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Multiscale evaluation of tunnel construction safety risk: a case study of an offshore tunnel construction in Ningbo

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Abstract

Based on the WBS-RBS method, in this study, the risk factors corresponding to the construction risk events of an offshore tunnel foundation pit in Ningbo were identified, and the fuzzy comprehensive evaluation method was used to evaluate the construction safety risk of the project. The system-level risk value was obtained by using the risk event deformation resulting from changes in two factors, namely, "mechanical property of soil" and "stiffness of the envelope structure", to calculate the new event-level risk value corresponding to the deformation using a finite element numerical model. The findings indicate that the tunnel project has a risk evaluation score of 62.78 and thus falls within the category of high-risk projects. A change in risk factors will alter the likelihood that risk events will occur, which affects the safety risk status of the entire project. When two factors are coupled, a project's system-level risk can increase dramatically.

Keywords: Risk coupling, Sensitivity analysis, Multiscale evaluation, Finite element simulation

Introduction

Tunnels provide the characteristics of reducing the length of a route, saving time, minimizing harm to the environment, and overcoming natural disasters [1]. As a submarine tunnel is an underground project, it is a sizable investment and is characterized by a protracted construction period, technological complexity, several unanticipated dangers, and a significant negative impact on society [2]. Accidents involving construction safety will result in numerous fatalities and significant financial losses [3].

The performance (response) of the higher scale of construction safety risk behavior is typically controlled by the characteristics of the next higher scale, and a "factor-level → event-level → system-level" risk chain is created when changes in risk factors cause the occurrence of risk events, which in turn cause changes in the risk level of the entire tunnel construction system [4]. Typical single-risk evaluation techniques and qualitative analysis including the risk matrix method [5] or hierarchical analysis [6], and quantitative analysis techniques, such as fault tree analysis [7], Monte Carlo simulation [8], and event tree analysis [9], are no longer able to fully describe the correlation

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characteristics between the scales of security risk behavior. The multiscale analysis method integrates the relevant scales to create a bridge that spans many scales by taking into account the cross-scale and cross-level properties of space and time. It is necessary to introduce the scientific method of multiscale analysis to achieve the connection and span between the scales of security risk behavior and to thoroughly understand their processes of action. At present, multiscale analytic methodologies for risk evaluation have been presented in studies in the sectors of resource utilization [10–14] and environmental science [15–18], and fewer studies have been performed in the area of construction safety. Due to variations in risk factors during the actual construction process, changes in risk events can lead to alterations in the risk level of the entire tunnel construction system. This gives rise to a risk chain from the factor level to the event level and ultimately to the system level. In tunnel construction, the manifestation (response) of safety risk behaviors at a higher scale is typically controlled by characteristics at a lower scale. Therefore, the use of classical methods such as the Delphi method, risk matrix method, or analytic hierarchy process alone is no longer sufficient to comprehensively describe the interrelationships among safety risk behaviors at different scales [4]. A multiscale analysis approach considers the cross-scale and cross-hierarchical characteristics in space and time. It establishes bridges connecting relevant scales, forming a linkage between multiple scales. To achieve connectivity and transcendence between safety risk behaviors at different scales, and to elucidate their underlying mechanisms profoundly, the introduction of scientific means for multiscale analysis is essential.

Numerical simulation and field monitoring have become important research methods in the field of civil engineering [19], and in the field of foundation pit engineering deformation control, both domestic and international researchers use numerical simulation among other approaches that are relatively mature [20–22]. Utilizing the project's measured data, research, and analysis of the foundation pit's deformation shape can effectively study the pit's deformation and comprehend its changing state, which is crucial for predicting the deformation of the pit [23]. The deformation characteristics of tunnel pit projects have been the subject of numerous research studies [24–28], but most of these studies have concentrated on management issues, and only a small number have combined risk assessment and engineering deformation analysis.

Engineering deformation is one of the indicators utilized in this study to test the project's safety risk, and engineering technology and risk management techniques are merged. A finite element simulation of the tunnel excavation and the deformation of the enclosure construction is conducted using an offshore tunnel in Ningbo as a case study. The inclusion of deformation as a risk index in the model for risk assessment has direct practical implications for enhancing safety management techniques.

Tunnel construction risk assessment

Methods

To ensure the efficient execution of tunneling projects, it is crucial to accurately identify safety concerns during the building process. It is necessary to correctly evaluate the security risk. The current methods for evaluating and identifying safety risks include hierarchical analysis, clustering, and fuzzy analysis [29]. However, it is challenging to accurately identify and assess safety risks in the construction process using the first two methods because of the many factors involved in tunnel construction, such as technical, environmental, and management issues [30]. As a result, in this section, the risk variables associated with the construction risk event of an offshore tunnel in Ningbo are identified using the work breakdown structure-risk breakdown structure (WBS-RBS) approach. Moreover, the fuzzy comprehensive evaluation approach is utilized to analyze the project's construction safety risk, create a system for evaluating risks, and offer evaluation indicators and baseline risk values for the third section's multiscale evaluation in Sect. 4.

Project overview

An offshore tunnel in Ningbo has a total length of 2280 m with a starting pile number of K6 + 040 and an ending pile number of K8 + 320. The section configuration is 11×30 m (u-shaped groove) + $(45 + 25 \times 60 + 45$ m (buried container section) + 12×30 m (u-shaped groove). This tunnel was built using an open excavation technique and a weir.

The special engineering soil is primarily composed of soft soil. The soft soil is mainly distributed in the upper part of the tunnel site. The lithology consists of layers of sand- and silt-bearing silt, and the local facies are changed to silt gravel sand, which is a typical tidal flat sedimentary soil. Soft soil typically has a thickness of 1 to 8 m, small distances typically have a thickness of 1 to 2 m, and long distances typically have a thickness of more than 4 m, up to a maximum of 8 m.

The row piles are constructed with Φ80 cm bored cast-in-place piles at a spacing of 100 cm from each other to support the enclosure construction. On the excavation surface of the row of piles, a 10-cm-thick C20 shotcrete is laid, and Φ8 mm steel mesh is laid in the shotcrete. Soil mass reinforcement and a partial water-stopping effect are present between the rows of piles. The 100×100 cm crown beam is attached as a whole to the top of the cast-in-place pile, and its top surface is fitted with retaining walls that match the access roads on both sides. Two lattice columns are positioned in the center of a 70×90 cm reinforced concrete support that is positioned between the crown beams on either side of the foundation pit. The support distances are 700 cm and 800 cm in the forward direction. This assistance form is appropriate for K6 + 370K8 + 020.

The establishment of a risk index system based on the WBS-RBS

Construction of a tunnel work breakdown structure

In this study, the foundation pit enclosure W1, foundation reinforcement W2, drainage construction W3, and foundation pit excavation W4 are decomposed in two stages in accordance with the construction sequence of an offshore tunnel in Ningbo, and the construction process WBS of an offshore tunnel in Ningbo is obtained, as shown in Fig. 1.

Construction of a tunnel risk breakdown structure

When the project's actual situation is considered, it is determined that risk events such as support deformation and instability R1, excessive deformation of the enclosure structure R2, excessive uplift at the bottom of the foundation pit R3, sudden rushing sand R4, and significant deformation of the seabed and other risk events R5 may occur during the tunnel's construction, as shown in Fig. 2.

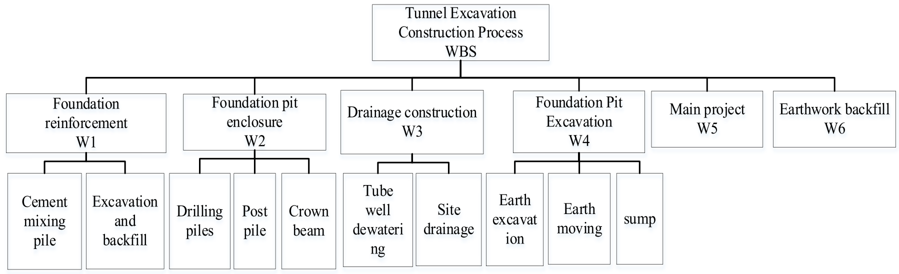

Fig. 1 Schematic diagram of the work breakdown structure of tunnel excavation work

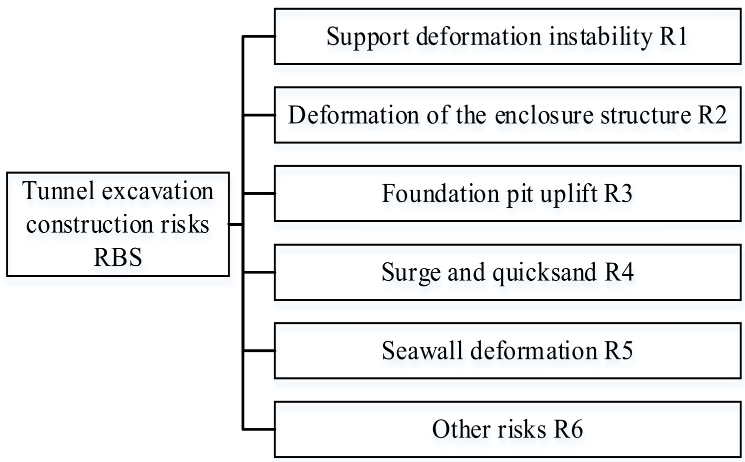

Fig. 2 Schematic diagram of the risk breakdown structure of tunnel excavation work

Support deformation instability The insufficient stiffness of the support and the wide spacing of the support will increase the danger of strength and stability failure of the support system.

Deformation of the enclosure structure Inadequate enclosure structure stiffness, depth, and incorrect foundation reinforcement will all cause structural damage to the enclosure structure during the foundation pit excavation process.

Foundation pit uplift The risk of the bottom of the foundation pit being raised upwards will eventually increase because the foundation pit excavation will compress the soil body in the area of silty soft soil and heavy rain will cause the soil body to absorb water and expand.

Surge and quicksand Groundwater seepage will affect the soil and create a seepage channel during the excavation of the foundation pit.

Seawall deformation On either side of the foundation trench, a seawall is constructed. The seawall is extremely heavy and tall. The foundation pit's safety will be substantially compromised by a distortion in the seawall, which could even cause it to collapse.

The risk assessment index system for tunnel construction

The project is close to the ocean and therefore is significantly impacted by tides and groundwater, which might easily result in plumbing issues, quicksand, and structural damage, according to the WBS-RBS report. Thus, a seawall cofferdam can be installed. The seawall is very tall and heavy, and it applies substantial pressure on the foundation pit's side, which could cause the foundation pit to become unstable as it is being dug out. Table 1 below displays the unique risk index system identity.

Risk evaluation of tunnel foundation pit excavation based on the fuzzy comprehensive evaluation method

Fuzzy comprehensive evaluation method steps

To address the issue that some assessment-related issues are challenging to characterize numerically, in the 1960s, the fuzzy comprehensive evaluation approach was proposed, and membership degree theory was used to convert qualitative evaluation into quantitative evaluation. The following are the precise evaluation phases of the fuzzy comprehensive evaluation method [26]:

The evaluation index system should be known The foundation of risk assessment is the evaluation index system, and the findings of risk identification and risk estimation must be coupled when choosing a risk index.

Table 1 Risk factors and risk events

Event-level risk	Factor-level risk
Support deformation instability	F1 Insufficient support stiffness
	F2 Large support spacing
	F3 Mechanical work impact
Deformation of the enclosure structure	F4 Insufficient stiffness of envelope structure
	F5 Insufficient enclosure depth
	F6 Weak mechanical properties of soil
	F7 Seawall self-weighting
Foundation pit uplift	F8 Poor soil reinforcement
	F9 Insufficient enclosure depth
	F10 High water absorption of cohesive soil
	F11 Rainfall
Surge and quicksand	F12 High water permeability of bottom soil
	F13 Poor precipitation effect of foundation pit
	F14 Overbreak
	F15 Enclosure is not closed
Seawall deformation	F16 Poor structural parameters of the seawall
	F17 Tide
	F18 Moving load
	F19 Unreasonable design scheme of construction monitoring
Other risks	F20 Construction machinery cross work
	F21 Toxic gas

Determine the factor set U: U = {u1,u2,...un}, i = 1, 2,..., n The factor set is a first-level index set made up of *n* factors, where *U* denotes the overall objective of risk assessment or the project's total risk value, and ui denotes the *i*th index factor.

Its weight set is *R* = {r1, r2, ...rn}, where ri represents the weight of indicator ui in the overall objective and satisfies the formula.

$$\sum_{i=1}^{n} R_{\mathrm{i}} = 1, (i = 1, 2, \ldots n) \quad (1)$$

$u_1 = \{u_{i1}, u_{i2}, \ldots, u_{in}\}$. Taking the support deformation and instability as an example, u_1 Support deformation instability = {insufficient support stiffness, large support spacing, mechanical work impact}.

The set of weights: $r_i = \{r_{i1}, r_{i2}, \ldots, r_{in}\}$, where r_{ij} represents the weight of u_{ij} in u_i and satisfies the formula.

$$\sum_{j=1}^{n} r_{\mathrm{ij}} = 1, (i = 1, 2, \ldots n; j = 1, 2, \ldots n) \quad (2)$$

Determine the evaluation set, $V, V = \{V_1, V_2, \ldots V_n\}$ The risk evaluation set mostly indicates the risk's size level, such as a high, medium, or even low risk.

Determine the weight R of each factor Calculate the weight of each risk using AHP and then the weight matrix *R*.

Establish the fuzzy relationship matrix S To ascertain the level of membership and fuzzy matrix *S*, use Delphi and other techniques.

Fuzzy comprehensive evaluation result processing For a thorough evaluation, which is commonly described by $C = R \times S$, a risk factor is chosen.

Determining factor set and evaluation criteria set

First-level factor set $U = \{U_1, U_2, U_3, U_4, U_5, U_6\}$ = {Support deformation instability, deformation of the enclosure structure, foundation pit uplift, surge and quicksand, seawall deformation, other risks}.

Second-level factor set $U_1 = \{U_{11}, U_{12}, U_{13}, U_{14}\}$ = {Insufficient support stiffness, large support spacing, mechanical work impact}.

$U_2 = \{U_{21}, U_{22}, U_{23}, U_{24}\}$ = {Insufficient stiffness of envelope structure, insufficient enclosure depth, weak mechanical properties of soil, seawall self-weighting}.

$U_3 = \{U_{31}, U_{32}, U_{33}, U_{34}, U_{35}\}$ = {Poor soil reinforcement, insufficient enclosure depth, rainfall, high water permeability of bottom soil}.

$U_4 = \{U_{41}, U_{42}, U_{43}, U_{44}, U_{45}\}$ = {High water permeability of bottom soil, poor precipitation effect of foundation pit, overbreak, enclosure is not closed}.

$U_5 = \{U_{51}, U_{52}, U_{53}, U_{54}\}$ = {Poor structural parameters of seawall, tide, moving load, unreasonable design scheme of construction monitoring}.

$U_6 = \{U_{61}, U_{62}\}$ = {Construction machinery cross work, toxic gas}.

Evaluation criteria set The evaluation standard set is represented by V and adopts a five-level scoring system: $V=(V_1, V_2, V_3, V_4, V_5)=$ {very low risk, low risk, medium risk, high risk, very high risk} = {0 ~ 20, 20 ~ 40, 40 ~ 60, 60 ~ 80, 80 ~ 100}.

Secondary fuzzy comprehensive evaluation

By enlisting the assistance of 10 monitoring units, construction units, academic researchers, and business professionals, risk assessments can be conducted, and scores can be assigned in accordance with the risk level division shown in Table 2.

The questionnaire responses can be sorted, and an event-level fuzzy evaluation matrix can be produced $R1 \sim R6$:

$$R1 = \begin{bmatrix} 0 & 0.3 & 0.4 & 0.2 & 0.1 \\ 0 & 0.2 & 0.3 & 0.4 & 0.1 \\ 0 & 0.1 & 0.2 & 0.4 & 0.2 \end{bmatrix}$$

$$R2 = \begin{bmatrix} 0 & 0.1 & 0.3 & 0.5 & 0.1 \\ 0 & 0.2 & 0.4 & 0.3 & 0.1 \\ 0 & 0.2 & 0.3 & 0.6 & 0.1 \\ 0 & 0.2 & 0.2 & 0.5 & 0.1 \end{bmatrix}$$

$$R3 = \begin{bmatrix} 0 & 0 & 0.4 & 0.4 & 0.1 \\ 0 & 0.2 & 0.4 & 0.2 & 0.2 \\ 0 & 0.2 & 0.2 & 0.5 & 0.1 \\ 0 & 0.1 & 0.6 & 0.2 & 0.1 \end{bmatrix}$$

$$R4 = \begin{bmatrix} 0 & 0.1 & 0.1 & 0.6 & 0.2 \\ 0 & 0.2 & 0.4 & 0.4 & 0 \\ 0 & 0.4 & 0.3 & 0.2 & 0.1 \\ 0.2 & 0.1 & 0.1 & 0.4 & 0.2 \end{bmatrix}$$

$$R5 = \begin{bmatrix} 0 & 0 & 0.1 & 0.1 & 0.8 \\ 0 & 0 & 0.2 & 0.4 & 0.2 \\ 0 & 0.1 & 0.4 & 0.5 & 0 \\ 0 & 0.2 & 0.2 & 0.5 & 0.1 \end{bmatrix}$$

$$R6 = \begin{bmatrix} 0 & 0.6 & 0.2 & 0.2 & 0 \\ 0 & 0 & 0.1 & 0.8 & 0.1 \end{bmatrix}$$

The event-level comprehensive evaluation vector can be calculated:

Table 2 Risk classification reference

Risk level	Grade range	Disposal principle
I	[0, 20]	Minimal risk, standard construction
II	[20, 40]	Low risk, calls for attention and monitoring
III	[40, 60]	Moderate risk, set up efficient safeguards, and improve monitoring
IV	[60, 80]	Serious risks, take effective measures and improve monitoring
V	[80, 100]	Extremely serious, appropriate control measures should be implemented right away to lower the risk

The comprehensive evaluation vector $S1$ of support deformation instability is:

$$S_1 = R_1 \times U_1 = (0.46, 0.319, 0.221) \times \begin{bmatrix} 0 & 0.3 & 0.4 & 0.2 & 0.1 \\ 0 & 0.2 & 0.3 & 0.4 & 0.1 \\ 0 & 0.1 & 0.2 & 0.4 & 0.2 \end{bmatrix} = (0, 0.224, 0.324, 0.308, 0.122)$$

The comprehensive evaluation vector $S2$ of the deformation of the enclosure structure is:

$$S_2 = R_2 \times U_2 = (0.31, 0.089, 0.5, 0.101) \times \begin{bmatrix} 0 & 0.1 & 0.3 & 0.5 & 0.1 \\ 0 & 0.2 & 0.4 & 0.3 & 0.1 \\ 0 & 0.2 & 0.3 & 0.6 & 0.1 \\ 0 & 0.2 & 0.2 & 0.5 & 0.1 \end{bmatrix} = (0, 0.169, 0.299, 0.532, 0.101)$$

The comprehensive evaluation vector $S3$ of excessive uplift at the bottom of the foundation pit is:

$$S_3 = R_3 \times U_3 = (0.298, 0.363, 0.212, 0.128) \times \begin{bmatrix} 0 & 0 & 0.4 & 0.4 & 0.1 \\ 0 & 0.2 & 0.4 & 0.2 & 0.2 \\ 0 & 0.2 & 0.2 & 0.5 & 0.1 \\ 0 & 0.1 & 0.6 & 0.2 & 0.1 \end{bmatrix} = (0, 0.145, 0.486, 0.357, 0.153)$$

The comprehensive evaluation vector $S4$ of water inrush and quicksand is:

$$S_4 = R_4 \times U_4 = (0.226, 0.171, 0.192, 0.410) \times \begin{bmatrix} 0 & 0.1 & 0.1 & 0.6 & 0.2 \\ 0 & 0.2 & 0.4 & 0.4 & 0 \\ 0 & 0.4 & 0.3 & 0.2 & 0.1 \\ 0.2 & 0.1 & 0.1 & 0.4 & 0.2 \end{bmatrix} = (0.082, 0.175, 0.191, 0.406, 0.146)$$

The comprehensive evaluation vector $S5$ of seawall deformation is:

$$S_5 = R_5 \times U_5 = (0.462, 0.148, 0.3, 0.095) \times \begin{bmatrix} 0 & 0 & 0.1 & 0.1 & 0.8 \\ 0 & 0 & 0.2 & 0.4 & 0.2 \\ 0 & 0.1 & 0.4 & 0.5 & 0 \\ 0 & 0.2 & 0.2 & 0.5 & 0.1 \end{bmatrix} = (0, 0.049, 0.215, 0.303, 0.409)$$

The comprehensive evaluation vector $S6$ of other risks is:

$$S_6 = R_6 \times U_6 = (0.7, 0.3) \times \begin{bmatrix} 0 & 0.2 & 0.6 & 0.1 & 0.1 \\ 0 & 0.6 & 0.2 & 0.2 & 0 \end{bmatrix} = (0, 0.32, 0.48, 0.13, 0.07)$$

The tremendous deformation of the enclosure construction, the large deformation of the seawall, and the inrush of water and sand are at a high-risk level and require control in accordance with the principle of the maximum degree of membership.

First-class fuzzy comprehensive evaluation

The system-level risk fuzzy evaluation matrix is as follows in light of the evaluation findings in the aforementioned section:

$$R = \begin{bmatrix} 0 & 0.224 & 0.324 & 0.308 & 0.122 \\ 0 & 0.169 & 0.299 & 0.532 & 0.101 \\ 0 & 0.145 & 0.486 & 0.357 & 0.153 \\ 0.082 & 0.175 & 0.191 & 0.406 & 0.146 \\ 0 & 0.049 & 0.215 & 0.303 & 0.409 \\ 0 & 0.32 & 0.481 & 0.131 & 0.070 \end{bmatrix}$$

First-class fuzzy comprehensive evaluation:

$$W = (0.212, 0.436, 0.065, 0.174, 0.074, 0.039)$$

The comprehensive evaluation vector of the construction risk of this tunnel project is:

$$S = W \bullet R = (0.014, 0.177, 0.298, 0.418, 0.139)$$

Risk assessment results

The construction risk comprehensive evaluation vector for this project is used as the upper, median, and lower limits of the score set in accordance with the quantification method of the fuzzy comprehensive evaluation method, and the risk value for this tunnel project can be calculated as shown below:

$$S(\text{upper}) = (0.014, 0.177, 0.298, 0.418, 0.139)\begin{bmatrix} 19 \\ 39 \\ 59 \\ 79 \\ 100 \end{bmatrix} = 71.637$$

$$S(\text{middle}) = (0.014, 0.177, 0.298, 0.418, 0.139)\begin{bmatrix} 10 \\ 30 \\ 50 \\ 70 \\ 90 \end{bmatrix} = 62.084$$

$$S(\text{lower}) = (0.014, 0.177, 0.298, 0.418, 0.139)\begin{bmatrix} 80 \\ 60 \\ 40 \\ 20 \\ 0 \end{bmatrix} = 51.624$$

$$\overline{S} = \frac{S(\text{upper}) + S(\text{middle}) + S(\text{lower})}{3} = \frac{71.637 + 62.084 + 51.624}{3} = 62.781$$

It is clear from the information above that the tunnel project has a high-risk total comprehensive risk score of 62.781. The project's construction safety management needs to receive adequate attention.

Finite element numerical simulation of the buried section

The tunnel deformation state reflects its safe and stable state [31]. Through tunnel deformation analysis and finite element numerical simulation, it is possible to effectively analyze the deformation of the foundation pit. In this section, a dark bury is chosen to establish a finite element model, validate the feasibility of the model, and obtain the risk factors that change the corresponding tunnel deformation of the foundation pit. Section 3 provides information for multiscale evaluation.

MIDAS GTS/NX provides a wide range of constitutive models, including elastic models, the Duncan-Chang model, the Mohr–Coulomb model, the modified Mohr–Coulomb model, and the modified Cambridge model. An elastic model is employed to simulate structural materials, while the modified Mohr–Coulomb model is used in simulating the excavation process of deep excavations.

Model parameters

The correct choice of soil and material parameters has a significant impact on modeling performance and the accuracy of numerical calculation results. The soil is simplified into three layers this time, namely, silt, silty clay, and totally weathered granite from top to bottom, in accordance with the project's actual circumstances. Table 3 displays the particular characteristics and attributes of each soil layer.

The stirring piles are represented similarly in MIDAS GTS/NX software; thus, the definition of supporting structure characteristics should be as close as feasible to actual engineering. Table 4 displays the precise enclosure construction support characteristics.

For this project's foundation pit enclosing construction, drilled cast-in-place piles were chosen. Due to the small enclosing interval of the cast-in-place piles during the specific construction process, the soil between the piles will "arch," which is difficult to control in a finite element numerical simulation. Additionally, the calculation amount of a single row of piles also accounts for the internal stress of the underground diaphragm wall, which is similar to that of the enclosure pile. The equal stiffness conversion principle is chosen in light of previous engineering projects' simulation results. The cast-in-place pile enclosure is changed into an underground diaphragm wall with equal stiffness, as shown in Fig. 3 below, which minimizes the number of structural elements in the model and the number of numerical simulation calculations. The equal stiffness principle can be expressed mathematically as follows:

$$\frac{1}{12(D+t)}h^{3}=\frac{1}{64}\pi D^{4} \tag{3}$$

Table 3 Soil material and property parameter table

Soil layer	Thickness (m)	Gravity γ (kN/m^3)	Cohesion c (kPa)	Internal friction angle φ (°)	Elastic modulus E (MPa)	Poisson's ratio μ	Secant stiffness E50ref (kN/m^2)	Tangent stiffness Eoedref (kN/m^2)
Silt	2.6	17.3·	8	5	9000	0.3	3000	3000
Silty clay	5.4	17.5	18	15	18,000	0.3	6000	6000
Completely decomposed granite	Thick-to-bottom border	24	40	32	60,000	0.2	1500	1500

Table 4 Supporting structure parameters

Name	Gravity *γ* (kN/m^3)	Elastic modulus *E* (GPa)	Poisson's ratio *μ*	Sectional dimension (m)
Interbracing	24	30	0.2	0.7 × 0.9
Tie beam	24	30	0.2	0.6 × 0.5
Erect column pile	24	30	0.2	Diameter 0.8
Lattice column	78.5	200	0.3	0.6 × 0.6
Top beam	24	30	0.2	1 × 1
Bored cast-in-place pile	24	30	0.2	Thickness 0.8

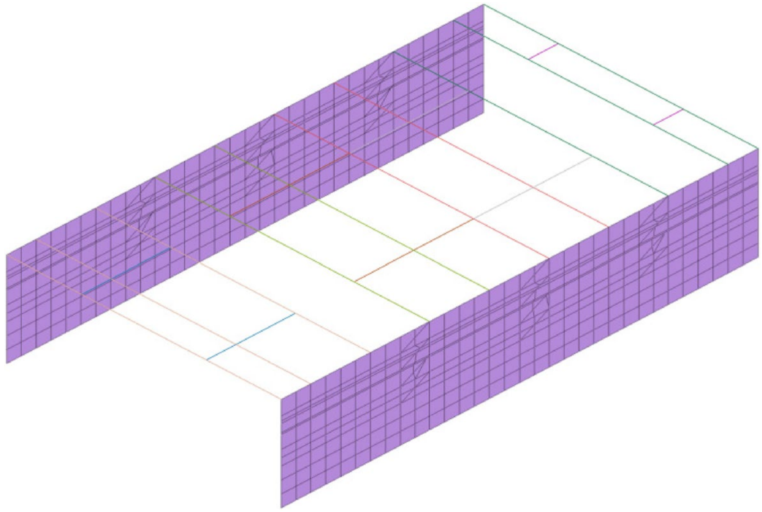

Fig. 3 Equivalent wall model

D = Diameter of retaining pile, mm.

T = Pile spacing, mm.

H = Equivalent wall thickness, mm.

The project's bored piles have an 800-mm diameter, and there are 1000 mm between each pile. The ground connection wall is 512 mm thick, as determined by the equal stiffness calculation formula. Figure 3 depicts the corresponding envelope structure model.

Mesh subdivision

According to the specifications, a model is established with an excavation depth of approximately 3 times the model depth to ensure calculation accuracy. The maximum excavation depth for this simulated tunnel foundation pit is 6 m, so a model size of $140 \times 40 \times 60$ is selected. The two-dimensional wireframe model created from the on-site plan layout CAD drawing is imported into MIDAS GTS/NX, and tunnel foundation pit geometric entities are generated through operations such as extrusion, expansion, and layering.

The model's computation accuracy is impacted by the meshing technique. The computation accuracy increases, but the calculation speed decreases as the mesh density increases. To ensure precision, fine meshing should be used in high-stress areas. Based on this, the soil close to the excavation surface is divided into a denser mesh in this tunnel foundation pit model to account for computation accuracy and efficiency. There are 43,960 nodes and 32,669 units in this model. Figure 4 displays the model in detail.

Result

(1) Deep horizontal displacement of the soil

Figure 5 illustrates the extracted and drawn values for the simulated value of the tunnel foundation pit and the measured value of the monitoring.

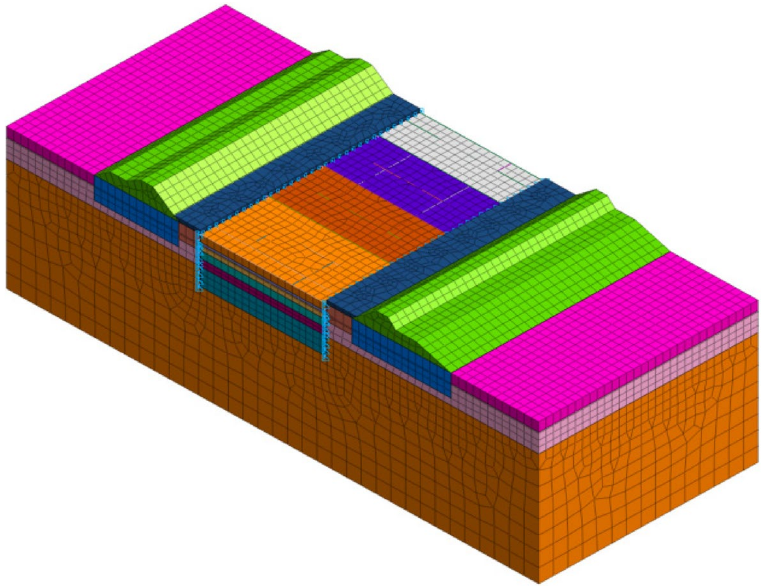

Fig. 4 Model entity meshing

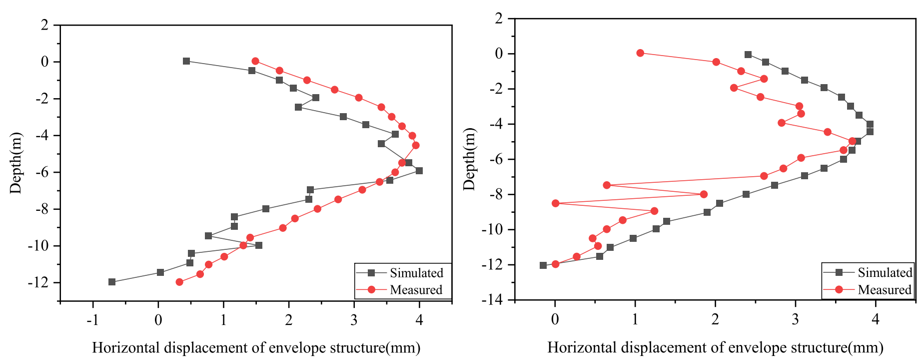

Fig. 5 Comparison curve for the depth–displacement variation in the measured points at the completion of the excavation

As shown in Fig. 5, the curves of the simulated value and the measured value are generally "bow-shaped". The numerical simulation computation is thought to be accurate and practical since the maximum displacement point is close to the excavation face, the changing trend is close, and the error is within the controllable range.

(2) Vertical displacement of the building envelope's top

The final displacement change value of each of the foundation pit model's four measuring locations is determined through simulation and numerical calculation. The actual measured values that were discovered at the four measuring stations are sorted and compared with the simulated values. Figure 6 illustrates the contrast between the real measured values and the simulated values.

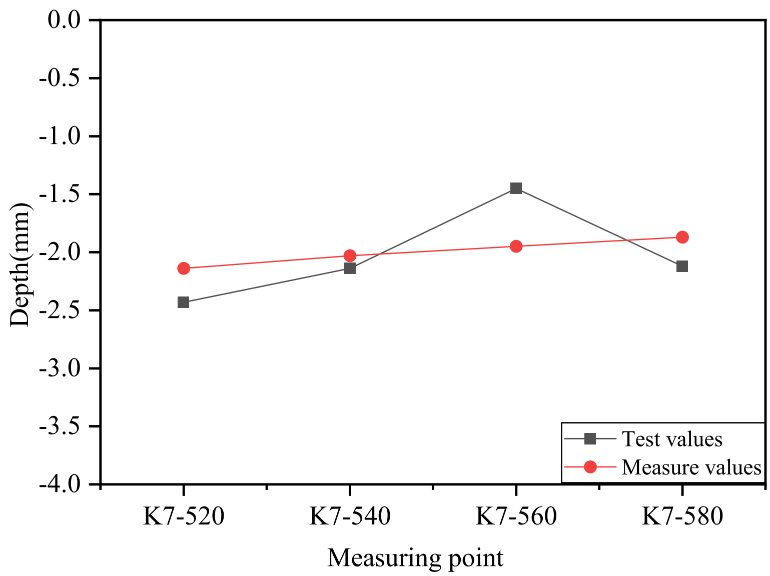

Fig. 6 Comparison of the vertical displacement at the top of the envelope at the completion of excavation

Figure 6 shows that the horizontal displacement of the four monitoring points exhibits a difference that is between the measured value and the simulated value within the controlled range, indicating that the numerical simulation computation is correct and practical.

In summary, there are certain differences between the simulated data and the field monitoring data. There are various causes for the discrepancy between the numerical simulation value and the monitoring value. The numerical simulation itself has several assumptions and simplifications, which is the fundamental cause. The reality on the ground and the actual modeling still diverge to some extent. It is discovered that the deformation law and the numerical value are essentially the same when comparing the simulated and measured values of the horizontal displacement of the deep soil and the lateral displacement of the retaining piles. These results can more accurately reflect the construction deformation characteristics of the tunnel foundation pit, which verifies the rationality of this model.

Multiscale evaluation of safety risk in foundation pit construction

Methods

There is a risk chain of "factor-level → event-level → system-level" in tunnel engineering construction, where changes in the factors will cause events to occur, which will subsequently cause accidents at the system level. The deformation of the enclosure and seawall can be determined by altering the parameter values of the risk factors in the finite element numerical model in Sect. 2. The event-level risk value corresponding to the change in the deformation can then be calculated, and A new system-level risk value for an offshore tunnel in Ningbo can be obtained.

In this section, the mechanical properties of the soil and the stiffness of the envelope structure are taken as examples to perform multiscale evaluations of tunnel construction safety risk under the influence of single-factor and double-factor coupling, respectively. The following formula is used to determine the new value at risk [32].

$$a_n = a_0 \times \left(1 + \frac{u_0 - u_n}{\mathrm{u}_0}\right) \tag{4}$$

a_n = New factor risk event value.
a_0 = Factor risk event initial value.
u_n = Maximum deformation value after the parameter change.
u_0 = Maximum deformation value before the parameter change.
The risk coupling level value adopts the following calculation formula [33].

$$C_m = \left[\frac{U_1 U_2 \ldots U_m}{\left(\frac{U_1 + U_2 + \cdots + U_m}{m}\right)^m}\right]^{\frac{1}{m}} \tag{5}$$

U_i is the order parameter of the ith risk factor, indicating the contribution of this factor to the safety level of the tunnel construction process.

Results and discussion

Multiscale evolution of security risk under the influence of a single factor

Soil mechanical properties In the finite element numerical model, the elastic modulus is a parameter that reflects the mechanical properties of the soil, so it is used as the characterization parameter for "weak soil mechanical properties", and the parameters are adjusted in the finite element numerical model to obtain the variation in risk events. The risk value of the deformation amount of the two risk events acquired by the change in the soil elastic modulus parameter is computed in accordance with the calculation method described above, and the multiscale analysis table of soil mechanical performance risk is obtained, as shown in Table 5. Figure 7 depicts the multiscale evolution of the soil mechanical performance risk.

As shown in Fig. 7, the danger value of excessive deformation of the enclosing structure ranges from 47.778 to 76.091, and the risk value increases by over 30, directly from medium risk to high risk, and close to very high risk. The risk value of substantial seawall deformation increased from medium risk to very high risk by a factor of 31 from 54.475 to 85.186. The coupling of the two events also increased from 0.698 to 0.880. The risk value of the system rises from 59.243 to 66.443, changing from medium risk to high risk, demonstrating the growing influence of the mechanical properties of soil on the risk value of the system, which requires adequate attention.

Table 5 Multiscale analysis of the soil elastic modulus risk

Factor-level variation parameters	Event level					System-level project value at risk
	Deformation of the building envelope		Seawall deformation		Coupling (WD)	
	Deformation	Risk value	Deformation	Risk value		
0.6E	4.73	76.091	2.33	85.186	0.880	66.443
0.8E	4.23	68.048	2.11	77.142	0.833	64.424
E	3.91	62.964	1.92	70.196	0.800	62.781
1.2E	3.69	59.361	1.78	65.078	0.776	62.112
1.4E	2.97	47.778	1.49	54.475	0.698	59.243

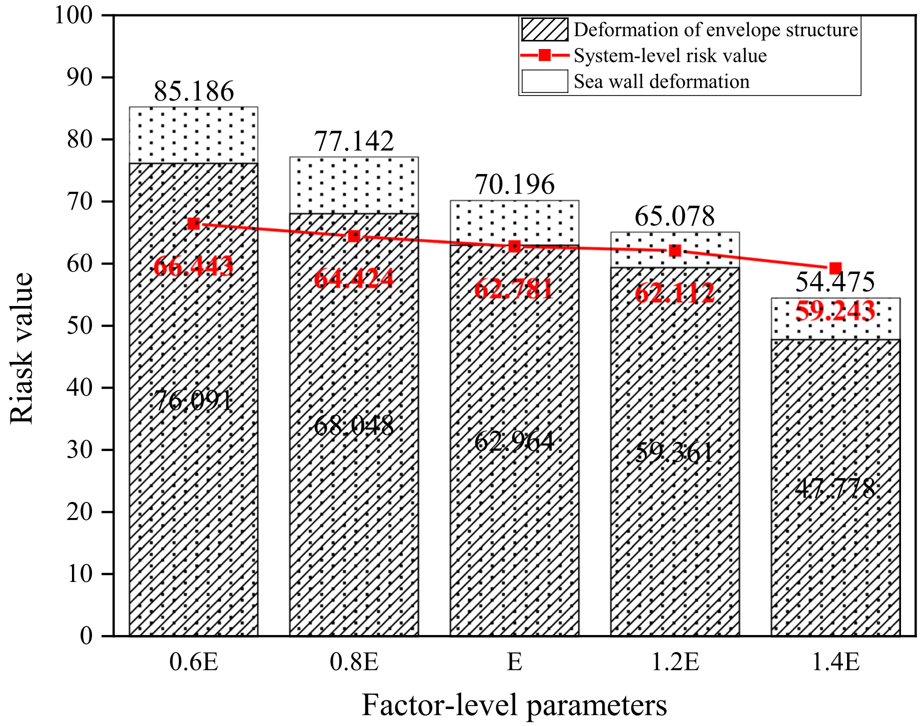

Fig. 7 Change in the risk evolution of the soil mechanical properties

First, it is necessary to prove the soil parameters in the investigation stage. Second, the mechanical qualities of the soil should be adequately enhanced during the construction design stage, as this may effectively regulate the deformation of the foundation pit and lower the project's construction risk. Since the strength of the soil can be increased and the overall stability of the tunnel foundation pit is improved, piles can be stirred as part of a soil reinforcing process.

Stiffness of the envelope structure The risk value corresponding to the deformation amount of the two risk occurrences achieved by changing the stiffness parameters of the enclosing construction is determined using the aforesaid calculation method, and the analysis table of the stiffness risk of the enclosure pile is obtained as shown in Table 6. The multiscale evolution diagram of the stiffness risk of the enclosure pile is shown in Fig. 8.

Table 6 Multiscale analysis of the stiffness risk of enclosure piles

Variation in factor-level parameters	Event level					System-level project value at risk
	Deformation of the building envelope		Seawall deformation		Coupling (WD)	
	Deformation	Risk value	Deformation	Risk value		
0.4 m	6.24	98.13	2.12	77.508	0.971	70.816
0.6 m	4.97	79.952	2.00	73.121	0.888	66.791
0.8 m	3.91	62.9	1.92	70.196	0.800	62.781
1.0 m	2.67	42.952	1.87	68.368	0.676	58.762

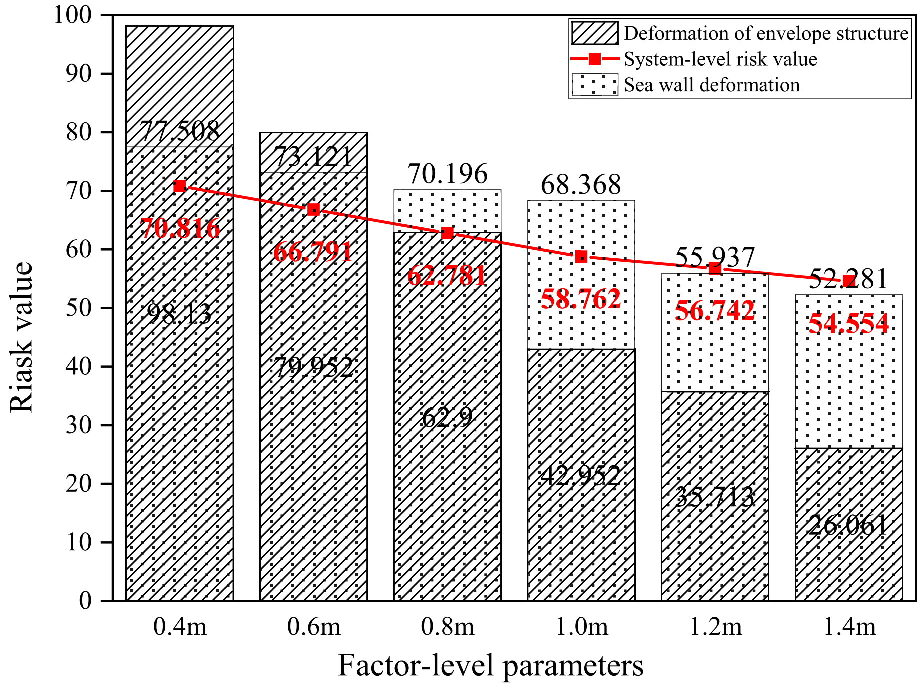

Fig. 8 Risk evolution diagram under the change in enclosure pile stiffness

Figure 8 demonstrates how changing the parameters of the envelope stiffness increases the risk value of excessive deformation of the envelope structure from 26.061 to 98.13 and the risk value to nearly 72, going from low risk to very high risk and almost to extreme value at risk. The risk value of a substantial seawall large deformation increased from medium risk to high risk by 25, going from 52.281 to 77.508. The coupling of the two events also increased from 0.553 to 0.971. The system's risk value rises from 54.554 to 70.816, changing from medium risk to high risk, demonstrating that the fencing pile has a growing impact on the risk value of the system and that critical components need to be controlled. Both the event-level risk value and the system-level risk value are significantly impacted by its change. As a result, it is crucial to adequately illustrate the rigidity of the enclosing structure during the design process. The construction quality of the enclosing structure must be ensured during the construction phase to guarantee the project's safety.

Multiscale evaluation of safety risk under the coupling of two factors

The original elastic modulus and stiffness of the enclosure construction are chosen as the mechanical properties of the soil, and the change in project risk value under the coupling condition is analyzed.

From Table 7, the proportional change in the deformation of the tunnel foundation pit when the risk factor soil mechanical performance is set to 0.6E and the thickness of the envelope is set to 0.4 m is noticeably greater than when the two factors act separately. The risk value of the envelope structure ranges from 62.964 to 100, which indicates that the level of risk has reached an extreme level, while the risk value of significant seawall deformation ranges from 70.196 to 80.5. The coupling degree is also close to the coupling

Table 7 Two-factor coupled multiscale analysis

Factor-level variation parameters	Deformation of the building envelope		Seawall deformation		Event-level value at risk			System-level project value at risk
	Maximum (mm)	Relative change rate	Maximum (mm)	Relative change rate	Deformation risk value of the envelope structure	Seawall deformation risk value	Coupling (WD)	
E	3.91	0	1.92	0	62.964	70.196	0.800	62.78
0.6E	4.73	20.97%	2.13	10.94%	76.091	85.186	0.880	66.44
0.4 m	6.24	59.59%	1.98	3.12%	98.13	77.508	0.971	70.82
0.6E-0.4 m	6.94	77.49%	2.18	13.54%	100	80.5	0.982	71.34

extreme value of 0.982. This demonstrates that these two factors have a positive coupling impact because the project's system-level risk value increased from 62.78 to 71.34, indicating that the project is high risk and could cause unanticipated harm (Fig. 9).

Project risk management measures

Optimization of soil parameters The project site is a tidal flat, and the area's unique rock and soil are primarily soft soil. Soft soil is unsuitable for the development of the project due to its high water content, high void ratio, high compressibility, poor strength, and delayed consolidation. Later, an uneven settlement of the tunnel box will occur. For the treatment of areas with great thickness, it is advised to adopt actions such as excavation and replacement, cement mixing pile composite foundation, and other actions.

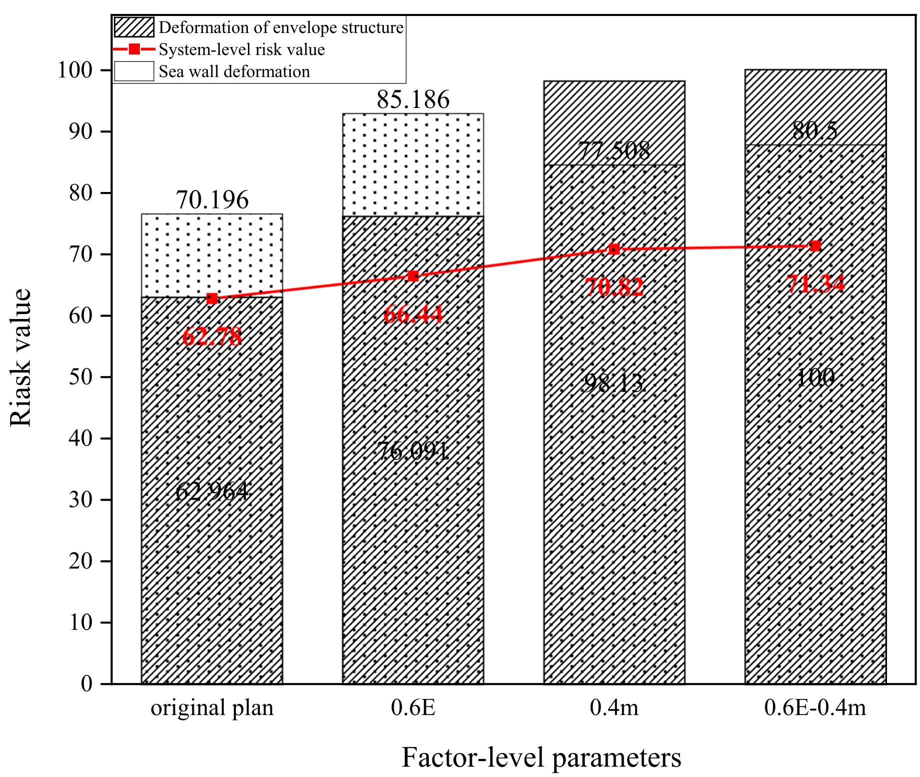

Fig. 9 Risk evolution diagram under the coupling effect of two factors

Precipitation and drainage The surrounding embankment and foundation pit may sustain damage from seepage, piping, and streaming soil when there is a high water level. To ensure the cement mixing pile waterproof curtain's ability to stop water flow in the event of an accident, quality control measures should be tightened. At the same time, proper pipe well dewatering, foundation pit monitoring, and early warning procedures should be followed.

Protection for foundation pit supports Conducting safety technical disclosure and training on the appropriate precautions are required before excavation. Safety police and signal personnel must keep an eye on the area while the foundation pit is being dug. The prepared construction plan must be strictly followed during construction. It is important to excavate the foundation pit in layers and portions. Strengthening the support system and stringently monitoring the connecting beam and concrete support construction quality are required in the area of deep excavation. It is essential to complete the steel support replacement work strictly before removing the concrete support and connecting beam.

Strengthen monitoring and feedback Create a monitoring team that will be on duty at the construction site 24 h per day for (1) monitoring and measuring while work is being done, (2) designating individuals and equipment for measurements during work to minimize human error, (3) repeating the measurement as soon as anomalous results are discovered, and (4) reviewing and monitoring the tools, procedures, and calculation process. This will allow time for the appropriate preventive actions to be performed so that during building, the foundation pit is ensured to be stable.

Conclusions

The offshore tunnel foundation pit's construction risk events are identified in this study, and the project's risk is assessed using the fuzzy comprehensive evaluation approach. To carry out the project's multiscale evaluation, we examine the coupling effect of the single component and the double factor. The conclusions are as follows:

(1) The fuzzy comprehensive evaluation approach gives this tunnel project a risk assessment score of 62.78 and a high-risk rating, suggesting that there is a high likelihood that risk events may arise during construction, necessitating adequate care.
(2) The deep horizontal displacement and the vertical displacement of the enclosure structure are studied and analyzed, the monitoring data are compared with the simulation results, and the finite element software MIDAS GTS/NX is used to numerically analyze the excavation and support the tunnel foundation pit. The foundation pit's deformation characteristics can be accurately reflected in the model.
(3) The multiscale assessment of the safety risk of the tunnel engineering project is carried out under the coupling action of single and double factors, using the stiffness of the retaining piles and the mechanical characteristics of the soil as examples. Changes in risk variables alter the likelihood of risk events, which can have an impact on the whole project. When there is a two-factor coupling, as opposed to a single factor, the project's system-level risk trends sharply upward.

Abbreviations

WBS Work breakdown structure
RBS Risk breakdown structure

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Authors' contributions

The authors confirm their contribution to the paper as follows: conceptualization, methodology, and investigation: Ping Wu; writing—original draft, investigation, and data collection: Feng Li; writing—review and editing: Li Jiamin Huang; and study conception and design and funding acquisition: Yidong Xu. All authors reviewed the results and approved the final version of the manuscript.

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Availability of data and materials

The datasets used or analyzed in this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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