularizing.

It is worth noting that the values of subjective indexes and the weights calculated by AHP, as they depend on expert knowledge and rich experience, have strong subjectivity. The question of how to carry out quantitative analysis more objectively remains for follow-up studies.
Future research work will consider sensitivity analysis of the factors of influence and the scientific selection of safety control measures, to establish a more thorough safety risk management system for heritage buildings.

**List of abbreviations**

SPA: set pair analysis; FEA: finite element analysis; EA: empirical analysis; BNs: Bayesian networks; IF: information fusion; ECM: extended cloud model; CMAM: chromatography multiply assessment method; AHP: analytic hierarchy process; CWM: clustering weight method; ZMLT: Zhengzhou Metro Line Three.

**Availability of data and materials**

All data generated or analysed during this study are included in this published article.

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**Authors' contributions**

QW has written the article; CY and LT have reviewed the whole text and have made comments and suggestions to improve it; JA provided the parameters of the project; JL processed the field data; FW made corrections to improve the paper. All authors read and approved the final manuscript.

**Competing interests**

The authors declare that they have no competing interests.

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