Comprehensive Risk Evaluation in the Long-Term Operation of Urban Subway Based on Multiple Indices

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The reasonable risk evaluation in the long-term operation of urban subway systems is of importance to the public safety and maintenance work of the subway. At present, the risk assessment always depends on a specified single factor which might result in a biased risk result. In order to take more influential factors into account, the multiple indices system is developed for the total risk evaluation in this work. The proposed multiple indices system is established on the basis of the logical structure of the analytic hierarchy process (AHP). It is based on the 7 selected factors in which the value of each factor is defined by its risk level and the corresponding weight is determined by the AHP calculation. The result obtained from the case study showed that the total risk level got from the proposed method is more reasonable than the traditional single index-based methods.

1. Introduction

As the world continues to urbanize, the number of cities becomes greater and greater especially in the lower-middle-income countries where the pace of urbanization is the fastest [1]. However, in most cases, the land space of a city is always limited, and there are no enough streets or roads which can be built arbitrarily to serve for the increasing amount of motor cars. Accordingly, the sharply increased population in these cities inevitably brings some negative impacts on both the society and the environment [2, 3]. Among them, the traffic pressure and air pollution which is primarily derived from the large use of private vehicles in daily city life are the most watched concerns in recent years [4]. To sustain growth, using the underground space and developing highly efficient transportation to mitigate the pressure become a promising alternative for many large cities [2, 5–9]. Since the first subway in the world was built and served for the public transportation in London in 1863 [10], as such an efficient and sustainable infrastructure is massively constructed in many large cities, which is expected to alleviate the transportation pressure and reduce the air pollution. By 2017, there are 178 cities from 56 countries in the world which have opened the subway systems and nearly 53.8 billion people traveled through the subways in their daily life [11, 12]. With the implementation of the national strategy of “building a resource-saving and environment-friendly society” in China, more and more underground subway systems were developed rapidly to alleviate the surface traffic pressure and to control the urban air pollution [13]. As of December 2019, the total length of subway in operation has reached up to about 5200 km in 37 cities of the mainland of China. More and more subway lines were built in dense and crowded urban areas. In many large cities like Beijing, Shanghai, Shenzhen, Guangzhou, Chengdu, and so on, the subway lines in operation are considerable dense where you can find a subway station within a distance of 0.5–1.0 km [14, 15]. Going underground nowadays for taking subway has become a routine experience for a large number of people in China. Although the subway brings many benefits to our daily life, the operation of the subway system can still cause some risks to the environment and the
society [3]. Specifically, the disturbances or damage caused by the operation of subway to the tunnel structures, nearby buildings, and infrastructures/facilities in the vicinity of the tunnels cannot be ignored.

The subway operation-induced risks include but are not limited to the long-term ground settlement, deformation and failure of adjacent pipelines, and leakage of linings [6, 13, 16]. For the subway in long-term operation, the risk can be caused by the subway train’s vibration, consolidation deformation of the ground, and variation of the groundwater table. Generally, the long-term ground settlement is produced slowly with the time. For example, the long-term ground settlement of the underwater tunnel in Dapu road of Shanghai is up to 120 mm after 16 years of the completion of the subway. Sustained ground settlement will endanger the safety of the tunnel and the operation of subway, such as cracking, leakage of linings, excessive deformation of adjacent underground structures, deterioration of the stability of rails, and enhancing the vibration of nearby structures. Up to now, a plethora of studies have been undertaken to estimate or control the ground settlement [15, 17–22]. On the basis of the classic Gaussian profile and equivalent beam method, Camós et al. [23] proposed a probabilistic model to predict the ground settlement caused by tunnelling. Chen et al. [24] employed three artificial neural network (ANN) methods including the back-propagation (BP) neural network, the radial basis function (RBF) neural network, and the general regression neural network (GRNN) to describe the evolution of maximum surface settlement and found that the GRNN is the most suitable method. Provadiakis et al. [25] presented an integrated 3D BIM-geology interaction method to estimate the tunnelling-induced settlement risk to adjacent buildings. Hu and Wang [26] introduced an efficient method to analyze the ground surface settlement caused by the shield tunnelling using the spatial random fields. Mahmoodzadeh et al. [27] compared the estimation results for maximum surface settlement of urban tunnelling which are derived from the long short-term memory (LSTM), deep neural networks (DNNs), K-nearest neighbor (KNN), Gaussian process regression (GPR), support vector regression (SVR), decision tree (DT), and linear regression (LR). They found that the DNNs method can be considered as the best method for prediction of the ground settlement. Zhou et al. [28] reported a quantitative evaluation of settlement for surrounding environment in underground construction using the complex network theory. To our knowledge, regardless of what type of method is utilized, most of attentions have been paid to the estimation of the settlement and the final risk assessment largely depends on the comparison of calculated result and threshold from technical standards or designed requirements. In these threshold-based methods, the risk is usually determined by one specific factor, such as the deformation at specific monitoring point. Moreover, most of the reported investigations are largely focused on the settlement risk caused by the construction of subway tunnels. To some degree, the ground settlement during construction can be considered as the short-term risk, whereas the operation of subway-induced risk might be called the long-term risk and it deserves more attention. At present, the discussion focused on the long-term risk during the subway operation is rarely conducted.

The purpose of this work is to discuss the total risk during the long-term operation of the subway and thus to establish the multiple indices-based evaluation method for assessing the total risk. In this work, we believe that the total risk is virtually not just limited to the value of subsidence at given points but also related to the rate of settlement, the leakage state of tunnel lining, the disturbance of construction conducted in the vicinity areas, and so on. The proposed evaluation method is based on multiple indices representing the influential factors from different perspectives, and both the field investigation and expert consultation are employed to identify these indices. The weight of each factor involved in the proposed method is determined by the analytic hierarchy process (AHP) algorithm. The developed total risk evaluation method could help to comprehensively understand the risk during the operation of the subway and will provide a reasonable impact level of the total risk to aid the routine management and further maintenances of the subway in a cost-effective way.

2. Definition of the Multiple Indices System

2.1. Logical Structure of the Multiple Indices System. The reliability of the result of an evaluation method largely depends on the rationality of the index/indices involved. Utilization of multiple indices can take more important influential factors into account than that of single evaluation index. However, the reliability of the indices system is not determined by the number of indices but the role of each index. In other words, the index representing the impact of an influential factor should be assigned a great weight, and all influential factors should be counted in the evaluation. Therefore, it is necessary to define the structure of the indices system and to identify factors involved. In this work, the analytic hierarchy process (AHP) is utilized to determine the logical structure of the multiple indices system. The AHP developed by mathematician Thomas Saaty is a method for assessing and prioritizing options [29]. It is a mathematically rigorous, proven process for prioritization and complex decision-making. It can help us to combine all relevant information and make informed decisions and enables decision-makers to arrive at the best decision, with a clear rationale for that decision via reducing complex decisions to a series of pairwise comparisons [30, 31].

The logical structure determined by the AHP for the risk evaluation is shown in Figure 1. \( C_{i1} \) refers to the first indicator of the indicator layer corresponding to the criterion layer \( B_1 \), and \( C_{i1} \) refers to the NTH indicator of the indicator layer corresponding to the criterion layer \( B_1 \). Similarly, \( C_{i1} \) refers to the first index of the index layer corresponding to the criterion layer \( B_k \), and \( C_{i1} \) refers to the NTH index of the index layer corresponding to the criterion layer \( B_k \). The decision objective is the value of the total risk level (TRL), while the criteria are the types of indices which will be further defined by the classification of identified indices. With the hierarchical structure diagram, the relationship between different indices/influential factors can be indicated clearly.
In particular, this paper compared the methods of questionnaire survey and finally adopted the method of the table comparison proposed by Lyu et al. [32]. Table 1 presents the differences between the traditional and new questionnaire. A consistent judgment from the new questionnaire can be guaranteed by using a trial calculation. The experts surveyed were engineers with at least 15 years of experience. Based on the obtained experts’ opinions, the trapezoidal fuzzy number can also be determined [32, 34].

2.2. Identification of the Potential Indices. A huge number of literature studies have indicated that the primary influential factors for the ground settlement risk included the cyclic vibration in the operation of the subway, lining leakage, loading of surface structures, geological conditions, disturbance of tunnelling, and regional ground settlement. To comprehensively understand the risk in the operation of the subway, the potential factors in the long-term operation of the subway are further identified using both the on-site investigation and questionnaire survey (see Figure 2). Excepted for the abovementioned 6 factors, there are other 6 factors identified. All of these potential factors can be grouped into 3 types, namely, the regional surface settlement, operation of subway, and the disturbance of construction. For each type, the factors involved are given in Table 2.

2.3. Optimization of Indices. Although in total 12 factors are identified, it is not true that every factor will be unanimously counted in evaluating the total risk. In order to improve the efficiency of the evaluation, the frequently used factors in practices should be counted into the evaluation while those rarely used ones could be ignored. Based on the statistical survey of the adoption rates of the abovementioned factors which are conducted in 102 subways lines from 27 Chinese cities including Beijing, Shanghai, Shenzhen, and Tianjin, the frequencies of the 12 factors are given in Figure 2.

If the adoption rate of the factor is up to 100% according to the result of statistic survey, the factor is directly counted into the multiple indices system. When the adoption rate of a factor is less than 30%, the factor will be ignored in this work. For the adoption rate of the factor falls in the rage of 30%–100%, its importance degree is then further evaluated to determine whether it should be counted into the evaluation. Therefore, the geological condition is directly counted into the risk evaluation due to its adoption rate of 100%, while the cyclic vibration in operation of subway and loading of surface structures are ignored in further estimation.

The importance of the factor is determined by the expert consultation. In total, we invited 50 experts and professionals to give scores for the factors with adoption rates between 30% and 100%. If he/she believes the factor is very important for the risk evaluation, a score of 5 points is given to the factor. Similarly, 4 points is given to the important factor, 3 points for fair factor, 2 points for poor factor, and 1 point for very poor factor. In all surveyed experts/professionals, if the total percentage representing the very important and important degree is no less than 60%, the factor then will become a qualified one for the final risk evaluation. The result of the total percentage representing the very important and important degree of each factor is shown in Figure 3. Therefore, 7 factors are finally selected as the qualified factors to establish the multiple indices system for the total risk evaluation, that is, maximum ground settlement, maximum rate of ground settlement, geological conditions, maximum settlement of tunnel, lining leakage, density of surface structures, and disturbance of tunnelling.

3. Determination of the Total Risk Level

3.1. Definition of the Total Risk Level. Based on the identified multiple indices, the total risk in the operation of the subway system can be comprehensively evaluated. Referring to the method in the literature [35], we define the TRL to represent the total risk as follows:

\[ TRL = \sum_{i=1}^{n} F_i w_i, \]

where \( F_i \) and \( w_i \) are the value and weight of the \( i^{th} \) factor, respectively. In this work, \( n = 7 \) as there are 7 factors. The value of \( F_i \) is determined by the risk grading system for each factor, which will be illustrated in the next section. The weight \( w_i \) for the \( i^{th} \) factor will be determined by the AHP [29].

3.2. Determination Values of Every Factor. Risk grading is developed for determination of the value of \( F_i \). The absolute value of each factor is hard to be defined because some factors are qualitative. In order to appropriately assess the contribution of each factor to the total risk, the risk grading

![Diagram](image-url)
is conducted to evaluate the influence caused by the \( i \)th factor. Consequently, the value of \( F_i \) can be determined according to its risk degree. The risk grading of the factor is developed based on the technical codes (including the technical code for monitoring measurement of subway engineering (DB11/490-2007), interim provisions of Shanghai municipality on the technical management of subway protection by construction along the subway line, regulations of Hangzhou city on the administration of urban rail transit, measures of Tianjin municipality for the administration of land subsidence control, regulations from Zhejiang provincial government on strengthening the prevention and control of land subsidence), literature studies, and engineering experiences. Although the risk evaluation for multiple factors is still not available, the risk assessment using single factor can be integrated together. The first is to establish the risk assessment index system and then to calculate the weight of the risk assessment index. The grading standard of the risk assessment will be established and the risk assessment model will be determined accordingly. In this work, we define 3 levels for the risk degree. Level 1 means the low risk, level 2 represents the moderate risk, and level 3 denotes the high risk. A score is given to each risk level. The score is 1 if the risk level is 1, 3 for risk level 2, and 5 for risk level 3. The value of \( F_i \) is then defined as the score of risk level of the \( i \)th factor. The risk grading system is given in Table 3.

### 3.3. Determination of the Weight

The AHP method is believed to be a quite suitable algorithm for decision-making of semiquantitative or qualitative problems. Many pieces of literature have shown that the AHP is always considered as a suitable method to address the risk evaluation problems. In this study, the AHP method is also utilized to determine the weight of the factor. The judgment matrix is developed by using the group decision-making theory. The procedure of AHP can be summarized as follows:

1. Establishment of the hierarchical structure. In general, the AHP hierarchies include three levels: objective level (top), criterion level (middle), and indicator/index level (bottom). Seven factors have been already identified which were involved in the multiple indices system. Inevitably, they will become the members of the index level. The hierarchical structure is shown in Table 4.

2. Development of the judgment matrix. As shown in Table 5, an initial value representing the importance degree of element \( Y_i \) can be defined by

### Table 1: Comparison between the traditional and new questionnaires (Lyu et al. 2020).

| Type                           | Traditional questionnaire | New questionnaire |
|-------------------------------|---------------------------|-------------------|
| Basic theory                  | Pairwise comparison       | Pairwise comparison |
| Consulting process            | Pairwise comparison       | Assign score to each factor |
| Large number of factors       | Complex                   | Simple            |
| Consistency of judgment       | Inconsistency may exist    | Consistency can be guaranteed by trial calculation |

| Table 2: Statistical adoption rate of factors. |

| Factor                                    | Adoption rate (%) |
|-------------------------------------------|-------------------|
| Regional surface settlement                |                   |
| Operation of subway                       |                   |
| Disturbance of construction                |                   |
| Maximum ground settlement                  |                   |
| Average ground settlement                  |                   |
| Maximum rate of settlement                 |                   |
| Geological conditions                      |                   |
| Maximum settlement of tunnel               |                   |
| Average settlement of tunnel               |                   |
| Lining leakage                             |                   |
| Cyclic vibration in operation of subway   |                   |
| Density of surface structures              |                   |
| Disturbance caused by nearby construction  |                   |
| Disturbance of tunnelling                  |                   |
| Loading of surface structures              |                   |

**Figure 2:** Statistical adoption rate of factors.
corresponding importance of the adjacent element \( Y_{ji} \). In this work, the initial value of \( Y_{ji} \) is in the range of 1–9. The ranking of all elements can be obtained by the intercomparison of their importance degrees. For each element, its importance is not just determined by the adjacent element but by a group of elements.

For \( n \) elements, the judgment matrix \( A \) can be described as follows:

\[
A = (Y_{ji})_{n \times n},
\]

in which \( Y_{ji} \geq 0 \), \( Y_{jj} = 1 \), and \( Y_{ij} = 1/Y_{ji} \). For \( n \)-order judgment matrix, there are \( n(n-1)/2 \) elements that are involved in the intercomparison.

(3) Weight calculation. The weight is determined by the following equation:

\[
A\delta = \lambda_{max}\delta.
\]

The value of \( \delta \) with orthogonalization is the weight of the factor. The calculation is usually performed by the power method, as follows:

(a) Suppose the initial vector \( \delta_k \).

(b) For \( k = 1, 2, 3, \ldots \), compute \( \delta_k = A\delta_{k-1} \), \( \delta_{k-1} \) is the vector after normalization.

(c) If the accuracy is given, assume \( \max|\delta_{ki} - \delta_{(k-1)i}| < \varepsilon \), \( \delta_{ki} \) is the component of vector \( \delta_k \). If the accuracy is unknown, then recalculation of step (b) is needed.

(d) Calculate \( \lambda_{max} \) and \( \delta \) according to equations (4) and (5).

\[
\lambda_{max} = \sum_{i=1}^{n} \frac{\delta_{ki}}{n},
\]

\[
\delta_k = \frac{\delta_{ki}}{\sum_{j=1}^{n} \delta_{kj}}.
\]

(e) Consistency checking: when the value of consistency check result (CR) is less than 0.1, the consistency of the judgment matrix is qualified [29]. Otherwise, it is necessary to rebuild the matrix. The CR can be obtained by

\[
CR = \frac{CI}{RI},
\]

where \( n \) is the order of the judgment matrix, \( CI \) is the calculated consistency, and \( RI \) is the mean random consistency of the \( n \)-order matrix which can be obtained from Table 6.

(4) Calculated result: the calculation is performed using MATLAB software. The key algorithm of AHP is as follows (Algorithm 1):

The result is shown in Figure 4. According to the calculated result of factor’s weight, the importance of factor can be ranked as follows:

(a) For regional ground settlement indices: geological conditions > maximum rate of ground settlement > maximum ground settlement

(b) For subway operating indices: maximum settlement of tunnel > lining leakage

(c) For engineering disturbance index: density of surface structures > disturbance of tunnelling

3.4. Proposed Model for the TRL. Based on the result of calculated weights using the AHP method, the comprehensive model for the total risk evaluation can be obtained as follows:

\[
TRL = \sum_{i=1}^{n} F_i w_i = 0.0436 F_1 + 0.1606 F_2 + 0.3549 F_3 + 0.3089 F_4 + 0.0618 F_5,
\]

where \( F_1 \) is the risk score of maximum ground settlement, \( F_2 \) is the risk score of the maximum rate of ground settlement, \( F_3 \) is the risk score of geological conditions, \( F_4 \) is the risk score of the maximum settlement of tunnel, \( F_5 \) is the risk score of lining leakage, \( F_6 \) is the risk score of the density of surface structures, and \( F_7 \) is the risk score of disturbance of tunnelling.

3.5. Total Risk Rating Evaluation. A total risk rating should be proposed to understand the degree of the total risk, which is expected to provide accurate and objective suggestions to the managers/operators of the subway. According to the existing risk rating using single index, the total risk of the subway in operation is also defined as three levels in this work. Level 1 means low total risk, level 2 represents moderate total risk, and level 3 denotes the high total risk. The level of the total risk is determined by the value of TRL. As the value of risk score for every factor falls in 1–5, the value of TRL will also be between 1 and 5. The level of the total risk is determined by the value of TRL. The TRL is, the more dangerous it is. The total risk rating is shown in Table 7.

For the specific case of subway in operation, the TRL could be quantitatively estimated by collecting the values of the proposed multiple indices. Thus, an appropriate comment on the TRL of subway in operation can be obtained by
comparing the magnitude of TRL with the proposed total risk rating. The risk level based on multiple factors can be comprehensively understood and thus a reasonable suggestion of early warning could be provided to the manager or contractor of the subway for further maintenances.

### Table 2: Preliminary identification of factors.

| Objective level | Criteria level | Index level (unit) |
|-----------------|----------------|-------------------|
| Regional surface settlement | Maximum ground settlement (mm) | |
| Risk level | Average ground settlement (mm) | |
| | Maximum rate of ground settlement (mm/d) | |
| | Geological conditions | |
| Operation of subway | Maximum settlement of tunnel (mm) | |
| | Average settlement of tunnel (mm) | |
| | Lining leakage | |
| Disturbance of construction | Cyclic vibration in operation of subway | |
| | Density of surface structures | |
| | Disturbance caused by nearby constructions | |
| | Disturbance of tunnelling | |
| | Loading of surface structures | |

### Figure 3: The total percentage representing very important and importance degree.

### Table 3: Risk grading for each factor.

| Factor | Risk degree (score) |
|--------|---------------------|
|        | Low 1               | Moderate 3 | High 5 |
| Maximum ground settlement (mm) | < 300 | 300–800 | > 800 |
| Maximum rate of ground settlement (mm/d) | < 0.08 | 0.08–0.14 | > 0.14 |
| Geological conditions | Hard formations | Soft formations | Mixed formations |
| Maximum settlement of tunnel (mm) | < 20 | 20–70 | > 70 |
| Lining leakage | No leakage | Partial leakage | Full leakage |
| Density of surface structures | Dense low-rise buildings | Dense moderate-rise buildings | Dense high-rise buildings |
| Disturbance of tunnelling (disturbed depth) (m) | < 0.8 | 0.8–1.5 | > 1.5 |
4. Case Study

The section of the line 1 from Wulin Square Station to Ding’an Road Station in Hangzhou subway is selected as the case to evaluate the total risk in the operation of subway, as shown in Figure 5. The study area is the largest commercial street which connects the biggest three commercial areas (i.e., Wulin, Hubin, and Wushan Business Circles) and has a large population. The Hangzhou Tower, Yintai Wulin Department Store, Hangzhou Department Store, GDA shopping Square, and other important buildings can be found in nearby areas. With a total length of 2.8 km, the studied subway section crosses under this commercial street. The line 1 was opened in November of 2012. As it located in urban with dense surface buildings, the operation of subway-induced risk was in the spotlight since the line 1 was opened in 2012.

The buried depth of the tunnel is 9.3 m–16.5 m. The designed tunnel segment clearance is 5500 mm. The tunnel lining is prefabricated reinforced concrete segments, with a concrete strength grade of C50 and impermeability grade of no less than S10. According to the geological conditions, the foundation soils are divided into different soil layers, as listed in Table 8 in detail.

Monitoring work was initiated before the operation of subway line 1, that is, from July 4 in 2012. The accumulated

```matlab
function [δ] = AHP(A)
for i = 1:n
    for j = 1:n
        if A(i, j) * A(j, i) = 1
            fprintf("\(i = \%d, j = \%d, A(i, j) = \%d, A(j, i) = \%d\)\), i, j, A(i, j), A(j, i)
        end
    end
end

quanzhong = zeros(n, 1);
for i = 1:n
    quanzhong(i, 1) = txx(i, 1)/sum(txx);
end

CR = CI/RI(1, n);
if CR >= 0.1
    fprintf
else
    fprintf
end

ALGORITHM 1: The algorithm of AHP using MATLAB.
```

Table 4: Selected factors for the multiple indices system.

| Objective level | Criteria level       | Index level (unit)          |
|-----------------|----------------------|-----------------------------|
| Risk level      | Regional surface settlement | Maximum ground settlement (mm) |
|                 | Operation of subway  | Maximum rate of ground settlement (mm/d) |
|                 | Disturbance of construction | Geological conditions |
|                 |                      | Maximum settlement of tunnel (mm) |
|                 |                      | Lining leakage              |
|                 |                      | Density of surface structures |
|                 |                      | Disturbance of tunnelling   |

Table 5: Pairwise comparison scale for the AHP preferences.

| Numerical rating | Verbal judgment of preferences |
|------------------|-------------------------------|
| 1                | Equally preferred             |
| 2                | Equally to moderately preferred |
| 3                | Moderately preferred          |
| 4                | Moderately to strongly preferred |
| 5                | Strongly preferred            |
| 6                | Strongly to very strongly     |
| 7                | Very strongly preferred       |
| 8                | Very strongly to extremely    |
| 9                | Extremely preferred           |
settlement of tunnel at the end of 2016 is shown in Figures 6–8. It can be found that the maximum settlement of tunnel is 68.18 mm.

The values of other factors were also obtained by field monitoring or site investigation at the same time, as shown in Table 9.

Based on the collected values, the risk level can be determined using the proposed TRL model, as shown in Table 10. The TRL evaluated using the proposed method is level 2, indicating that the total risk in the operation of the subway is moderate. However, the estimated risk level is low if the Zhejiang provincial code is utilized, while the risk is high if the Tianjin provincial code is employed. Single index-based risk evaluation always paid more attention to the specific factor but overlooked contributions of other influential factors. As a result, the risk often will be underestimated in the one index-based evaluation. The proposed TRL evaluation method is based on multiple factors, which

| n  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 |
|----|----|----|----|----|----|----|----|----|----|----|----|----|
| RI | 0  | 0  | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 | 1.51 | 1.54 |

![Figure 4: Calculated weight of factors.](image)

| Value of TRL | Level of total risk |
|--------------|---------------------|
| 1.0 ≤ TRL ≤ 2.4 | Low (level 1) |
| 2.4 < TRL ≤ 3.7 | Moderate (level 2) |
| 3.7 < TRL ≤ 5 | High (level 3) |

![Figure 5: The studied section of subway line 1 in Hangzhou.](image)
could include the contribution of every influential factor. In this case, contributions from different aspects will be taken into account properly and the evaluated risk level can be considered the TRL. An objective and reasonable risk level obtained using the proposed method will benefit the further maintenance for the subway system in operation.

In order to verify the effectiveness of the proposed TRL method, monitoring data from Wulin Square Station to Ding’an Road Station from January 1, 2020, to December 21, 2020, were selected for comparison (see Figures 9–11). It can be seen that the cumulative maximum settlement value of the Fengqi-Wulin Square interval tunnel is 29.8 mm, the cumulative maximum settlement value of the interval tunnel section from Longxiangqiao Station to Fengqi Road Station is 100.7 mm, and the cumulative maximum settlement value of the interval tunnel section from Ding’an Road Station to Longxiangqiao Station is 10.6 mm. Therefore, the maximum cumulative land subsidence value of the tunnel section between Wulin Square Station and Ding’an Road Station is less than 300 mm. According to the TRL evaluation method, the total risk is low and special attention is not suggested to the management and maintenance work of the tunnel. The

| Number | Soil layer       | Detail description                                      |
|--------|------------------|--------------------------------------------------------|
| ①      | Miscellaneous fill soil | Mainly composed of construction and domestic waste (1.2~4.7 m) |
| ②      | Plain fill soil   | Generally composed by the silty soil with organic matters (0.4~3.6 m) |
| ③      | Silty soil        | Containing lots of humic substances and scrap micas (3.3 m) |
| ④      | Clayey silt       | With many iron oxides and scrap micas (0.8~13.2 m) |
| ⑤      | Silty soil        | With organic matters and silty soils (2.0~4.6 m) |
| ⑥      | Silty soil        | With organic matters and sludge soils (1.4~6.0 m) |
| ⑦      | Clay              | With organic matters (2.0~8.0 m) |
| ⑧      | Clay              | With organic matters (1.5~5.9 m) |
| ⑨      | Gray clay         | With organic matters and silty soils (3.2~10.4 m) |
| ⑩      | Silty clay        | With organic matters (1.0~3.6 m) |
| ⑪      | Silty clay        | With organic matters and scrap micas (4.2~7.2 m) |
| ⑫      | Gravel sand       | With organic matters and scrap micas (1.6~8.0 m) |

Table 8: Property description of soil layers in tunnel section.

Figure 6: Monitored settlement of tunnels from Fengqi Road Station to Wulin Square Station. (a) Left tunnel. (b) Right tunnel.
Table 9: Values of monitored factors involved in the evaluation.

| Objective               | Criteria                      | Index (unit)        | Values          |
|-------------------------|-------------------------------|---------------------|-----------------|
| Risk level              | Regional surface settlement   | Maximum ground settlement (mm) | 27.29          |
|                         |                               | Maximum rate of ground settlement (mm/d) | 0.15          |
|                         | Operation of subway           | Geological conditions | Soft formations |
|                         | Disturbance of construction   | Maximum settlement of tunnel (mm) | 68.18          |
|                         |                               | Lining leakage      | Completely impermeable |
|                         |                               | Density of surface structures | Dense high-rise buildings |
|                         |                               | Disturbance of tunnelling | Disturbance depth < 0.8 m |

Figure 7: Monitored settlement of tunnels from Longxiang Bridge Station to Fengqi Road Station. (a) Left tunnel. (b) Right tunnel.

Figure 8: Monitored settlement of tunnels from Ding’an Road Station to Longxiang Bridge Station. (a) Left tunnel. (b) Right tunnel.
| Evaluation methods | Indices | Weight | Calculated value | Threshold | Risk level |
|--------------------|---------|--------|------------------|-----------|------------|
| Maximum ground settlement (mm) | 0.0436 | | | | |
| Maximum rate of ground settlement (mm/d) | 0.1606 | | | | |
| Geological conditions | 0.3549 | | | | |
| Maximum settlement of tunnel (mm) | 0.3089 | 3.1572 | | Level 2: 2.4–3.7 | Moderate |
| Lining leakage | 0.0618 | | | | |
| Density of surface structures | 0.0468 | | | | |
| Disturbance of tunnelling | 0.0234 | | | | |
| Zhejiang provincial code | Accumulated ground settlement (mm) | 27.29 | | Low risk: 300 mm | Low |
| Tianjin provincial code | Maximum rate of ground settlement (mm/a) | 54 | | High risk: > 50 mm/a | High |

**Figure 9:** Monitored settlement of tunnels from Fengqi Road Station to Wulin Square Station.

**Figure 10:** Monitored settlement of tunnels from Longxiang Bridge Station to Fengqi Road Station.
fact is that the tunnel and nearby structures are safe till now, which indicates that the TRL method proposed in this paper is effective.

5. Conclusions

The appropriate risk evaluation in the operation of the subway is of importance to the manager or operator of the subway system. Traditionally, the risk level is always estimated using single index in which just the contribution of a specific factor is counted. One index-based evaluation method often overlooks the impacts of other influential factors, resulting in a biased result of the risk. In this paper, a multiple indices-based evaluation method is proposed to comprehensively understand the total risk in the operation of the subway system in urban areas. Some conclusions could be drawn as follows:

(1) The multiple indices system is developed based on the logical structure of the AHP. The adoption rate is used to preliminarily screen the identified factors, while the importance degree investigation is utilized to further optimize the qualified factors. The developed indices system for evaluating the total risk in the operation of the subway involves 7 factors, that is, maximum ground settlement, maximum rate of ground settlement, geological conditions, maximum settlement of tunnel, lining leakage, density of surface structures, and disturbance of tunnelling.

(2) The TRL is defined as the sum of products of the factor’s value and its weight. The value of each factor is determined by its risk level, and its weight in the proposed multiple indices system is defined by the AHP.

(3) The total risk is graded into 3 levels. Level 1 indicates the lowest level of the total risk, and level 3 means the highest risk.

(4) In the case study, the TRL evaluated using the proposed method is level 2, indicating that the total risk in the operation of subway is moderate. The result showed that the risk obtained from the proposed TRL method is more reasonable than other one-index-based methods, in which the impacts of more influential factors are virtually taken into account. An appropriate risk evaluation is vitally important to the management and maintenance of the subway systems.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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