Risk assessment and implementation of deformation disaster for operation tunnel based on entropy weight-grey relational analysis

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\section*{ABSTRACT}
Prevention is of paramount importance in tunnel engineering, especially in operation tunnel. In this study, the deformation data of Suzhou Metro Line 1 are used to evaluate the health of shield tunnel during operation. Firstly, the relationship between effective ratio of bending rigidity and tunnel deformation is analyzed, the results show that the effective ratio of bending rigidity has a negative power relationship with the tunnel deformation, and the conversion from deformation data to effective ratio of bending rigidity is realized and the corresponding risk classification criterion are established. Secondly, Grey Relational Analysis and Entropy Weight Method are used to deal with the deformation data, which overcomes the problem that data selection is not representative. Finally, the optimum effective ratio of bending rigidity is obtained successfully to complete the risk assessment of operation tunnel, and the assessment result is highly consistent with actual project. In addition, the corresponding application named Operation Tunnel Deformation Risk Assessment System is developed by using computer technology, which saves time for assessment and increases flexibility. The risk assessment method passes validation in the case tunnel, which can provide a reference for the disaster prevention in operation tunnel.

\section*{1. Introduction}
Underground infrastructure is an important part of infrastructure construction in the world, and underground traffic is a dependent way that people live and works today (Pan et al. 2019). The construction of modern urban transit has also created a wide market for the urban rail transit industry. However, the rapid development of tunnel construction has also brought many challenges to us. In the process of tunnel excavation and operation, affected by geological factors (Wang et al. 2017a, 2017b), excavation disturbances, loads, environment factors and other conditions, tunnel has been
plagued by disease problems such as tunnel deformation, tunnel fires and water leakage (Wang et al. 2019a, 2021a, 2021b, 2022). These problems will lead to a decrease in the strength of tunnel lining, result in a reduction in tunnel service life and seriously endanger lives and properties (Dimitrova et al. 2020).

In China, about a quarter of the tunnels are in stage of disease development, which puts a threat to the security of operation tunnel. Therefore, the reasonable evaluations of operation tunnel affected by disease problems and the proposal of specific measures are of great significance to improve the safety of tunnel and prolong its service life. Casagrande (1965) first put forward the concept of ‘calculated risk’, and pointed out that risk is a means to consider and evaluate accidents caused by uncertain factors in engineering, and that is a natural part of geotechnical engineering (Tang 2008). At present, the methods of risk assessment in engineering mainly include qualitative analysis, quantitative analysis and comprehensive analysis of the two. In tunnel engineering, the health of tunnel lining structure is a relatively vague concept, and there are many factors affecting the health of tunnel lining structure. Scholars in this field have used many methods to deal with this problem, such as fuzzy theory (Yang et al. 2014), BP neural network model, grey relational analysis (Shi 2018) and analytic hierarchy process etc. For tunnels in operation, the first thing the risk assessment does is to determine the evaluation index, in other words, the selected evaluation index should be representative. For example, Lin and Zhao (2019) selected seven indexes such as longitudinal settlement curvature and segment joint deformation of shield tunnel through entropy weight method and set pair theory, Shi (2018) selected six indexes such as lining cracks and water leakage of tunnel as the basis of evaluation, both have successful application results. The central part of risk assessment is how to evaluate scientifically and reasonably. At present, in the field of shield tunnel risk assessment during operation, mathematical methods are widely used. For example, Wang et al. (2016) used array to judge the weight and degree of membership of evaluation index, the improved model can more fully reflect the health of tunnel. Wu et al. (2016) used cloud model to solve the uncertainty problem of risk assessment in practice, which has been well applied in engineering.

However, the risk assessment of construction tunnel is the focus of scholars (Mikaeil et al. 2019; Li et al. 2020), while few studies on operation tunnel. Existing research about operation tunnel mostly focuses on the tunnel fires (Ntzeremes et al. 2020; Shahrour et al. 2020; Hua et al. 2021). In addition, in the field of risk control, prevention is more important than treatment, and the deformation data of tunnel in the operation period are crucial for predictive maintenance. There are encouraging signs that the tunnel deformation monitoring technology has been developed very well (Wang et al. 2018; Farahani et al. 2019; Zhou et al. 2020), but the deformation data had not been well applied to the risk assessment of operation tunnel.

There is no denying that scholars have done a lot of research on the risk assessment of operation tunnel, which has guiding significance for the evaluation and early warning of lining structure safety. However, the current risk assessment of operation tunnel lining structure affected by diseases is mostly based on expert scoring method and fuzzy evaluation because of the complex disaster mechanism and other reasons (Lin et al. 2020), which can be vulnerable to subjective factors. Furthermore, the risk assessment process of operation tunnel is comprehensive and complex, the result of
assessment would be distorted because of the unrepresentative indicators and some other problems, thus the real health reporting cannot be obtained.

Based on the above all, this work selects the representative parameter, effective ratio of bending rigidity (ERBR) for actual engineering as the criterion for the disaster risk classification. The deformation data of Suzhou Metro Line 1 are full used to analyze the relationship between ERBR and deformation of shield tunnel, which has never been explored before. After that, Grey Relational Analysis (GRA) and the Entropy Weight method (EWM) are used to deal with the deformation data, so that the useful data can be screened accurately and quickly. Based on screened data, GRA was used again, to get the corresponding ERBR so that the health of shield tunnel can be known. Moreover, a corresponding software is developed to achieve efficient and accurate diagnosis. The risk assessment model proposed in this study has reference significance for using the accurate monitoring data rationally, simplifying the multi-index risk assessment work and making an accurate diagnosis of operation tunnel.

2. Risk identification of deformation disaster for operation tunnel

For the shield tunnel lining structure, the relationship between deformation and the decrease of lining strength is interdependent and interactive. The decrease of tunnel lining structure strength will lead to the change of tunnel lining deformation; for the same reason, the change of tunnel lining deformation reflects the decrease of tunnel lining strength (Wu et al. 2020). In this study, the change in structural strength caused by the damage to tunnel lining structure is transformed into the change of ERBR, that is, the strength decrease caused by the damage to the tunnel structure is equivalent to the decrease of ERBR. The decline and key value of ERBR are the focal points in the acquisition of criterion for the risk assessment of shield tunnel lining structure.

There is no accepted version for the calculation of ERBR, it is generally determined empirically based on a large amount of engineering experience and test results. Hu et al. (2003) indicated that the value of ERBR can cause the internal force to change by 10%, Gao et al. (2021) derived the fitting formulas of coefficient of soil reaction, circumferential relative bending rigidity and ERBR. At present, the determination of ERBR has great arbitrariness and uncertainty. According to the research (Peng et al. 2013), the value of ERBR varies from 0.1 to 0.85 in the range of joint stiffness in practice. Select 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.85, 0.90, a total of 10 representative values to be the basis for study. ANSYS software is used to analyze the relationship between ERBR and deformation of tunnel lining. Using the deformation value of tunnel lining to get the critical value of ERBR, so the criterion can be obtained to get the risk level of operation tunnel, thus the health conduction can be judged and relevant suggestions can be obtained.

2.1. Risk index conversion

2.1.1. Engineering background

In order to ensure the feasibility of this study, relevant data about DK5+275m～DK5+275m section of the downline area of Leyuan Station-Tayuan Station of Suzhou Metro Line 1 (Zhang 2015) was use to do research. Distributed
Fiber Optic Sensing (DFOS) was applied to monitor the deformation, thus higher-precision deformation data that proved to be reliable and effective of the tunnel were obtained. The calculation data of shield tunnel lining segment is shown in Table 1 (Zhang 2015), and physical and mechanical parameters of surrounding rock in tunnel section is shown in Table 2 (Zhang 2015). In Table 2, the first column is the stratum distribution from ground to bearing stratum, in a total of 7 strata. The parameters would be used for subsequent analysis and calculation.

### 2.1.2. Relationship between ERBR and calculating displacement

The relationship between maximum calculating displacement of top lining and ERBR is shown in Figure 1. It can be seen that the maximum calculating displacement decreases with the increase of ERBR. Similarly, the ERBR decreases with the increase of the maximum calculating displacement. However, the variation of the two is non-linear. The value of displacement changes quickly when the value of ERBR is small, but a low rate of change appears with the increase of value of ERBR. This variation is close to the characteristics of power function. The above two are fitted by power function and then it can be found that when the power index is 0.581, the coefficient of determination is up to 0.9946. The fitted function is expressed as:

\[
d_{\text{top}} = 3.6929\eta^{-0.581}, \quad 0.1 \leq \eta \leq 0.9, \quad R^2 = 0.9946
\]  

(1)

where \(d_{\text{top}}\) is the maximum calculating displacement of top lining structure and \(\eta\) is ERBR.

Figure 2 shows the relationship between the calculating displacement of bottom lining and ERBR. It can be seen that the relationship between the two is similar to the variation trend of the calculating displacement of top lining and ERBR. The functional relationship between calculating displacement of bottom lining and ERBR can be expressed as:

\[
d_{\text{bttn}} = 1.1449\eta^{-0.455}, \quad 0.1 \leq \eta \leq 0.9, \quad R^2 = 0.994
\]  

(2)

However, the researches on tunnel vault deformation of shield tunnel in China are mainly based on the monitoring data from engineering practice (Sun et al. 2020; Sui et al. 2021). The structure monitoring of operation tunnel is also considered from the aspects of tunnel convergence value, ballast settlement, ellipticity, deformation and other factors (Zhao and Chen 2018). There is no unified standard for the deformation limit of the radial

| Name                          | Value          |
|-------------------------------|----------------|
| Buried depth at the top (m)   | 15–20          |
| Buried depth of groundwater (m) | 30.1            |
| Aquifer thickness (m)         | 8.4            |
| Elastic modulus (C50 concrete) (MPa) | 3.45e4     |
| Outer diameter of segment (mm) | 6.2e3          |
| Inner diameter of segment (mm) | 5.5e3          |
| Segment width (mm)            | 1.2e3          |

Table 1. Calculation data of shield tunnel lining segment in tunnel section (Zhang 2015).
displacement of the shield tunnel, the deformation limit of tunnel lining often depends on field cases in engineering practice. Therefore, the deformation control standards of Beijing subway (Wu 2012), Shanghai subway (Wang and Liu 2004) and Shenzhen subway

| Stratum                  | Top stratum level (m) | Thickness (m) | Water content (%) | Unit weight (kN/m$^3$) | Cohesion (kPa) | Internal friction angle (°) |
|--------------------------|-----------------------|---------------|-------------------|------------------------|---------------|-----------------------------|
| Miscellaneous fill       | 1.19                  |               |                   |                        | 6             | 12                          |
| Clay                     | -1.19 to 2.86         | 3.03          | 25.5              | 19.8                   | 39.8          | 16.4                        |
| Silty clay               | -2.50 to 0.63         | 1.98          | 28.4              | 19.5                   | 21.2          | 16.1                        |
| Gray silt                | -4.12 to -1.37        | 3.84          | 31.0              | 19.0                   | 10.8          | 25.6                        |
| Grey silty clay          | -13.84 to -5.29       | 8.35          | 30.7              | 19.1                   | 8.7           | 18.0                        |
| Powdery clay with silt   | -20.32 to -10.64      | 9.68          | 25.6              | 19.6                   | 9.5           | 26.0                        |
| Gray silt                | -22.64 to -24.40      | 7.17          | 28.4              | 19.2                   | 8.1           | 25.8                        |

Figure 1. Relationship between ERBR and calculating displacement of top lining.

Figure 2. Relationship between ERBR and calculating displacement of bottom lining.
This study based on the deformation control standards of each city and the fact that the calculating displacement has a slightly smaller value than the monitoring displacement in engineering practice, the control value of Shenzhen Subway (50% of the control value) in the standards is selected as the control value of deformation. Based on the calculating displacement of bottom lining, the values of $d_{bottom}$ corresponding to 100, 80 and 70% of the control value of deformation are selected as the judgment values of lining deformation. As shown in Figure 2, the green line is the early warning line, the orange line is the alarm line and the red one is the overrun line. The corresponding values of ERBR of three judgment values are 0.64, 0.48 and 0.29, respectively. Therefore, the risk classification based on deformation of shield tunnel lining began to take shape. As shown in Figure 3, the risk classification based on deformation of shield tunnel lining is preliminary divided into four sections. When ERBR lies within the range of 0.10–0.29, the operation tunnel is damaged so that the corresponding risk assessment result is ‘overrun’; When ERBR lies within the range of 0.29–0.48, the operation tunnel is in danger so that the corresponding risk assessment result is ‘alarm’; When ERBR lies within the range of 0.48–0.64, the operation tunnel is in a relatively safe state but can get worse so that the corresponding risk assessment result is ‘early warning’; When ERBR is greater than 0.64, the operation tunnel is in safe so that the corresponding risk assessment result is ‘safe state’.

### 2.2. Risk classification of shield tunnel lining deformation

Due to the lack of risk classification criterion based on the deformation of shield tunnel lining at this stage, the relationship analyzed above between ERBR and deformation of tunnel lining as well as the relevant engineering specifications are used, and the relevant study (Liu 2015) and the experience of tunnel operation and management (Yi and Wu 2020) are used as reference in this study, the risk classification criterion of shield tunnel lining based on deformation is finally established. At the same time, the level of risk is graded from A to E and level A is the lowest risk level. The relevant contents are shown in Table 4 and Figure 4.

### Table 3. Situation of metro track deformation control standards in China. (Wu 2012; Wang and Liu 2004; Shenzhen Metro 2007)

| Subway                  | Control item                              | Control value (mm) |
|-------------------------|-------------------------------------------|---------------------|
| Beijing Subway          | Lateral deformation of track              | 3                   |
|                         | Vertical deformation of track             | 3                   |
| Shanghai Subway         | Lateral height difference of track        | 4                   |
|                         | Vertical deformation of track             | 4                   |
|                         | Absolute displacement of subway structure| 20                  |
| Shenzhen Subway (2007)  | Lateral height difference of track        | 4                   |
|                         | Vertical deformation of track             | 4                   |
|                         | Absolute displacement of subway structure| 20                  |

Due to the complexity of site construction, monitoring errors and other factors, Beijing Subway generally takes 80% of the value as the actual control value, Shenzhen Subway and Shanghai Subway generally take 50% as the control value.

(Shenzhen Metro, 2007) in China are collected to provide ideas for the criterion of classification about lining deformation of operation tunnel, as shown in Table 3.
3. Risk assessment of shield tunnel lining during operation

In the previous section, the deformation of shield tunnel lining is transformed into ERBR and the risk classification of shield tunnel lining is obtained successfully. However, many shield tunnel lining data during operation are waiting to be processed. How to select the appropriate data as the analysis data is the premise to realize the risk assessment of operation tunnel lining. In this study, EWM and GRA are used to compare and analyze the deformation data of shield tunnel lining during operation, and thus provide a theoretical basis for the study of the relationship between the best matching deformation data and ERBR. Based on the above work, the risk assessment of operation tunnel is finally realized by combining the risk classification standards summarized before.

3.1. Entropy weight method

EWM is used to analyze and evaluate the data by analyzing the degree of data confusion. In other words, in each set of data corresponding to different indicators, the greater the degree of dispersion, the greater the degree of differentiation, the more
information can be derived, so the greater the weight of this set of data in all data set. Finally, the comprehensive weight of each indicator can be calculated, and the larger the comprehensive weight, the stronger the instability of the indicator (Zhu et al. 2020). Assuming that the number of evaluation object is $m$ and the number of evaluation indicator is $n$, then the specific steps are as follows.

Standardization processing of data. Set $Z$ to sample matrix containing $m$ evaluation objects and $n$ evaluation indicators:

$$Z = (z_{ij})_{m \times n}$$ (3)

If the evaluation indicator is positive indicator, then it is normalized to:

$$X_{ij} = \frac{Z_{ij} - \min Z_{ij}}{(\max Z_{ij} - \min Z_{ij})}$$ (4)

If the evaluation indicator is reverse indicator, then it is normalized to:

$$X_{ij} = \frac{\max Z_{ij} - Z_{ij}}{(\max Z_{ij} - \min Z_{ij})}$$ (5)

The decision matrix after standardized can be expressed as:

$$R = (x_{ij})_{m \times n}$$ (6)

where $x_{ij}$ is the evaluation value of object $i$ under the evaluation indicator $j$.

Calculating the proportion. The proportion can be calculated as:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}$$ (7)

where $p_{ij}$ is the proportion of $x_{ij}$.

Calculating the information entropy. The entropy can be calculated as:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} p_{ij} \times \ln p_{ij}$$ (8)

where $e_j$ is the information entropy of the evaluation indicator $j$.

Calculating the information entropy redundancy. The information entropy redundancy can be calculated as:

$$d_j = 1 - e_j$$ (9)

where $d_j$ is the information entropy redundancy of the evaluation indicator $j$.

Calculating the entropy weight. The entropy weight can be calculated as:

$$w_j = d_j/\sum_{j=1}^{n} d_j$$ (10)

where $w_j$ is the entropy weight of evaluation indicator $j$. 
3.2. Grey relational analysis

GRA is a part of grey system theory and has been applied in various fields to deal with the complex relationship among different sequence (Morán et al. 2006). The procedure of GRA can be divided into 4 sections: grey relational generating, reference sequence definition, grey relational coefficient calculation and grey relational grade calculation (Kuo et al. 2008). The sequences are converted to a comparability sequence, and then the reference sequence should be identified to calculate the difference between each experiment sequence and the reference sequence, after that, relational coefficient and grade should be confirmed, to analyze the correlation between them. In conclusion, the principle of GRA is to calculate the relational degree by analyzing the similarity between the undetermined sequence and the reference sequence. The higher the similarity, the higher the calculated relational degree, which means an optimism relationship existing in it (Kuo et al. 2008). The analysis steps are as follows.

Confirming the reference sequence of deformation of operation tunnel. The optimum deformation data of the operation tunnel is taken as the reference sequence $X_0$, and other deformation data collected at different time are used as the experiment sequences $X_i$.

Calculating the difference between each experiment sequence and the reference sequence one by one, as shown in Equation (12):

$$|X_i - X_0| = |X_{ij} - X_{0j}|, i = 1, ..., m; j = 1, ..., n$$ (12)

Solving the relational coefficient between each experiment sequence and the corresponding reference sequence:

$$\xi_{ij} = \frac{\min_j \left[ \min_i \left( |X_{ij} - X_{0j}| \right) \right] + \mu \max_j \left[ \max_i \left( |X_{ij} - X_{0j}| \right) \right]}{|X_{ij} - X_{0j}| + \mu \max_j \left[ \max_i \left( |X_{ij} - X_{0j}| \right) \right]}, i = 1, ..., m; j = 1, ..., n$$ (13)

where $\xi_{ij}$ is the relational coefficient, and $\mu$ is the distinguishing coefficient. The value of $\xi_{ij}$ is between 0 and 1, which reflects the degree of similarity between the location object $i$ to be selected and the reference location object under the location influencing factor $j$. The value of $\mu$ is also between 0 and 1, and the smaller the value of $\mu$, the greater the difference between $\xi_{ij}$. In general, $\mu = 0.5$.

Calculating the similarity between each experiment sequence and the corresponding reference sequence:

$$p_{ij} = \frac{1}{n} \sum_{j=1}^{n} \xi_{ij}(j), i = 1, ..., m$$ (14)

where $p_{ij}$ is the similarity between the reference sequence $X_0$ and the experiment sequence $X_i$. When the value of $p_{ij}$ is next to 1, meaning that a better relevance
existing in the two, that is, the better the data matches, the better the requirements can be met in this study.

3.3. Entropy weight-grey relational analysis

The role of the two methods in this study is to analyze the relationship among the data. Judging from the deformation data of a monitoring period, if all the data were used for analysis, a heavy workload would occur and that is not practical in engineering practice. The combination of the two methods can screen the most unfavorable deformation data out from numerous deformation data and provide a basis for subsequence analysis or optimization, thus greatly improving the efficiency of risk assessment. In addition, the grey correlation analysis can also deal with the data analyzed by ANSYS and the most unfavorable deformation data obtained by monitoring, to find the optimum monitoring deformation data and the corresponding ERBR, and then the current condition of the operation tunnel can be obtained. The risk assessment process is shown in Figure 5.

The advantage of EWM is to analyze the fluctuation degree among data, while the advantage of GRA is to analyze the similarity degree, although the evaluation directions of the two are opposite, the purposes are to evaluate the matching degree, and the accurate similarity value that represents the similarity of data can be obtained, and this value represents the range of criterion function. In the next work, as long as the minimum value of a criterion function has been set or the criterion calculation results of all data have been compared, the evaluation indicator of each group can be
obtained and the optimum data can be found. The process of solution of unsolved parameter is shown in Figure 6.

4. Method application for operation tunnel risk assessment

4.1. Displacement data analysis and selection

The deformation monitoring of shield tunnel lining is a daily maintenance, and the assessment of tunnel lining is updated with time. The assessment cycle of the case is once a month, and the frequency of deformation monitoring of tunnel lining is once a week. In this study, the deformation data used are the monitoring data after processing, with a distribution of circumference, a total of 360 monitoring points (Zhang 2015). Ideally, the deformation of operation tunnel should be closer to the non-deformation. Therefore, in the process of using the GRA, the reference matrix is null vector matrix with zero accumulative deformation, and the evaluation matrix consists of 4 groups of monitoring data in each monitoring period. The results obtained by using GRA are shown in Table 5. The evaluation similarities of four groups are all greater than 0.9, and the Group 2 is the highest and the Group 3 is the lowest. According to the criterion of GRA, the data of Group 3 are the most unfavorable deformation data in the monitoring period.

The difference between the EWM and GRA is, EWM pays more attention to the change of data, that is, each monitoring point of the shield tunnel lining structure represents an assessment unit, each assessment unit will fluctuate in the same monitoring period. The greater the degree of fluctuation or confusion, the more unstable the assessment unit, thus the greater the weight of data. The total weight can be obtained by summing the weights of each evaluation unit of each group of data, that is, the total weight of the group of data. The results by using EWM are shown in Table 6. It can be seen that the Group 3 has the highest weight, and the Group 1 has the lowest weight. According to the criterion of EWM, the data of Group 3 are the most unfavorable deformation data in the monitoring period.
The perspectives of two methods are different and each has its advantages and disadvantages, so the results obtained by two methods are unified into reverse indicators through normalization, to make sure that the analysis is comprehensive. The results are shown in Table 7. It can be seen that the combination result of Group 3 is the lowest, which means that the data of Group 3 have the strongest representativeness and can best reflect the most unfavorable conditions of shield tunnel lining during operation.

### 4.2. Obtaining the effective ratio of bending rigidity

In the range of joint stiffness in engineering practice, ERBR varies from 0.1 to 0.85. In this study, 76 groups of calculating displacement data under different ERBR (with a unit change of 0.01) are calculated and numbered from 1 to 76. The displacement matching matrix $H$ is constructed based on the displacement data of 76 groups, as shown in Formula 15. In addition, the reference matrix $X_0$ is made up of the data of Group 3, as mentioned above.

$$H = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}, \quad m = 1, 2, 3, \ldots, 360, \quad n = 1, 2, 3, \ldots, 76$$

In particular, GRA is used again, to compare the displacement matching matrix and the reference matrix, and the optimal matching displacement array can be obtained, which is named as $X_i$, and $i$ is the array number, thus the ERBR ($\eta_i$) of $X_i$ can be identified by the array number. Table 8 shows the partial results and the corresponding ERBR, it can be found from Table 8 that the similarity of the array with...
a number of 72 of is the highest with a value of 0.6725, and the corresponding ERBR is 0.81, that is, under the current condition of operation tunnel, the ERBR is 0.81.

### 4.3. Risk assessment of operation tunnel

According to Figure 4, the shield tunnel lining during operation is safe when the value of ERBR is between 0.75 and 0.85, and the operation tunnel requires only normal monitoring. The result obtained by assessment model with a value of 0.81 falls within this interval. According to the operational condition of Leyuan Station-Tayuan Station of Suzhou Metro Line 1, the shield tunnel lining is in healthy, which is corresponding to the results that obtained by using the assessment model. This case illustrates that the risk assessment model of operation tunnel based on GRA and EWM is viable and feasible, and can accurately judge the disaster risk of tunnel deformation during operation.

However, the application of proposed method is subject to the accuracy of data. The monitoring technology of tunnel lining structure displacement is very strict, at present, only DFOS can meet the data requirements, while the application of DFOS in tunnel is in development stage and there are few tunnel cases of DFOS applied in China. Further validation on proposed method is required if the deformation data are obtained by other monitor methods.

### 5. Application for risk assessment of operation tunnel

If the assessment method is to play a guiding role in engineering practice, the final step must focus on the convenience of the application of the method, and fortunately computer technology can provide great convenience for risk assessment.

With the existing research, the completed process of risk assessment generally includes five parts: determining monitoring indicators, obtaining monitoring data, establishing assessment model, obtaining assessment level and giving treatment plans. The main purpose of this application is to make the risk assessment of operation tunnel conveniently and efficiently, the load interface is shown in Figure 7. In the developed application of this study, the monitoring indicators, assessment model and corresponding treatment plans have been already designed. What are needed to type in the application is the monitoring data and the specific engineering background data.

Table 8. Results of GRA and corresponding ERBR.

| Number | Similarity of GRA | ERBR | Number | Similarity of GRA | ERBR |
|--------|------------------|------|--------|------------------|------|
| 1      | 0.5931           | 0.10 | 40     | 0.6364           | 0.49 |
| 2      | 0.5945           | 0.11 | 41     | 0.6375           | 0.50 |
| 3      | 0.5953           | 0.12 | 42     | 0.6386           | 0.51 |
| 4      | 0.5961           | 0.13 | 43     | 0.6397           | 0.52 |
| 5      | 0.5975           | 0.14 | 44     | 0.6408           | 0.53 |
| 6      | 0.5987           | 0.15 | 45     | 0.6419           | 0.54 |
| ...    | ...              | ...  | ...    | ...              | ...  |
| 20     | 0.6140           | 0.29 | 70     | 0.6698           | 0.79 |
| 21     | 0.6151           | 0.30 | 71     | 0.6712           | 0.80 |
| 22     | 0.6162           | 0.31 | 72     | 0.6725           | 0.81 |
| 23     | 0.6173           | 0.32 | 73     | 0.6722           | 0.82 |
| 24     | 0.6184           | 0.33 | 74     | 0.6719           | 0.83 |
| 25     | 0.6195           | 0.34 | 75     | 0.6712           | 0.84 |
5.1. Data inputting

The risk assessment application is developed using Visual Basic 6.0. The input interface of the application is shown in Figure 8. The information typed in here is used to form the displacement matching matrix. Make sure that all parameters are input, then click the ’Build matching matrix’ button. Here, the formation of the displacement matching matrix will be carried out in the backstage based on ANSYS.

5.2. Treatment of information

After the displacement matching matrix is constructed, the application will automatically jump to the assessment interface, as shown in Figure 9. Click ’Import displacement data’ and ’Get the most unfavorable displacement matrix’ in turn, to process displacement data and output the most unfavorable displacement data together with the number of group. After all preparations have been made, click ’Risk assessment’ can realize the risk assessment of tunnel deformation during operation based on measured displacement data, and the assessment result is presented to the risk level buttons below.
5.3. Results calculated by system

After following the steps in the previous section, in this case, as shown in Figure 9, the most unfavorable displacement data are from ‘Group 3’ and the button of ‘A’ is selected, which means that the deformation risk assessment result of operation tunnel is A, that is, the tunnel is in safe. By using EWM and GRA, the most unfavorable displacement data can be extracted easily and both point to the fact that the most unfavorable, in other words, the most representative displacement data are from ‘Group 3’. According to formula 2 and Figure 4, ERBR in this case falls within the range of 0.70–0.85, so the calculated result presented to users is ‘A’. The result calculated by this system is consistent with result that obtained by using the assessment model in Section 4.3. Hence, the developed system is reliable in this research for assessment.

6. Conclusion

In this article, a new risk assessment model and a self-developed software were applied to assess the risk level of shield operation tunnel. Based on the Suzhou Metro Line 1 deformation data of the shield tunnel lining during operation, the relationship between ERBR and tunnel deformation was analyzed, the results showed that ERBR has a negative power relationship with tunnel deformation, and ERBR was selected as criterion to establish the deformation risk assessment model of operation tunnel. Moreover, GRA and EWM were comprehensively used to deal with the deformation data to overcome the problem that data selection is not representative. ERBR is obtained successfully by using GRA to complete the risk assessment of operation tunnel. Finally, a software was developed to make sure that the assessment can be realized conveniently and efficiently. The detailed descriptions are as follows.

There is a negative power relationship between ERBR and tunnel deformation, the tunnel deformation decreased with the increase of ERBR, which provides meaningful suggestion to reduce the risk of shield tunnel lining structure, that is, ERBR can be seen as the sign of tunnel health. The boundary values for tunnel failure were obtained according to the failure criterion of shield tunnel lining, and then the risk classification criterion of shield tunnel lining based on deformation was finally established, and the level of risk was graded from A to E.
In practice, many monitored displacement data can be obtained by DFOS or other monitor methods, so that data screening is a significant part of data analysis. In this study, the most unfavorable displacement data in a monitoring cycle were sift out quickly and accurately by the combination using of GRA and EWM. GRA was used again, to compare the displacement matching matrix and the reference matrix, and the optimal matching displacement array and corresponding ERBR were obtained so that the health of shield tunnel can be known. The feasibility and effectiveness of model were verified by the deformation data of DK5 +275m–DK5 +275m section of the downline area of Leyuan Station-Tayuan Station of Suzhou Metro Line 1.

A self-developed software named Operation Tunnel Deformation Risk Assessment System was developed by using computer technology. The risk assessment of operation tunnel was conveniently, rapidly and accurately implemented by computer technology, which further validated that the proposed model is effective and feasible.

However, the proposed model only targets at shield tunnel. In the future, other types of tunnels are also worth to be investigated. Besides, the software still needs to be further improved. For example, users can obtain three-dimensional model by inputting corresponding parameters, or the software can receive real-time displacement data of construction site, to make the more exact assessment.

**Disclosure Statement**

The authors have no relevant financial interests to disclose.

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**Data availability statement**

The data that support the findings of this study are available from the corresponding author, Yingchao Wang, upon reasonable request.

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