Safety evaluation of urban underground utility tunnel with the grey clustering method based on the whole life cycle theory

Shaonan Suna, Congyu Xub, Ailing Wanga, Yixin Yangb and Mengqi Sun

aSchool of Water Conservancy, North China University of Water Resources and Electric Power, Zhengzhou, China; bSchool of Management Engineering, Zhengzhou University, Zhengzhou, China

ABSTRACT
The construction of urban underground utility tunnel is a complicated process. With the rapid development of urbanization in China, the safety problem of utility tunnel is becoming more and more prominent. To evaluate the safety of utility tunnel, this study proposed an evaluation model based on the whole life cycle theory. Firstly, combining with the characteristics of utility tunnel, the construction period was divided into four phases: preliminary planning, design, construction and operation and maintenance. Through literature analysis and expert investigation method, 26 evaluation indices were selected, and the whole life cycle safety evaluation index system of urban underground utility tunnel was established; Secondly, the entropy weight method was used to determine the weight of each index; Thirdly, in order to evaluate the security of the utility tunnel in the whole life cycle, a grey clustering evaluation model was constructed. Finally, a case study was conducted to explain the application of the proposed model and to verify the validity of the model, the results indicated that the model could provide a new way to evaluate the safety state of the utility tunnel project.

1. Introduction
At present, China is in an important period of rapid urbanization development. By the end of 2019, the number of cities in China had increased from 132 in 1949 to 684, the urbanization rate of permanent residents had reached 60.6%, and the built-up urban area was about 60,300 square kilometers. The length of urban road and rail transit reached 459,200 km and 6,059 km, respectively (Wang 2020). Urban residents' requirements for public infrastructure are also increasing. The State Council issued the Opinions on Strengthening Urban Infrastructure Construction in 2013, and proposed to fully launch the pilot project of utility tunnel in 36 large and medium-sized cities in about 3 years (The State Council 2013). In 2014, the central finance gave a 3-year special fund subsidy to pilot cities, and the specific amount of subsidy was determined by the scale of the city. In 2015, Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD 2015a) issued “Technical code for urban utility tunnel engineering: GB50838 - 2015” and “Notification of the printing of the guidelines for the planning of the urban underground utility tunnel” (MOHURD 2015b). In 2016, MOHURD also issued “Notification of the design system of the national building standard of the urban underground utility tunnel and the sponge city” (MOHURD 2016), these ensured the implementation of the utility tunnel from the policy level. Utility Tunnel is a structure and ancillary facility combined with the urban underground space, which can accommodate more than two types of municipal pipelines (You, He, and Wang et al. 2019). Utility Tunnel in China has been rapid development, since 2015, the annual building scale is shown in Figure 1.

However, there are still many obstacles in the development of the utility tunnel, such as the higher cost and the longer construction period, and many very big uncertainties in each stage and especially there are certain safety risks. Therefore, for the good development of urbanization, this paper conducted a more comprehensive evaluation and analysis of the safety of urban underground utility tunnel from the perspective of the whole life cycle, built a whole life cycle utility tunnel safety evaluation index system, and established a grey clustering evaluation model based on entropy weight method. The model could provide theoretical and practical guidance for evaluating the safety of urban underground utility tunnel.

2. Literature review
In 1966, the Product Life Cycle (PLC) theory was first put forward by Professor Raymond Vernon, an economist from Harvard University in the United States. It was originally intended to explain the transnational operation of the American manufacturing industry. At
the same time, there were also many research on cost control and quality management in the manufacturing process. Li and Wang (2019) used the triple difference method to identify the impact of product life cycle, the model was constructed to analyze the transfer process of China’s export market from southern countries to northern countries caused by the improvement of product quality under the background of product life cycle. Li, Lu, and Xiang et al. (2012) proposed a quality data model oriented to product life cycle and the overall structure of quality control system, and established a comprehensive quality evaluation system. Zhang and Han (2017) established a product life cycle cost control model to solve problems such as lack of historical data and fuzzy human judgment.

The whole life cycle theory has been applied in the building field since the 1990s, which is often used in the measurement and evaluation of building carbon dioxide emissions. For example, Zheng and Xu (2019) built the whole life cycle assessment model of prefabricated buildings to identify the influencing factors of carbon emissions at each stage, and to measure and evaluate the total carbon emissions of a project in Chongqing. Moreover, this theory has also been applied in sustainable development evaluation of the whole life cycle of buildings, application of building information modelling (BIM) technology, cost management and performance assessment. Ren, Zhou, and Guo (2019) divided the whole life cycle of prefabricated buildings into five stages, constructed an evaluation index system for sustainable development of prefabricated buildings and tested the application effect. Yang, Wang, and Yang (2020) divided the whole life cycle of the project into four stages for petrochemical construction enterprises, proposed the evaluation index of the key performance of cost management, and built the evaluation model of the key performance of cost management.

Alaghbandrad and Hammad (2020) studied the framework for multi-purpose utility tunnel cost assessment and cost sharing of from the lifecycle perspective. Song, Xiao, and Cheng et al. (2020) took the Huanxian Tunnel of Yinxin Railway as an example and introduced BIM technology into the whole life cycle management of tunnel engineering. In related studies of utility tunnel, Cen and Wang (2019) divided the whole life cycle of utility tunnel into three stages of decision-making, construction and operation transfer based on the perspective of stakeholders to identify indicators, and established a systematic performance evaluation system. Zhang and Li (2018) introduced BIM technology as technical support in each stage of the whole life cycle of the utility tunnel, and conducted corresponding research on the application of BIM technology in the intelligent control of the utility tunnel.

In the research of urban underground utility tunnel, the research of China’s utility tunnel is mainly the tracking study of foreign countries. In recent years, the research of scholars on the utility tunnel mainly focuses on the key technology of design and construction, the financing mechanism, financing risk, charging and pricing mechanism in China. Yan, Xiao, and Yang et al. (2019) designed a new shield tunneling and construction method, which improved the mechanization and automation degree of utility tunnel open-cut construction. Gu, Zhang, and Ye (2018) studied the key design technologies such as pipeline into the utility tunnel, section of the utility tunnel, embedded depth, structural calculation and foundation treatment. Zhao, Qin, and Wang et al. (2018) identified eight major risk factors of Public–Private Partnership (PPP) mode financing for utility tunnel, filtered the risk factors, and put forward relevant suggestions for risk avoidance according to the results. Qiao, Liu, and Zhang et al. (2018) proposed the cost allocation method between the government and pipeline units according to the
principle of beneficiary payment, and constructed the charging pricing model. The research abroad has
turned to the application of new materials and the
potential hazards affecting the safety of utility tunnel.
Meng et al. (2020) introduced a new building compo-
site material of alkali activated steel fiber reinforced
polymer and studied its impact resistance in order to
study the explosion-proof ability of utility tunnel.
Huang et al. (2020) developed a new type of cement-
tions composite material and applied it to the rein-
cement of saline soil foundation of a utility tunnel
project to improve the seismic performance of utility
tunnel. Wang, Tan and Zhang et al. (2020) studied
the mechanism of small hole gas leakage and diffusion
under natural ventilation and mechanical ventilation
according to the characteristics of gas diffusion in the
utility tunnel, and proposed the ventilation strategy for
emergency accidents.

More works on the use of probabilistic method
in the performance of utility tunnel. Lin ,Guo,and Ni
et al. (2020) proposed a novel prefabricated utility
tunnel (L-shaped and F-shaped), and derived the
longitudinal equivalent flexural stiffness of the cross-
section. Strains are evaluated as a function of internal
pressure through sealing test and numerical simula-
tion. The fragility analysis of Utility tunnel is impor-
tant, the fragility multi-dimensional curves were
generated (Ni, Mangalathu, and Liu 2020). The AE
technology is also adopted to instrument a novel
prefabricated utility tunnel to provide insights into
the leakage behavior of the structure during the seal-
ing test (Lin, Deng and Ma et al. 2020).

Risk management accounts for most of the safety
research on the utility tunnel. Some studies used prob-
abilistic risk assessment method (Ni, Mangalathu, and
Yi 2018; Ni and Mangalathu 2018). A dynamic quanti-
tative risk analysis method for gas pipelines is de-
veloped, it could analyze the whole process of a gas
pipeline accident (Fang et al. (2019)). By a statistical
analysis of disasters of utility tunnel at home and
abroad, Guo, Qian, and Wang et al. (2019) classified
the types of disasters in the operation and mainte-
nance stage, and clarified the mechanism of disasters
and countermeasures. Yang, Zhu, and Li et al. (2018)
used Kent method to identify the influencing factors of
safety risks in the utility tunnel system, and con-
structed the basic accident tree model of the utility
tunnel. Qiang, Shang, and Lu et al. (2019) built a risk
identification system for the whole life cycle of the
utility tunnel from both qualitative and quantitative
aspects, and established the risk matrix and calculated
the weight by using Delphi method and analytic hier-
archy process. Zhang and Zhang (2019) established
a risk assessment index system for the whole life
cycle of utility tunnel, and carried out risk assessment
by adopting fuzzy analytic hierarchy process (AHP). In
the study of utility tunnel safety evaluation, Huang and
Lin (2020) summarized the influencing factors of fire
safety of utility tunnel from four aspects of “human,
machine, environment and pipe”, and put forward an
evaluation model based on AHP-evidence theory to
evaluate fire safety of utility tunnel. Chen, Zhao, and
Xiao (2018) established an index system for environ-
mental safety evaluation of utility tunnel, and estab-
lished a fuzzy comprehensive evaluation model to
evaluate the environmental risk degree of utility tun-
nel. Shang, Lu, and Miao et al. (2019) used expert
investigation method, analytic hierarchy process
(AHP) and fuzzy comprehensive evaluation method
to construct the whole life cycle safety assessment
model of utility tunnel to evaluate the safety of utility
tunnel. In general, there is not enough emphasis on
the utility tunnel safety evaluation in China, the safety
studies of utility tunnel mainly have focused on the risk
research of construction stage and operation stage,
which are lack of integrity and comprehensiveness.
Only a few studies have focused on the issue from the
perspective of the whole life cycle. Moreover,
previous studies have not found an appropriate method
for safety evaluation of utility tunnel.

Therefore, based on the whole life cycle theory
and relevant literatures, this paper firstly established an
evaluation index system for utility tunnel safety eva-
uation, and then constructed a grey clustering evalua-
tion model based on the entropy weight method.
Finally, the model validity and applicability were ver-
ified through case studies.

3. Whole life cycle theory

Professor Raymond Vernon, an American economist
of Harvard University, put forward the product life
cycle theory (PLC) for the first time in his paper
“International Investment and International Trade in
the Product Cycle” in 1966, intending to explain the
motivation and timing of U.S. multinational compa-
 ries’ foreign investment. He believed that a product
had to go through four stages of germination, growth,
maturity and decline, and the impact of a product on the environment was a process “from
cradle to grave”. Later, the enterprise life cycle theory
and industrial life cycle theory were derived, which
had been applied in many fields such as economy,
management, and technology. In the 1960s, Life Cycle
Assessment (LCA) emerged in the United States. It
was a tool for evaluating the environmental load
and resource consumption of products, production
processes, and services during the whole life cycle
(Hong, Wang, and Chang 2012). In the 1990s, it was
widely used in the construction field to evaluate the
carbon emissions of building materials or the entire
building. In recent years, it was also often used for
sustainable development evaluation, cost manage-
ment and performance evaluation of engineering
projects. In 2002, BIM technology was proposed, because of its wide application in construction projects, it derived a concept of the whole life cycle of buildings, referred to as BLM (Building Life cycle Management). BLM draws on the concept of whole life cycle information management of manufacturing products, considered all stages of the project as a whole, used digital methods to create an information platform to manage and shared the information; it is an embodiment of integrated thinking.

In the construction field, engineering projects are usually divided into five stages: material production, transportation, construction, operation management, demolition and recycling. As a complex and emerging engineering project, based on the project’s characteristics, the urban underground utility tunnel can be divided into four stages: planning, design, construction and operation and maintenance. The main works of each stage are shown in Figure 2.

4. Methodology

There are many commonly employed evaluation methods such as fuzzy comprehensive evaluation (FCE), analytic hierarchy process (AHP), grey correlation analysis. However, the results obtained through FCE and AHP tend to be subjective; and because of the difficulty in determining the reference sequence or the optimal vector, the grey correlation analysis may not be applicable to this study (Wang 2020). In addition, due to the difficulty to obtain multiple samples, some commonly methods such as structural equation model (SEM), principal component analysis (PCA), factor analysis (FA) and BP neural network are also not suitable for this study.

Grey clustering analysis has the advantages of both grey system theory and clustering analysis, and can solve the multi-index evaluation problem with small samples and poor information. The evaluation results by this method are intuitive and reliable. It is widely utilized in many fields such as production, life and environmental quality assessment. Grey system theory is a method to handle uncertainty problem with small data samples and imprecise information (Liu 2004), which was founded by Professor Deng Julong in 1982, its research characteristics are consistent with the current research status of urban underground utility tunnel. The grey clustering evaluation method is one of the classic methods of grey system. So, in this paper, we chose Grey clustering analysis method to evaluate the safety of utility tunnel.

There are two important kinds of whitening weight functions in grey clustering, one is the endpoint triangular whitening weight function, and the other is the center point triangular whitening weight function. The endpoint triangle whitening weight function have more than two grey classes crossing phenomenon, the second is that the sum of its index value belongs to each grey cluster coefficients is not 1 (Liu and Xie 2011), which is not reasonable and normalized.

Furthermore, the endpoint triangle whitening weight function may appear that the sum of some index of each grey cluster coefficient is not equal to 1. The original intention of the center points triangular whitening weight function is to improve the above two problems, but it is still found that the sum of the clustering coefficients is not 1 in the follow-up observation in the center points triangular whitening weight function (Wang, Qiang, and He 2014). Based on the above two kinds of functions, this paper constructed a mixed center point triangular whitening weight function, which can make the calculation process standard and the calculation results accurate. Moreover, for the issue of safety evaluation, due to the complexity of the reality and the incomplete information, it is difficult to accurately quantify the relevant indices and classify the grey categories. At the same time, urban underground utility tunnel is a complex system engineering, each stage of preliminary, planning, design, construction and operation and maintenance is crucial to the safety of the project.

On this account, in this paper, based on the whole life cycle theory, Grey Clustering method with the center points triangular whitening weight function was chosen for evaluation.

4.1. Basic algorithm

4.1.1. Dividing the evaluation grey category

Grey category is conceptual category with unclear boundaries, and the division is to generate corresponding whitening weight functions according to the grey categories. The whitening values are calculated by different evaluation indicators in the whitening weight functions, the values are classified and
summarized to determine which category the clustering object belongs to (Qiang 2017). At present, the safety grade and grey category of utility tunnel project lack of unified standards and requirements. According to the existing safety evaluation research of utility tunnel (Zhu 2017) and with reference to expert opinions, (We investigated ten experts in the industry, among which four have worked for more than ten years and three have worked for more than five years; There are three people in the design unit, five people in the construction unit and two in other units.) The safety level of the urban underground utility tunnel was divided into five grey categories: very unsafe, less safe, basic safe, relatively safe and very safe. The corresponding safety classification standards are shown in Table 1. The values of each index are also quantified into five grey categories, whose value range is shown in Table 2.

### 4.1.2. Construction of the whitening weight function

Grey Clustering is a method that can be applied by incidence of grey matrices or grey bleaching weight functions. In this work, we use triangular center-point mixed whitening weight functions. The steps are as follows:

**Step1:** Assume that the number of experts is \( n \), the number of indicators is \( m \), and the number of grey categories is \( s \), then \( x_{ij} (i = 1, 2 \ldots n; j = 1, 2 \ldots m) \) represents the sample \( i \)-th expert observation value of index \( j \).

**Step2:** Assume the grey category number is \( k \), \( \lambda_j \) is the mixed center point of the grey category \( k \), extend the grey category to the left and right directions, connect the center point \( k + 1 \) with the center point of the grey category \( k - 1 \), then, the mixed center point whitening weight function of the index \( j \) about the grey category \( k \) can be obtained. First, Establish the turning points of the standard criteria data intervals, obtaining values for \( \lambda_j^1 \), \( \lambda_j^2 \)… and \( \lambda_j^5 \), determine the turning point of the very unsafe grey category as \( \lambda_j^1 = 55 \) and the very safe grey category as \( \lambda_j^5 = 95 \), then determine the center point of the less safe, basic safe, and relatively safe grey category as \( \lambda_j^2 = 65, \lambda_j^3 = 75, \lambda_j^4 = 85 \), the whitening weight function graph is shown in Figure 3.

**Step3:** Determine the whitening weight function of each index about the five gray categories.

The number of triangular functions is related to the safety evaluation index levels. Five functions are proposed since they are five classes, which are obtained from Equations (1–5), and in addition, Figure 3 shows the graph of the triangular center-point mixed whitening weight functions.

\[
f_j^i = \begin{cases} 
0, & x \not\in [0, 65] \\
1, & x \in [0, 55] 
\end{cases} 
\quad (1)
\]

\[
f_j^2 = \begin{cases} 
65 - x, & x \in [0, 55] 
\end{cases} 
\quad (2)
\]

\[
f_j^3 = \begin{cases} 
x - 65, & x \in [55, 65] 
\end{cases} 
\quad (3)
\]

\[
f_j^4 = \begin{cases} 
x - 75, & x \in [75, 85] 
\end{cases} 
\quad (4)
\]

\[
f_j^5 = \begin{cases} 
x - 85, & x \in [85, 95] 
1, & x \in [95, 100] 
\end{cases} 
\quad (5)
\]

(3) Calculation of comprehensive grey clustering coefficient

According to the whitening weight function \( f_j^i \) obtained in the previous step, the second-level index relative weight \( \eta_j \), where \( \eta_j = \frac{m_j}{\sum_{i=1}^{m} m_j} \), \( m \) is the number of the first-level indicators corresponding to this indicator, and the index \( j \) value \( x_{ij} \) of the object \( i \), the comprehensive grey clustering coefficient \( \sigma_i \) can be calculated with Equation (6).

\[
\sigma_i = \frac{m}{\sum_{j=1}^{m} f_j^i (x_{ij}) \eta_j (i=1 \ldots n; j=1 \ldots m)} \quad (6)
\]
(4) Calculating the Comprehensive evaluation coefficient $y^k$ according to the weight of the first-level index $w_i$, using Equation (7).

$$y^k = \sum_{i=1}^{n} \sigma_i w_i, (i = 1, 2 \ldots n, j = 1, 2 \ldots m) \quad (7)$$

(5) Determination of the grey category to which the evaluation object belongs to, applying Equation (8). It is judged that the evaluation object $i$ belongs to the grey category $k^*$. 

$$\max_{1 \leq k \leq 5} \{y^k\} = y^{k^*} \quad (8)$$

### 4.2. Determination of the index weight

The calculation methods of index weight can be divided into subjective weighting method and objective weighting method according to the different weighting methods. Subjective weighting methods mainly include Delphi method, AHP, etc., objective weighting methods mainly include entropy weight method, principal component analysis method, and coefficient of variation method. Entropy weight method was chosen because it can well reflect the objective weight of each evaluation index. At the same time, by combining with appropriate subjective weight method, a more scientific

| Table 3. Sources of the whole life cycle safety evaluation indexes r of utility tunnel. |
|---|---|
| Safety factors | Literature sources |
| The overall urban planning, underground space and traffic. | Bu, Wang, and Jin et al. (2016) |
| Geological conditions | Li and Li (2019) |
| the completion of perfect laws and regulations. | Bu, Wang, and Jin et al. (2016) |
| The government to play a leading role, and the government’s support | Wang, Chen, and Li et al. (2018) |
| The huge investment of the utility tunnel is a huge burden on the government. | Liu and Li (2017) |
| The reasonable distribution of operation cost | Qiao, Liu, and Zhang et al. (2018) |
| The utility tunnel should be designed and constructed in combination with the underground space and traffic as well as the sponge city. | Tan, Chen, and Wang et al. (2016) |
| The key points of utility tunnel design include section design, passage size design, foundation buried depth design, node design and so on. | Gu, Zhang, and Ye (2018) |
| Compatibility of pipelines should be considered in the design. Sewage pipes should be designed separately. | Canto-Perello and Curiel-Esparza (2006) |
| In the design of the utility tunnel, the ancillary facilities such as escape, alarm, smoke exhaust, ventilation and lighting should be considered. | Canto-Perello and Curiel-Esparza (2013) |
| The pipeline with potential danger should be designed for disaster prevention, and corresponding safety measures should be taken. | Canto-Perello, Curiel-Esparza, and Calvo (2009) |
| The requirements of civil defense. | Wang (2017) |
| Quality, cost and schedule risks, systematic risks (natural, policy, economic and social) and non-systematic risks (technology, management and decision-making). | Wei and Liu (2017) |
| Pipe corrosion. | Xu, Shao, and Wu (2014) |
| Harmful or combustible gas in operation | Chen, Zhao, and Xiao (2018) |
| The buried depth of the utility tunnel | Yang (2020) |
| Acts of sabotage and terrorism | Feng, Sun, and Wu et al. (2019) |
| The existing maintenance methods. | Jiang, Ren, and Xu et al. (2019) |
| Internet of Things, BIM, big data and other advanced technologies | Weng and Zhang (2018) |
| Natural disasters | Guo (2019) |
and reasonable index weight can be obtained. Entropy weight method is an objective weighting method; it determines the index weight according to the variability of indices. Generally, the smaller the information entropy of an index is, the greater the variability of the index becomes, thus the more information it provides, and the greater its weight, decision makers should pay more attention to this indicator. (Yin, Zuo, and Yin 2018). The specific calculation steps of the entropy method are as follows:

4.2.1. Normalization of raw data

Assume that the number of indicators is $m$, the number of experts is $n$, the original evaluation matrix $R = (r_{ij})_{m \times n}$ can be obtained, where $r_{ij}$ represents the evaluation value of the expert $j$ of the object $i$. Since the dimensions of the elements in the matrix are different, it is difficult to directly compare them, so they are uniformly normalized.

For efficiency indicators, normalized results can be calculated with Equation (9).

$$r'_{ij} = \frac{r_{ij} - \min_j (r_{ij})}{\max_j (r_{ij}) - \min_j (r_{ij})}, \quad (i = 1, 2 \ldots n; \ j = 1, 2 \ldots m) \quad (9)$$

For cost indicators, normalized results can be calculated with Equation (10).

$$r'_{ij} = \frac{\max_j (r_{ij}) - r_{ij}}{\max_j (r_{ij}) - \min_j (r_{ij})}, \quad (i = 1, 2 \ldots n; \ j = 1, 2 \ldots m) \quad (10)$$

Finally get the normalized matrix $R' = (r'_{ij})_{n}$.

(2) Calculation of information entropy

$$H_j = -k \sum_{i=1}^{n} f_{ij} \ln f_{ij} \ (i = 1, 2 \ldots n; \ j = 1, 2 \ldots m) \quad (11)$$

Where $f_{ij}$ represents the characteristic proportion of the object $i$ under the index $j$. $f_{ij} = \frac{r'_{ij}}{\sum_{i=1}^{m} r'_{ij}}, k = \frac{1}{\ln n}$.

(3) Calculating the weights of second-level indicators

$$w_j = \frac{1 - H_j}{\sum_{j=1}^{m} (1 - H_j)} = \frac{1 - H_j}{m - \sum_{j=1}^{m} H_j} \quad (i = 1, 2 \ldots n; \ j = 1, 2 \ldots m) \quad (12)$$

(4) Calculating the weights of first-level indicators

$$w_i = \sum_{j=1}^{s} w_j, \quad (i = 1, 2 \ldots n, \ j = 1, 2 \ldots s) \quad (13)$$

5. Index system

5.1. Establishment of a safety evaluation index system

This paper started from the four stages of the whole life cycle of the utility tunnel, referring to the construction and research status of utility tunnel in domestic and foreign and read the relevant literature of utility tunnel from China National Knowledge Infrastructure (CNKI) and the core database of web of science in the past ten years.

Table 4. The whole life cycle safety evaluation index system of utility tunnel.

| First-level indicators | Second-level indicators | Index explanation |
|------------------------|-------------------------|-------------------|
| A1 Planning            | A11 Collaborative planning | The degree of collaborative planning |
| A12 Preliminary investigation | The degree of detail of the preliminary investigation |
| A13 Complete laws and regulations | The perfection degree of the laws and regulations |
| A14 Government policy support | The degree of government policy support |
| A15 Financing mode selection | Risks in choosing the financing model |
| A16 Fee pricing mechanism | The reasonable degree of the pricing mechanism |
| A2 Design              | A21 Collaborative design | The degree of collaborative design |
| A22 Structure design | The degree of structural design |
| A23 Internal pipeline design | The degree of internal pipeline design |
| A24 Auxiliary facilities design | The degree of auxiliary facilities design |
| A25 Disaster prevention design | The degree of disaster prevention design |
| A26 Air defense design | The degree of air defense design |
| A3 Construction        | A31 Insufficient cost risk | Insufficient cost risk during the construction |
| A32 Schedule delay risk | Schedule delay risk during the construction |
| A33 Construction quality risk | Construction quality risk during the construction |
| A34 Construction technology level | Construction technology level during the construction |
| A35 Human factor | Management and decision-making risks during the construction |
| A36 Material equipment risk | Material and equipment supply risks during the construction |
| A37 Engineering change risk | Engineering change risk during the construction |
| A38 Pipeline corrosion | Pipeline corrosion risk during the operation |
| A39 External environmental safety | Internal environmental safety risk during the operation |
| A4 Operation and maintenance | A41 External planning mistakes | External planning mistakes risk during the operation |
| A42 Structural maintenance system | Human sabotage risk during the operation |
| A43 Intelligent technology application | The perfection degree of the structural maintenance system during the operation |
| A44 Force majeure risks during the operation | The application degree of intelligent technology during the operation |
| A45 Pipeline corrosion | Pipeline corrosion risk during the operation |
| A46 Internal environmental safety | Internal environmental safety risk during the operation |
| A47 External planning mistakes | External planning mistakes risk during the operation |
| A48 Human sabotage | Human sabotage risk during the operation |
| A49 Structural maintenance system | The perfection degree of the structural maintenance system during the operation |
| A50 Intelligent technology application | The application degree of intelligent technology during the operation |
| A51 Force majeure | Force majeure risks during the operation |
Through reading the literature, this study identified the factors that affect the safety of the whole life cycle of the utility tunnel, and extracted the safety evaluation indicators of the utility tunnel. The sources of the indicators are shown in Table 3. In addition, we invited relevant experts in this industry to discuss and study the scientificity, effectiveness, and comprehensiveness of the extracted urban underground utility tunnel safety evaluation indicators. By listening to the expert’s comments and combining with the current status of urban underground utility tunnel in China, this study established a full life cycle safety evaluation index system for urban underground utility tunnel, which includes four first-level indicators and 26 second-level indicators. The index system is shown in Table 4.

6. Case study

6.1. Project overview

The utility tunnel project is located in Zhengzhou City, Henan Province. Schematic diagram of underground utility tunnel is shown in Figure 4. The branch line has two compartments (as shown in Figure 5). One compartment contains 12 power cables and 18 communication cables; the other compartment contains two heat supply pipes with a diameter of 600 mm and a middle water pipe with a diameter of 300 mm (long-term Reserved) and a water supply pipe with a diameter of 300 mm. The cable accommodates 12 power cables and 18 communication cables. In August 2018, the construction of the project was completed.

6.2. Application of proposed approach

6.2.1. Development of the decision matrix

Five experts were invited to score the safety levels of the 26 indicators of this project according to centesimal system. Three of them are engaged in the related work of the utility tunnel, and two of them are engaged in the safety management of the engineering project. These experts have been working for more than 5 years. Taking the early planning stage as an example for calculation, the original evaluation matrix R was:

\[
R = \begin{pmatrix}
78 & 95 & 98 & 100 & 84 \\
65 & 61 & 58 & 64 & 63 \\
83 & 85 & 75 & 77 & 81 \\
86 & 84 & 81 & 78 & 87 \\
69 & 100 & 99 & 75 & 97 \\
71 & 69 & 74 & 73 & 75
\end{pmatrix}
\]

The normalized matrix \( R' = (r'_{ij})_{n} \) was obtained by Equations (9) and (10).

For example, for \( A_{12} \), it is an efficiency indicator, \( \max_{i} (r_{ij}) = 100, \min_{j} (r_{ij}) = 78, r'_{12} = \frac{95-78}{100-78} = 0.7727 \). Similarly, \( R' \) can be obtained.

\[
R' = \begin{pmatrix}
0.0000 & 0.7727 & 0.9091 & 1.0000 & 0.2727 \\
1.0000 & 0.4286 & 0.0000 & 0.8571 & 0.7143 \\
0.8000 & 1.0000 & 0.0000 & 0.2000 & 0.6000 \\
0.8889 & 0.6667 & 0.3333 & 0.0000 & 1.0000 \\
0.0000 & 1.0000 & 0.9677 & 0.1935 & 0.9032 \\
0.3333 & 0.0000 & 0.8333 & 0.6667 & 1.0000
\end{pmatrix}
\]

6.2.2. Determine the index weights

The information entropy H was obtained by Equation (11), the weight of each indicator w was obtained by Equation (12). For example,

\[
f_{1} = \frac{1}{\ln n} = \frac{1}{\ln 5} = 0.6213, \quad f_{12} = \frac{1}{\sum_{i=1}^{n} f_{ij}} = \frac{1}{0.7727 + 0.9901 + 1 + 0.2727} = 0.2615,
\]

\[
f_{1} = 0, f_{13} = 0.3077, f_{14} = 0.3385, f_{15} = 0.0923, \quad H_{11} = -k \sum_{i=1}^{n} f_{ij} \ln f_{ij} = 0.6213 \times 0.2615 \times \ln0.2615 + 0.3077 \times \ln 0.3077 + 0.3385 \times \ln 0.3385 + 0.0923 \times \ln 0.0923 = 0.8078
\]

Figure 4. Schematic diagram of underground utility tunnel.
Table 5. The whole life cycle safety index system weight of utility tunnel.

| First-level indicators | Weights $w_i$ | Second-level indicators | Information entropy $H_j$ | Weight $w_j$ | Relative weights $r_{ij}$ |
|------------------------|---------------|-------------------------|---------------------------|--------------|---------------------------|
| $A_1$                  | 0.8078        | $A_{11}$                | 0.0344                    | 0.1675       |                            |
|                        | 0.8350        | $A_{12}$                | 0.0296                    | 0.1441       |                            |
| 0.2054                 | $A_{13}$      | 0.7865                  | 0.0382                    | 0.1860       |                            |
| $A_2$                  | 0.7853        | $A_{21}$                | 0.0385                    | 0.1874       |                            |
|                        | 0.8200        | $A_{22}$                | 0.0322                    | 0.1568       |                            |
| 0.2381                 | $A_{23}$      | 0.7542                  | 0.0440                    | 0.1848       |                            |
| $A_3$                  | 0.7596        | $A_{31}$                | 0.0381                    | 0.1600       |                            |
|                        | 0.7213        | $A_{32}$                | 0.0499                    | 0.2096       |                            |
| 0.3009                 | $A_{33}$      | 0.7872                  | 0.0381                    | 0.1600       |                            |
| $A_4$                  | 0.7956        | $A_{41}$                | 0.0366                    | 0.1537       |                            |
|                        | 0.7907        | $A_{42}$                | 0.0335                    | 0.1511       |                            |
| 0.2556                 | $A_{43}$      | 0.7278                  | 0.0488                    | 0.1909       |                            |
|                        | 0.7852        | $A_{44}$                | 0.0385                    | 0.1506       |                            |
|                        | 0.8179        | $A_{45}$                | 0.0326                    | 0.1276       |                            |
|                        | 0.8484        | $A_{46}$                | 0.0272                    | 0.1064       |                            |
|                        | 0.7966        | $A_{47}$                | 0.0364                    | 0.1424       |                            |

Calculating the weight of each index

$$w_j = \frac{n_i}{\sum_{i=1}^{n_i} w_{ij}} = \frac{1}{1.0 - H_j} = \frac{0.8087}{26 - 0.4172} = 0.0344$$

(where, 20.4172 = 0.8087 + 0.8350 + … + 0.7966)

$$\eta_{ij} = \frac{(n_i/0.0344 + 0.0296 + 0.0382 + 0.0325 + 0.0385 + 0.0322) = 0.1675$$

Then we obtained the entropy values of all indices through MATLAB software. Similarly, according to Equations (12)-(13), the index weights were obtained as shown in Table 5.

6.2.3. Determine the safety level

The center points triangular whitening weight function values and Comprehensive clustering coefficients were obtained by Equations (1–6), the results were shown in Table 6. The score for each indicator was an average of expert scoring. For example:

$$\sigma_j^3 = \sum_{j=1}^{m} f_j^3(x_{ij}) \cdot \eta_j = 0.0000 \times 0.1675 + 0.5000 \times 0.1441 \times 0.0900 \times 0.1860 \times 0.9000 \times 0.1582 + 0.0000 \times 0.1874 + 0.0000 \times 0.1568 = 0.3818$$

The comprehensive grey clustering coefficient was calculated from Equation (7): the results are shown in Table 7. For example:

$$\gamma^3 = \sum_{j=1}^{n} \sigma_j^3 w_j$$

$$= 0.3818 \times 0.2054 + 0.0721 \times 0.2381 + 0.1225 \times 0.3009 + 0.1368 \times 0.2556 = 0.1674$$

In Table 7, where $\gamma^3=0.4836$, $k = 4$, it belongs to relatively safe grey category.

6.3. Results and discuss

6.3.1. About the case study

In this section, the results obtained regarding the safety evaluation of the utility tunnel project will be presented.
Table 6. Whitenization weight values and comprehensive clustering coefficients of indices. (A₁₁–A₁₆).

| Indices | Scores | $t^1_1$ | $t^2_1$ | $t^3_1$ | $t^4_1$ | $t^5_1$ | Grey category $k_1$ | Grey category $k_2$ | Grey category $k_3$ | Grey category $k_4$ | Grey category $k_5$ |
|---------|--------|---------|---------|---------|---------|---------|---------------------|---------------------|---------------------|---------------------|---------------------|
| A₁₁     | 90     | 0.0000  | 0.0000  | 0.0000  | 0.5000  | 0.5000  | 0.0000              | 0.0000              | 0.3818              | 0.4250              | 0.1931              |
| A₁₂     | 80     | 0.0000  | 0.0000  | 0.5000  | 0.5000  | 0.0000  | 0.0000              | 0.3818              | 0.4250              | 0.1931              |
| A₁₃     | 76     | 0.0000  | 0.0000  | 0.9000  | 0.1000  | 0.0000  | 0.0000              | 0.3818              | 0.4250              | 0.1931              |
| A₁₄     | 76     | 0.0000  | 0.0000  | 0.9000  | 0.1000  | 0.0000  | 0.0000              | 0.3818              | 0.4250              | 0.1931              |
| A₁₅     | 90     | 0.0000  | 0.0000  | 0.0000  | 0.5000  | 0.5000  | 0.0000              | 0.0000              | 0.3818              | 0.4250              | 0.1931              |
| A₁₆     | 86     | 0.0000  | 0.0000  | 0.9000  | 0.1000  | 0.0000  | 0.0000              | 0.3818              | 0.4250              | 0.1931              |

Table 7. Comprehensive grey clustering coefficient table.

|                | Very unsafe $k_1$ | Less safe $k_2$ | Basic safe $k_3$ | Relatively safe $k_4$ | Very safe $k_5$ |
|----------------|-------------------|-----------------|------------------|----------------------|-----------------|
| $y^2$          | 0.0147            | 0.0590          | 0.1674           | 0.4836               | 0.2753          |

(1) From the above results, the safety of the case is relatively safe, which verifies that the model is feasible in evaluating the safety of the utility tunnel. At the same time, the analysis based on the above-mentioned weight ranking results shows that among the safety factors that affect the whole life cycle of the utility tunnel, the indicators in the construction phase ($w = 0.3009$) have a larger weight, the operation and maintenance phase ($w = 0.2556$) is smaller, and the design ($w = 0.2381$) and planning phases ($w = 0.2054$) are much smaller, obtaining the following relation: $w_3 > w_4 > w_2 > w_1$.

(2) The two indicators of construction quality risk and construction technology level in the construction-phase account for a relatively high weight. In the actual construction process, quality control should be strengthened to eliminate as much as possible the potential safety hazards in the construction phase.

(3) Factors such as internal environmental safety and external planning mistakes in the operation and maintenance stage also have a greater impact on the safety of the utility tunnel. To reduce external planning mistakes risk, long-term considerations and an overall scientific plan should be made in the early stage. To reduce internal environmental safety risks, a comprehensive visualized intelligent operation and maintenance management platform can be established to monitor internal security risks in every time. In general, the intensity of daily operation and management should be strengthened and regular inspections and prevention and supervision of potential safety hazards should be implemented.

(4) Disaster prevention design has a higher weight in the design stage, so safety measures should be formulated to reduce the safety risks in the later construction and operation stages of the utility tunnel.

6.3.2. About the methodology

In relation to the method, grey clustering, was applied in the analysis of safety evaluation of the utility tunnel project, with which it was possible to assign weights to each of the index, which allows us to establish the model of the whole life cycle safety evaluation of urban underground utility tunnel.

It should be noted that in this work, we invited five experts to rate the safety level of 26 indexes of the project according to centesimal system and established the normalized matrix starting from the use of the grey clustering method; however, it is necessary to establish an in-depth evaluation of the value corresponding more precisely to each index.

7. Conclusions

Safety evaluation is crucial to the implementation of the utility tunnel, this paper introduced the grey clustering analysis to construct an evaluation model for utility tunnel based on whole life cycle theory. Based on the theory of whole life cycle, the construction period is divided into four phases: Planning, design, construction and operation and maintenance. This study established the whole life cycle of urban underground utility tunnel safety evaluation index system; the safety evaluation index system established from the perspective of the whole life cycle can systematically and comprehensively reflect the safety status of the utility tunnel. Through the analysis of the ranking results of the weights, it is possible to clarify the safety influencing factors that should be paid attention to during the whole life cycle and can provide a basis for investing funds, resources and management in the safety construction and management of the utility tunnel. The case analysis shows that the model can effectively evaluate the safety status of a utility tunnel project in the whole life cycle.
The Grey clustering methodology helps to assess safety level of the utility tunnel in an objective way, based on weights of the index that are evaluated, this can be complemented with more restrictive methods for the weights can be found those that are appropriate to the conditions and characteristics of the place of study. The proposed research is a starting point for the evaluation of safety level. There are several applications of grey clustering: however, safety assessment of urban underground utility tunnel is not very widespread. Therefore, taking this research as a reference, the evaluation can be carried out by establishing the index system corresponding, verifying risk evaluation even quality evaluation could be applied.

One limitation in this research should be noted. The construction of the urban underground utility tunnel is a complicated process. In the future research process, we hope to invite more experts to give guidance on the safety research of the utility tunnel. And add more cases for comparative analysis to verify the effectiveness of this model. At the same time, considering that many pipelines in the integrated pipeline gallery may cause multiple safety accidents, the interaction of pipelines will cause more serious accidents. If these factors are taken into account, the evaluation results will be more scientific and effective, which is also the direction that needs to be studied in the future. In the future, it can also be compared with other methods, such as response surface method or surrogate model, to verify the scientific nature of this method.

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Notes on contributors
Shaonan Sun is a professor at North China University of Water Resources and Electric Power in China. He received a Ph.D degree from Hohai University in 2012. His research areas include BIM technology development and application, engineering safety management and Construction management

Congyu XU is a Master’s degree candidate at the School of Management Engineering at Zhengzhou University in China. Her main research area is engineering project safety management.

Ailing Wang is a professor at Zhengzhou University in China. Her research areas include engineering management, engineering cost management and BIM technology development and application.

Yixin Yang is a Master’s degree candidate at the School of Management Engineering at Zhengzhou University in China. Her main research area is property management.

Mengqi Su is a Master’s degree candidate at the School of Management Engineering at Zhengzhou University in China. Her main research area is engineering cost management.

Author contributions
Shaonan Sun proposed innovation points, provided research platforms and research funds, guided and modified the manuscript. Congyu Xu analyzed the data, and wrote the manuscript. Ailing Wang provided the case information, guided and modified the manuscript. Yixin Yang and Mengqi Su helped the data collection.

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