



Review Article

Resilience of shield tunnel subjected to adjacent construction disturbances: A review

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Abstract

With the intensive and rapid development of urban underground space, there are more and more adjacent construction disturbances to the existing shield tunnels, posing serious challenges to their safety operation and maintenance. Resilience is an integrated representation of the ability of the engineering systems to resist disaster disturbances and recover function, and it can comprehensively reflect the impact of adjacent construction disturbances on the whole disaster chain of shield tunnels. However, the field currently faces challenges related to vague definitions of resilience, diverse evaluation indicators and measures, and an emphasis on evaluation rather than enhancement. Hence, this paper firstly summarized the definition of engineering resilience, especially the resilience of shield tunnels, and proposed the resilience definition of shield tunnels under adjacent construction disturbance, considering the basic connotation of resilience and disturbance characteristics. Secondly, the existing resilience evaluation frameworks for shield tunnels were summarized and analyzed, and the applicability of the existing framework for the shield tunnel under adjacent construction was discussed in light of the disturbance characteristics. Building on the mechanism and deformation characteristics, the resilience evaluation indexes and evaluation methods were reviewed based on the indicators of influencing factors and indicators of effectiveness of the entire disaster chain. Afterwards, the synergistic enhancement technology of shield tunnel resilience was summarized into 4 aspects: optimal structural design, disturbance transmission blocking, structural performance enhancement, and stratum grouting. Finally, research prospects in this field were analyzed systematically. This paper is intended to provide a meaningful reference for the in-depth research and application of structural resilience of shield tunnels subjected to adjacent construction disturbances.

Keywords: Existing shield tunnels; Resilience; Adjacent construction; Evaluation models; Enhancement strategy

1 Introduction

The development and utilization of urban underground space is an effective way and an inevitable trend for addressing the problem of urban traffic congestion and enhancing the functionality of urban services. Shield tunnels, a critical component of underground infrastructure,

have been developing rapidly in recent years. By the end of 2023, the total operating mileage of rail transit, predominantly composed of shield tunnels, had extended to 10 866 km (Wang et al., 2024). However, as the urban underground space construction tends to be intensive and rapid development, the existing shield tunnels are disturbed frequently by the adjacent construction, liking the adjacent pit excavation (Bolton et al., 2014; Shi et al., 2015a; Vinoth & Aswathy, 2022), proximity tunnel crossing (Lueprasert et al., 2017; Soga et al., 2017; Islam & Iskander, 2024) and ground surface surcharge (Yamamoto, et al., 2012; J. Zhang, et al., 2021), which is very likely to cause

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structural deformation, lining concrete damage and water seepage, making a serious threat to the safe operation of existing shield tunnels (W. Zhang et al., 2022). Hence, how to evaluate the impact of adjacent construction disturbances on existing shield tunnels and the effect of post-disturbance restoration are critical challenges in improving the safe operation and maintenance of shield tunnels.

Currently, research on the influence of adjacent construction disturbance on shield tunnels mainly focuses on the underlying mechanisms, deformation patterns, and control measures. As a deterministic, phased, and controllable disturbance, the study of the impact of adjacent construction disturbances on shield tunnels needs to be further integrated with the requirements of the resilience concept. Factors such as structural performance, economic cost, organizational management and impact time should be considered comprehensively to analyze the whole process of evolution in the disaster chain of pre-disaster state, disaster evolution and post-disaster recovery of the tunnels in terms of robustness, redundancy, adaptability and recoverability, so as to provide scientific theoretical guidance for the decision-making of disaster response and post-disaster restoration of the project (Lu et al., 2020; Huang et al., 2022; Chen et al., 2023).

Research on the structural resilience of underground infrastructures such as shield tunnels induced by different disasters has also received extensive attention, such as earthquakes (Singh et al., 2022; Chen et al., 2023), fires (Z. Zhang et al., 2024), and floods (Huang et al., 2022). However, the resilience of shield tunnels under adjacent construction disturbances remains vaguely defined currently, and the evaluation indexes and evaluation methods are diverse and inconsistent, with an emphasis on evaluation rather than enhancement. It is precisely these issues that impede the study and practical application of shield tunnel resilience under adjacent construction disturbances. Constructing a fundamental theoretical framework and method for the resilience evaluation of shield tunnels, considering the specific characteristics of adjacent construction disturbances, is a pressing research issue. Developing targeted enhancement strategies that align with the development needs of shield tunnel resilience and leverage multidisciplinary integration is also crucial. The aim of all these efforts is to achieve resilience characterized by strong robustness, sufficient redundancy, quick recovery, and intelligent adaptation for shield tunnels under adjacent construction disturbances (Lu et al., 2022; Zheng et al., 2022a; Du et al., 2023; Ji & Li, 2023).

In light of this, the definitions of engineering resilience, particularly the resilience of shield tunnels, were first summarized, considering the basic connotation of resilience and the structural characteristics. The resilience evaluation frameworks for shield tunnels were then summarized and analyzed, and their applicability was discussed in light of the adjacent construction disturbances. Then, the mechanism and deformation characteristics of existing shield tunnels under adjacent construction disturbances were

summarized. On this basis, existing resilience evaluation indicators and methods for shield tunnels were reviewed. Finally, the collaborative enhancement technologies for the resilience of shield tunnels were summarized, and future research directions for the resilience were envisioned, aiming to provide references for disaster prevention and mitigation research and practice for shield tunnels affected by adjacent construction disturbances.

2 Resilience evaluation method for shield tunnels

2.1 Definition of shield tunnel resilience

Resilience originally meant ‘to return to the original state’, and it has evolved to signify ‘the ability of an object or system to resist and absorb external disturbances and to recover to its original state or adapt to a new state after being disturbed’ over time (Alexander, 2013; Bo et al., 2022). Since Holling (1973) introduced the concept of resilience into the ecosystem, the principle has been applied and developed across various disciplines, including ecosystems, social systems, and engineering systems. There is now a growing consensus on the basic connotations of resilience, including robustness, redundancy, adaptability, and recoverability.

However, the functions, structure compositions, and types of disasters vary significantly across different systems, leading to distinct definitions of resilience, as shown in Table 1. Engineering resilience, in particular, refers to the ability of engineering structural systems to resist and recover from environmental changes or disasters. Thus, engineering resilience is more emphasized in the robustness, redundancy, rapidity, and recoverability of the system. Nevertheless, the definitions of resilience for different engineering systems under various disasters also differ slightly. Therefore, it is necessary to analyze resilience evaluation theories based on the characteristics of both the disaster types and the engineering systems.

The resilience of shield tunnels is a subset of the resilience of infrastructure engineering structures and is typically analyzed based on the adaptive cycle theory (Holling, 2001; Holling & Gunderson, 2001), generalized disaster likelihood and consequence severity (J. Liu et al., 2022; Zhai et al., 2023), structure vulnerability (Huang et al., 2023, 2024), and network connectivity (Abdulla et al., 2020; Abdulla & Birgisson, 2021). According to the adaptive cycle theory (Fig. 1), resilience systems undergo dynamic evolutionary cycles in a multi-stable state. The openness of the system exposes it to external disturbances, while stakeholder involvement promotes positive system evolution (Holling & Gunderson, 2001; Redman, 2014; Nelson et al., 2020).

However, similar to an ecosystem but not identical, engineering systems exhibit distinct characteristics across their whole lifecycle and function requirements, as illustrated in Fig. 2. Typically, engineering systems progress through 3 primary phases, including construction, service,

Table 1
Resilience definition of different systems.

| Types | Definition | Key features | References |
|--------------------------|---|--|---|
| Psychological resilience | The psychological phenomenon representing the capacity of individuals to cope successfully with significant change, adversity, or risk | A trait or a process | Tekaya et al., 2024 |
| Ecological resilience | The capacity of ecosystems to exhibit adaptive evolution and recovery in response to environmental change or disasters | Adaptability and recoverability | Holling, 1973 ; Wagner and Breil, 2013 |
| Society resilience | The capacity of social systems, such as cities and communities, to maintain system function and resume evolution in response to environmental change or disasters | Redundancy, learning, and recoverability | Tyler and Moench, 2012 ; Meerow et al., 2016 |
| Engineering resilience | Resistance and recoverability of engineering systems to environmental changes or disasters | Robustness, redundancy, rapidity, and recoverability | Huang et al., 2022 ; Shadabfar et al., 2022 ; Chen et al., 2023 ; S. Liu et al., 2024 |

and failure phases. In the construction phase, the engineering system incrementally develops and enhances its functionality until it meets the design specifications, representing the exploitation phase of engineering systems. During the normal service phase, the performance of the

engineering system remains relatively stable, fulfilling its intended design functions. Meanwhile, over time, its performance would gradually deteriorate, signifying the conservation phase or recession phase of the systems. When the performance of the engineering system diminishes or falls below the established functional requirements, it enters the failure phase.

When considering the impact of disaster disturbances, the structural performance of the system may decrease or fail, representing the release phase of the system. Following a performance loss or functional decline in the engineering system, structural repairs are necessary to restore the system to its normal functional state, marking the recovery phase. Therefore, [Ayyub \(2014, 2020\)](#) asserts that engineering structure resilience is a unique attribute reflecting the ability of the system to perform its functions.

Building on the fundamental connotations of underground infrastructure resilience ([Tierney & Bruneau, 2007](#); [Attoh-Okine et al., 2009](#); [Ayyub, 2014, 2020](#)), [Huang and Zhang \(2015, 2016\)](#) introduced the concept of resilience to the tunnel domain. They defined tunnel resilience as the ability of a tunnel to absorb sudden external environmental disturbances and recover rapidly from such

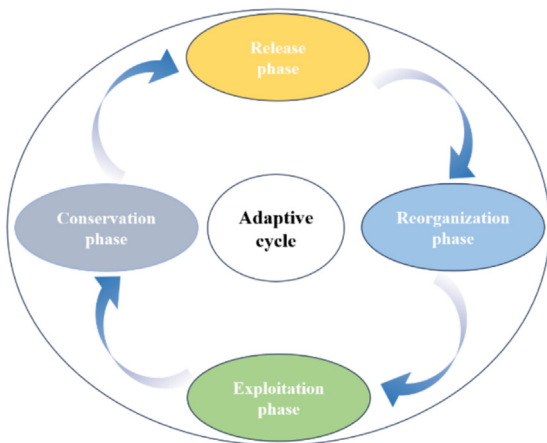


Fig. 1. Schematic diagram of the adaptive cycle theory.



Fig. 2. Schematic diagram of the whole life cycle of the engineering system considering disaster disturbances.

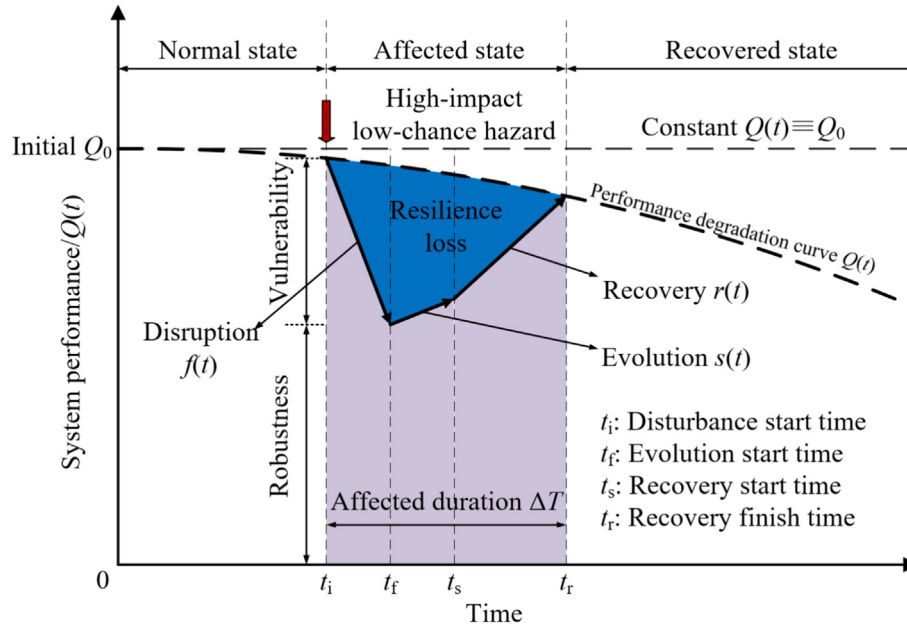


Fig. 3. Definition and framework for quantitative analysis of shield tunnel resilience under sudden disasters (Huang & Zhang, 2016, reproduced with permission, courtesy of Elsevier).

disruptions. They categorized the evolution of tunnel performance post-disaster into disturbance, evolution, and recovery stages, as illustrated in Fig. 3.

However, unlike sudden disasters such as earthquakes and floods, adjacent construction disturbances are characterized by their predictability and controllability. The timing, intensity, and scope of construction disturbances are relatively certain. Moreover, effective measures are typically implemented to reinforce existing shield tunnels before the commencement of adjacent construction, ensuring that the performance of the existing tunnels does not fall below the permissible levels required for their functionality during the disturbance. As a result, the disaster response process should be expanded from the 3 stages typical of sudden disasters, including disaster disturbance, disaster evolution, and post-disaster recovery, to 4 stages under adjacent construction disturbances, including pre-disturbance enhancement, disaster disturbance, disaster evolution, and post-disaster recovery, as illustrated in Fig. 4.

Pre-disturbance enhancement involves analyzing and predicting the impact of adjacent construction disturbances on the structural stresses and deformations of existing shield tunnels based on the design and construction plans of the new adjacent project, the condition of the existing tunnels, and the geological conditions. Targeted measures, such as deformation control and structural performance enhancement, are then implemented to improve the resilience of shield tunnels, enabling them to resist and absorb the impacts of adjacent construction disturbances. Disaster disturbance refers to the development of disturbances caused by adjacent construction on shield tunnels and their response under the implemented control measures. Disas-

ter evolution covers the period after the completion of adjacent construction, during which the disturbance effects continue to evolve. Appropriate control measures and repair or enhancement decisions must be made based on the ongoing development of disturbances. Post-disaster recovery involves recovering from deformation and restoring or enhancing the performance of tunnels based on the target functionality and predetermined decisions after adjacent construction disturbances have ended.

Synthesizing the definitions of shield tunnel resilience and other engineering systems, as well as the characteristics of adjacent construction disturbances, the resilience of shield tunnels under adjacent construction disturbances can be defined as follows: the ability of existing shield tunnels to resist disturbances caused by adjacent construction, to mobilize resources to enhance resistance before the disturbances begin, and to either self-recover or mobilize resources for rapid and economical structural repair after the disturbances, in order to restore the target functionality of the tunnels.

2.2 Resilience evaluation framework for shield tunnels under adjacent construction disturbances

The resilience evaluation of shield tunnels needs to comprehensively consider and characterize the fundamental aspects of robustness, redundancy, resourcefulness, and adaptability (Ayyub, 2014; Huang & Zhang, 2016). Robustness reflects the ability to resist disaster disturbances. Redundancy indicates the extent to which the structural system can meet or maintain functional requirements. Resourcefulness encompasses both economic and social dimensions, reflecting the recoverability of structural

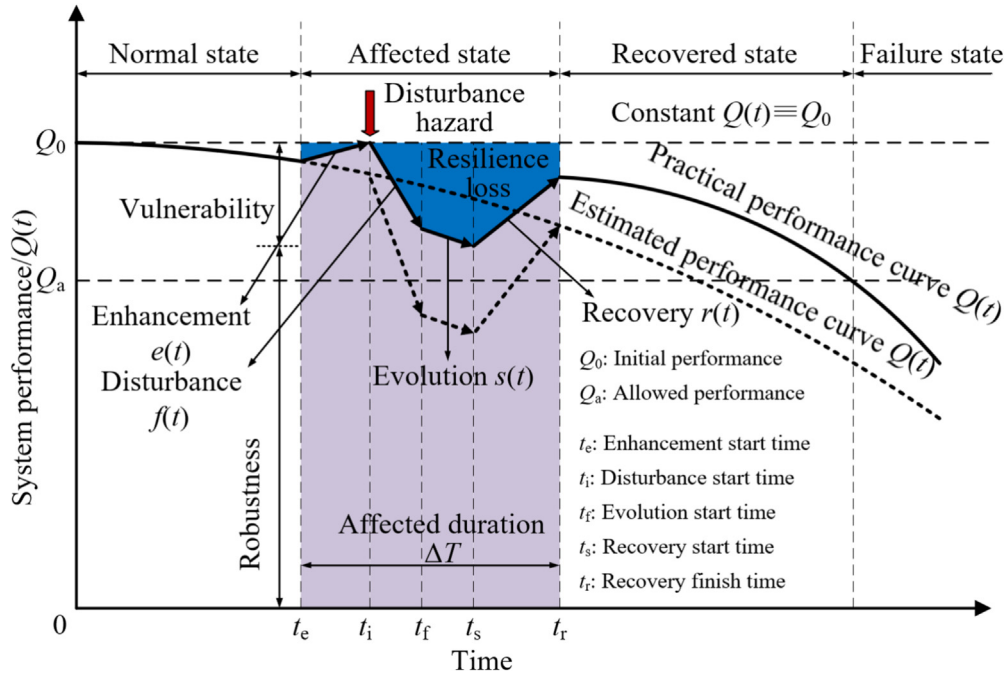


Fig. 4. Definition and quantitative framework of shield tunnel resilience under adjacent construction disturbances.

systems, which is also closely related to rapidity. Adaptability refers to the capacity for rapid self-recovery and self-learning, and it has been defined as rapidly by some scholars. Therefore, the key to assessing the resilience of shield tunnels lies in quantifying the interrelationships among these four aspects (Pandey & Sadri, 2022).

Regarding infrastructure resilience, Tierney and Bruneau (2007) developed a resilience evaluation model to capture the entire process of functionality degradation and recovery following external disturbances. They proposed that resilience value is the area enclosed by the initial functionality curve and the elapsed functionality curve over the disturbance impact time. Conversely, Attoh-Okine et al. (2009) defined the resilience value as the ratio of the area under the performance evolution curve to the area under the initial performance curve over the disturbance impact time. Ayyub (2014, 2020), building on the connotation of infrastructure resilience, divided the disaster disturbance process into damage and recovery phases. Its quantitative calculation of resilience is based on the integral of the performance curve over time, with additional consideration of the timing of disaster disturbance.

For the resilience evaluation of shield tunnels, Huang and Zhang (2015, 2016) divided the performance evolution of shield tunnels under sudden disaster into three stages: disturbance, evolution, and recovery, as illustrated in Fig. 1. Based on this, the resilience value R_c of shield tunnels can be calculated by Eq. (1). The weight coefficients F , S , and R can be determined by Eqs. (2)–(4).

$$R_c = \frac{F(t_f - t_i) + S(t_s - t_f) + R(t_r - t_s)}{t_r - t_i}, \quad (1)$$

$$F = \frac{\int_{t_i}^{t_f} f(t) dt}{\int_{t_i}^{t_f} Q(t) dt}, \quad (2)$$

$$S = \frac{\int_{t_f}^{t_s} s(t) dt}{\int_{t_f}^{t_s} Q(t) dt}, \quad (3)$$

$$R = \frac{\int_{t_s}^{t_r} r(t) dt}{\int_{t_s}^{t_r} Q(t) dt}, \quad (4)$$

where t_i , t_f , and t_s represent the initiation times of disturbance, evolution, and recovery, while t_r represents the termination of the recovery phase. $f(t)$, $s(t)$, and $r(t)$ represent the actual performance curves during the disturbance, evolution, and recovery stages, while $Q(t)$ denotes the conventional performance evolution curve.

Building on the resilience analysis models of Ayyub (2014, 2020), Huang and Zhang (2015, 2016), Lin et al. (2022) considered the impact of the initial performance Q_0 of tunnels. They proposed that the resilience model for tunnels can be represented by Eq. (5). The structural capacities F , S , and R for the disturbance stage, evolution stage, and recovery stage can be calculated using Eqs. (6)–(8).

$$R_c = \frac{F + S + R}{Q_0(t_r - t_i)}, \quad (5)$$

$$F = \int_{t_i}^{t_f} f(t) dt, \quad (6)$$

$$S = \int_{t_f}^{t_s} s(t) dt, \quad (7)$$

$$R = \int_{t_s}^{t_r} r(t) dt. \quad (8)$$

Unlike sudden disasters, the enhancement measures taken before the commencement of adjacent construction improve the system performance of existing shield tunnels, as shown in Fig. 4. Based on the 4-stage evolution characteristics of shield tunnel performance development, including pre-disturbance enhancement, disaster disturbance, disaster evolution, and post-disaster recovery under adjacent construction disturbances, the resilience evaluation framework for shield tunnels under adjacent construction disturbances can be represented by Eq. (9). The structural capacity E during the enhancement stage can be calculated using Eq. (10), while F , S , and R can be calculated using Eqs. (6)–(8).

$$R_c = \frac{E + F + S + R}{Q_0(t_r - t_i)}, \quad (9)$$

$$E = \int_{t_i}^{t_e} e(t) dt, \quad (10)$$

where $e(t)$ refers to actual performance curves during the enhancement stage.

Compared to the resilience evaluation framework proposed for sudden disasters, this framework for adjacent construction disturbances more comprehensively incorporates characteristics such as adjacent construction, structure functional redundancy, and functional suitability. It introduces initial performance values (Q_0) and performance allowable values (Q_a), and further clarifies the categories of functional suitability requirements, where achieving or exceeding Q_a is a fundamental prerequisite for the normal operation of existing shield tunnels, as shown in Fig. 4. Also, there are still a number of key issues in the established evaluation frameworks that need to be urgently discussed and unified. For example, how to determine the Q_0 and Q_a , how to take into account the impact of structure decay, how to consider the impact of economic costs, how to determine the separate time phase of the entire disaster chain, and how to quantify the relevance of human interventions in the process of the disaster chain.

3 Impact mechanism and deformation characteristics of shield tunnels under adjacent construction disturbances

3.1 Mechanisms of adjacent construction disturbances

There are 3 types of disturbance to the existing tunnels from adjacent construction, including adjacent pit excavation, proximity tunnel crossing, and ground surface surcharge. Among them, unloading and lowering of the water table during the excavation of the adjacent pit excavation will lead to changes in the additional stress and displacement fields of the surrounding soil, and then the tunnel produces a force and deformation response during this process (Zhang et al., 2013; Zhou et al., 2015; Liang

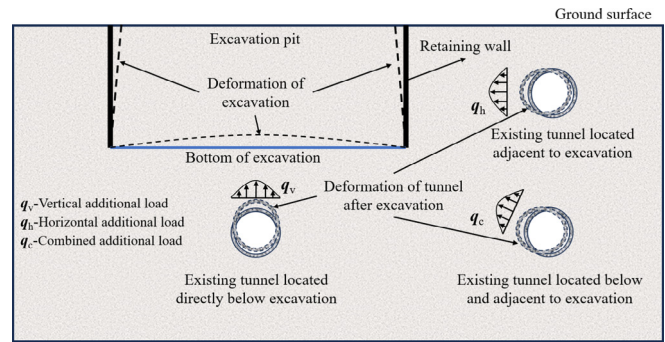


Fig. 5. Schematic diagram of the disturbance mechanism of adjacent pit excavation on the existing tunnel.

et al., 2017, 2018; Vinoth & Aswathy, 2022). As shown in Fig. 5, when the excavation pit is located directly above the shield tunnel, the excavation of the pit leads to the release of stresses in the soil at the bottom of the pit, and the stresses at the top of the tunnel are passively reduced, thus the tunnel is subjected to additional stresses upwards, leading to vertical uplift deformation of the tunnel; when the excavation pit is located on the side of the shield tunnel, the excavation of the pit makes the lateral earth pressure of the shield tunnel decrease, resulting in tunnel convergence, and produce obvious lateral displacement deformation (Huang et al., 2011; Ng et al., 2013; Huang et al., 2015; Liao et al., 2015; Shi et al., 2015b; Li et al., 2019; Bi et al., 2022; Tanoli, et al., 2022; D. Zhang et al., 2022a).

The influencing mechanism of proximity tunnelling through existing shield tunnels is complex, which is mainly closely related to the relative position, crossing angle, tunnel spacing, ground conditions, boring parameters, and reinforcement schemes (Jin et al., 2019; G. Wei et al., 2021; Fu et al., 2022). According to the relative positions of the new tunnels and the existing tunnels, there are 4 types of proximity crossing disturbances including over-crossing disturbances, under-crossing disturbances, superimposed-crossing disturbances and parallel-crossing disturbances, as shown in Fig. 6. For the over-crossing disturbances, the upper tunnel boring produces excavation unloading and ground stress release, resulting in the existing shield tunnel is subjected to upward additional stress, so that the tunnel structure produces vertical uplift deformation and lateral convergence (Ghaboussi et al., 1983; Zhao et al., 2021; Z. Zhang et al., 2022). For the under-crossing disturbances, the new tunnels cause stratigraphic losses and stratigraphic disturbances, resulting in the existing tunnels showing a tendency of ‘downward pulling and upward compression’ in terms of stress changes, as well as lateral convergence and vertical settlement deformations (Zhang et al., 2014a; Lin et al., 2019; Feng et al., 2023; Jiang et al., 2023; Islam & Iskander, 2024).

Ground surface surcharge refers to the phenomenon of filling a large amount of earth or construction materials above the existing shield tunnel, which leads to an increase

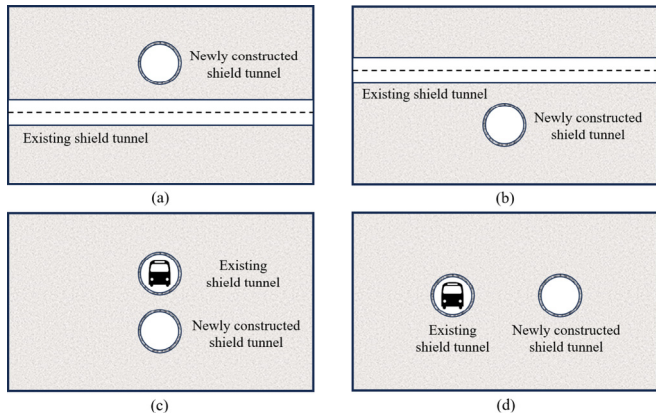


Fig. 6. Different types of proximity crossing disturbances. (a) Over-crossing disturbances, (b) under-crossing disturbances, (c) superimposed-crossing disturbances, and (d) parallel-crossing disturbances.

in the additional stresses in the ground and the existing tunnel, and produces a disturbing effect on the existing tunnel, resulting in the phenomenon that leads to the differential settlement and transverse convergence of the tunnel (Wang & Zhang, 2013; Huang et al., 2017; Liang et al., 2023). The disturbance influence of ground surface surcharge is closely related to the surcharge size, surcharge location, tunnel depth, tunnel diameter, stratum conditions, tunnel stiffness, and control measures (Shao et al., 2016; Yang et al., 2017; J. Zhang et al., 2019, 2021; Wei et al., 2022).

3.2 Deformation characteristics of shield tunnels

The deformation characteristics of shield tunnels under disturbance are crucial for selecting the resilience evaluation indicators, which generally include vertical deformation, horizontal deformation, convergence deformation, segment dislocation, and structural cracks. However, distinct disturbance mechanisms are caused in existing shield

tunnels by different types of adjacent construction activities, resulting in significant differences in the deformation characteristics of these structures. The deformation characteristics of existing shield tunnels under different types of adjacent construction disturbances are summarized in Table 2.

Vertical and convergence deformations in existing shield tunnels can result from adjacent pit excavation, proximity tunnel crossing, and ground surface surcharge, potentially leading to structural cracks. The occurrence of horizontal deformation depends on whether the adjacent construction disturbance induces additional horizontal stress on the tunnel, which mainly includes lateral excavation, parallel tunnel crossing, and lateral surface loading. Moreover, since shield tunnels can be approximated as infinitely long linear annular segmented structures, the disturbance from adjacent construction has sectional characteristics. The uneven distribution of additional stresses can lead to segment dislocation within the shield tunnel, which warrants significant attention.

Based on the mechanisms and stress-deformation characteristics of adjacent construction disturbances on existing shield tunnels, the evaluation of the impact of adjacent construction disturbances on shield tunnel structures should primarily consider vertical deformation and convergence deformation indicators. Additionally, other deformation indicators specific to the type of disturbance should also be taken into account.

4 Evaluation method for shield tunnel resilience under adjacent construction disturbances

The evaluation indicators for structural resilience need to comprehensively reflect the fundamental aspects of robustness, redundancy, resourcefulness, and rapidity, accounting for the initial performance of systems and their changes over time, as well as the post-disaster recovery process and effectiveness (Ayyub, 2020). Based on this, the log-

Table 2
Deformation characteristics of shield tunnel under different types of adjacent construction disturbances.

| Types of adjacent construction disturbance | | Vertical deformation | Horizontal deformation | Convergent deformation | Segment dislocation | Structural crack |
|--|------------------------------|----------------------|------------------------|------------------------|---------------------|------------------|
| Adjacent foundation pit excavation | Crossing existing tunnels | ✓ | O | ✓ | ✓ | O |
| | Adjacent to existing tunnels | ✓ | ✓ | ✓ | ✓ | O |
| Proximity tunnel crossing | Over-crossing | ✓ | O | ✓ | ✓ | O |
| | Under-crossing | ✓ | O | ✓ | O | O |
| | Parallel-crossing | | ✓ | ✓ | O | O |
| | Overlaying-crossing | ✓ | O | ✓ | O | O |
| Ground surface surcharge | Crossing existing tunnels | ✓ | O | ✓ | ✓ | O |
| | Adjacent to existing tunnels | ✓ | ✓ | ✓ | O | O |

Note: “✓” means it’s bound to happen; “O” means it probably happens.

ical relationship of the resilience indicators for shield tunnels is shown in Fig. 7. The external effectiveness indicators of shield tunnel resilience include 4 dimensions: structural performance, tunnel functionality, economic costs, and affected time. In essence, the resilience of shield tunnels is determined by intrinsic impact factors such as technical, organizational, social, and economic dimensions.

The essential step in devising a scientific and reasonable resilience evaluation method for shield tunnels, while accounting for adjacent construction disturbances, hinges on systematically integrating intrinsic impact factors to predict pre-disaster resilience and leveraging external effectiveness indicators for comprehensive disaster chain analysis.

4.1 Resilience evaluation based on impact factor indicators

Resilience evaluation based on impact factor indicators primarily considers the influence of factors in technical, organizational, social, and economic dimensions. Each of these impact factor indicators is assessed and graded accordingly, and a comprehensive evaluation method is employed to establish an indicator system and evaluation methodology.

Based on this approach, Q. Wei et al. (2021) developed a tunnel construction safety resilience evaluation indicator system that considers the unique characteristics of tunnel

engineering, geological conditions, and emergency management. They analyzed the impact of complex factors such as construction disturbances and emergency management on tunnel construction safety resilience. Borghetti et al. (2021) studied the impact of emergency measures on tunnel fire resilience through case analysis. Su et al. (2024) considered factors such as disaster severity, geological vulnerability, resistance, recoverability, and adaptability to construct a resilience evaluation model for the geological environment of urban deep underground spaces. Luo et al. (2023) developed an underground space resilience indicator system encompassing 5 dimensions including the organizational structure, infrastructure, environment, society, and economy, and established an evaluation model of underground space resilience based on the entropy weight method. Emanuel and Ayyub (2019) considered stakeholder preferences in the resilience evaluation system, studying the connotations and methods of urban infrastructure resilience evaluation through 4 basic models. Shadabfar et al. (2022) discussed the resilience connotations of infrastructure such as underground space structures based on resilience design concepts, and provided a comprehensive review of resilience evaluation models, technical methods, and computing platforms.

To some extent, resilience evaluation based on impact factor indicators aligns with existing safety and risk assessment methods. However, while safety and risk assessment

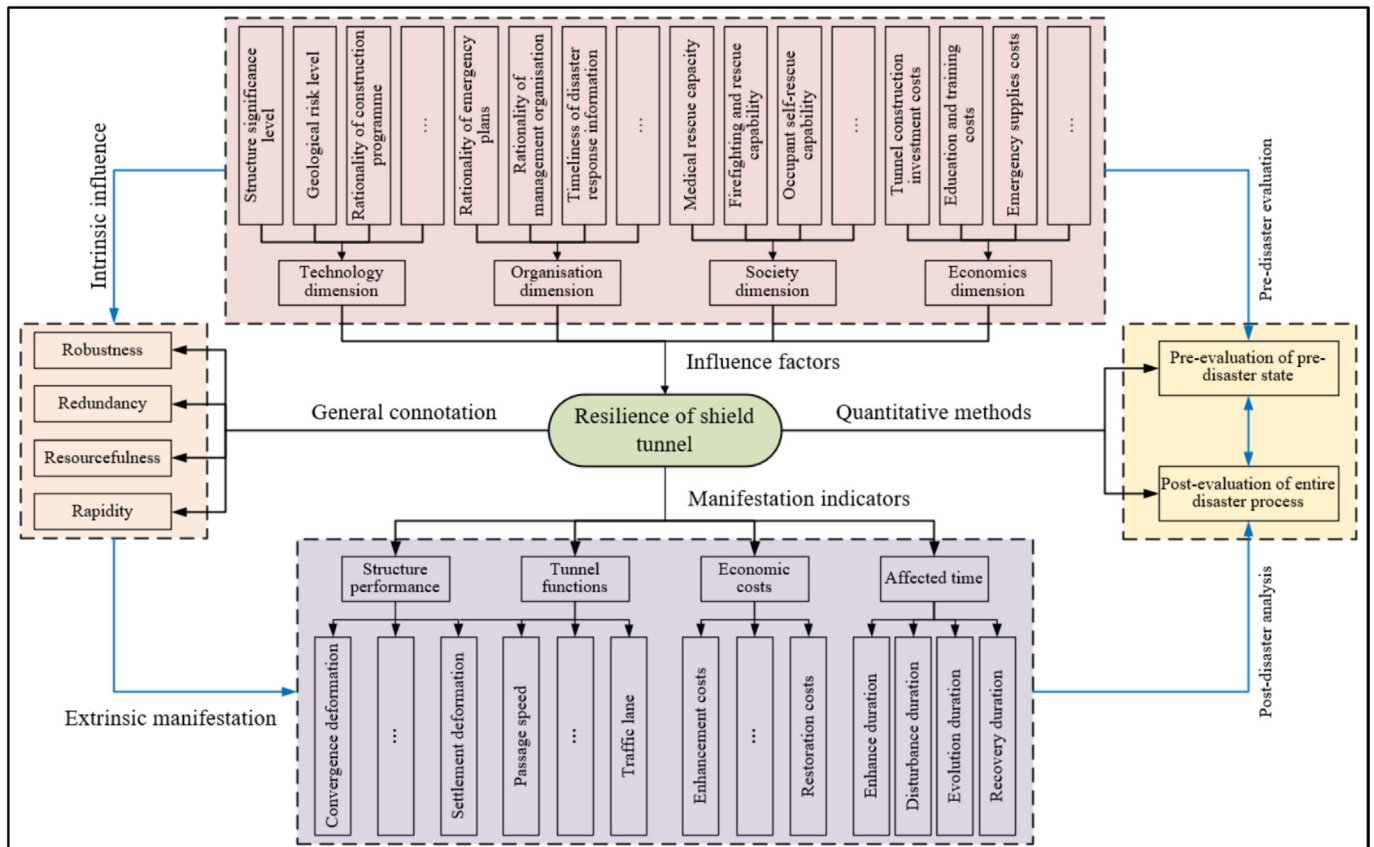


Fig. 7. Intrinsic logic of shield tunnel resilience.

typically focus on the instantaneous state at a specific point in time, resilience evaluation takes into account the entire disaster chain, providing a more comprehensive and elevated evaluation of the performance over the entire process, as shown in Table 3. Hence, the key to ensuring the scientific and accurate results of this resilience evaluation lies in reflecting the dynamic evolution of resilience and its interaction with the environment.

4.2 Resilience evaluation based on effectiveness indicators

The resilience evaluation based on effectiveness indicators during the disaster chain primarily considers dimensions such as structural performance, tunnel functionality, affected time, and economic costs. As shown in Table 4, performance dimension indicators serve as the general foundational indicators for the resilience evaluation of shield tunnels. These indicators focus on structural deformation, including convergence, settlement, differential settlement, ellipticity, and longitudinal settlement, all of which take into account the time-dependent characteristics of deformation indicators. However, the initial or maximum allowable values of deformation indicators are not

uniformly quantified, leading to variations in the calculation methods for the same resilience performance indicator Q among different researchers.

For instance, Huang and Zhang (2015, 2016) used the ratio of initial deformation to time-varying deformation as the performance indicator Q . Lin et al. (2022) and Jiang and Hao (2022) used the ratio of deformation redundancy to the maximum allowable value as the performance indicator Q . Hua et al. (2024) used the longitudinal relative differential settlement as the index of tunnel structural resilience performance, as shown in Fig. 8. Meanwhile, Zhu et al. (2024) employed a piecewise function based on historical maximum deformation values to characterize the performance indicator Q .

The effectiveness indicators for tunnel functionality are highly specific. Current resilience evaluations of shield tunnels mainly target traffic tunnels, represented by the speed of trains or vehicles passing through the tunnel and the network connectivity efficiency of the tunnel. Affected time encompasses the entire process duration, including enhancement time, disturbance time, evolution time, and recovery time, making it a crucial dimension in the resilience evaluation of shield tunnels. Presently, the quantifica-

Table 3
Comparison of safety, risk, and resilience evaluation of engineering structures.

| Items | Definition | Key indicators | Time characteristics |
|------------|--|---|----------------------|
| Safety | Be capable of withstanding and maintaining the necessary stability during and after the fortuitous events. | Factor of safety, load-bearing capacity | Instantaneous |
| Risk | The combination of the probability of occurrence and the loss of an accident or disaster | Probability, loss | Instantaneous |
| Resilience | Resistance and recoverability of engineering systems to environmental changes or disasters | Robustness, redundancy, resourcefulness, and rapidity | Entire time process |

Table 4
Statistics on effectiveness indicators for shield tunnel resilience.

| Dimensions | Indicators | Calculation method | References |
|------------------------|---|---|---|
| Structural performance | Convergence deformation, ΔD | $Q(t) = \frac{\Delta D_0}{\Delta D(t)}$ | Huang & Zhang, 2015, 2016 |
| | | $Q(t) = \frac{\Delta D_{max} - \Delta D(t)}{\Delta D_{max}}$ | Lin et al., 2022 |
| | | $Q(t) = \begin{cases} \frac{1}{1 + 2.5 \times 10^{-4} \left(\frac{\Delta D(t) + \Delta D_{max, his}}{2} \right)^2}, & (\Delta D(t) \leq \Delta D_{max, his}) \\ \frac{1}{1 + 2.5 \times 10^{-4} \Delta D(t)^2}, & (\Delta D(t) > \Delta D_{max, his}) \end{cases}$ | Zhu et al., 2024 |
| | Settlement deformation, u | $Q(t) = \frac{u_{max} - u(t)}{u_{max}}$ | Lin et al., 2022 |
| | Differential settlement, ΔS | $Q(t) = \frac{\Delta S_{max} - \Delta S(t)}{\Delta S_{max}}$ | Lin et al., 2022 |
| | Longitudinal settlement, ω | $Q(t) = \frac{\omega_{max} - \omega(t)}{\omega_{max}}$ | Jiang & Hao, 2022 |
| Tunnel functions | Longitudinal relative differential settlement, S_{re} | $Q(t) = \frac{S_{re}(t)}{S_{re0}}$ | Hua et al., 2024 |
| | Ellipticity, ΔE | $Q(t) = \frac{\Delta E_0}{\Delta E(t)}$ | Ni, 2021 |
| | Traffic speeds | $Q = \frac{\text{Open lanes}}{\text{Total lanes}} \times \frac{\text{Reduced speed limit}}{\text{Normal speed limit}}$ | Khetwal et al., 2019 |
| Affected time | Network efficiencies Affected duration | $Q(t) = E_f(t) = \frac{1}{N(N-1)} \sum_{i \neq j} \frac{1}{d_{ij}}$ $\Delta T = t_r - t_i$ | Zhang et al., 2018 Huang & Zhang, 2015, 2016; Lin et al., 2022 |
| Economic costs | Restoration costs | $C_{total} = C_{disruption} + C_{repair}$ | Zhang et al., 2018 |

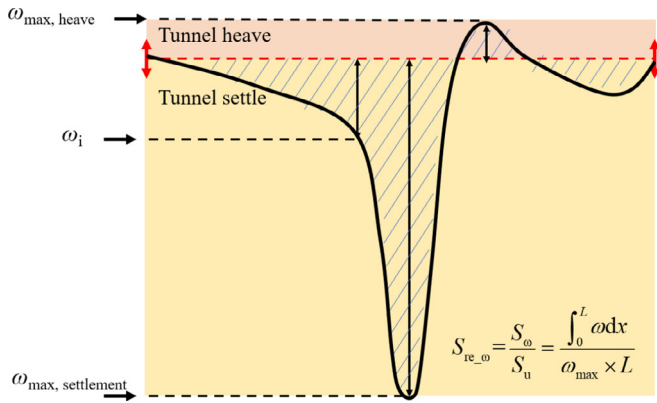


Fig. 8. Relative unevenness of the longitudinal settlement as the performance index (Hua et al., 2024, reproduced with permission, courtesy of Elsevier).

tion of affected time mainly considers absolute duration or the integration of structural system performance over time.

Economic cost is an essential dimension that distinguishes resilience evaluation from risk evaluation. Zhang et al. (2018) conducted a quantitative analysis of disaster losses and repair costs for shield tunnels under sudden disaster disturbances. For the resilience of existing shield tunnels under adjacent construction disturbances, the investment cost during the pre-disturbance enhancement phase constitutes a significant, if not the primary, part of the overall economic costs and serves as a critical basis for enhancement decision-making. Therefore, it should be subject to quantitative analysis. Furthermore, Han et al. (2023) constructed a three-dimensional space of performance-time-cost to interpret the evolution laws of composite performance and recovery costs over time, as

shown in Fig. 9. And they explored in-depth the interrelationships among structural functionality, affected time, and economic cost, and proposed a resilience evaluation framework for underground space structures based on the three-dimensional space of functionality, time, and cost, as shown in Fig. 10.

Both resilience evaluation based on impact factor indicators and effectiveness indicators can reasonably assess the resilience of shield tunnels under adjacent construction disturbances. Furthermore, in addition to deterministic evaluation, some scholars have analyzed the impact of uncertainty on resilience evaluation by means of probabilistic methods (Francis & Bekera, 2014), such as the uncertainty of disasters (Gidaris et al., 2022), geological conditions (Chwała et al., 2023), and performance recovery (Talebiyan & Duenas-Osorio, 2020). As a functional system, the resilience evaluation of shield tunnels should be a dialectical unity of both methods, rather than being independent or even oppositional. Systemic issues in evaluating the resilience of shield tunnels under adjacent construction disturbances still demand further research.

5 Research on resilience enhancement of shield tunnels

Shield tunnels were operated within a complex geotechnical environment characterized by multiple fields such as stress field, displacement field, and seepage field, and multiple phases including solid phase, liquid phase, and gas phase. The significant coupling interaction between the structure and geotechnical environment necessitates that resilience enhancement for shield tunnels considers the entire disaster chain impact mechanism, including disaster action, structure response, disaster control, and resilience

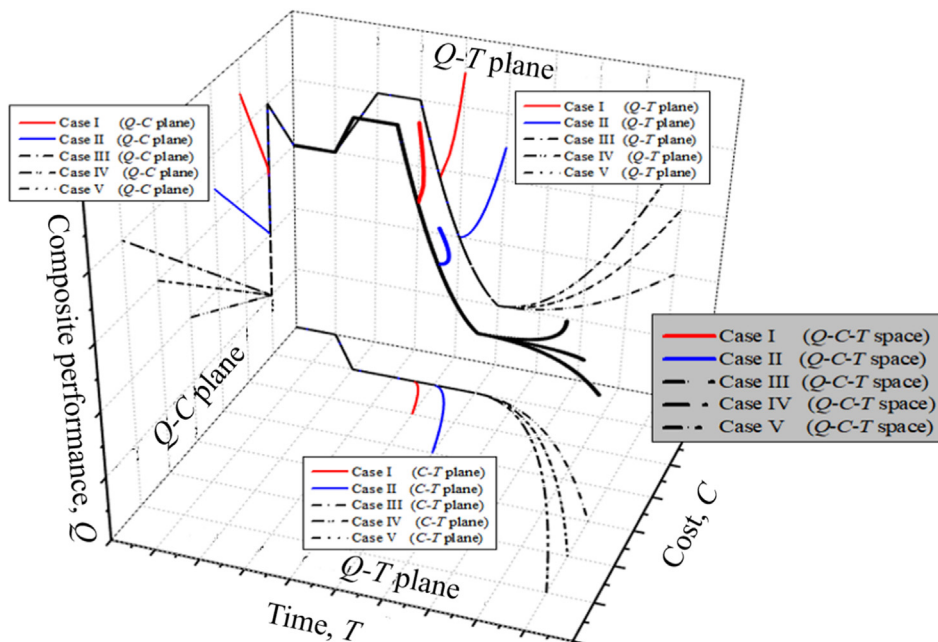


Fig. 9. Performance-time-cost three-dimensional space (Han et al., 2023).

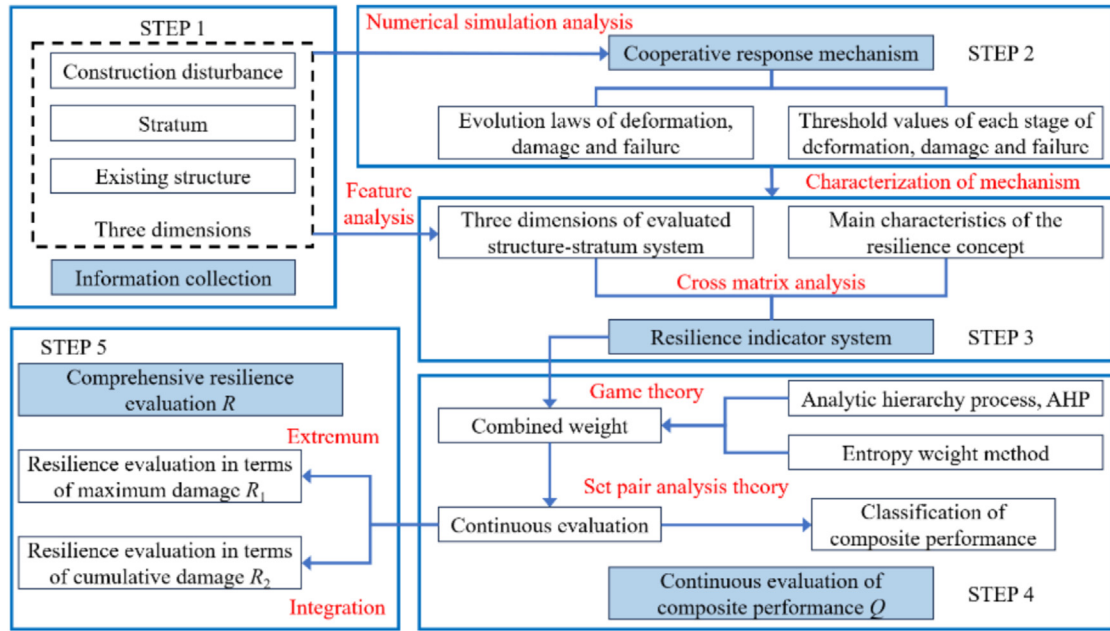


Fig. 10. Framework for the resilience assessment of underground structure-stratum (Han et al., 2023).

enhancement (Gu et al., 2023). It is crucial to explore coordinated resilience enhancement strategies between shield tunnels and the geotechnical environment. It is particularly noteworthy that, as a comprehensive engineering system, resilience enhancement of shield tunnels requires a holistic consideration of various factors. According to the intrinsic logic of shield tunnel resilience in Fig. 7, shield tunnel resilience enhancement should be carried out in terms of the 4 influencing factors including engineering technology, organizational management, economic cost, and social security.

Hence, the systematic logic for enhancing resilience of the tunnels is illustrated in Fig. 11. In the first, and innermost, layer of the diagram is the target for shield tunnel resilience enhancement. The second layer is the enhance-

ment requirement of shield tunnel resilience, including strong robustness, sufficient redundancy, intelligent adaptation, and quick recovery. The third layer is the strategic dimension of shield tunnel resilience enhancement, including engineering technology, organizational management, economic cost, and social security, which are closely inter-related to the resilience enhancement requirements of the second layer.

Engineering technology is the fundamental basis for enhancing the resilience of shield tunnels and is currently the primary research focus in this area. Based on the disturbance mechanisms of adjacent construction disasters on shield tunnels, the coordinated resilience enhancement technologies can be approached from several aspects: structure optimization design, blocking disturbance transmission, enhancing structural performance, ground reinforcement, and auxiliary enhancement. The strategies and methods for enhancing the resilience of shield tunnels are summarized in Table 5.

The optimization design of shield tunnels is a crucial technical means to enhance pre-disaster structural resilience. Currently, scholars both domestically and internationally have proposed structural design optimization methods based on reliability and robustness concepts to effectively improve the pre-disaster resistance resilience of shield tunnels, as shown in Table 5. However, existing optimization methods based on reliability and robustness primarily aim to reduce structural damage or lower economic costs while ensuring structural performance requirements. They do not systematically consider post-disaster functional recoverability or the reciprocal coupling effects between the tunnel structure and the surrounding ground. In light of this, Xiao et al. (2023) proposed the concept of resilience design and fortification goals for



Fig. 11. Systematic logic for enhancing the resilience of shield tunnels.

Table 5
Summary of strategies and methods enhancing the resilience of shield tunnels.

| Strategies | Methods | Content | Enhancing principle | References |
|-----------------------------------|--------------------------|--|---|--|
| Structure optimization design | Reliability optimization | Point estimation method | Considering the variability of stratigraphic | Rosenblueth, 1975; Zhao & Ono, 2000; Kroetz et al., 2018; Li et al., 2023 |
| | | Support vector machine Logistic regression model Moving least squares Response surface methodology | | Zhao et al., 2014 Zhang & Goh, 2016 Lü et al., 2017 Hamrouni et al., 2017; Liu et al., 2022b |
| | Robustness optimization | Fuzzy set 3D robust design | Considering economic costs Considering the variability of longitudinal stratigraphic | Gong et al., 2014 Gong et al., 2015 |
| | | Multi-objective optimization | Robustness and cost multi-objective optimization Maximizing robustness and minimizing cost | Wang, 2019 D. Zhang et al., 2019 |
| Blocking disturbance transmission | Isolation piles | Constrained multi-objective algorithm | Robustness and cost optimization in the limits | Hua et al., 2022 |
| | | Conventional isolation piles Buried isolation piles | Displacement blocking Provides blocking action and reduces traction | Zheng et al., 2015 Du, 2018; Xu et al., 2018 |
| Enhancing structural performance | Structure form | Increase lining thickness Optimization of joints | Increase structural resistance Improved structural stiffness and enhanced waterproofing | Meng et al., 2023 L. Zhang et al., 2019; Y. Zhang et al., 2022; Zhang et al., 2023a; Zhang et al., 2023b |
| | | Construction materials | Fiber-reinforced concrete | Improve the resilience of structural material Zhang et al., 2020; Tong et al., 2022; D. Zhang et al., 2022b |
| | Structural reinforcement | Restoration with carbon fiber reinforced polymer Restoration with aramid fiber reinforced polymer Restoration with plate | Structure restoration and reinforcement Structure reinforcement | Li et al., 2014 Liu & Zhang, 2014; Ai et al., 2017 Zhao et al., 2016; Liu et al., 2017; D. Zhang et al., 2021 Zhang et al., 2014b; Zhang et al., 2014 |
| Ground reinforcement | Deformation recovery | Minor disturbance grouting | Recovery from deformation due to soil volume change | Du, 2018; Zheng et al., 2022b |
| | Strata reinforcement | Real-time compensating grouting | Improvement of strata mechanical properties | |

shield tunnels. They developed a resilience design indicator system that takes into account structural redundancy, robustness, recoverability, and economic efficiency. Ultimately, they established a ‘design + evaluation’ method for the resilience design of shield tunnels.

Blocking disturbance transmission involves installing isolation facilities between existing shield tunnels and newly constructed adjacent structures to block stress transmission paths or limit soil displacement. This method aims to reduce the intensity of construction disturbances and thus collaboratively enhance the resilience of the tunnel. For excavation disturbances due to adjacent construction, blocking piles are typically placed between the lateral retaining structures of the excavation pit, or uplift piles are installed on both sides of the tunnel when excavating the overlying pit. However, the design of blocking piles

and uplift piles must comprehensively consider the conflicting effects of blocking and traction (Zheng et al., 2015; Du, 2018; Xu et al., 2018). However, blocking disturbance transmission is not usually applicable in densely built-up urban centers, and the construction of blocking piles and uplift piles may also result in adjacent construction disturbances to existing shield tunnels.

Enhancing structural performance focuses on improving the resistance of shield tunnels through modifications to structure form, material, and reinforcement. Structure reinforcement is a key method for post-disaster recovery of existing shield tunnels. However, current research on the role of structure reinforcement in enhancing tunnel resilience predominantly emphasizes technical methods, lacking quantitative analysis that considers performance, time, and economic costs. Some structural performance enhancing

measures, such as restoration with fiber reinforced polymer or plate, are expensive.

Ground reinforcement primarily improves its resistance to deformation and effectively blocks the stress transmission in the soil surrounding the tunnel. Simultaneously, the volumetric expansion of the soil due to grouting can be utilized to control the deformation and its recovery in existing tunnels, as shown in Fig. 12. This method can effectively repair structure issues such as segment joint openings and segment misalignment induced by uneven vertical settlement and lateral deformation, thereby collaboratively enhancing the resilience of shield tunnels. Unfortunately, grouting reinforcement is subject to significant uncertainty due to the stratum's invisibility. Close integration with site monitoring is generally required.

Additionally, auxiliary measures such as controlling ground surface surcharge, optimizing adjacent construction sequences, increasing the stiffness of support structures for nearby excavations, and improving monitoring schemes can reduce the impact of adjacent construction on the geotechnical environment. These measures aim to minimize the initial disturbance, enhance early warning ability, and improve control efficiency for disaster-related disturbances. Lei et al. (2023) proposed 7 key resilience enhancement technologies for underground space engineering, including micro-disturbance construction techniques, equivalent stiffness reinforcement for connected structures, anti-corrosion and anti-cracking concrete technology, waterproofing and drainage technology, high-durability anchoring, non-structural energy-dissipating seismic reduction, and disaster prevention and mitigation technologies during operation and maintenance.

According to the statistics by B. Liu et al. (2024), as shown in Figs. 13 and 14, ground improvement, zoned excavation, isolation or uplift pile, pit bottom loading, and field monitoring are commonly used methods to control the tunnel displacement induced by adjacent construction, especially disturbances by adjacent pit excavation. It is found that with the improvement of the ground condi-

tions, the use of displacement control methods was correspondingly reduced. Deformation control of existing shield tunnels under adjacent construction disturbances is a key indicator of their resilience level. However, current resilience enhancement research is mainly application-oriented, which primarily focuses on analyzing the mechanisms and effects of deformation control by engineering methods.

Particularly, it is worth paying attention to the fact that with the rapid development and application of artificial intelligence (AI) technology, the accuracy and time-efficiency of disaster evolution reasoning, performance prediction, resilience evaluation, and decision-making of resilience enhancement will be improved markedly (Shen et al., 2023; Alkhaleel, 2024). It will greatly facilitate the resilience enhancement of the shield tunnels under adjacent construction disturbances. In reality, shield tunnels, as complex functional systems, still lack resilience enhancement strategies considering the combined impact of engineering technology, organizational management, economic costs, and social security.

6 Discussion and prospects

It is evident that significant advancements have been made in resilience analysis theories, evaluation indicators, and enhancement methods by scholars both domestically and internationally, based on the aforementioned studies on the resilience of shield tunnels under adjacent construction disturbances. However, several key issues still urgently remain to be thoroughly addressed as follows.

6.1 Intensity quantification of adjacent construction disturbance

As an inherent property of engineering structure systems, resilience represents the capability of a system to respond to disaster-induced disturbances, resulting in vary-

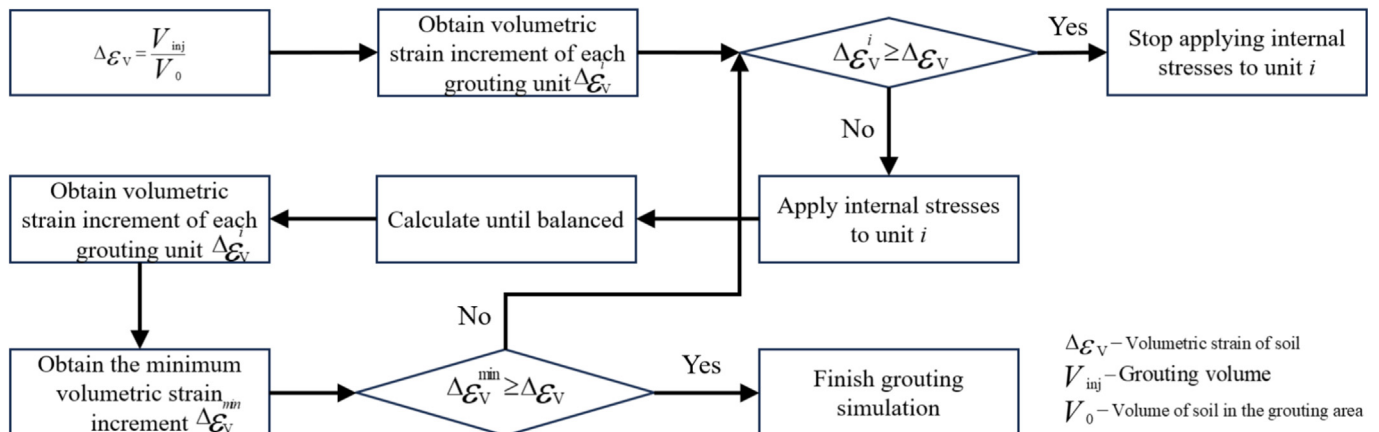


Fig. 12. Simulation method for lateral grouting in shield tunnel with large lateral deformation (Zhang et al., 2014b).

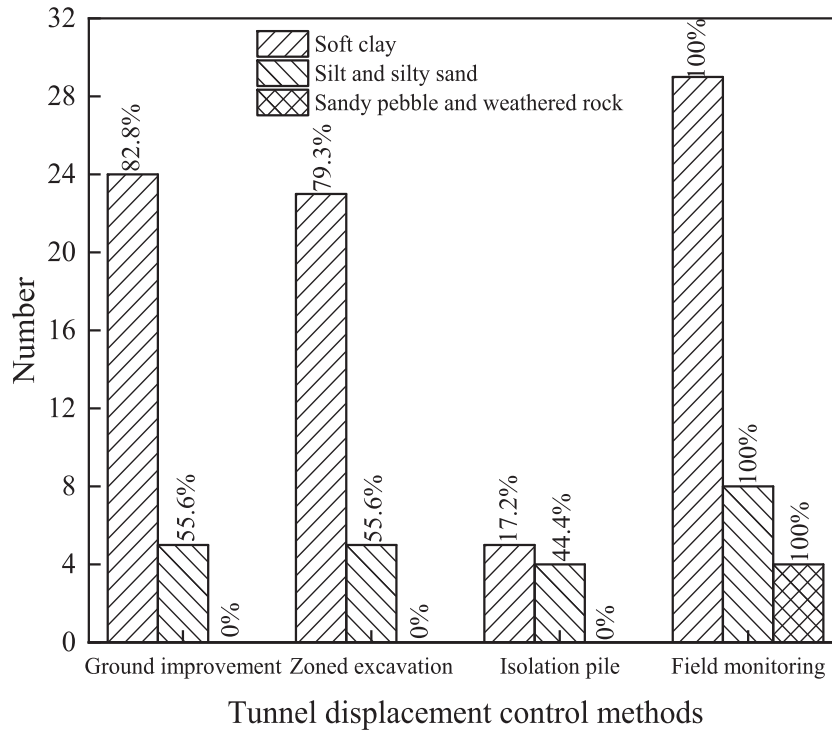


Fig. 13. Proportion of displacement control methods for lateral tunnel (B. Liu et al., 2024, reproduced with permission, courtesy of Elsevier).

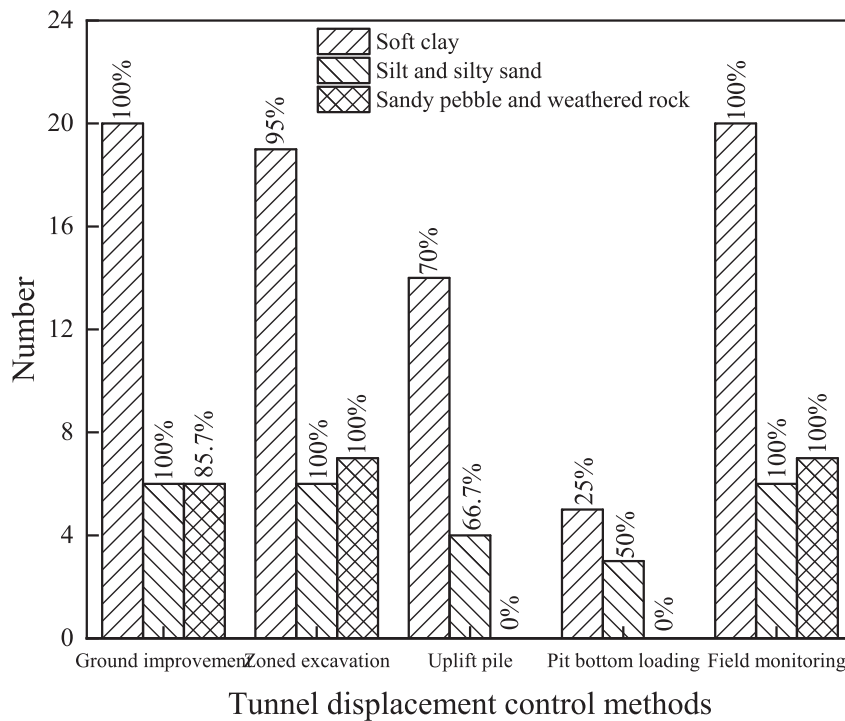


Fig. 14. Proportion of displacement control methods for the underlying tunnel (B. Liu et al., 2024, reproduced with permission, courtesy of Elsevier).

ing responses under different disturbance intensities (Huang et al., 2024; Shen et al., 2025). Although the response of the same shield tunnel system may differ when subjected to various adjacent construction disturbances, its resilience level should remain relatively consistent. Therefore, resilience evaluation of shield tunnels under adjacent

construction disturbances must account for the impact of disturbance intensity or adjust the evaluation results accordingly.

The disturbance intensity of adjacent construction on shield tunnels can be defined as the maximum impact that adjacent construction may have on the shield tunnel with-

out reinforcement or enhancement measures. This is mainly related to the potential deformation of the existing shield tunnels and the relative position of the adjacent construction project to the tunnels. Accordingly, research on the intensity of adjacent construction disturbances can be conducted from 2 perspectives. Firstly, predict and analyze the deformation impact of adjacent construction on the existing tunnels using existing theoretical analysis, numerical simulation, and simplified analysis methods, then classify disturbance intensity levels, and ultimately determine the disturbance intensity coefficients based on the magnitude of the deformation. Secondly, classify disturbance impact levels based on the relative position of the adjacent construction influence area to the existing shield tunnel, and use this classification to determine the disturbance intensity coefficient eventually. After that, the intensity coefficient can be accounted into the resilience evaluation framework and resilience calculation formulas, as a correction factor or evaluation indicator. It deserves in-depth study for more accurate resilience evaluations.

6.2 Resilience evaluation indexes and resilience level grading

Resilience evaluation indicators for shield tunnels include those based on impact factor indicators and those effectiveness indicators characterizing the entire disaster chain process currently. The selection of these indicators is, to some extent, both targeted and reasonable. However, the grading of evaluation indicators and resilience levels remains relatively subjective, utilizing methods such as the multiple-level grading systems (Su et al., 2024). The determination of indicator thresholds lacks a necessary scientific and rational basis. Additionally, the permissible or maximum values of performance indicators based on structural deformation are derived from current standards (Lin et al., 2022; Han et al., 2023), which often include safety margins, potentially leading to an underestimation of the resilience level of the structure. Therefore, it is imperative to study and analyze the limit or permissible values of evaluation indicators to enhance the scientific basis of indicator thresholds and resilience grading. This is crucial for improving the rationality and accuracy of resilience evaluations for shield tunnels under adjacent construction disturbances.

6.3 Time-dependent resilience prediction of the entire disaster chain

The resilience of shield tunnels undergoes a dynamic evolution process, with resilience evaluation indicators exhibiting significant time-dependent characteristics. Research on predicting resilience evaluation indicators, such as structural deformation, using empirical models and deep learning algorithms is relatively advanced and has established a solid foundation for resilience prediction analysis (Shen et al., 2023; D. Zhang et al., 2024). It is

essential to go beyond the limitations of single engineering case studies (B. Liu et al., 2024). A case database of adjacent construction disturbances should be established to improve the rationality and generalization of resilience indicator prediction models by investigating the disturbance mechanisms of adjacent construction on shield tunnels, the evolution of indicators, and the impact of enhancement measures.

Furthermore, a dynamic evaluation method for shield tunnel resilience under adjacent construction disturbances should be developed, considering the relationship between disturbance intensity, resilience indicators, and resilience levels. It includes constructing a time-dependent resilience prediction model for the entire disaster chain process, providing a basis for enhancing shield tunnel resilience and disaster response decision-making.

6.4 Synergistic enhancement strategy for shield tunnel resilience

Current research on enhancing the resilience of shield tunnels mainly focuses on the impact of individual factors such as structure repair or grouting on deformation indicators, with limited studies on the synergistic effect of structure and soil interactions on resilience indicators (D. Zhang et al., 2021; Gu et al., 2023). Existing studies are mainly application-oriented, lagging in theoretical exploration, and lacking in multi-objective optimization methods with multi-measure and enhancing strategies that consider resilience recovery targets, duration time, and economic costs. Based on the resilience requirements of shield tunnels under adjacent construction disturbances, it is crucial to integrate intelligent algorithms and technologies such as machine learning, physical information neural networks, knowledge graphs, and pre-trained models. This integration aims to analyze the mapping relationship between influencing parameters and resilience indicators.

A comprehensive method that considers resilience goals, affected time, and economic costs should be proposed to quantify the correlation between multi-measure, multi-objective resilience enhancement strategies in a structure-soil context. Additionally, a decision support knowledge base and a large language model for the vertical domain of shield tunnel resilience should be constructed, equipped with autonomous decision-making and reasoning capabilities. This approach will enable intelligent, rapid, and scientifically sound decisions for ensuring and enhancing the resilience of shield tunnels throughout the entire disaster chain under adjacent construction disturbances.

7 Conclusions

The resilience objectives of ‘strong robustness, sufficient redundancy, quick recovery, and intelligent adaptation’ are fundamental requirements for shield tunnels. Resilience

evaluation provides a new and novel approach for assessing the impact of adjacent construction disturbances on shield tunnels. However, there are challenges such as the ambiguous definition of resilience, diverse evaluation indicators and measurement methods, and a focus on assessment over enhancement.

It is evident that current resilience evaluation models face applicability issues concerning adjacent construction disturbances and fail to effectively address the time-dependent and systematization of resilience evaluation, by summarizing and analyzing the fundamental theories and evaluation methods of resilience for existing shield tunnels. To address these challenges, a resilience evaluation framework should be established that encompasses 4 stages: pre-disaster enhancement, disaster disturbance, disaster evolution, and post-disaster recovery. This framework should incorporate evaluation indicator systems that consider intrinsic influencing factors such as technology, organization, society, and economy, as well as representational dimensions like structural performance, tunnel functionality, affected time, and economic cost.

Resilience enhancement technologies primarily focus on practical applications, with application practices outpacing theoretical research. There remains a lack of multi-measure, multi-objective optimized resilience enhancement methods and strategies that consider resilience recovery targets, recovery time, and recovery costs. Future research should focus on 4 key areas: quantifying the intensity of adjacent construction disturbances, classifying resilience evaluation indicators and resilience levels, predicting time-dependent resilience throughout the entire disaster chain, and enhancing the synergy between shield tunnels and the surrounding soil. Strengthening research in these areas will better promote disaster prevention, mitigation, and resilience enhancement for shield tunnels affected by adjacent construction disturbances.

Data availability

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

CRedit authorship contribution statement

Dong-Mei Zhang: Writing – original draft, Conceptualization, Visualization, Funding acquisition, Supervision, Writing – review & editing, Validation. **Bin-Lin Gan:** Data curation, Visualization, Writing – review & editing, Investigation, Conceptualization, Writing – original draft, Formal analysis. **Zhong-Kai Huang:** Supervision, Conceptualization, Formal analysis, Writing – review & editing. **Rui Zhu:** Investigation, Visualization, Data curation. **Wei Zhang:** Investigation, Data curation, Visualization.

Declaration of competing 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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