

Integrated Influence Zone Calculation Method for the Existing Metro Tunnel Under the Influence of Adjacent Construction

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Abstract Adjacent construction around metro tunnels is a common situation in urban cities, which usually leads to the disturbance of surrounding soils and existing tunnels. Based on the influence zone theory, construction risks can be described in a graded manner. However, the calculation of the influence zone in existing research is mostly based on a single indicator, which is difficult to adapt to the increasingly stringent requirements of real projects. To address this limitation, a normalized method for the influence function and a weighted combination method for multi-indicators were proposed. These methods can combine any number of indicators to obtain an integrated result of the influence zone, facilitating direct guidance of engineering. Based on a case study of the Metro construction in Qingdao, a series of numerical simulations and calculations of the integrated influence zone was carried out. The results show that the shape of the integrated influence zone in this case is a necked bottle, i.e., the new tunnel causes a greater influence when it is below the existing tunnel. The change of soil layer and the weight of indicators both play important roles on the shape of the influence zone. The relevant conclusions and methods provide a basis for the safety assessment of similar projects.

Keywords Metro tunnel · Adjacent construction · Influence zone · Multi-indicators

1 Introduction

The ever-growing density of China's urban rail transit network has resulted in a surge of adjacent construction projects, such as the construction of new tunnels near existing metro tunnels. These tunnels can cause significant disturbances to the surrounding soil, resulting in a redistribution of the stress field and soil deformation. It is therefore essential to pre-evaluate the risk of the existing tunnels being affected by these disturbances in order to mitigate any potential negative impacts. The influence zone is an effective and visual tool for pre-evaluation, which is a designated area around an existing structure where construction activities may have an impact on the structure or environment. The systematic study of the influence zone originated in Japan [1], and it indicated that the degree of influence of adjacent construction is related to the type and scale of the construction, the locations between new and existing structures, geological conditions, and other factors. Based on this, a typical influence zone of the tunnel was proposed, which is shown in Fig. 1a. Qiu [2] applied mathematical mechanics to quantitatively describe the degree of influence and refined the typical influence zone, which is shown in Fig. 1b. Based on the framework proposed by Qiu, studies for the influence zone of two-hole [3–5] and three-hole [6, 7] parallel tunnels were carried out by numerical simulation. In these studies, factors such as the depth, distance, relative position, and construction sequence of tunnels were analyzed in relation to the influence zone. With the improvement in computing ability, the three-dimensional (3D) numerical simulation of the tunnel boring process becomes a reality. Wang et al. [8]

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simulated the whole process of tunneling based on Shenzhen Metro Line 3, and divided the transverse and longitudinal influence zone with the Mohr–Coulomb criterion and displacement change rate, respectively. Li et al. [9] established a finite element model of Beijing Metro Line 16, used the stiffness migration method to simulate the shield tunnel boring process, and analyzed the variation in the ground deformation and the structural internal force.

Studies related to the influence zone usually involve the comparison of multiple groups of different conditions, so most of them are based on numerical simulation. However, apart from numerical simulation, some scholars have tried the model test and the theoretical analysis. Boonyarak and Ng [10] simulated the process of tunnel excavation through an annular valve device and presented the influence of new tunnels with different depths on the existing tunnel. Through a reduced-scale model, Choi and Lee [11] studied the influence of the tunnel size, the distance between tunnels, and the earth pressure coefficient on the mechanical behavior of the existing tunnel, then proposed the minimum spacing to avoid tunnel interactions. Zhou et al. [12] deduced the stress state of rock mass around a tunnel by elastoplastic theory and the Hoek–Brown nonlinear failure criterion, and proposed the influence zone of the tunnel subjected to adjacent constructions. Zhou et al. [13, 14] deduce a prediction formula for the deformation of the ground surface and the existing tunnels caused by twin-tunnel construction and analyzed the influence range of the horizontal settling trough based on several engineering cases.

In general, many studies on influence zones are based on the evaluation criterion summarized by Qiu, and scholars have chosen different indicators to complete quantitative evaluations. However, these evaluations mostly adopt a certain indicator or analyze the same case several times through several different indicators, but rarely combine

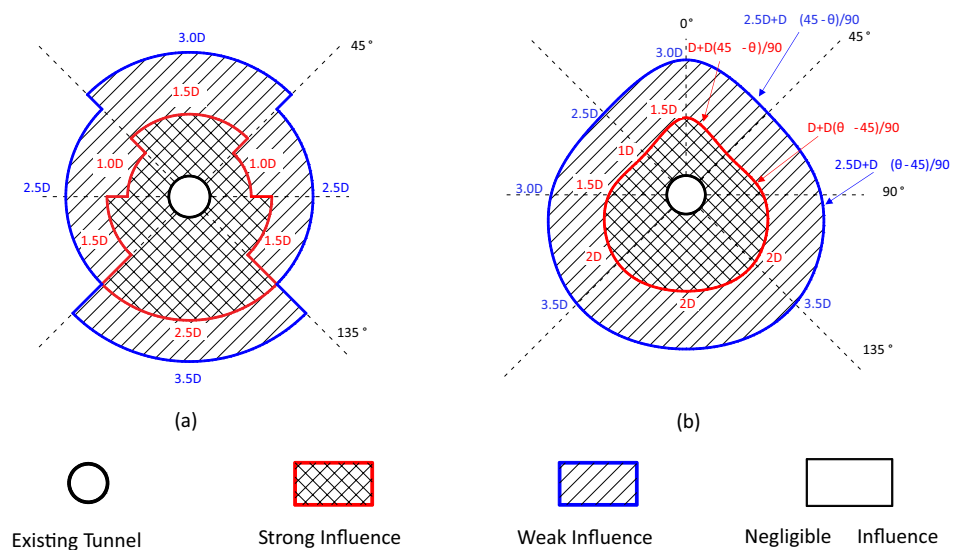
different indicators to propose an integrated evaluation. A single indicator can only reflect a certain aspect of the structural safety or environmental influence, which is no longer suitable for actual projects with increasing complexities and restrictions. Based on this condition, this paper introduces the classic evaluation method for the influence of adjacent construction on tunnels and proposed an integrated method for establishing an influence zone. For the typical situation where the construction of a new tunnel around an existing metro tunnel, a normalization method for influence function and a multi-indicator weighted combination method are proposed. Based on a metro project in China, the construction process of a typical situation is simulated by the finite element method and then the corresponding integrated influence zone is proposed. In addition, the shape and properties of the integrated influence zone are analyzed and compared with existing studies.

2 The Evaluation Method for the Adjacent Construction

2.1 Environmental Evaluation Indicator

The influence of adjacent construction on the environment is mainly manifested by soil deformation and stress redistribution, so relevant evaluations can be made in these two dimensions. For soil deformation, the ground settlement is usually used as the evaluation indicator. In China, 30 mm has long been used as the control value for ground settlement [4, 7]; the standard for urban rail transit projects requires the ground settlement to be less than 30 mm (hard to medium hard soil) or 35 mm (medium soft to soft soil) for overlapping tunnels [15]. If there are buildings set on the ground, the settlement is also required to meet the control value for

Fig. 1 The influence zone proposed by (a) Japanese guidance and (b) Qiu



the structures [16, 17]. As for the soil stress condition, it usually refers to the stress value or elastic-plastic state, which is mostly obtained through theoretical analysis or numerical simulation. Whether the plastic zone of the soil around the tunnels is interconnected or not can be an indicator to distinguish two states of the soil stress condition. Meanwhile, some studies [3, 8, 18] made more detailed judgments based on yield criterion, for example, the Mohr–Coulomb criterion can be expressed as:

$$I_F = p \sin \varphi + \frac{q}{\sqrt{3}} \left(\cos \theta - \frac{1}{\sqrt{3}} \sin \theta \sin \varphi \right) - c \cos \theta \quad (1)$$

$$p = \frac{1}{3} (\sigma_1 + \sigma_2 + \sigma_3) \quad (2)$$

$$q = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \quad (3)$$

$$\theta = \frac{1}{\sqrt{3}} \mu_\sigma = \frac{1}{\sqrt{3}} \left(2 \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} - 1 \right) \quad (4)$$

where I_F is the judgment value of the soil elastoplastic condition, θ is the stress lode angle, c is the cohesive force, φ is the friction angle, p is the average stress, q is the equivalent stress, and $\sigma_1, \sigma_2,$ and σ_3 are the principal stress. According to the change in I_F before and after the tunnel construction, the stress state of the soil can be distinguished.

2.2 Structural Evaluation Indicator

The structural performance of tunnels is also an important aspect of safety evaluation, and relevant indicators can also be divided into two dimensions: deformation and stress of the tunnel. The deformation property can be reflected by many evaluation indicators, such as vertical displacement, horizontal displacement, convergence deformation, and longitudinal differential deformation. Among them, many standards limit the convergence deformation of the tunnel: the convergence value of the tunnel should be less than 20 mm [19] or 0.2% of the tunnel’s outer diameter [15]; the ellipticity of the tunnel should be less than $\pm 6\%$ [20]. From another point of view, stress refers to the load-bearing state of the tunnel, specifically reflecting whether the stress reaches the ultimate strength of the material. Many studies have evaluated the tunnel state based on the change in tunnel stress. In the Japanese guidelines [1], the additional stress generated by the new tunnel on the existing tunnel is used as an indicator, and the allowable increase values of tensile and compressive stresses are 0.5 MPa and 2.0 MPa, respectively. [21] took additional compressive stress of 1.2 MPa

and 2.0 MPa as grading values of different influence degrees for tunnels in soft soil. These absolute values of additional stress are generally determined by the material properties but ignore the different working states of existing tunnels. For tunnels with different reinforcement, the same grading value may amplify or reduce the degree of influence. Therefore, the relative value of the stress [7] or the reliability [6] have also been used to evaluate the condition of tunnels, for example, the internal force level of the tunnel [7] is defined as:

$$C_s = \sqrt{\frac{M^2 + N^2}{M_u^2 + N_u^2}} \quad (5)$$

where M and N are the current bending moment and axial force of the tunnel, and M_u and N_u are the design ultimate value of the bending moment and axial force. This indicator reflects the distance between the current state and the limit state on the internal force envelope diagram.

2.3 Calculation Method for the Influence Zone

Based on the above-mentioned environmental and structural evaluation indicators, influence values under different adjacent degrees are usually calculated by multiple sets of working conditions, and then the influence zone is divided by comparison with corresponding grading values. In tunneling engineering, the adjacent degree generally refers to the relative distance:

$$x = \frac{S}{D} \quad (6)$$

where x is the adjacent degree, S is the distance between the new tunnel and the existing tunnel, and D is the dimension of the adjacent project, which is generally taken as the diameter of the new tunnel.

The typical three-level influence zone of the tunnel is shown in Fig. 1 and it is divided by two thresholds of the adjacent degree in each direction. As shown in Table 1, three levels are often used to characterize the strong, weak, and negligible influence conditions and guide the relevant projects to take appropriate measures.

The current evaluation system mostly uses a single indicator to determine the three-level influence zone, while few combine different indicators for an integrated evaluation. A single evaluation indicator often has limitations, which are manifested in two aspects:

On the one hand, for most indicators, the adjacent degree and influence are negatively correlated, which means that the closer the distance between tunnels, the stronger the influence. However, the influence can be qualitatively divided into positive and negative influences, and a strong influence does not always mean unsafe. In the case of two tunnels with parallel axes, when the new tunnel is built above or below

Table 1 The principle of the three-level influence zone

Influence zone	Characteristic	Measure
Strong influence (I)	The influence of a new tunnel on the existing tunnel is large and can be a danger if not handled properly.	A targeted construction plan must be adopted, and safety risk management should be implemented for both existing and new tunnels.
Weak influence (II)	The new tunnel has some impact on the existing tunnel, but the influence is weak.	Extra measures should be decided based on the capacity of the existing tunnel to resist the additional force and deformation.
Negligible influence (III)	The new tunnel has essentially no influence on the existing tunnel.	No need to consider the influence of new tunnel construction

the existing tunnel, the vertical unloading effect of construction is enhanced with the decreasing adjacent degree, resulting in a significant reduction in the stress of the existing tunnel, which has a positive influence for structure. While the opposite situation is observed when the new tunnel is built on the side of the existing tunnel, this stress increases with decreasing adjacent degree, which shows a negative influence. Thus, the adjacent degree here shows different effects in different directions, and if the tunnel stress is used as the only indicator, the classical influence zone can only reflect the absolute strength of the influence and cannot distinguish whether it is positive or negative. This would leave the influence zone without guidance in some directions when engineers focus more on the negative influence during evaluation.

On the other hand, the complexity and sensitivity of tunneling engineering have increased dramatically with the increase in adjacent projects; thus, increasingly diverse and strict requirements are proposed. Still taking the case of construction above or below an existing tunnel as an example, smaller distance between tunnels improves the structural force but leads to larger vertical displacements of the existing tunnel, making it difficult to meet the stiffness requirements. Therefore, it is no longer practical to use a single indicator to propose a useful influence zone.

3 Integrated Influence Zone Method

3.1 Normalization Method for the Influence Function

The influence function is a function that describes the relationship between the adjacent degree and the value of an indicator. The corresponding influence function can be fitted by data points, and scholars generally fit it to the following form:

$$I = f(x) = Ae^{Bx} + C \quad (7)$$

where I is the value of an indicator, x is the adjacent degree, and A , B , and C are the coefficients to be fitted.

This influence function is a typical nonlinear curve, which can be fitted by the least squares method. It is worth noting that the available combinations of coefficients to be fitted are not unique. When there are several orders of magnitude differences between the coefficients, the adjacent degree x will be approximately ignored, making the guidance of the fit much less meaningful. Therefore, the three coefficients of the influence function should be as small and close as possible. Thus, the Levenberg–Marquardt method [22] is recommended to obtain the parameter vector with the minimum function value in several optimization steps. According to the fitted influence function and the grading values of the corresponding indicator, several thresholds of the adjacent degree x_1, x_2, \dots, x_n can be back-calculated, where n is the number of thresholds and generally $n = 2$, which means that two thresholds divide three different influence levels.

Obviously, there are differences in the grading values between different indicators; for example, the surface settlement of 10 mm and the additional structural stress of 0.5 MPa are grading values of weak and negligible influence, respectively, but their values differ by two orders of magnitude. Such differences make it difficult to make comparisons in quantity between multiple indicators. Thus, a feasible solution is to normalize the influence function of each indicator so that any normalized influence function has the same grading value Z_i at each threshold x_i . For a case with the three-level division, the two thresholds of the adjacent degree are x_1 and x_2 ($0 < x_1 < x_2$), and the normalized grading values are set as Z_1 and Z_2 ($Z_1 > Z_2 > 0$), based on which the normalized influence function can be defined as

$$\alpha_I = g(x) = Z_2 \left[\frac{f(x)}{f(x_2)} + k \left(e^{B(x-x_2)} - 1 \right) \right] \quad (8)$$

By merging similar terms, this function can also be expressed as

$$g(x) = \left(\frac{Z_2 A}{f(x_2)} + \frac{Z_2 k}{e^{Bx_2}} \right) e^{Bx} + \left(\frac{Z_2 C}{f(x_2)} - Z_2 k \right) = A' e^{Bx} + C'$$

The normalized function $g(x)$ maintains the same line shape and trend as the original influence function $f(x)$. By setting the condition $g(x_i) = Z_i$, the coefficient k can be calculated

$$k = \frac{\frac{Z_1}{Z_2} - \frac{f(x_1)}{f(x_2)}}{e^{B(x_1-x_2)} - 1} \tag{9}$$

For any indicators, the corresponding normalized influence function can be obtained by presetting the same normalized grading values Z_1 and Z_2 . The value of the normalized function represents the following: $|\alpha_l| \geq Z_1$ means strong influence, $Z_1 < |\alpha_l| \leq Z_2$ means weak influence, and $|\alpha_l| < Z_2$ means negligible influence. To facilitate the subsequent evaluation, a positive value of α_l implies that the construction has a detrimental effect on the existing structure, while a negative value implies a beneficial effect.

3.2 Weighted Combination Method for Multi-Indicators

The normalization makes different indicators have numerical additivity and comparability. Based on these properties, the influence of each indicator can be combined to obtain an integrated evaluation, such as using the weighted method, which can be expressed as

$$I_c = \sum_{i=1}^n \omega_i \alpha_{l,i} \tag{10}$$

where I_c is the integrated influence function, n is the number of indicators, ω_i is the weight of the i th indicator, and $\alpha_{l,i}$ is the normalized influence value of the i th indicator.

The essence of the weighted combination method is a linear variation, so when the sum of all weights is 1 ($\sum_{i=1}^n \omega_i = 1$), the weighted influence function will inherit the property of the normalized influence function, which is the function value represents different degrees of influence based on the preset grading values Z_i . This property makes it easy to evaluate the influence with any number of indicators. Thus, based on engineering experience and related requirements, the weights can be set by certain strategies to show the preference of each indicator. There are various strategies for weight setting; for example, when there is no specific preference, the average principle can be applied:

$$\omega_i = \frac{1}{n} \tag{11}$$

Or conservatively, considering all indicators, the indicator with the maximum influence can be selected as the basis for the evaluation, so the maximum principle can be applied:

$$\omega_i = \begin{cases} 1 & \forall j \in \{j|1 \leq j \leq n\}, \alpha_{l,i} \geq \alpha_{l,j} \\ 0 & \exists j \in \{j|1 \leq j \leq n\}, \alpha_{l,i} < \alpha_{l,j} \end{cases} \tag{12}$$

More detailed differentiation of the weights can also be obtained by the analytic hierarchy process (AHP) or expert scoring system. Many studies [23–25] have been carried out on the weight of various indicators in tunneling, and the consensus can provide a basis for determining the weights.

4 Case Study

4.1 Project Profile

To specify the integrated influence zone method, a series of numerical simulations are conducted based on a Metro construction project, and the integrated influence zone of this case is analyzed. The project is in Qingdao, China, and the plan is shown in Fig. 2. North Qingdao station is an interchange station for Metro Line 3 and Line 8. The tunnels of Line 8 are laid along the sides of Line 3 and underneath cross Line 3 with an angle of 16° after 250 m away from the station. Line 3 tunnels are the existing tunnels with a burial depth of 10 m; Line 8 tunnels are newly built by the mining method with a distance of 1.8–4.4 m from Line 3.

4.2 Validation of Basic Numerical Model

In order to ensure the reasonableness of the subsequent multi-conditions analysis, a basic model for simulating the process of adjacent constructions is established, and the results are compared with the monitoring data. This model is established by Plaxis 3D, and its schematic is shown in Fig. 3. The model size is $X \times Y \times Z = 200 \text{ m} \times 130 \text{ m} \times 70 \text{ m}$. Tunnels are simulated using the elastic plate, and the soil and rock are simulated based on the Mohr–Coulomb model with the parameters shown in Table 2. During the simulation process, the twin tunnels of Line 3 are first constructed under the initial ground stress, and then the right line tunnel and left line tunnel of Line 8 are constructed sequentially.

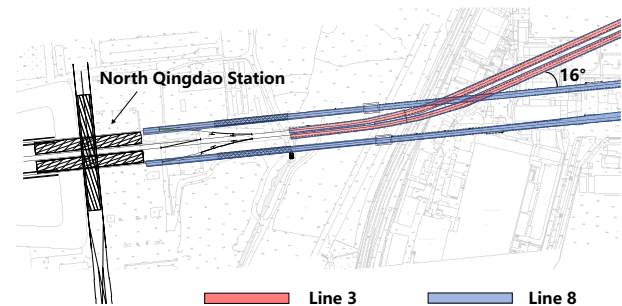


Fig. 2 Plan of Metro Line 3 and Line 8 in Qingdao

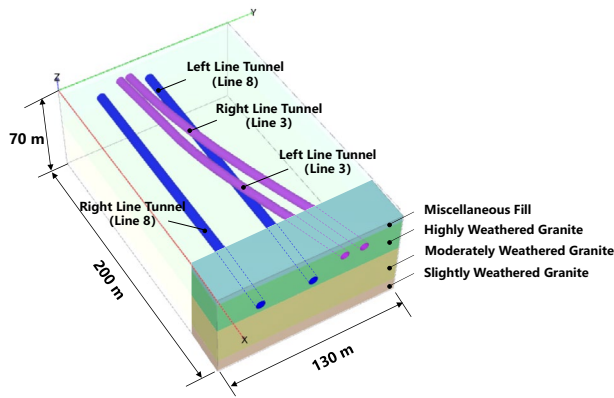


Fig. 3 Diagram of the numerical model for Line 3 and Line 8

The monitored data come from the total station arranged in tunnels of Line 3, and the displacement of Line 3 is measured during the construction of Line 8. The plan of the monitoring points is shown in Fig. 4. The spacing between adjacent monitoring sections is 5 m and is locally densified to 3.5 m in the undercrossing area. Further, the locations of the maximum deformation of Line 3 are marked in Fig. 4. The maximum vertical settlement occurs in the crossing section of the left line with a value of -2.11 mm (V_{min}), and the maximum heave deformation occurs in the right line with a small value of 0.07 mm (V_{max}); the maximum horizontal displacement occurs at the undercrossing sections of the right line, with the values of 0.93 mm (H_{max}) and -1.11 mm (H_{min}) in different directions.

For the numerical model results, when the right line tunnel of Line 8, which is far from the existing tunnels of Line 3, is constructed, the displacement of the existing tunnel is small: the maximum settlement is 0.35 mm and the maximum horizontal displacement is 0.2 mm. After the construction of both tunnels of Line 8, the existing tunnels are obviously affected, which is shown in Fig. 5. The tunnels mainly settle in the vertical direction, showing a typical settlement trough along the X axis. The horizontal displacement of the tunnels shows a sine shape along the

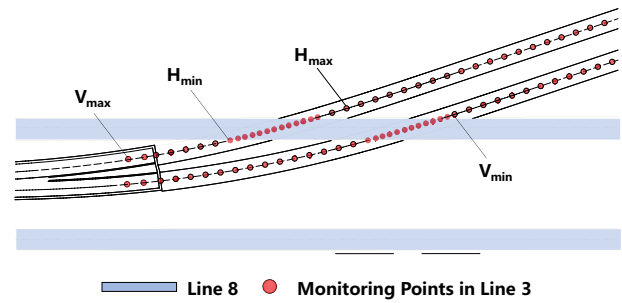


Fig. 4 Plan of the monitoring points in the Line 3 tunnels

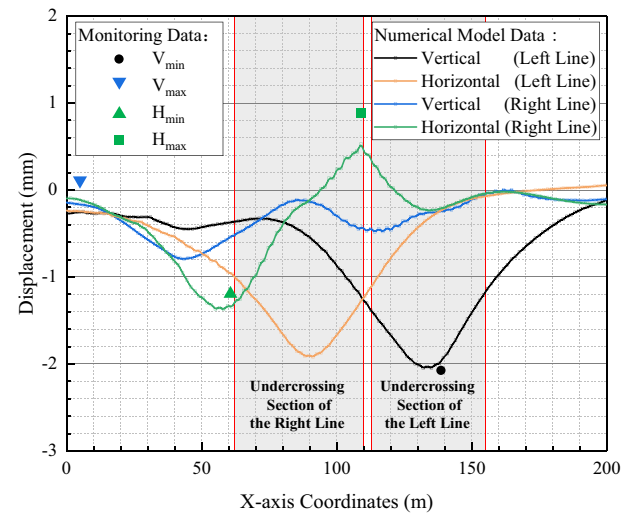


Fig. 5 Displacement of the Line 3 tunnels after the construction of Line 8

X axis, and the amplitude of the right line is larger with the maximum value appearing at the two boundaries of the undercrossing section. Meanwhile, the calculation results of the numerical model and the monitoring data are in good agreement, indicating that the simulation method is reasonable, and this basic model can be used for subsequent analysis.

Table 2 Parameters adopted for the numerical model

Material	Thickness (m)	Density (kN/m ³)	Elastic modulus (kPa)	Poisson's ratio	Cohesion (kPa)	Friction angle (°)
Miscellaneous fill	5	18.0	9.00×10^3	0.30	10	20
Highly weathered granite	25	23.8	5.00×10^5	0.28	29	35
Moderately weathered granite	30	24.2	2.00×10^6	0.22	100	42
Slightly weathered granite	10	25.2	3.60×10^6	0.16	665	49
Concrete of tunnel	0.35	25.0	3.35×10^7	0.20	\	\

4.3 Calculation of the Integrated Influence Zone

In order to obtain sufficient data for calculating the influence zone, a series of 3D models for the construction of a new tunnel around an existing tunnel are established. The input parameters of the models are identical to the above calibrated parameters in the basic model, while only the position of the new tunnel is changed in different conditions. More specifically, the calculation scheme is shown in Fig. 6. Two tunnel axes are parallel and the vertical angle, which is the angle between the tunnel center connection line and the horizontal line, is set to 45°, 0°, -45°, and -90°. In each direction, the adjacent degrees are set to nine different values from 0.25 to 4.0. Notably, the 45° condition is calculated only for the first four adjacent degrees to ensure the new tunnel is not above the ground and the angle of 90° is not considered due to the shallow burial depth of the existing tunnel. With these models, the influence of the existing tunnel can be quantitatively characterized by different indicators and the corresponding influence function can be fitted.

During the calculation, the horizontal and vertical convergence deformations of the tunnel, the internal force level of the tunnel, and the ground settlement above the tunnel are used as indicators. For consistency, the influence degree of each indicator is defined as

$$I = \frac{I_{new} - I_0}{I_0} \tag{13}$$

where I_0 is the indicator value after the construction of the existing tunnel only, I_{new} is the indicator value after the construction of both the new and existing tunnels. The influence I is indicated by positive values for adverse influence on the existing tunnel, and negative values for beneficial influence. Based on the relevant studies and standards, the grading values between different influence levels are shown in Table 3.

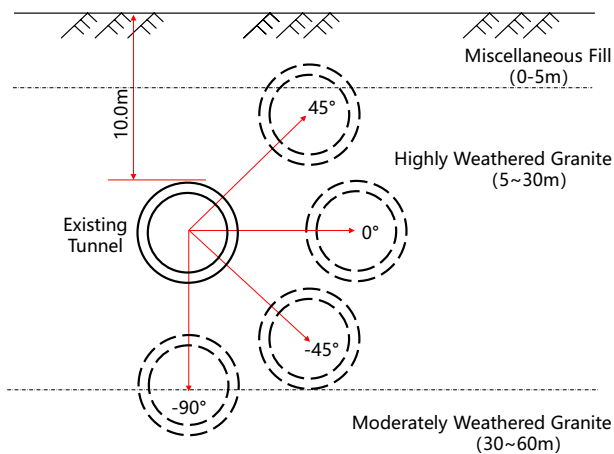


Fig. 6 The relative position of the tunnels

Table 3 The grading values of four indicators

Indicator	Strong/weak influence (%)	Weak/negligible influence (%)
Horizontal convergence	2	0.5
Vertical convergence	2	0.5
Internal force level	20	5
Ground settlement	100	10

As an example, the calculation results and fitted influence functions of the internal force level are shown in Fig. 7. As the adjacent degree increases, the influence of the construction on the existing tunnels decreases, while the effect of the influence in different directions is not the same; the construction directly beneath the existing tunnel will reduce the internal force to a lower level than the pre-construction state, so the influence is positive. Not all indicators present the same trend as Fig. 7, for the multilayer soil situation involved in this case study, the ground settlement decreases sharply when the new tunnel is fully buried in the moderately weathered soil. For this trend change caused by the layer change, the data before or after the first mutation point can be ignored to ensure the fitting effect. By this processing, situations with large negative influence are focused on and a more conservative influence function can be constructed.

With fitted influence functions under each indicator and direction, the normalization can be performed based on Eqs. (8) and (9). In this case, the normalized grading values are set to $Z_1 = 3$ and $Z_2 = 1$, which means that a strong, weak, and negligible influence on the existing tunnel will be observed when the normalized influence value is in the intervals $\alpha_I \geq 3$, $1 \leq \alpha_I < 3$, and $\alpha_I < 1$, respectively. As an

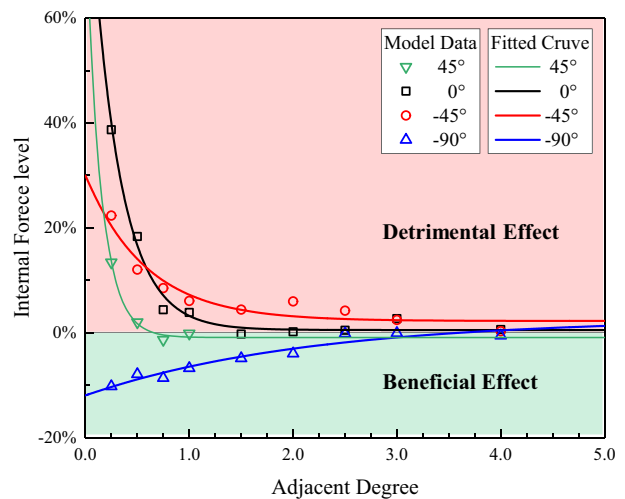


Fig. 7 Influence function for the internal force level in each direction

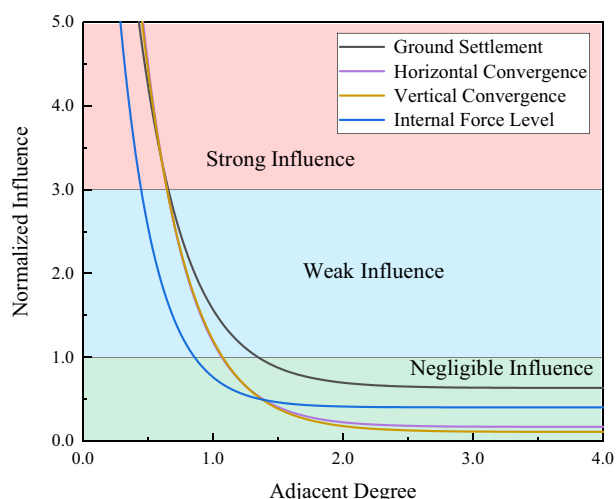


Fig. 8 Influence function for each indicator at a vertical angle of 0°

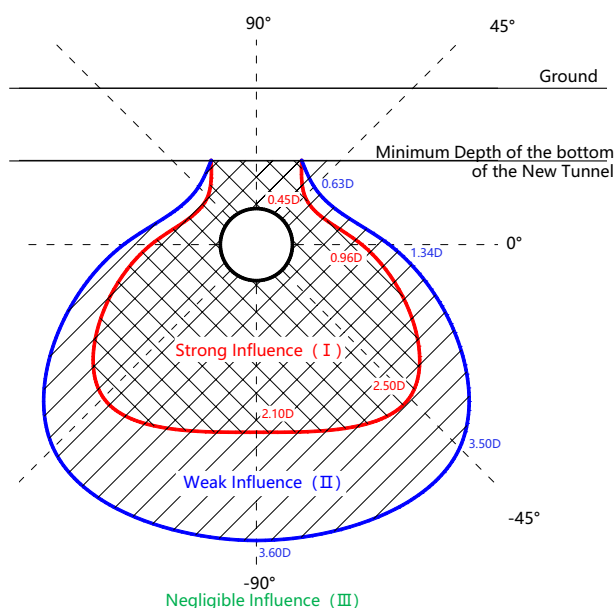


Fig. 9 Intergrade influence zone under the maximum principle

example, the normalized functions of the vertical angle of 0° are shown in Fig. 8. The figure shows that different indicators have different changing trends with the adjacent degree: the function of the ground settlement lies above the rest functions, indicating that it has the largest thresholds of the adjacent degree, while the internal force level is the opposite. A larger threshold means that the influence decreases more slowly with the increase in the adjacent degree.

In this case study, the strongest influence is considered as the result, so an integrated influence function with weights based on the maximum principle can be obtained by Eqs. (10) and (12). Two thresholds for each direction are

back-calculated, and the result is presented in the form of the influence zone shown in Fig. 9. The influence zone of this case is in the shape of a necked bottle: the influence zone is smaller when the new tunnel is built above the existing tunnel, and larger otherwise. The boundary of the strong influence zone is nearly horizontal and located at the demarcation of the soil layers, reflecting the characteristics of the multilayer condition. In addition, the difference between the two thresholds, which is the distance between the red line and blue line in Fig. 9, increases with the increasing depth of the new tunnel.

The above influence zone is based on the result of parallel tunnels, which is a special case where the angle between two tunnel axes in the horizontal plane is 0°. As for the tunnel crossing project, the horizontal angle of the two tunnels can be any value between 0° and 90°. Based on the previous method, the results of the undercrossing conditions (the vertical angle is -90°, the horizontal angle is from 0° to 90° and the adjacent degree is from 0.25 to 4) are calculated and it shows the different correlation between horizontal angle and indicators. When the horizontal angle increases from 0° to 90°, the undercrossing construction gradually changes from a positive influence to a negative influence on the convergent deformation and internal force level of the existing tunnel, but slightly changes the ground settlement. The integrated threshold of the adjacent degree rises as the horizontal angle increases and reaches a maximum of 2.20 D at the horizontal angle of 90°, which is only a 0.10 D difference compared to the 0° condition. Thus, the horizontal angle in the undercrossing condition has a much weaker influence when compared with the vertical angle. Based on this and Fig. 9, we can speculate that the left line tunnel of Line 8 in the above case is in the strong influence zone of the tunnels of Line 3.

4.4 Comparative Analysis

Referring to the results of the established research, the integrated influence zone proposed by this study is compared and analyzed. Figure 10a shows the difference between this paper and Qiu [2], the two are closer when the vertical angle is below 0°; Fig. 10b shows the difference between this paper and Wen [4], the necked bottle shape and the thresholds are partly similar. It can be concluded that the influence zone proposed in this paper has some common perceptions with the established studies, but still exists some differences due to the multilayer condition and the integrated method. From another perspective, the weight setting of each indicator is also an important factor in the influence zone. In this paper, the influence is considered conservatively by the weight set, which indicates that the largest threshold is selected to represent the final influence. But if equally considering all indicators with Eq. (11), the result will be quite different, which is shown in Fig. 10c. The area of the

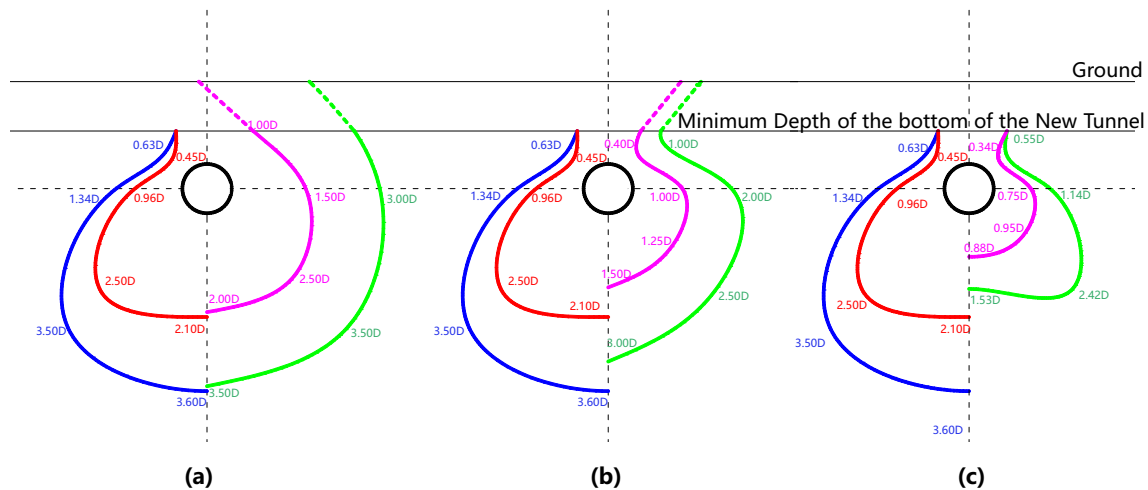


Fig. 10 Comparison of the influence zone between this study and (a) Qiu, b Wen, c the average principle

influence zone decreases a lot, especially in the lower part of the existing tunnel. Thus, the reasonable choice of weights is important and the specificity of the evaluation object and environment should be considered. For example, in the rock layer, the displacements of the layers and structures caused by adjacent construction are pretty small but the variation in stress is quite large, so the weight of the indicator related to strength should be enhanced; while in the soft soil area, the load-bearing capacity of tunnels is usually sufficient but the displacement is more difficult to control, so indicators related to stiffness should be favored.

5 Conclusions

This paper systematically investigates the evaluation indicator and method of the influence zone aimed at adjacent tunnel construction. To obtain an integrated result, a normalization method for influence functions and a multi-indicator combination method is proposed. The process of establishing an integrated influence zone is demonstrated through a case study verified by monitoring data in site, and the main conclusions are drawn as follows:

(1) A single indicator has obvious limitations and cannot be effectively used for the evaluation when adjacent construction occurs in some specific directions of the existing tunnel. By normalizing the influence function and setting weights, different indicators can obtain comparability and additivity, which makes it possible to consider all indicators comprehensively.

- (2) Based on the metro project in Qingdao, China, the shape of the influence zone is like a necked bottle, which means that building a new tunnel underneath the existing tunnel will have a greater influence. The layer crossed by the new tunnel also plays an important role in the shape of the influence zone.
- (3) The horizontal angle of the crossing tunnels has a different correlation with structural and environmental indicators, but it shows a much weaker influence when compared with the vertical angle of the tunnels.
- (4) The setting of weights plays an important role in the calculation of the influence zone. For common cases, the maximum or average principle can be applied. While for the case with several unique characteristics, quantitative analysis, such as AHP or expert scoring system, should be conducted to improve the usefulness of several favored indicators.

This paper has some limitations and we hope that future research will take a further step. Numerical simulations were chosen as the easily available data in this paper due to the many different working conditions involved, and engineering monitoring data were used to validate the base model. However, the small amount of monitoring data makes it difficult to verify all working conditions, and there must be discrepancies between the numerical simulation and the actual situation. Therefore, future research could explore alternative data sources, such as using model experiments, to bring the results closer to reality. As for the integrated method, its result is finally expressed in the form of the influence zone, which is a two-dimensional cross-section. Therefore, when the influence zone is added to the longitudinal dimension of the

tunnel, the representation method of the influence space and the corresponding integrated method are still to be explored.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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