Proceedings of the 20th ICSMGE – Post-conference Volume – Rahman and Jaksa (Eds)

Resilient evaluation and control in geotechnical and underground engineering

Gang Zheng, Xuesong Cheng, Haizuo Zhou, Tianqi Zhang, Yu Diao, Wei Guo
MOE Key Laboratory of Coast Civil Structure Safety, Tianjin University, Tianjin 300072, China and Department of Civil Engineering, Tianjin University, Tianjin 300072, China

Ruozhan Wang & Fan Yi
Department of Civil Engineering, Tianjin University, Tianjin 300072, China

ABSTRACT: Resilient cities and societies are significantly required for modern cities, social security, and sustainable development. However, lots of structures in geotechnical and underground engineering are of low resilience due to the uncertainties of soil properties and the surcharges, and the complex interaction between soil-water-structures. The damage accidents or even progressive collapse accidents happened from time to time in deep excavation, shield tunnel, pile foundation, and embankment projects all over the world. Therefore, it is important to reveal the development and termination mechanisms of the progressive failure to resist natural or human-induced serious disasters, maintain its functions to an extreme extent, and restore its functions as soon as possible after disasters. It is of great importance to build the evaluation and controlling design theories of resilience against progressive failure, improve the resilience of structural units, systems, and the associated large-scale urban in geotechnical and underground engineering, improve their disaster resistance to disasters or accidents, adaptation and recovery capacity, ensure the safety of construction projects for the development of resilient cities. This paper summarized the connotation and development of resilience and pointed out that its evaluation and control methods can be divided into the following four levels of design: permissible stress design method, reliability-based design method, robustness method, and recoverable performance method based on the failure probability, ability to prevent progressive collapse under unforeseen events and its recoverability from disasters. The recent research studies on each of these levels in geotechnical and underground engineering structures are reviewed, summarized, and analyzed. The progressive collapse in the deep excavation engineering, underground engineering, shield tunnels, and column-supported embankment engineering are taken as examples to discuss the existing research studies on the resilience against the progressive collapse to provide references for establishing design theories and frameworks in geotechnical and underground engineering.

KEYWORDS: Excavation engineering; Shield tunnel engineering; Resilience; Progressive collapse; Reliability; Robustness; Recoverability

1 INTRODUCTION

The utilization of underground space is one of the most effective ways to solve traffic congestion, shortage of land resources, expansion of urban spaces, and alleviation of environmental deterioration. It is also an important way for the economy and human society development to build a sustainable, resource-saving, and environment-friendly society. For this purpose, underground spaces have been intensively developed in large and medium-sized cities, such as underground shopping malls, transportation hubs, complexes, parking lots, subway tunnels and stations, and comprehensive pipeline corridors. The transportation infrastructures are also being optimized and developed to provide strategic support for stable economic growth, coordinate developments of regional urban and rural areas, developments of land and space, improvements of productivity distribution, and optimizations of industrial structures.

Geotechnical engineering is the science that explains the mechanics of soil and rock and their applications to the development of humankind. It includes, without being limited to, the analysis, design, and construction of slopes, excavations, soil and foundations, tunnels, and other systems that are made of or are supported by soil or rock. Underground structures are often related to the structures built beneath the earth's surface, such as tunnels, subway stations, underground shopping malls and car parks, and so on. The development of underground space and the construction of transportation infrastructure involves many geotechnical and underground engineering problems which are almost ubiquitous. The large-scale engineering structures are supported or embedded in soil with their system safety largely depending on the interactions between soil and structures. The safety of geotechnical structures has a significant influence on large-scale engineering structures. Geotechnical engineering is being recognized as one of the high-risk construction fields as it often faces high risks of complex engineering geological and hydrogeological conditions and harsh surrounding environments. These risks are roughly reflected in the following two aspects:

(1) Low integrity and high risk of progressive collapse

Compared with other engineering structures, geotechnical engineering is a complex interaction system composed of structure, soil, and groundwater. Soil is one of the most complex engineering materials because of its uncertainties in geotechnical parameters, the physical analyzing models, and the environmental conditions (excess heat, cold, snow, earthquakes, fire, and flooding) during the construction and service procedures. The integrities of the connections between each component of the structure are much lower than that of the architectural structures, resulting in lower integrity and robustness of the system.

Take the deep excavation project, for example, the whole retaining system is composed of the weakly connected or not connected remaining piles (walls) and scattered struts systems. However, the current design methods are still based on the component design, without considering the integrity and robustness of the entire retaining system. Huang and Gu (2008) also pointed out that the safety stock of the retaining system is relatively low because they are mostly designed as temporary structures. Another example is the shield tunnel which is made up of concrete segments and spliced together using lots of bolts which are the weak and sensitive parts of the shield tunnel (Huang et al., 2012, 2016). Therefore, the entire shield tunnel is relatively low in integrity and high in fragility.

It can be seen from the above discussions that some geotechnical structures, such as the deep excavation and the shield tunnels structures, can be considered low-resilience structures. Once local failure occurs, there is a high risk for the surrounding structures to be damaged in progressive failure. The robustness of the intervention ability before the disaster is poor.

(2) hard to rescue, repair, and rebuild after damage, but easy to cause cascading damage to adjacent structures under or above the ground

As the underground structures are often deeply embedded underground, the local failure induced accident develops rapidly with a large range of damage. It is extremely hard to intervene, rescue, and control the disaster during the damage developing process. The damaged structures generate a large number of solid rubbish which is deeply buried underground. After the damage occurs, most or all the engineering functions are lost and difficult to repair. With the continuous development of urban underground space, many adjacent unground structures system have been constructed. Once an underground structure is damaged, it will lead to different degrees of change in the constraints of the surrounding soil. A severe change may result in excessive deformation or even collapse of the adjacent structures forming a chain of damage to the adjacent projects.

These risks make the geotechnical and underground structures one of the well-known engineering fields with the highest risks of damage. A large number of engineering accidents in the world show that once damaged, the accidents for geotechnical and underground engineering structures rapidly develop with large scopes of destruction. The current design theory cannot predict the damage location and damage range, nor effectively evaluate and control the damage. As a result, underground engineering accidents occur frequently, resulting in serious social impact and huge economic and property losses.

In 2019, the 13th Chinese National Conference on Soil Mechanics and Geotechnical Engineering (CNCSMGE) with the main theme of “Quality Improvement and Sustainability Development of Geotechnical Engineering” held in Tianjin, gave the consensuses: the prospects of Geotechnical Engineering should have the quality of Resilience, Green, Intelligence and Humanism. The "Resilience of geotechnical engineering" is defined as: "Geotechnical engineering is closely related to people's livelihood, and geotechnical engineering is almost ubiquitous in engineering construction. Breakthrough traditional safety concepts, establish a new safety concept for geotechnical engineering and improve rock and soil engineering. The resilience performance of geotechnical engineering to resist serious disasters caused by natural disasters or man-made factors, maintain its functions to the greatest extent, and restore its functions as soon as possible after a disaster is an important quality of geotechnical engineering to support the construction of a resilient city and a resilient society.”

Improving the resilience of geotechnical and underground engineering structures and preventing them from causing large-scale collapse due to local small-scale damage in unexpected situations is of great significance to the safety of urban and major infrastructure constructions. How to improve the safety and resilience of structures in geotechnical and underground engineering, improve their ability to resist local failure caused by unexpected factors and its induced progressive failure and collapse, restore their functions as soon as possible and realize the resilient design for underground structures are the major problems that geotechnical and underground engineers must solve.

This paper summarized the connotation and development of resilience and pointed out that its evaluation and control methods can be divided into the following four levels of design: permissible stress design method, reliability-based design method, robustness method, and recoverable performance method based on the failure probability, ability to prevent progressive collapse under unforeseen events and its recoverability from disasters. The recent research studies on each of these levels in geotechnical and underground engineering structures are reviewed, summarized, and analyzed. The progressive collapse in the deep excavation engineering, underground engineering, shield tunnels, and column-supported embankment engineering embankment are taken as examples to discuss the existing research studies on the resilience against the progressive collapse to provide references for establishing design theories and frameworks in geotechnical and underground engineering.

2 CONNOTATION AND DEVELOPMENT OF RESILIENCE

2.1 *Concept and development of resilience*

The term resilience originated from the Latin "resiliere". Holling (1973) firstly proposed the concept of ecosystem resilience stands for an ecosystem with the ability to resist changes from the outside world and maintain the number of organisms and their relationships. The concept of resilience has since been extended to various academic fields such as ecology, materials science, psychology, economics, engineering, etc.

The concept of resilience was extended to the field of urban planning in the 1980s after that basic concepts such as "Resilient Cities" and "Urban Resilience" emerged (Hao and Xu, 2015). In the field of engineering, resilience is also understood to be related to its recoverability, that is, the ability of a system to functionally recovered from external disturbances.

The exploration of the eternal question of "how safe is enough to be safe" drives the continuous development of engineering design concepts. Shadabfar et al. (2022) believed that the engineering design concepts were started from allowable stress design (ASD), gradually developed to load and resistance factor design (LRFD), then performance-based design (PBD), and eventually resilience-based design (RBD). Among them, the ASD and LRFD concepts make the safety levels to be acceptable in practice using the structural reliability analysis method, without directly considering the performance of the entire system, nor the accidental disasters of the system and the balance between the possible losses and the current construction cost. As a result, the PBD concept was started to appear, apply and develop in the field of earthquake engineering, and gradually expanded from the displacement-based design under the action of the earthquake to the risk-based design which incorporates the repair costs, downtime losses, casualties, and other loss probabilities into system performance metrics. However, the PBD concept often does not consider the post-disaster recovery of the infrastructures, from which the design concept is further developed into the RBD concept.

Bruneau et al. (2003) from the Multidisciplinary Research Center for Earthquake Engineering (MCEER) at the University of Buffalo introduced the recoverability theory into the field of civil engineering and proposed a conceptual framework for earthquake resilience. MCEER believes that resilience includes at least eleven aspects (see Fig. 1) to achieve three aims of high reliability, low disaster consequences, and rapid recovery; four dimensions of technical, organizational, social, and economic dimensions; four evaluation indexes of robustness, rapidity, resources, redundancy. The robustness and rapidity are to evaluate the resilience effect. The resources and redundancy are used to evaluate recoverability (Bruneau and Reinhorn, 2006). Therefore, resilience is a more comprehensive evaluation system for system security.

In the field of earthquake engineering, the concept of resilience has received extensive attention (NEES/E-defense, 2010; Lv et al., 2017). The 16th World Conference on Earthquake Engineering was held in Santiago, Chile, with the theme of “Resilience - A New Challenge for Civil Engineering” and pointed out that the design and construction of Earthquake Resilient Structures is the basic requirement for realizing resilient cities (Lv et al., 2017).

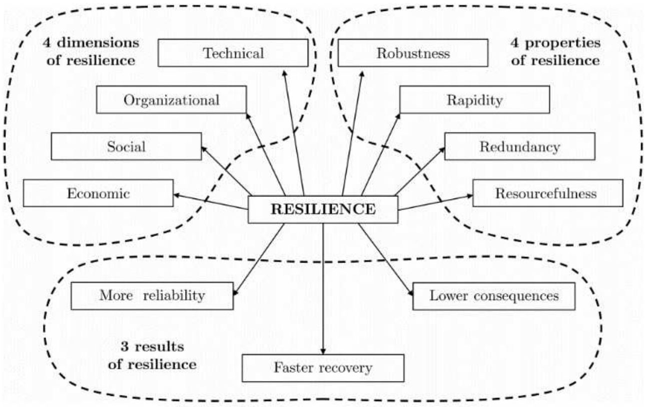


Figure 1. The targets, dimensions, and properties of resilience.

The concept of resilience has gradually extended from earthquake-resistant structures to resilient cities and resilient societies, with its connotations including robustness before a disaster, sustainability during the disaster, and recoverability after the disaster (Zhou, 2016). The robustness before a disaster mainly refers to the ability of the structure to withstand potential disaster and maintain its stability. Sustainability during disasters mainly refers to the ability of the system to self-adjust and adapt during disasters or to control and mitigate disasters under human prevention and intervention. The recoverability after a disaster refers to the ability to artificially restore the original state or achieve a new balance state to prevent future disasters. The problems to be solved for resilient cities and societies include not only earthquakes but also all unexpected events and sudden disasters, such as climate change, natural disasters (storms and floods, etc.), wars, and even epidemics of infectious diseases.

2.2 *Resilience assessment indicators and methods*

The connotation of resilience is larger than that of risk, and resilience assessments include not only risk assessment but also recovery assessment. A resilient system can deal with unexpected disasters in two ways: absorption and recovery. The studies believe that resilience includes four performance indicators, namely robustness, rapidity, resource, and redundancy, see Fig. 1 (Shadabfar et al., 2022). The robustness, resource, and rapidity play their roles in different stages after accidental disasters. The robustness is mainly reflected in the absorption stage. The higher the robustness, the less likely the damage will develop. The higher the resources and rapidity, the less the recovery time to restore the system performance, as shown in Fig. 2. Redundancy is also considered an important feature of resilient systems. When the redundancy is high, the system has spare components or force transmission paths for damaged components in unexpected disasters, thereby reducing the consequences of disasters and reducing the impact of disasters on the overall performance of the system.

In most projects, the system resilience when an unexpected disaster occurs should be evaluated in the dimensions of space and time. For example, Bruneau et al. (2003) pointed out that the system resilience index R can be used as the envelope of the performance curve after the disaster occurs, such as the shaded area under the integral of the performance curve Q(t) versus time (t) curve as shown in Fig. 2. In different fields, many scholars have proposed different definitions of the performance curve Q(t), including deterministic performance indicators and probability-based performance indicators. The used calculation methods of the toughness indicator R are similar to that shown in Fig. 2.

In the field of geotechnical and underground engineering, Huang and Zhang (2016) proposed a toughness evaluation method for shield tunnels under extreme loads (such as ground overload), using the lateral convergence of the tunnel as the tunnel performance indicator. The resilience index Re is defined as the ratio of the integrated time-history curve of the performance index under extreme overloading to that under normal overloading. They pointed out that the toughness index Re of the tunnel can be heavily improved if the tunnel performance recovery period is shorter.

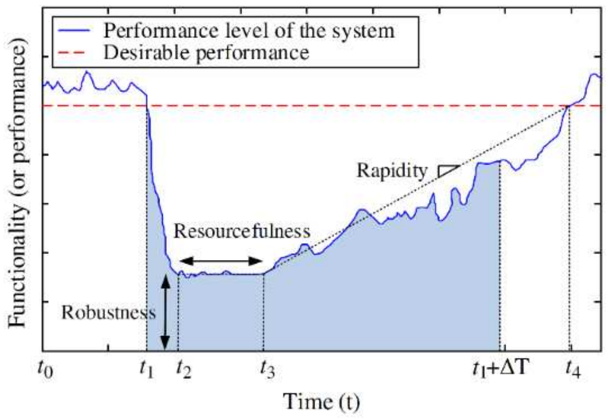


Figure 2. Schematic to calculate the system resilience index (Shadabfar et al., 2022).

2.3 *Framework of resilience design*

Two limit states of the structure in structural and geotechnical engineering, such as the serviceability limit state and ultimate limit state, are widely used for designing. But in fact, engineering structures are often facing the relatively serious large-scale progressive failure problem. The damage has the characteristics of "progress" and "disproportionality", more like the "domino" phenomenon. The subsequent damage follows the initial damage, and the scope of the final damage is much larger than the initial one (Ellingwood and Leyendecker, 1978). Breen (1975) pointed out that the design to resist progressive collapse is “an advanced limit state” for building structure, that is, consider the overall safety limit state of the structure (the limit state of preventing progressive failure) based on the serviceability and ultimate limit states.

According to the above-mentioned limit states, resilience can comprehensively evaluate the safety of the system. However, the present design methods in various engineering structures can only guarantee the resilience of the structure to a certain extent or from a certain aspect. From the perspectives of whether to consider the probability of failure, the ability to prevent continuous damage in unexpected situations, and the ability to recover after accidental disasters, the existing design methods to ensure the resilience of engineering systems can be generally divided into the following four levels: (1) the permissible stress design method using the factor of safety to prevent single or sub-item of the components and structures from reaching their ultimate limit states; (2) reliability-based design method using the theory of probability and statistics to evaluate the ability of the structure to complete the predetermined functions within the specified time and under the specified conditions, and predict the failure probability under the predetermined failure mode; (3) robustness method refers to the design method of ensuring the engineering structures withstand disproportionate collapse induced by unexpected events, or have the ability to resist progressive collapse which can also be called the resilience of the structure against progressive failure; (4) performance recoverable method refers to the abilities of the engineering structures to withstand extreme conditions, and to quickly restore their original service performance through reinforcement and engineering measures. The author believes that the above four levels of safety performance design methods constitute the system resilience of engineering structures in geotechnical and underground engineering.

3 RELIABILITY DESIGN IN GEOTECHNICAL AND UNDERGROUND ENGINEERING

3.1 *Uncertainties in geotechnical engineering*

The uncertainty of geotechnical engineering mainly includes the following aspects: (1) uncertainties of soil properties and their profile distributions; (2) uncertainties of analytical models, such as constitutive and analytical models; (3) uncertainties of surcharges and resistances; (4) uncertainties in construction procedure; and (5) uncertainties of boundary conditions, etc. Among them, the most basic feature of geotechnical engineering is the uncertainty of soil parameters, which originated from natural variabilities of soil properties and random test errors, insufficient test numbers, test methods, and field differences. Soil parameters have not only their variabilities but also spatial variabilities which can be described by the random variable model (Lumb, 1966) and the random field model (Vanmarke, 1977), respectively.

The reliability analysis methods used in geotechnical engineering are similar to those used in structural engineering. However, structure in geotechnical engineering is a complex system formed by soil, groundwater, and structure, and the complex interactions between them. The safety problems in geotechnical engineering have many unique characteristics in structural engineering, such as the large uncertainties of soil parameters, the complexity of the interactions between soil and structure, the soil arching effect and other unique stress distributed characteristics, various water-soil coupling effects such as large strain deformation, seepage, erosion, inrush, and instantaneous destruction. It is often accompanied by large deformation problems, soil erosion, soil collapse, and dynamic problems of instantaneous damage. Therefore, the safety evaluation and design of geotechnical structures are more complicated. In addition, the analyses of the interactions between soil and structure cannot separate the actions and resistances of the soil stratum. This is because the actions of the soil stratum are sometimes determined by its resistance, such as the effective earth pressure. The resistance of the stratum is sometimes determined by or related to the action of the stratum. For example, the bearing capacity of a shallow foundation depends on its applied surcharges.

3.2 *Permissible stress design method (Factor of safety method)*

The permissible stress design method (factor of safety method) is an important method for design and stability evaluation in geotechnical engineering. The parameters mostly used in geotechnical engineering are random variables with small changes that may lead to a different level of changes in soil properties. In the design of geotechnical infrastructures, it is often necessary to select a larger safety reserve to deal with possible deviations, and then use a factor of safety in the permissible stress calculation to express the degree of safety, which is also called the factor of the safety method. However, this method does not consider the uncertainty of soil mass which makes it hard to evaluate the reliability of the structures.

Take the stability analyses of slopes and foundations, for example, although the calculated factors of safety indicate that the infrastructures are stable, instability accidents often occur, such as the slope collapse of Liuhuangkou of the Ninghua Highway in Panzhihua City, Sichuan, China, in July 1997, the landslide accident at the entrance of the Dongronghe No. 1 tunnel of the Chengdu-Kunming Railway, in 1994 (Zheng 2007). An underwater slope with a height of 30 m, length of 75 m, and a slope ratio of 1:1 with a factor of safety of 1.25 collapsed during the LASH construction in the San Francisco Port in August 1970. The following reliability analysis using the Taylor series expansion method showed the failure probability of the slope was 18 % which indicated that the slope has a higher risk of instability failure. It also shows the limitations of using factors of safety method to evaluate stability problems in geotechnical engineering. The reliability analysis can reveal engineering problems from another aspect.

3.3 *Reliability-based design method*

In the late 1960s, researchers started to conduct reliability studies in the field of geotechnical engineering based on those methods used in structural engineering. Casagrand (1966) analyzed the risk problems in the design of foundation and geotechnical structures which starts the reliability analyses in geotechnical engineering. Lumb (1970) studied the probability distribution forms of the shear strength parameters and concluded that most of the physical and mechanical parameters of soil can be approximately described by the normal distribution function. Asaoka and Grivas (1981) analyzed the variability of undrained shear strength of cohesive soils.

Wu and Kraft (1970) applied the reliability theory to the typical geotechnical problems and the slope stability analyses. Alonso (1977) studied the uncertainty of the slope through a single probability-based slice method. Sivandran (1979) used the fixed value and the reliability analysis methods to study the slope stability of the embankment. The results showed that the reliability analysis method was more realistic.

Babu and Murthy (2005) analyzed the reliability of typical unsaturated soil slopes and concluded that the reliability index is better than the traditional factor of safety method for capturing the damaged area. Duncan (2000) compared the results from the safety factor method and the reliability analysis method and concluded the validity and superiority of the reliability analysis method in geotechnical engineering. He also pointed out that the reliability analysis is more suitable as a supplement to the safety factor method, rather than replacing it. Many scholars have discussed this finding. Cherubini et al. (2001) pointed out that Duncan's point is limited by current design methods. The reliability analysis is more urgently required when facing greater uncertainty problems in geotechnical engineering.

At present, the reliability analysis methods used in geotechnical engineering are various and constantly being developed. The classical reliability analysis methods include the first-order second-moment method, Monte Carlo (MC) method, stochastic finite element method, response surface methodology, Duncan method, and so on. Due to the limitations of classical methods, many scholars have conducted deep research on the reliability analysis for typical geotechnical engineering structures. For the tedious derivation problem in the first-order second-moment method, Xu et al. (2000) used a genetic algorithm to solve the equations which avoided the complicated derivation problem in varying degrees.

Aiming at solving the drawbacks of the MC method that the derived functions are hard to explicitly express and require a large amount of calculation time, Deng and Zhu (2002) proposed and demonstrated a Finite Element Monte- Carlo method using neural networks. This method can be directly used in the deterministic structural finite element analysis program which can greatly reduce calculation steps and calculation time to improve the efficiency of reliability analysis. Zheng et al. (2003) integrated the immune algorithm into the reliability analysis in geotechnical engineering and validate that using case studies. The method avoids the complicated derivation process for the nonlinear and complex functions. Ge (2007) compared the characteristics of the immune and genetic algorithms. He pointed out that the search target of the immune algorithm has the characteristics of dispersion and independence, while those of the genetic algorithm has the characteristics of singleness and exclusiveness. However, the optimization efficiency of the immune algorithm is lower than that of the genetic algorithm. Olsson and Sandberg (2002) introduced the Latin Hypercube Sampling (LHS) method to stochastic finite element analysis. They pointed out that LHS is more computationally efficient than the standard Monte Carlo sampling method. Zuo et al. (2013)

proposed a fourth-order moment method based on an artificial neural network and verified its effectiveness and accuracy.

3.4 *Robustness method*

In 2013, at the 18th International Congress of Soil Mechanics and Geotechnical Engineering (ICSMGE) held in Paris, France, the ideal geotechnical design standards for 2050 were discussed in the joint seminar of TC205. The robust design for geotechnical and tunnel engineering is mentioned. At the 19th International Conference on Soil Mechanics and Geotechnical Engineering held in Seoul, the joint seminar of TC205 and TC 304 have been identified two principal types of robustness by the group: (1) the ability of the final design to accommodate events and actions that were not foreseen or consciously included in the design; and (2) the sensitivity of the final design to variations of the known parameters within their anticipated range of uncertainty (ISSMGE, 2017). For the first type of robustness, there are many research results in the fields of structure and bridge engineering but small in the field of geotechnical engineering. This section mainly focuses the research development on the second type of robustness.

The reliability-based design method needs to determine firstly the random distribution of soil parameters, and then calculate the probability of failure. The random distributions of soil parameters cannot be accurately determined due to sampling and statistical errors because the variabilities of geotechnical parameters are often overestimated or underestimated (Juang et al. 2013). In addition, the model error and the uncertainty of the construction level are also difficult to be calibrated. Based on the inaccurate statistical law of input parameters, the results of the reliability design will be affected (Huang et al., 2014). This can further lead to over- or under-reliable reliability. The robustness analysis method can consider the variability of the standard deviation of soil parameters, and effectively evaluate their response to the sensitivity of the system.

The robustness design was first proposed by Taguchi (1986) for quality controlling design in the field of industry. The idea is to reduce the sensitivity of the system to the difficult controlling design parameters by adjusting the easily controlling parameters, see Fig. 3. Juang et al. (2012) introduced this concept to the infrastructure design in geotechnical engineering. Compared to the reliability design and factor of safety design methods, the robustness design method can more reasonably reflect the safety level and performance of the infrastructures in geotechnical engineering.

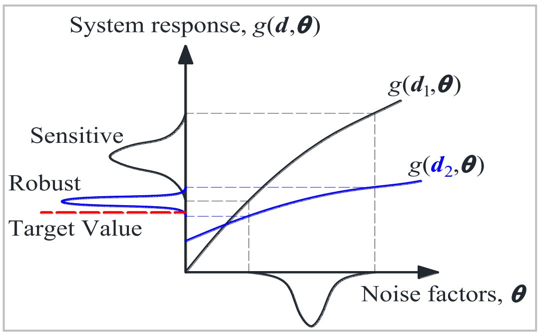


Figure 3. The core idea of robustness design (Juang et al., 2012).

The standard deviation of failure probability was used as the measurement criteria of robustness in the earliest robustness design method in geotechnical engineering (Juang et al., 2012; Huang et al, 2014). This method can also be called a feasibility level-based robustness index, which means the probability (or feasibility) that meets the design requirements (the target failure probability in reliability design) is taken as the robustness index, among which the higher the feasibility level of robustness, the more robust the design. Although this method is mathematically accurate, it requires too much calculation time. This is because the method used the first-order reliability method to calculate the failure probability, the point estimation method to calculate the standard deviation of the failure probability, and the multiple objective optimization algorithms to find the optimal design with the premise of robustness and cost control. Therefore, it is necessary to conduct more studies to further improve this method.

Gong et al. (2014) proposed a more efficient robustness design framework by adopting a gradient-based robustness measurement method. The system responses to the uncertainty of the inputs (i.e. the normalized gradient) are mainly used as the robustness level. The higher the sensitivity the less robust the design. Khoshnevisan et al. (2015) proposed a robustness design method that can consider simultaneously the performance requirements, design robustness, and cost-efficiency. The method reflects the robustness of the design through the variabilities of the function with its form of transforming and the performance requirements of the system calculated by the reliability. The robustness design can be obtained from the same calculation step or the so-called coupling calculation. The robustness design can be carried out efficiently using this coupling method. Peng et al. (2017) used the Monte-Carlo-based weight technology to calculate the failure probability of the geotechnical structures and to replace the multi-objective optimization with a series of single-objective optimizations. The method is more efficient and convenient for the robustness design in geotechnical engineering.

Huang et al. (2014) used the multi-objective optimization method and the confidence level to calculate the variability of the structural failure probability of the gravity retaining wall. They optimized the wall body through parameter variability and failure probability analyses. In the field of shield tunneling, Zhang et al. (2019) found the optimal control knee point in the design of steel plate reinforcement in large deformation tunnels through robustness design to optimize its robustness and cost. Wang (2019) applied the robustness design concept to the cross-section design of double-lined water-conveying shield tunnels and a large-diameter shield tunnel to optimize the structural design.

It should be pointed out that the concepts of robustness design currently used in geotechnical engineering are slightly different from those used in the field of structural engineering. The latter emphasizes the ability of the structure to resist progressive collapse in the event of local failure (Ye et al., 2008). The former mainly comes from the inability to accurately obtain the variability of geotechnical parameters. The uncertainty of parameter variability is usually considered to enable a reliability assessment of the failure probability in geotechnical engineering. However, local failure of soil and structures occurs frequently in geotechnical engineering which even leads to large-scale progressive failure. The research and evaluation of the robustness in geotechnical engineering should expand the connotation and extension to avoid progressive failure caused by local failure. The evaluation and control methods of the anti-progressive collapse ability of the geotechnical and underground engineering structures must be established to provide reasonable abilities to prevent progressive failure of the geotechnical structures. Reasonable control of the degree of damage provides a basis and guarantee of the functional maintenance, recoverability, and ease of repair after the progressive failure, even if the geotechnical engineering has a reasonable resilience.

3.5 *Performance recoverable method*

Recoverability is another type of resistance in structural engineering. A very important aspect of structural resistance is its recoverability after earthquakes which refers to the structures that could be restored to their designed functions without repair or a little repair after an earthquake (Lv et al., 2011). Compared to the traditional earthquake-resistant structures, it has better performance in protecting people's lives and properties during earthquakes and in rapid recovery after earthquakes. The function of restorable structures includes rocking structures, self-centering structures, repairable structures with replaceable members, and so on. In addition to these methods of using structural members, Anastasopoulos et al. (2010) proposed the concept of rocking isolation to allow the foundation to be lifted off, transfer the plastic hinge originally formed in the superstructure to the foundation soil, reduce or avoid plastic deformation or even collapse of the superstructure to ensure the safety of the superstructure (Wang et al., 2021).

Because the structures in geotechnical and underground engineering are deeply buried in the ground, it is difficult to repair once damaged. For example, a completed subway tunnel constructed by the shield method may be misaligned between the segments due to earthquakes, ground stacking, excavation of adjacent excavations, or tunnel leakage. If the excavation opening is large enough, it may also cause groundwater leakage or even lead to a large amount of soil gushing into the tunnel, as shown in Fig. 4(a), and even cause severe deformation, subsidence, misplacement, damage, or even collapse of the tunnel, as shown in Fig. 4(b). Figs. 4(c) and 4(d) show the leakage at the starting shaft of the tunnel resulting in a large amount of groundwater and sediment gushing into the tunnel. The tunnel segment was severely damaged because the ground outside the starting shaft sunk and cracked. After the accident, tens of meters of the tunnel could not be repaired but had to be excavated and rebuilt.


(a) (b) (c) (d)

Figure 4. Damage and repair process of shield tunnel accident (a) groundwater and soil gushing into the tunnel, (b) segments settling and misplacement, (c) tunnel settlement, (d) excavation of the damaged tunnel.

It is necessary to conduct the performance recoverable design methods for the shield tunnels, especially in (1) high construction risk sections such as the originating and receiving sections, and connecting passage sections, (2) the high geological risk sections, such as boundaries between soft and hard soil layers, ground fissures, (3) sections passing through extremely important infrastructures, such as the operating tunnels, high-speed railways, rivers and lakes, and other high environmental risk sections with extremely serious damage consequences in the event of an accident and so on. The performance recoverable design is to make the degree of large deformation or tunnel damage controllable, self-recovered, or easily repaired after the disaster caused by unexpected events such as water leakage, sand leakage, earthquake, and so on.

For the recoverability of geotechnical and underground engineering, the rapid repair technologies for damaged geotechnical and underground engineering structures are an important way to improve engineering toughness in addition to improving the recoverability of the engineering structure itself during the recoverable design stage. In 2016, Huang and Zhang (2016) reported a case of recovering the deformation of the tunnel by grouting on both sides of a shield tunnel that was damaged under extreme ground overload four years ago. They pointed out that the grouting greatly improved the tunnel performance. If the tunnel deformation can be recovered earlier and faster (shorten the tunnel performance recovery period), the toughness index can be greatly improved. In terms of active grouting and quick repair of tunnel deformation, Zheng (2021) pointed out that the grouting efficiency and recovery effects of the traditional grouting methods, such as sleeve valve pipe low, are poor for sandy soil with higher permeability or soft clay with strong structure. The active control technology of balloon expansion and deformation grouting method can achieve a better recovery effect.

Wu and Ou (2014) concluded through model tests that the shield tunnel segments connected by shape memory alloy (SMA) bolts can reduce the amount of joint opening. The Shantou Bay Tunnel, the first large-diameter sea-crossing tunnel in the eight-degree earthquake-resistant area in China with a total length of 6.68 km and a section of 3.05 km under the sea, has adapted the memory alloy bolts to connect segments to improve its self-recoverable abilities after earthquakes.

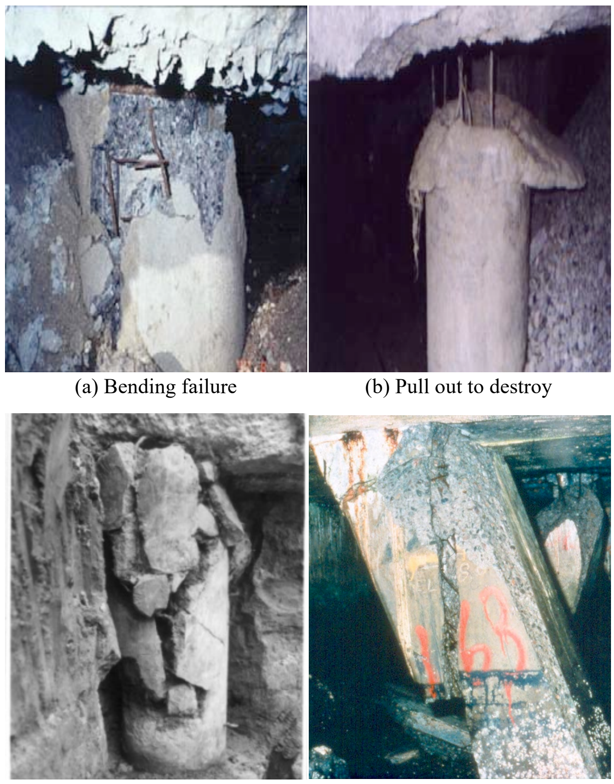

(a) Bending failure (b) Pull out to destroy (c) Bending shear failure (d) Shear failure

Figure 5. Photos of typical pile damage after the earthquake (Washi et al. 2003; Qingdao et al., 2004; Zhang et al., 2018).

In previous major earthquakes, it was found that many piles were damaged in varying degrees, especially at the pile caps and connections between piles and pile caps which are weakest (Huang et al., 2002, Tang, 2010). Take the 1995 Hanshin Earthquake, for example, the piles of the Hanshin Viaduct were bent and damaged which made some parts of the pile foundation separated from the bearing platform as shown in Fig. 5(a) to 5(b). In Kobe City, the action of inertial force made the top of the pile foundation of the high-rise apartment buildings suffer bending shear failure as shown in Fig. 5(c). In 1989, Loma Prieta earthquake made the pile foundation suffer shear failure near the pile top due to lateral displacement of soil as shown in Fig. 5(d). The historical earthquake damage indicated that the pile-cap joint can be damaged by the earthquake-induced soil deformation, or the bending, shearing, and uplifting caused by the inertial action of the superstructures (Zheng et al., 2013). As the pile foundation is designed to support the superstructures and is difficult to be repaired after damage, its seismic performance has received extensive attention.

The seismic capacity of the pile-cap connection joint has received considerable attention. The traditional connection nodes between piles and caps are often treated as "fixed connections" where large internal forces were generated under the action of earthquakes. As shown in Fig. 6, the bending moment of the pile top under the embedded condition is significantly larger than that under the free pile top condition. The joints are prone to damage when the pile top is fixed and the post-earthquake repair is difficult. With the development of seismic design, the rapid recovery of functions has become an important target for toughness design. However, it is difficult to ensure the rapid recovery of structural functions after earthquakes only by improving the seismic capacity of joints. To improve the recovery of the pile foundation, some scholars have proposed a rocking self-resetting structure (Guan et al., 2018; Antonellis, 2015; Ha and Kim, 2014; Ko et al., 2019). Since the pile-cap connection determines whether the system is allowed to sway and reset, the design of the pile-cap connection becomes an important part of determining the stress and deformation mode of the pile-superstructure system during earthquakes. Therefore, the seismic design of the pile foundation-cap connection is one of the key issues for the toughness improvement of the pile foundation.

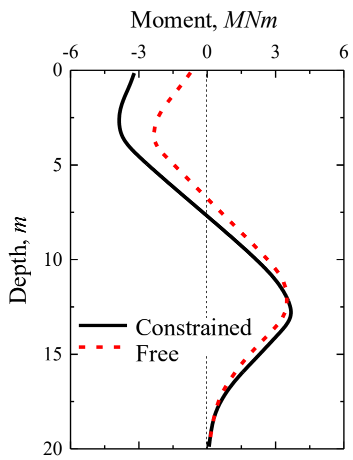


Figure 6. Influence of constraint conditions on bending moment distribution along with pile (Finn, 2015).

Studies in literature focused on the influence of anchoring types, steel bars, and filling materials on the seismic performance of the pile and pile-cap connection. Washi et al. (2003) proposed a simple connection between the pile and pile head to investigate the effects of anchoring types of reinforcement. A series of laboratory model tests are conducted to compare the effects of the proposed simple connection nodes without anchor reinforcement. They concluded that the proposed connection could reduce the rotational constraint by 70% more than those of traditional connections. Qingdao et al. (2004) proposed a method of using the conical gaps on the pile head to improve the rotational ability of the connection between piles and pile heads which can effectively reduce the bending moment at the pile head, see Fig. 7. Some scholars believed that strengthening the nodes is beneficial to improving the bearing capacity and energy dissipation capacity of the nodes. Zhang et al. (2018) and Larosche et al. (2014) studied the effect of embedded depth on the seismic performance of the pile and concluded that deeply embedded joints have a good seismic performance to effectively improve the stiffness, bearing capacity, and energy dissipation capacity of the nodes. However, because strengthening the nodes also similarly increases the surcharge onto the nodes, some scholars believed that weakening the connection of the nodes to a certain level is beneficial to earthquake resistance. The stress state of the nodes can be improved by installing filling materials at the connection between the pile head and the cap (Lehman et al. 2013).

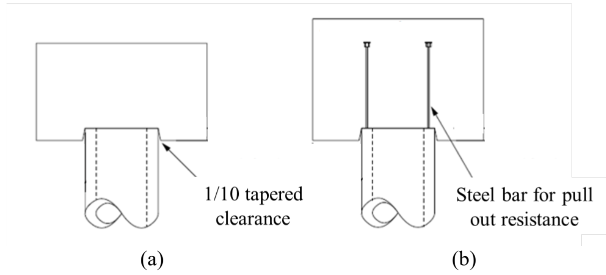


Figure 7. Improved simple connections (a) bearing pile, and (b) tension pile.

To improve the recovery toughness of the pile foundation, Guan et al. (2017, 2018) proposed a liftable pile group joint for bridges supported by pile-group foundations and verified using quasi-static tests. Compared with the traditional fixed pile group joint, the connection point of the liftable pile group joint can effectively reduce the residual displacement of the bridge structure, see Fig. 8, and the damage to the pile foundation. Ha et al. (2014) and Ko et al. (2019) studied the impact of pile foundation-cap connection on the superstructure and pile foundation through centrifuge tests. Disconnecting the pile and cap can effectively reduce the internal force of the pile body, reduce the structural responsiveness of the superstructure, prevent damages to the pile foundation and superstructure, and improves their recoverability. Antonellis (2015) studied the seismic response of swaying pile foundation bridges through numerical simulation. He found that, compared with the fixed foundation, the inelastic response of the upper structure under the dynamic action will decrease significantly when the cap on the upper part of the pile foundation is allowed to sway. All of this could help to improve the overall recoverability of the structure.

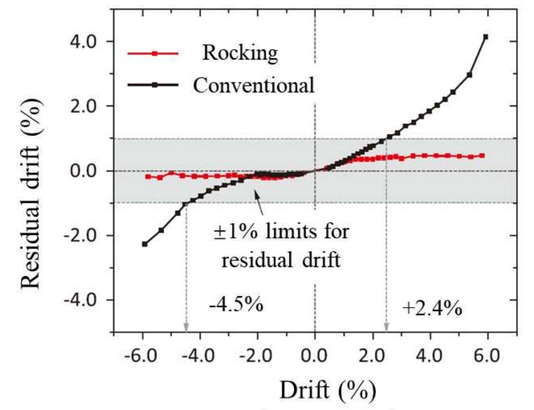
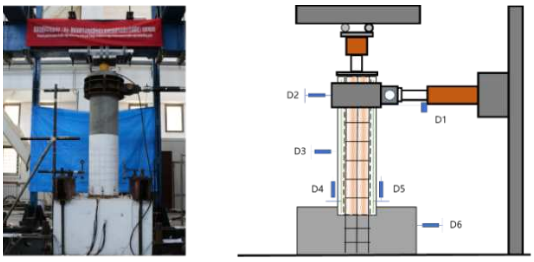


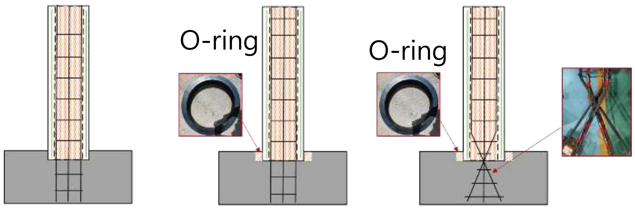
Figure 8. Residual deformation (Guan et al., 2017)

In general, studies in the literature improved the resilience of the connections between the pipe and pile cap to prevent pile head damage and improve the overall recoverability. For example, laminated rubber, spring, or other materials with better deformation properties are commonly installed within the region of the embedded pile in the pile cap to improve the rotational restraint of the pile cap and energy dissipation capacity of the joint, avoid damage to the pile and the bearing platform concrete and recover the position between the pile and the bearing platform after the earthquake. As shown in Figs. 9 and 10, the authors conducted a series of quasi-static laboratory tests to investigate the influences of the pile-cap connection on the bearing capacity of the pile foundation. The pile is made of an AB-type PHC pipe pile with a cracking bending moment of 138 kN·m and a bending capacity of 238 kN·m. The conventional connection and that installed with a rubber O-ring are used in test No. CT1 and CT2, respectively. The pile in test No. CT3 changed the angles of the anchored steel bar to reduce the resistance of the bending moment and the rotational constraint of the node. The hysteresis curves and secant modulus curves of the piles with the pile-cap connection using the three types of connections are shown in Figs. 11 and 12, respectively. Compared to the conventional connection method used in test No. CT1, the horizontal bearing capacity of the pile with Test No. CT2 and CT3 were reduced by about 23 % and 21 %, respectively.



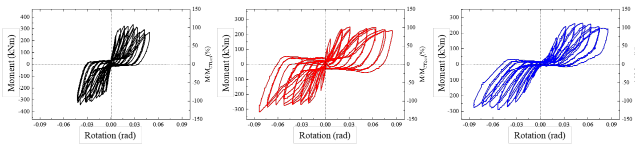
(a) (b)

Figure 9. Pile-cap connection in the quasi-static test (a) photo and (b) sketch of the model test setup.



(a) (b) (c)

Figure 10. Three types of pile-cap joints (a) CT1, (b) CT2, and (c) CT3.



(a) (b) (c)

Figure 11. Hysteresis curve of the three kinds of pile-cap connections (a) CT1, (b) CT2, and (c) CT3.

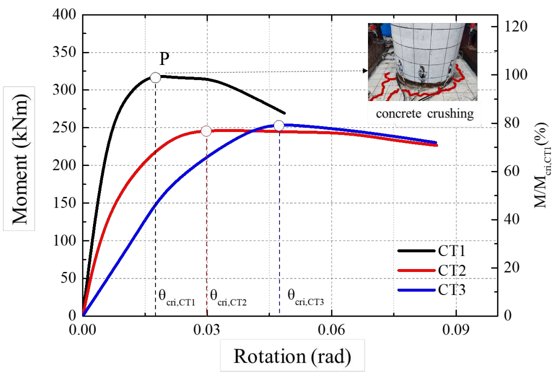


Figure 12. Secant modulus of the piles with three kinds of pile-cap connections.

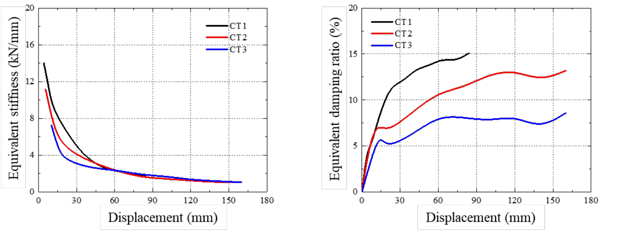
The relationships between the bending moments and anchoring angles of the three-node connection forms in Fig. 12 show the peak bending moment of the pile with Test No. CT1 was 318kN·m when the angle of 0.018 rad. The concrete of the pile was significantly crushed at this time, accompanied by slight cracks on the pile surface. For the same angle, the bending moments of the pile with Test No. CT2 and CT3 are 216kN·m and 149kN·m which are smaller than those of Test No. CT1 of 32% and 53%, and are of 85% and 55% of their corresponding peak bending moments, respectively. This is indicating that the piles with Test No. CT2 and CT3 have larger strength recoverability than that with Test No. CT1.

The failure modes and ductility of the three types of node connections are analyzed through the bending moments versus the anchoring angles curves. When the peak bending moment is reached, the bending moment of the conventional connection is used in Test No. CT1 significantly decreased with its slope of 0.439kN·m/rad. The pile is brittlely damaged with the slopes of the bending moment of the components in Test No. CT2 and CT3 reduced to 0.109 and 0.170kN·m/rad, respectively. The components with the rubber O-ring can effectively maintain their bearing capacity and significantly increase their ductility. Compared to the conventional connection used in Test No. CT1 with its limit angle of 0.048 rad, the components used in Test No. CT2 and CT3 have not reached their limit magnitudes even with their limit angle of 0.086 rad.

In the later loading stage of model test No. CT1, the bending moment of the pile is not the controlling failure criteria because the concrete of the pile was significantly crushed accompanied by slight cracks on the pile surface. The model test results from No. CT2 and CT3 showed that the installation of the rubber O-ring could effectively increase the limit rotation angle of the pile head and improve the connection resilience of the pile cap by avoiding damage to the concrete at the pile head when the angle is large. In engineering practice, for the B-type PHC pipe pile with a higher flexural bearing capacity, i.e. cracking moment of 164 kN m, flexural bearing capacity of 311 kN m, the connection using those of test No. CT2 and CT3 could effectively improve the connection resilience of the pile cap by avoiding damage to the concrete at the pile head when the angle is large. For the A-type PHC pipe pile with low flexural bearing capacity, i.e. the cracking moment of 118kN m, the flexural bearing capacity of 176 kN m, the bending failure of the pile using the connection of test No. CT1 was occur. For the pile with node connections as those of test No. CT2 and CT3, the resilience of the pile is improved by avoiding the bending damage to the pile body at a large turning angle. For the A-type PHC pile filled with the core material, the ultimate bending resistance is increased.

The equivalent stiffness and equivalent damping ratio versus loading series curves of the pile with the three types of pile-cap connections are shown in Fig. 13. The loading series is the ratio of the actual loading displacement to the yield displacement. The equivalent stiffness is the ratio of the applied horizontal force to the horizontal displacement. It shows that with the increase of loading series, the structure is damaged with the equivalent stiffness reducing slowly. The pile with connections as test No. CT2 and CT3 reduced the equivalent stiffness of approximately 40%-50% under different loading series compared to the pile with conventional connection as test No. CT1. Jiang et al. (2014) concluded that the decrease of the restraint stiffness of the pile cap is beneficial to reduce the bending moment and the damage to the pile cap. The variation of the equivalent damping ratio versus the loading series curves for the pile with three types of connections is shown in Fig. 9(b). It shows that the equivalent damping ratio is related to the energy dissipated in the plastic deformation. For the pile with the conventional connection as that of test No. CT1 has relatively large damping due to the large plastic damage to the concrete. The damping of the pile with connection as that of model test No. CT2 is relatively small for the first two loading stages and reduces approximately 20% more than that of the pile with conventional connection as that of test No. CT1.

Since the damage to the pile-cap connection is difficult to be directly discovered, evaluated, and repaired during the earthquake, the pile-cap connections as shown in Fig. 10(b) and 10(c) are simple, versatile, and durable with higher resilience. Compared with the pile with conventional connection, the pile with new connections has advantages of higher redundancy, ductility, and reduction of pile top bending moment which is helpful to promote the seismic resilience of the pile.



(a) Equivalent stiffness (b) Equivalent damping ratio

Figure 13. Equivalent stiffness and damping ratio versus loading series curves of the pile with the three types of pile-cap connections (Yang et al., 2014).

4 RESILIENCE AGAINST PROGRESSIVE FAILURE IN EXCAVATION ENGINEERING

4.1 *Limitations of existing design methods*

The retaining system of the deep excavation is composed of vertical piles (walls) and horizontal struts (anchors). The integrity of the retaining system is relatively weak due to the following reasons: (1) weak connections between vertical structures which are composed of rows of retaining piles and connected only through the capping beam on the pile head. Even if the diaphragm walls are installed, the connections between wall sections are still weak. (2) little mutual connections between the horizontal struts which are often made of steel pipes with no or weak connections. It is also true when using anchors as there is no connection between the anchors even when waler beams are installed. (3) weak connection between the vertical structure and the horizontal struts (anchors) because they are designed by assuming only bearing compression forces. In addition to the uncertainties of geotechnical engineering, the retaining system of the deep excavation has lower integrity than the superstructures of structural engineering.

In recent years, several collapse accidents of the deep excavation have occurred in Singapore (Xiao et al. 2009, 2010; Artola 2005; Whittle and Davies 2006), Hangzhou (Zhang and Li, 2010; Li and Li 2010), Cologne (Haak 2009) and other places. The analyses of these accidents showed that the instabilities of the deep excavation are complex failure processes, especially in the case of deep excavation, irregular plane shape, and complex supporting structures. The damage may be induced by local failure from retaining structures or stability failure of soil mass which in turn causes the retaining structures to collapse on a large scale. That is, the collapse of a deep excavation is a progressive failure process (Zheng et al. 2014, 2011, 2014; Cheng et al. 2016, 2017).

The retaining system of a metro excavation collapsed in Singapore, causing huge economic losses and serious damage to Nicoll Road (Xiao et al. 2009). The ninth level of struts first yielded, and the load transferred to the adjacent eighth level of struts, which failed in a “domino-like” progressive failure in the section. This led to the partial collapse and eventually resulted in substantial damage to an approximately 100 m section of the Nicoll Highway carriageway adjacent to the abutment of Merdeka Bridge (Xiao et al. 2009, 2010; Artola 2005; Whittle and Davies 2006). The excavation accident that occurred at Xianghu Station of Hangzhou Metro Line 1 was also due to the large-scale collapse induced by local failure (Zhang et al. 2010; Li and Li 2010). The collapsed length in this accident was up to 70 m, as shown in Fig. 14.

(a) (b)

Figure 14. Retaining system of deep excavation and its failure at Xianghu Station of Hangzhou Metro Line 1 (a) Excavation retaining system (b) Failure scene of the retaining system.

The current stability design theories simplified the excavation into a two-dimensional plane strain problem to calculate the stabilities of several cross-sections without considering the progressive failure induced by the failure of the excavation in the latitudinal direction (Liu et al. 1997; Chang 2000; Ukritchon et al. 2003; Zhang et al. 2006; Hsien et al. 2008; Huang et al. 2008; Liu and Wang 2009; Cheng et al. 2015). However, the excavation is a complex interactional system between supports, soil, groundwater, and structures (including piles) inside and outside the excavation. The damage transmission cannot reflect the development mechanism and process of progressive failure caused by local failure. In terms of the overall safety performance of the excavation, evaluation and control methods have not been systematically established. The existing reliability and robustness analyses in geotechnical and underground engineering cannot reflect the resilience performance of excavations against progressive failure developed under extreme accidental conditions.

4.2 *Progressive failure mechanism*

Local failure, progressive failure, and overall safety performance in excavation engineering have attracted more and more attention from scholars and engineers. Goh and Wong (2009) found through numerical analyses that the accidental failure of one to two levels of struts would not induce failure to the entire retaining system under the condition that the struts could provide enough compressive bearing capacity. Zheng et al. (2011, 2014) conducted numerical simulations and case studies and concluded that local failure can easily lead to progressive failure in excavation with a lower redundancy of the retaining system. Redundancy design theory is suggested for the design of excavations. The redundancy problems of the retaining system in excavation engineering are classified with corresponding design methods introduced to prevent progressive failure, such as increasing the force transmission path and reinforcing at certain intervals, and so on. Pong et al. (2012) pointed out that the design of retaining walls should have sufficient structural safety, robustness, and redundancy, which can avoid the progressive failure of structures induced by the overloaded failure of a single component. Three-dimensional and two-dimensional plane strain analyses were also carried out for the failure of the single strut. Itoh et al. (2016) simulated the failure of the anchor head of the anchored pile-supported excavation through a centrifuge test and concluded that both earth pressures in the active and passive zones increased during the excavation process. They also found that the diaphragm wall collapsed instantly once the anchor head exceeded its tensile strength. Goh (2018) conducted numerical analyses to study the failure problems of the multi-channel struts and pointed out the transferring path and percentage of the failure load. Zhao et al. (2018) summarized the influencing factors of the anchor failure in the excavation, analyzed the influence range of single anchor failure, and pointed out that the most dangerous position is at the pile head or near the bottom of the excavation. Han et al. (2018) took an anchored pile retaining deep excavation in a sandy soil layer as the engineering background to simulate the failure process of the single and two-level anchors. Xia et al. (2018) simulated the multi-level braced excavation, adopted the concept of stiffness (deformation) redundancy, verified their influence through the removal of struts at different layers, and back-calculated the redundancies of the structures.

Lu and Tan (2019) summarized typical excavation failure cases in China in the past 30 years and divided these failure cases into 15 failure modes. Choosrithong and Schweiger (2020) analyzed the strut failure problem using Plaxis software and found that the surcharge of a strut before failure was transferred to its adjacent struts. Ser and Sayin (2020) analyzed the reason and mechanism of the collapse of a certain tied-back excavation project and proposed control and improvement methods. Zheng et al. (2021) studied the load transfer mechanism of an anchored pile retaining system caused by local failure through numerical simulations.

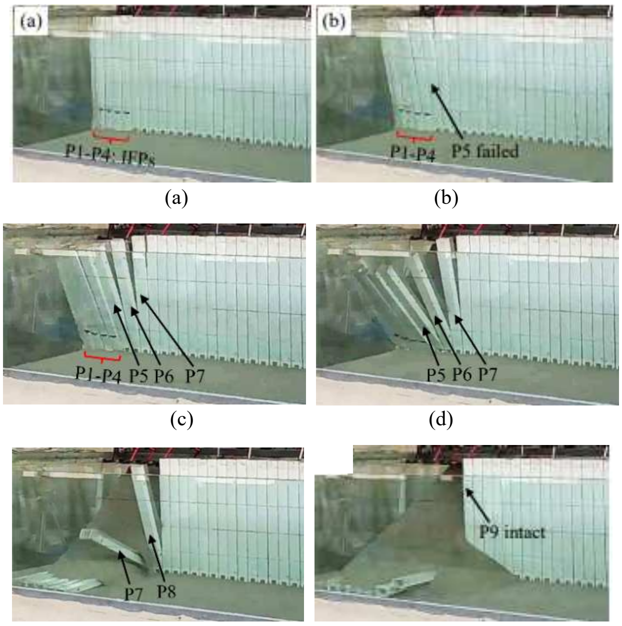
The case studies of the deep excavation showed that the overall safety limit state (the limit state of preventing progressive failure) is equally important to the traditional ultimate limit state and the serviceability limit state. In recent years, Zheng et al. (2016, 2017, 2020), Han et al. (2018), Xia et al. (2018), and Cheng et al. (2016) have conducted a series of numerical and large-scale model tests to investigate the development of progressive failure along with the depth, width, and length of the excavation caused by local failure. They have preliminarily revealed the development and termination mechanisms of the progressive failure of cantilever contiguous piles, internal struts, and anchored pile retaining excavations. The studies laid the foundation for further research on resilience design theory in the field of excavation engineering.

4.2.1 *Cantilever pile retaining excavation*

For the most typical cantilever pile retaining system, Cheng et al. (2015, 2016) showed that the local failure of the retaining piles forms a significant soil arching effect in the active zone. The earth pressures are transferred to the adjacent intact retaining piles, resulting in a rapid increase in the soil pressure and internal force. The peak increase ratio of the bending moment in an adjacent pile induced by partial collapse is defined as the load transfer coefficient to evaluate the increase in the internal force and check the safety after the local failure occurrence (Cheng et al. 2016, 2017).

Zheng et al. (2016) and Cheng et al. (2016) proposed basic criteria to predict the occurrence of resilience failure only if the load transfer coefficient is larger than the factor of safety of the bearing capacity of the adjacent piles. The large-scale model test was conducted to simulate the progressive failure process of the adjacent piles induced by the local failure of contiguous piles, as shown in Fig. 15. The model tests showed that the local collapse of the excavation induced the soil pressure and internal force of the adjacent pile to increase instantaneously, and then the soil outside the excavation slipped into the excavation, inducing the unloading of the active zone of the adjacent pile. The unloading process is relatively time-lagged. With the increasing range of local collapse induced resilience to damage, the collapse terminated naturally instead of endless collapse when the unloading of the soil insufficiently induced the soil arching effect to generate damage to adjacent retaining piles. For cohesive soil, it can be judged that the cohesive soil outside the excavation does not necessarily slip into the excavation when the retaining pile partially collapses. The subsequent unloading effect induced by the collapse of the soil will be significantly reduced and time-lagged with possible lower safety of the retaining system.

Zheng et al. (2016) and Cheng et al. (2017) found through numerical studies that local failure often occurs in the middle edge of the square excavation, and the maximum load transfer coefficient first increased and then decreased with the number of failed piles. The progressive collapse terminated when it reached a certain range. The spatial effect may be another reason for the natural termination of progressive collapse.



(a) (b)

(c) (d)

(e) (f)

Figure 15. Collapse process after failure of four cantilever contiguous piles (Cheng et al. 2016) (a) before collapse (b) 2.0 s after the partial collapse, (c) 2.8 s after the partial collapse, (d) 3.2 s after the partial collapse, (e) 4.28 s after the partial collapse and (f) final stable status.

Even for the simplest cantilever pile retaining system, the mechanism of local failure-induced progressive failure is relatively complex. The initial failure range, soil strength and compressibility, capping beam, embedded depth of the retaining piles, and other factors will affect the occurrence and development of progressive failure (Cheng et al. 2016; Zheng et al. 2020). Assuming that the initial bending damage of the four piles occurred in the cantilevered pile, the embedded depth of the retaining pile heavily influenced the load transfer coefficients, as shown in Fig. 16. For the smaller embedded depth of the retaining pile with lower stiffness, the soil pressure transferred to the adjacent pile due to the redistribution of earth pressure, making the adjacent pile have greater additional displacement. This additional displacement further led to the redistribution of earth pressure to the other adjacent piles until stable deformation and stress redistribution were finally achieved. Therefore, the smaller the pile embedment depth is, the larger the influence scale of the internal force redistribution in the pile, the lower the load transfer coefficient of the adjacent piles when the local failure occurs, and the lower the possibility of progressive collapse (Cheng et al., 2016; Zheng et al., 2020). Conversely, the greater the embedded depth of the retaining pile with higher stiffness, the higher the possibility of progressive collapse.

The better the soil conditions are, the higher the lateral displacement stiffness provided by the soil in the passive area. After a local failure occurs, the load transfer coefficient of adjacent piles is higher, which indicates that progressive failure is more likely to occur under the same factor of safety or lower robustness and resilience.

Zheng et al. (2020) used the finite difference method to conduct a case study of an overturning and collapse accident of an excavation retained by double-row piles. The influence of local over-excavation on the internal force, deformation, and stability of the double-row piles is investigated. The ratio of the resisting moment to the overturning moment suffered by the pile during construction time was used to evaluate the stability of the piles. The mechanism of occurrence and development of progressive failure due to overturning failure was also studied. After local over-excavation, the overturning failure is mainly transferred outside the over-excavation area through the soil arching effect in the active zone and the loading transfer effect through the capping beam. The anti-overturning status value decreases instantaneously, with its minimum magnitude determining the occurrence and failure scale of overturning progressive failure. If the anti-overturning status value does not consider the load transfer effect of the capping beam, the range of overturning failure outside the over-excavation area will be seriously underestimated. For overturning progressive failure, the capping beam cannot reduce the risk of progressive failure but increases the degree of overturning outside the over-excavation area and expands the scale of overturning failure, which is different from that of bending progressive failure.

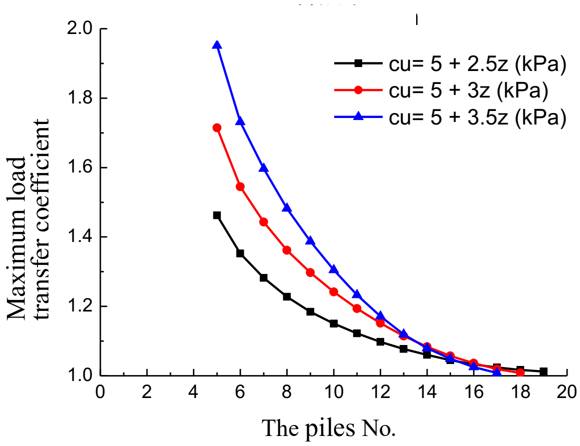


Figure 16. Load transfer coefficients after the failure of 4 piles (Zheng et al. 2016).

4.2.2 *Braced excavation engineering*

The progressive failure is often generated from a point of the retaining system and transferred along with the depth, latitude, and longitude directions of the excavation according to the case studies of the collapses of the deep, large, and long excavation.

(1) Progressive failure along the longitudinal direction

To further reveal the influence of local failure on the overall safety performance and the mechanism of progressive failure under complex retaining structures, Zheng et al. (2020a) studied the effect of local failure on the retaining system through model tests, as shown in Fig. 17. For the same excavation depth, the lateral displacements of the braced excavation were much lower than those of the cantilevered pile retaining excavation, with its lateral movement stiffness only provided by the soil in the passive zone. Therefore, the local failure induced greater additional earth pressure and internal forces in the retaining piles adjacent to the initial failure area, as shown in Fig. 18. After local failure, the redistribution of earth pressure behind the cantilever piles ranged significantly larger than those of the braced piles. When the released load due to strut failure cannot be transferred to the intact struts outside the failure area through the redistribution of internal forces but is concentrated on the adjacent struts as shown in Fig. 19, it can lead to strut failure due to these additional loads and then trigger widespread progressive failure.

(2) Progressive failure along latitude direction

Zheng et al. (2014) conducted a case study of excavation using the discrete element model to investigate the development and evolution process of progressive failure. The diaphragm wall on the left side of the excavation was sheared and broken due to over-excavation. A sliding surface was generated in the soil outside the excavation. The wall above the breakpoint of the diaphragm wall is rotationally deformed. This is because the

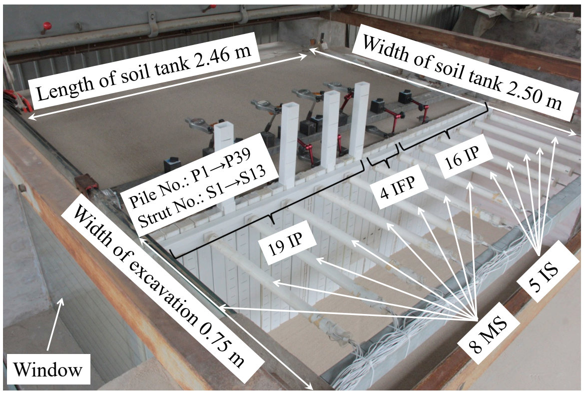


Figure 17. Platform of large-scale model tests and excavation model (Zheng et al. 2020a).

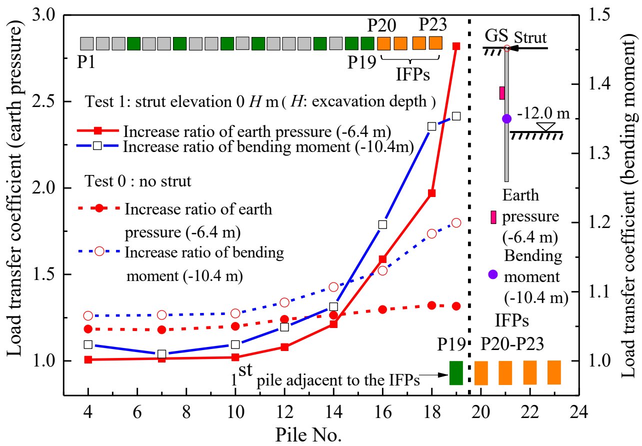


Figure 18. Comparison of earth pressures and load transfer coefficients of braced or cantilever contiguous piles (Zheng et al. 2020a).

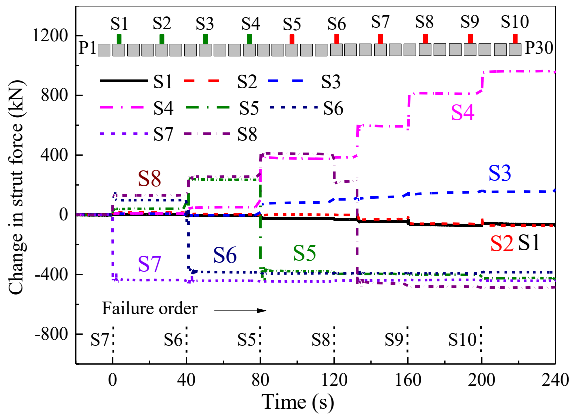


Figure 19. Time curves of strut forces with partial failure (Zheng et al. 2020a).

connection of steel struts and the diaphragm wall were designed as a compression node in traditional methods but did not effectively consider the displacement away from the struts, which made the struts quickly lose their efficiency. The diaphragm wall below the breaking point was transformed into a cantilevered pile and overturned into the excavation under the action of the earth pressure outside the excavation. As the diaphragm wall above the breaking point lost its efficiency, the diaphragm wall together with the soil mass slid into the excavation following the sliding surface through the breaking point. At the same time, the right wall turned into a cantilever structure with overturning failure. After the above-mentioned failure occurs in a section of the excavation, the progressive failure will further expand in the longitudinal direction of the excavation, resulting in large-scale collapse.

Zheng et al. (2021) conducted a case study on the metro excavation collapse of the Nicoll Highway carriageway in Singapore to investigate the progressive failure process of the retaining system induced by an initial failure under different ultimate bearing capacities and the load transferring process in the vertical direction under different initial failure degrees. The research results showed that the load transfer after the initial failure of the strut mainly acted on the adjacent levels, resulting in a rapid and large increase in its axial forces, while the other levels of struts were slightly affected. The initial failure is more likely to trigger the subsequent damage to the immediate level of the strut and develop upwards along the vertical direction. When a certain level of struts fails, the bending moment of the diaphragm wall exceeds its ultimate bending capacity. The diaphragm wall broke down which in turn induced the overall collapse of the excavation.

Therefore, the progressive failure of the excavation often transmits along with its depth and latitude directions with its process of local failure developing into overall collapse. The structure is first damaged somewhere. Then the damaged element releases its sustained load to its adjacent elements. After that, the following element is damaged due to the increased load. The transferring and overloading processes continue to happen until finally leading to the overall collapse of the excavation.

4.2.3 *Anchored pile-supported excavation*

Zheng et al. (2020b) studied the collapse caused by local anchor failure using finite difference software and large-scale physical model tests to reveal the earth pressure redistribution and load transfer along with the retaining system after local anchor failure. For the support using a single level of anchor, the anchor failure induces a significant increase in the axial load to the adjacent three to four levels of anchors and of the shear force and bending moment to the capping beam. With the increase in the failed anchors, the axial load transfer coefficient increases gradually until reaching the final constant magnitude. The pile within the damage range gradually transferred to the cantilevered form with the maximum bending moment first decreasing and then increasing to a constant magnitude. The load (bending moment) transfer coefficients of the pile are generally larger than those of the anchors. That is, the damage is only transmitted within the anchor for a small number of failed anchors. Otherwise, the failure progressively developed into the retaining piles. In addition, the greater the excavation depth is, the lower the soil strength and the higher the load transfer coefficient of the retaining piles and anchors. In the multi-level anchored pile excavation, the local failure of the first level of the anchor has a great influence on the adjacent intact anchors due to the decrease in the bending moment of the retaining pile. The opposite is true for the localized failure of the lowest level of the anchor. However, localized failure of one level of anchor among the multi-levels of anchors has a relatively smaller influence than that of a single level at the same depth. However, the effects of simultaneous local failure of a whole column of multiple levels of anchors are significantly greater than that of a single level of the anchor and are more likely to induce progressive failure. The design or construction measures, such as reinforcing the anchor at certain interval levels, can be used to control the failure of local anchors within a certain level. When the localized failure of several levels of anchors induces adjacent anchors to fail in sequence, the initial anchor failure position does not affect the development and transmission path of progressive failure. After the failure of a whole column of multi-level anchors, the progressive failure range expanded horizontally in an inverted trapezoid shape. The capping and waler beams are easily damaged which in turn induces the bending failure of the retaining piles and accelerates the progressive collapse procedure. Therefore, the design of the capping and waler beams must consider the effects of the localized failure of anchors to improve the overall safety performance of the excavation against progressive failure.

4.3 *Resilience design criteria*

For different types of retaining structures used in deep excavations, such as cantilever piles, braced piles, and anchored piles retaining systems, three-level resilience design criteria could be considered for resilience design, named (1) prevent local failure, (2) prevent the generation of progressive failure and (3) control range of progressive failure. The details of each design criterion are discussed in this chapter.

1st level: prevent local failure

This level of resilience can be achieved by improving the reliabilities and stabilities of the local components. Zheng et al. (2011, 2014) proposed the following methods to prevent local failure:

(a) reinforce the connecting nodes of the retaining system,

(b) ensure sufficient ductility of the components,

(c) carefully design the key components.

The key components are the components that make the excavation retaining system have low redundancy after their removal or destruction. However, there are no well-accepted methods to evaluate the redundancy and robustness of the excavation. It is necessary to conduct further studies for the identification and design of key components. Since the cost of eliminating the possibility of local failure is not cost-effective, it is necessary to consider the following second level of resilience design against progressive failure.

2nd level: Prevent the generation of progressive failure

This level of resilience ensures that progressive failure along the depth, latitude, and longitude directions cannot be generated after the occurrence of the local failure. To achieve this target, it is necessary to establish design theories to improve the redundancy and robustness of the entire retaining system. Zheng et al. (2014) proposed a redundancy design theory through the investigation of the mechanism and control measures of progressive failure in the early stage. The force transmission paths are optimized through a reasonable arrangement of the components of the retaining system to prevent the generation and reduce the degree of progressive failure. The purpose is to increase the force transmission path of the retaining system with no or little lost increase of the retaining system through the reasonable arrangements of the enclosure and retaining system and necessary connection measures to prevent the weakening and damaging of the local components and the large deformation, instability or even progressive failure of the entire retaining system.

Zheng et al. (2014a) used the discrete element method to simulate the progressive failure of the ring beam and radical retaining system. It is found that the probability and degree of failure of the system are significantly lower than those of the unbraced system due to more force transmission paths in the angled retaining system after a component is damaged under the applied surcharge, as shown in Fig. 20. A redundancy evaluation index was proposed, as shown in Eq. (1). After comparing the redundancy evaluation index of different ring beam supports, it is found that reasonably increasing the force transmission path can effectively improve the redundancy of the retaining system.

$$R_5 = \frac{L_{\mathrm{intact}} - L_{\mathrm{design}}}{L_{\mathrm{intact}} - L_{\mathrm{damage}}} \tag{1}$$

where L_{intact} is the ultimate bearing capacity of the complete structure, L_{damage} is the ultimate bearing capacity of the structure after the component is damaged, and L_{design} is the design bearing capacity of the original structure.

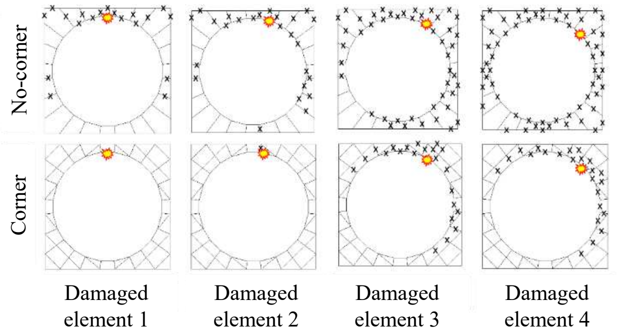
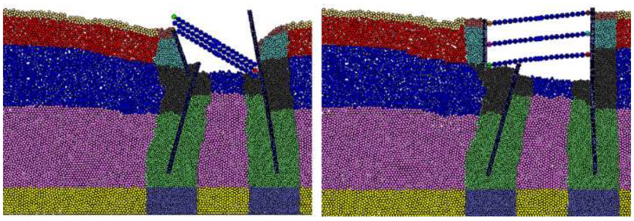


Figure 20. Progressive collapse of internal struts and ring beam.

For the multilayers braced excavation, Zheng et al. (2014b) conducted a case study on the Xianghu Station of Hangzhou Metro using the discrete element method to investigate the stability of using weak and strong connections between the braced piles and the diaphragm wall (see Fig. 21). In the case of a weak connection between the struts and the diaphragm wall, the diaphragm wall is rotated counterclockwise due to the instability of the left edge of the excavation, which makes the three struts fall off. In the case of a strong connection between the struts and the diaphragm wall, the joints can sustain large tensile and shear forces. Even if the left wall fails, the struts are still connected, which prevents the excavation from seriously collapsing. It can be concluded that improving the resilience of the retaining system greatly reduces the collapse degree of the excavation. For the multilayers of braced excavation, as shown in Figs. 10 and 17, the stability of the excavation can be fundamentally improved as long as the first level of strut and the head of the retaining pile (wall) are reliably connected.



(a) (b)

Figure 21. Effects of connections between inner struts and diaphragm wall on stability excavation (a) weak connection (b) strong connection.

The target of the second level of resilience design criteria is to prevent local failure from triggering progressive failure. From the points of balancing the cost of controlling and the loss of damage, the third level of resilience design criteria should also be considered. That is when local failure triggers progressive failure, can the range of development be controlled by appropriate structural measures?

3rd level: control range of progressive failure

If progressive failure has been generated in the excavation, efforts have to be made to control it within a limited range and degree according to the surrounding environmental conditions. Zheng et al. (2021) proposed a blocking element method to terminate the transfer of progressive failure. Taking the cantilever pile retaining excavation, as an example, a method of reinforcing the pile at certain intervals has been proposed to control the development of progressive bending failure. As shown in Fig. 22, several reinforced piles are installed at certain distances with greater embedded depth and pile strength to resist overturning and damage to the retaining piles. It is found that properly designed reinforced intervals can effectively control the development of progressive failure. When the number of reinforced piles is insufficient, the progressive failure crossovers the reinforced piles and continues to develop and in turn makes the reinforced piles fail. Taking the retaining structure shown in Fig. 22 as an example, the method of using two reinforced piles in each interval is insufficient to control the range of progressive failure as that induced by the local failure extends to the piles beyond the 5th~6th piles. If three reinforced piles are adapted in each interval, the progressive failure terminates at the 4th pile.

For the long strip excavation with a single level of the strut, it was pointed out earlier that the load released by the failed struts will concentrate onto their adjacent struts to induce progressive failure. To terminate the development of progressive failure, a certain number of struts can be reinforced at intervals.

However, the cantilever pile and single level of braced excavation are relatively simple. Further studies on the control of the range of progressive failure in complex retaining structures, such as multilayers of strut and anchor supported excavation, are still needed. According to the transmission path of progressive failure, rapid rescue after a local failure accident to terminate progressive failure is another research target in this level of resilience design.

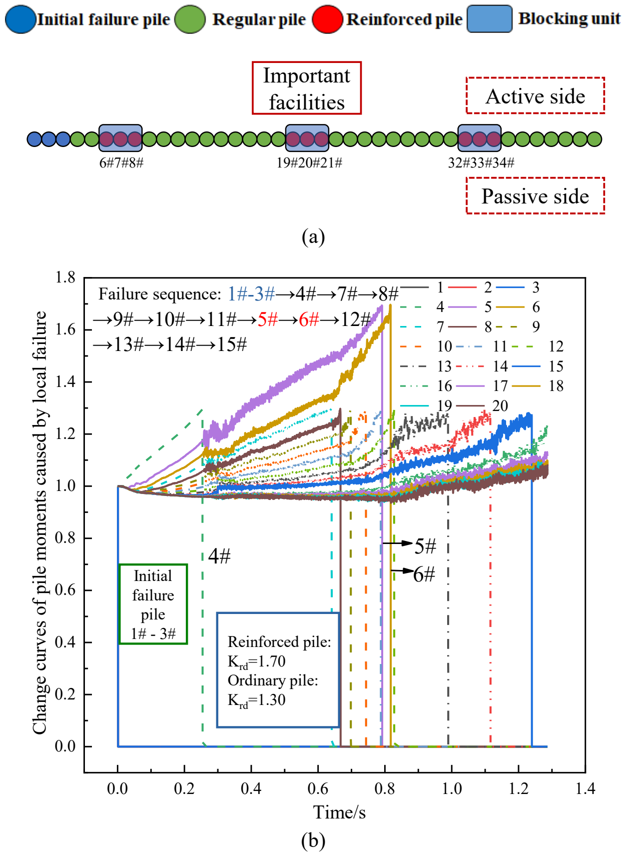
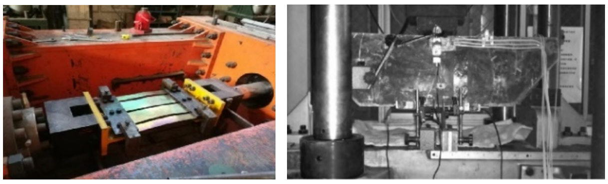


Figure 22. Effects of reinforced piles at certain intervals to terminate progressive failure in excavation retained by cantilever contiguous pile (a) schematic diagram, (b) increase of bending moment versus time curves.

5 RESILIENCE AGAINST PROGRESSIVE FAILURE IN SHIELD TUNNEL ENGINEERING

5.1 *Seismic resilience of shield tunnel*

Many scholars have conducted meaningful explorations and research on the seismic resilience of shield tunnels constructed with different materials, structural forms, and shock absorption measures. The traditional ways of improving the seismic resiliences of shield tunnels are generally achieved by increasing the thickness of the segments, setting up secondary linings, and strengthening the foundation which has limited effects of improvement. Xi (2017) and Liao (2019) reduced the seismic activity at the tunnel structure by setting SMA flexible damping nodes at the weak position of the pipe ring, see Fig. 23(a). They concluded that the SMA damping structure has a good damping effect to make the structure have a certain self-recoverability. Hu (2015) analyzed the seismic resilience of shield tunnels constructed using the steel fiber reinforced concrete lining, see Fig. 21(b). He concluded that the seismic performance of the steel fiber reinforced concrete lining was better than that of the ordinary concrete lining, and within a certain range, the greater the content of steel fiber to reinforce the concrete, the better the resilience of the lining.



(a) SMA damping node (b) Steel fiber reinforced concrete lining

Figure 23. Methods to improve seismic resilience of shield tunnel.

Studies on the seismic performance of tunnels embedded in different soil conditions were conducted to optimize subway lines and measures of reinforcement. Wang et al. (2018) studied the influence of soil stiffness on the seismic response of the shield tunnel. They found that the dynamic response of the shallow tunnel in the weaker stratum was larger under the action of an earthquake. Li et al. (2021) used a three-dimensional finite element model to consider the interactions between shield tunnels and soil stratum to explore the seismic safety of shield tunnels passing through strata with varying stiffnesses. They concluded that sudden changes in stratum stiffnesses lead to the earthquakes response being significantly amplified which should be paid attention to in seismic design. Huang et al. (2009) used the finite difference program FLAC2D to analyze the shock absorption effect of tunnels after ground improvement. They found that the ground improvement can effectively reduce the internal force and deformation of the tunnel structures. The smaller the internal force and deformation of the structure, the more significant the shock absorption effect. Tian et al. (2019) used the finite element software MIDAS/NX to analyze the seismic response of the double-line shield tunnel in the form of spatial position. They found that the horizontal parallel tunnel had the largest dynamic response which is the most unfavorable combination of line seismic design. They improved once again that strengthening the soil around the tunnel can achieve the purpose of improving the seismic capacity of the tunnel.

5.2 *Progressive failure of shield tunnels*

By the end of 2020, urban rail transit lines with a total length of 7,978.19 km have been opened in 45 cities in China. In some mega-cities, the subway tunnel network sharply increased in the last decade. The cities are still expanding their subway networks now with the new shield tunnels often located in an environment with many buildings, dense population, roads, and pipelines. The effects of an accident on the surrounding environment may be catastrophic.

Shield tunneling is a highly mechanized tunnel construction method. Compared with traditional construction methods, the shield tunneling method is relatively safe and fast. As an engineering structure with a length much longer than its cross-sectional, the shield tunnel design is often based on the typical cross-sections embedded in the representative stratum to ensure the safety of the whole tunnel structure. This design criterion is based on the assumption that the working conditions of each segment among the typical cross-section are consistent. However, various unexpected events may result in localized damage to the lining segments or joints between them during the tunnel construction or operation stages. Local failure of segments of the shield tunnel embedded in the confined aquifer can even lead to a groundwater leakage disaster with the water and earth pressures significantly changed around the tunnel. The redistribution of loads and internal forces may lead to large-scale tunnel deformation, segment dislocation, joint opening, segment damage, and even collapse.

Cases of progressive damage or even collapse of shield tunnels induced by local failure have been reported many times. This kind of accident was being attracted great attention from scholars and engineers. On July 1, 2003, a large amount of groundwater and sand flowed into the tunnel during the excavation of the connecting passage between Pudong South Road Station and Nanpu Bridge Station at Shanghai Metro Line 4. The accident induced the collapse of the constructed tunnel with a total length of approximately 264 m (Zhang et al. 2017). Up to now, there are many examples of the shield tunnels reconstructed using the cut and cover method to remove difficult-to-repair tunnel structures and rebuilt using the cast-in-place method.

Furthermore, the parallel, overlapping, and overlapping of tunnels lines heavily increase the risk of tunnel construction. Because the tunnel is deeply buried in a complex surrounding environment, it will consume huge financial and material resources to carry out the repair work once the tunnel is damaged. The occurred cases of tunnel accidents due to accidental or human factors show that the progressive failure or collapse of the tunnel may be due to the localized damage induced soil loss and force concentration on the segments. The existing segment design theories consider the soil only as a design load but ignore the complex interactions between the soil and the tunnel segments during the dynamic developing process of the above-mentioned disasters.

Although the tunnel has sufficient safety reserve to resist the design load in serviceability and ultimate limit states, the stress distributions along the tunnel cross-sections heavily change once localized damage occurred. The performance of the segments in resisting the development of local damage or even collapse still needs further studies. Therefore, it is necessary to carry out in-depth studies on the mechanism of progressive failure and the overall safety performance of the shield tunnels.

5.3 *Progressive failure mechanism*

The research works in the literature related to the progressive failure during the construction of shield tunnels mainly focused on the reason analyses and developing process of the accidents, and the repairing measures after the accidents. However, there are relatively few studies on the developing and terminating mechanism of progressive failure caused by a local failure during the construction of shield tunnels in confined aquifers in soft soil, and their impact on tunnels and strata. Several studies have laid a foundation for the theoretical resilience design against progressive failure in shield tunnel engineering.

Referring to the research idea used in the progressive failure of the superstructure, Liu and Huang (2015) carried out a series of model tests to investigate the resistance of through-joint assembled concrete linings against the progressive collapse. A hydraulic loading system was used to apply multi-points concentrated forces to simulate the soil resistance, hydraulic and earth pressure, and ground surcharge onto the shield tunnel. They concluded that fully utilizing the plastic deformation of the structure was helpful to improve the overall safety of shield tunnels from the perspective review of the structural mechanics. Liu and Sun (2020) defined the progressive failure of underground shield tunnels by comparing them to the studies on building structures. By sorting out the case studies on the collapse accidents of the shield tunnels that occurred during the construction process, they summarized the process of progressive failure includes the following four stages: initial failure stage, ring joint failure, segment joint failure, and tunnel collapse.

Zhang et al. (2017) studied the hydraulic gradient distribution of seepages in shield tunnels using a FEM model and investigated the effect of localized leakage and erosion in different positions of the shield tunnel using a DEM model on the displacement and earth pressure on the tunnel cross-section, and the change of the ground settlement.

Ye et al. (2021) investigated the relationship between erosion-induced structural damage and lining displacement parameters for shield tunneling using a finite element method, which properly simulated the interaction between the eroded soil and tunnel structure as well as the details of the segments. The structural damage mechanism and its relationship with the lining displacement parameters were then clarified by conducting a series of parametric studies.

Zhao et al. (2017) conducted a case study of a leakage accident at Wuhan Metro Line 7 to investigate the effects of water leakage on the excavation surface, deformation of the segments, the stress on the segments and bolts, the opening and deformation of the transverse and longitudinal joints. It is found that the seepage of pore water can greatly decrease the hydraulic pressure onto the tunnel, increase the segment opening and misalignment, and even lead to damage to the tunnel segments and bolts. Zheng et al. (2014, 2016, 2017) analyzed the mechanism of occurrence and development of accidents induced by water leakage, soil erosion, water and sand leakages using model tests, numerical simulations, and a simplified theoretical model.

After the water and soil leakage accident happened in the shield tunnel, soil erosion can induce a localized cavity which can increase the earth pressure on the tunnel and even damage the tunnel structure. For example, the AB section of Metro Line 1 is a double-lane shield tunnel, soil erosion of 20 m^3 occurred at the waler of the 796th steel segmental lining on Jan 17, 2016. The accident made the concrete segments in the range of 798th to 802nd rings of the right-line tunnel compressed and spalled, as shown in Fig. 24 (Zheng et al. 2017). It can be seen that localized water leakage and soil erosion influenced the safety of the shield tunnel not only in its longitudinal direction but also in the adjacent tunnels. Zheng et al. (2017) investigate this case using the FEM modeling and found that the water leakage at the waler of the tunnel lining loosened the side segments. Parametric studies were also conducted to investigate the lateral deformation and force concentration on the tunnel with different loosening angles and degrees. The loosening areas firstly induced the concrete spalling under compression inside of the segment joints, and then made the top bolts yield in tension or even broken. Zheng et al. (2018) used the DEM method to simulate the influence of the cavity formed by soil erosion at different positions of the tunnel cross-section. The results showed that the soil erosion at the waler part of the tunnel loosened the surrounding soil and formed a soil arch outside of the loose area. The tunnel cross-section becomes more oblate with its internal force sharply increased. The soil erosion at the top and bottom of the tunnel cross-section may lead to the reversion of the directions of their bending moment. If soil erosion occurred at the tunnel shoulder, the position of the maximum bending moment shifted to the soil erosion position which endangered the safety of the adjacent segments.

Noticing the fact that a local failure may induce a large-scale progressive failure of the shield tunnel, Zheng et al. (2015) simulated the failure process using the PFC3D software. It was found that, after the failure of a middle ring segment, the internal force of the adjacent segments and bolts increased rapidly, and then progressively failed. In turn, the shield tunnel undergoes a domino-like progressive failure as shown in Fig. 25.

A series of model tests using the scaled shield tunnel embedded in sand embedment were conducted by Zheng et al. (2017) to study the effect of the local failure on the progressive failure along the longitudinal direction of the shield tunnel as shown in Fig. 26. The transmission mechanism of the internal forces on the adjacent segments and the development of the earth

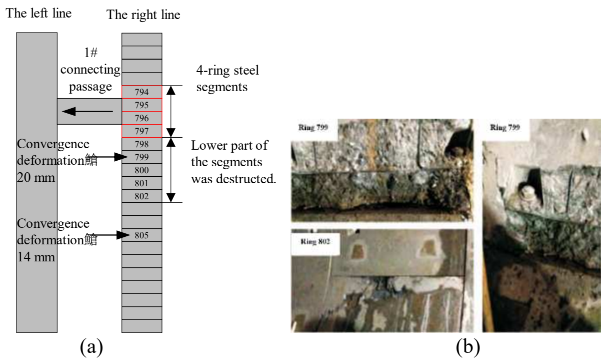


Figure 24. Damage to the shield tunnel due to soil erosion (a) sketch of the lining ring, (b) photos of the concrete spalling.

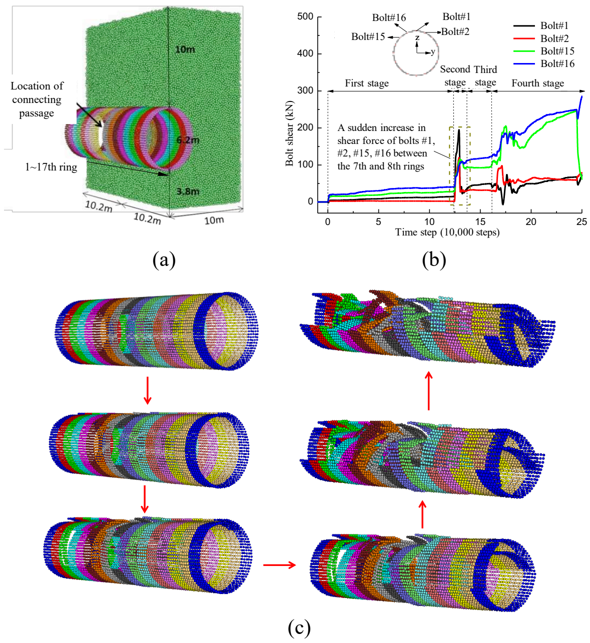


Figure 25. Numerical modeling of progressive failure in shield tunnel (a) PFC 3D Model and localized failed position (b) internal force development of bolts, (c) progressive failure process of the tunnel.

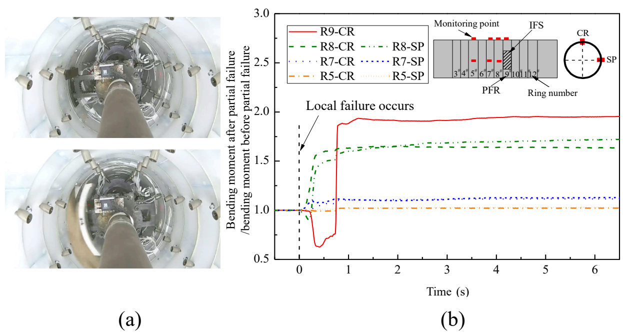


Figure 26. Progressive failure process of shield tunnel (a) photos of the model test (b) monitored bending moment on segments.

pressure after progressive collapse along the longitudinal direction were investigated. The results showed that the time duration of the soil arching effect induced by the local failure of the segment was very short with little influence on the adjacent rings. With the surrounding soil continuously pouring into the tunnel, the soil began to loosen, and the bending moment of the segment increased significantly. It is also found that the deeper the tunnel was buried the greater the increase in the bending moment of the adjacent segments and the higher the risk of progressive failure.

5.4 *Resilience design criteria*

The shield tunnel design is often based on the typical cross-sections embedded in the representative stratum without considering the resilience against progressive failure in the length direction of the entire shield tunnel. When local failure may induce large-scale progressive failure or even collapse of the whole tunnel, and the tunnel is constructed in some special conditions, such as passing through important infrastructures and facilities, large-scale damage or collapse to the tunnel is particularly serious, the resilience of the tunnel is suggested to be evaluated to ensure the toughness of the tunnel.

Similar to the resilience design against progressive failure in the excavation engineering, the same three-level of resilience design criteria are used in tunneling engineering, named as (1) prevent local failure, (2) prevent the generation of progressive failure, and (3) control the range of progressive failure to enable the tunnel to maintain the required safety and service performance after local disasters, such as local water leakage and soil erosion and structural damage, and so on.

1st level: prevent local failure
This level of resilience requirements could be achieved by improving the reliability of the segment and joints and preventing the known various risks. Mo and Chen (2008) and Chen and Mo (2009) summarized many engineering cases to sort the risk sources that may induce local failure during tunnel construction procedures. Engineers can take attention according to the forms of structural damage caused by these risk sources to avoid local failure.

2nd level: prevent the generation of progressive failure
The cross-sectional design method for the shield tunnels cannot reflect the change in the internal force of the adjacent structures after the localized damage. It is impossible to reinforce the tunnel structure with an unknown target. A design framework is proposed based on the beam-spring model to optimize the tunnel structure and improve its overall safety performance. As shown in Fig. 27, the design framework includes the following five steps: determine the forms of the local failure, (2) determine the key parameters, (3) build a numerical model, (4) determine the optimization direction, and (5) formulate an optimization plan.

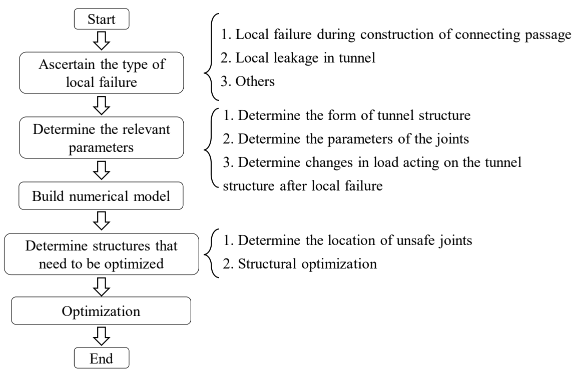


Figure 27. Design framework to optimize shield tunnel.

A Tianjin tunnel is used to illustrate the steps of using the proposed design framework. According to construction experience in Tianjin, the local failure usually happens at the location of the communication channel, tunnel entry, and exit holes. It is assumed that local failure occurs at the location of the connecting passage in step (1) as shown in Fig. 28(a). The pore water pressure and earth pressures are applied onto the segment lining as stress as shown in Fig. 28(b). It is assumed that after the local failure, an unloading area is generated near the shoulder of the first ring. All the loads acting on the tunnel structure disappear due to the generation of the unloading area as shown in Fig. 28(b). Taking the local failure of the inner joints adjacent to the first and second ring and their joints as an example, it is found that the shear forces of the inner ring and their joints significantly increased. A large tensile force is generated and exceeds its bearing capacity. It has to optimize and improve the shear and tensile bearing capacities of these joints. To formulate an optimization plan, the concrete below the bolt has to be reinforced. Trolleys and longitudinally connecting steel frames between segments can also be installed to improve the safety resilience of the shield tunnel. The proposed design framework can also be used for stress analyses after the soil and water leakage induced by different risk sources on the entrance and exit doors of the tunnel to optimize its overall safety.

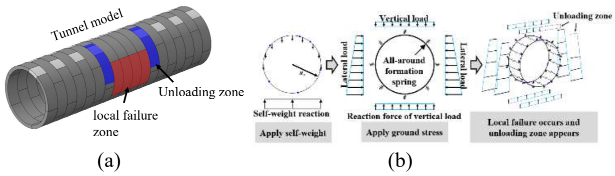


Figure 28. Load-structure model and simulation procedure (a) Schematic representation of the numerical model (b) Simulation process.

3rd level: control range of progressive failure
One method to control the range of progressive failure induced by the localized failure of the weak ring is to strengthen the weak ring and the rings around them. According to the burial depth of the tunnel, there are three types of reinforcement design for the concrete segments, such as shallow buried, medium buried, and deeply buried. As shown in Fig. 29, the 9th ring is found to be weak through numerical analyses. Two cases are studied to investigate the influence of the range of reinforced rings on the performance of the tunnel. One is only to reinforce the 8th to 10th rings, and the other is to reinforce the 6~8th to 10~12th ring. As shown in Fig. 30(a), the tunnel was still damaged with only one ring reinforced on both sides of the weak ring. The failure of the 9th ring still induces damage to the 8th and 10th rings, and then further extends to the 7th and 11th rings. This short-distance reinforcement could not effectively control the occurrence of progressive collapse. As shown in Fig. 30(b), the tunnel is not damaged with the second method of reinforcement. The maximum bending moment of the 9th ring trends to decrease which means a larger range of ring reinforcement could effectively reduce the occurrence of the progressive failure.

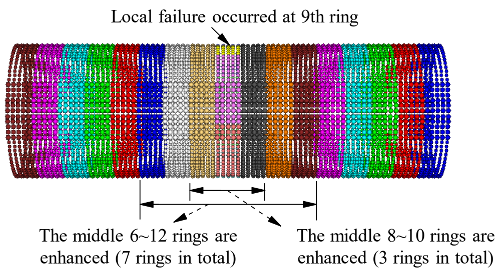


Figure 29. Schematic illustration of the range of reinforcement.

The second method to control the range of progressive failure induced by the localized failure of the weak ring is to install a temporary supporting frame. Take the same case as an example, lateral steel frames are installed onto the 8th and 10th rings as shown in Fig. 31. The time history diagram of the newly added vertical displacement value of each ring is shown in Fig. 32. It can be seen that the displacements of the 8th and 10th rings are controlled after localized failure, but those far from the weak rings increase slowly. If the lateral steel frame is not installed, the local failure induces a rapid increase in the lateral deformation of

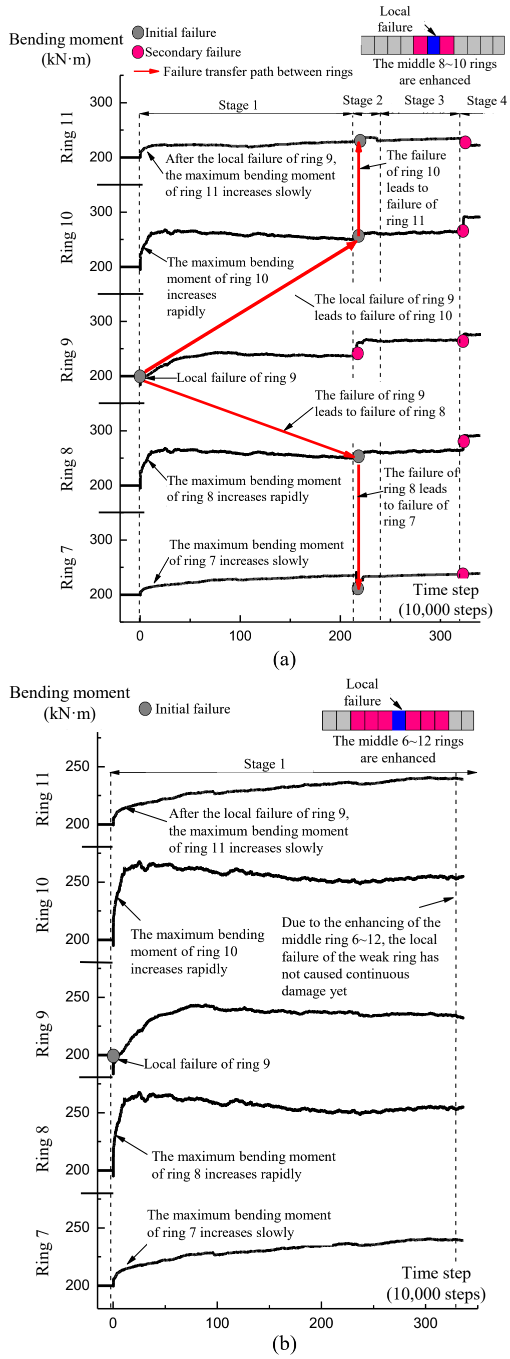


Figure 30. Bending moment developing curves after (a) only reinforce the 8th to 10th rings, and (b) reinforce the 6~8th to 10~12th rings.

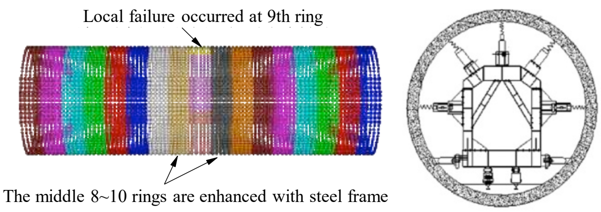


Figure 31. Weak ring reinforcement using the lateral steel frame.

the adjacent rings and finally the progressive failure of the tunnel. Therefore, adding a lateral steel frame at the weak rings could effectively reduce their deformations, but its length of influence is limited. To effectively against the progressive failure along the longitudinal direction of the tunnel, the inner steel frames have to be continuously installed at certain intervals. The method of

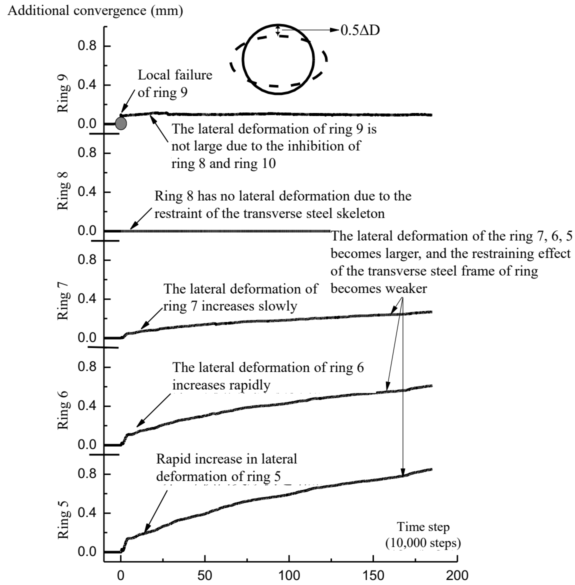


Figure 32. Displacement developing curves after reinforcing the 8th to 10th rings.

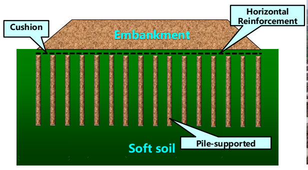
optimizing and improving the robustness of the tunnel structure mainly starts from the segments to strengthen them in advance the poor geological conditions or may be damaged in the later stage of construction, to against the occurrence of the progressive failure. The effect of adding the lateral steel frames is limited because they are mainly used as the temporary support structure in the parts of the tunnel where local damage or collapse has occurred or the dangerous sections during construction.

The third method to control the range of progressive failure induced by the localized failure of the weak ring is to reinforce the soil outside of the tunnel. After the local failure of segments, the soil outside the tunnel usually flows into it with soil arches generating around the tunnel. The unloading effect of the loose area and the loading effect of the arch foot area constitute the force transmission path along the longitudinal direction of the tunnel. To cut off the force transmission path against the development of progressive failure, the following measures can be taken: (1) reinforce the soil outside of the weak ring using freezing or grouting methods to let them meet the strength requirements, (2) install the diaphragm wall around the weak section to prevent a large range of soil erosion, and (3) reduce the overburden pressure at the top of the tunnel through excavation or replace them with lightweight materials. For example, soil excavation and backfill with EPS sheet were successfully used in the Ninghai West Road tunnel on Shanghai Metro Line 1.

6 RESILIENCE AGAINST PROGRESSIVE FAILURE IN EMBANKMENT ENGINEERING

6.1 *Composite foundation*

The composite foundation is one of the main soft soil treatment methods using the reinforced bodies constructed during the ground treatment together with the natural soil body around them to support surcharges, see Fig. 33. By utilizing the bearing capacity of the soil between the reinforced material, the composite foundation can effectively increase the bearing capacity and stability of the ground. It also has the advantages of reducing the differential settlement of the embankment, being cost-effective and construction time-saving. As there is no strong connection between the reinforced material, even if the horizontal geosynthetic layers are adapted to interlock them, the strength of their connections is still much lower than that of the superstructure. Therefore, the integrity of the composite foundation under the embankment is relatively weak.



(a)


(b)

Figure 33. Rigid pile-supported embankment (a) sketch of the method (b) photo of the method.

Composite foundations are widely used in large-scale soft soil reinforcement projects to construct highways, railways, dockyards, and so on. It has been successfully applied in Beijing-Tianjin Intercity High-speed Railway, Beijing-Shanghai High-speed Railway, Mujia Passenger Dedicated Line, Japan Shinkansen, Malaysia High-speed Railway, LGV South Europe Atlantic high-speed railway, etc. The application of composite foundation can effectively improve the bearing capacity and disaster resistance of urban transportation facilities. The material used for the vertical reinforcement or their strength and stiffness after construction can be classified into four categories as shown in Table 2 (Liu and Sun, 2020; Zheng et al. 2012; 2020) with some photos shown in Fig. 34.

Table 1. Categories of composite foundation (Zheng et al. 2020).

Category / Strength characteristics	First species (granular columns)	Second species (Semi-rigid columns)	Third species (Rigid piles)	Fourth species (Combined columns)
	Sand column Stone column Sand-gravel column	Cement mixing column Lime column Rammed cement-soil column Lime-fly ash column Grouted gravel column Chemical churning column Sand bag well Geosynthetic-encased stone columns Bag-grouting columns	CFG pile Prestressed pipe piles Prestressed square pile Concrete plie Bored pile Spiral bored pile X-shaped concrete piles Y-shaped concrete piles Large-diameter tubular pile	Precast concrete stiffened cement mixing columns Profile steel stiffened cement mixing columns Cast-in-situ concrete stiffened cement mixing columns Concrete core sand columns Soil-cement core sand columns
Bond strength	None	Low-Medium	High	
Shear strength	Low-Medium	Low-Medium	High	Medium-High
Compressive strength	Low	Low-Medium	High	Medium-High
Tensile strength	None	None-Low	Low-High	Low-High
Bending strength	None	None-Low	Low-High	Low-High


(a)


(b)


(c)


(d)

Figure 34. Types of composite foundation (White and Pham, 2007)
(a) Granular column (b) semi-rigid column (c) rigid column
(d) reinforced rigid column.

The rigid column is an effective and efficient method of composite foundation technology to be widely used in engineering practice because of its ability in improving the bearing capacity and reducing the settlement of soft soils. In addition to the traditional rigid column with circular and square column cross-sections, the X-type and Y-type cross-sectional concrete columns have also been developed (Liu et al. 2008; Wang et al. 2011; Liu and Zhao, 2016). The composite column such as concrete-cored and shaped steel-cored deep cement mixing columns have been successfully proposed and applied in engineering practice due to their higher bearing capacity (Xiang et al. 2009; Fu et al. 2013; Chen et al. 2013; Kong and Zhou 2014; Liu et al. 2010).

6.2 *Development of embankment stability analyses*

Investigating the failure modes of embankments on different types of columns is conducive to evaluating the failure process of the embankment and its overall resilience assessment. Studies in literature have shown that the failure modes and post-destruction properties of different types of columns under embankments are quite different. The sand or gravel column undergoes shear failure under embankment loads because these types of reinforcements have little flexural stiffness to resist bending moments (Liu and Sun, 2020). Zheng et al. (2020), Zhang et al. (2014), and Abusharar and Han (2011) conducted a series of numerical studies to investigate the effects of column spacing, column diameter, properties of the column, and soil on the stability of gravel column. They concluded that the stability evaluation method of equivalent shear resistance may overestimate the stability of the embankment as the column and soil do not reach their limit states at the same time.

The semi-rigid column, such as jet grouting columns and cement mixing columns, may undergo several types of failure modes such as shear failure, bending failure, compression failure, inclination, lateral movement, and soil flow between columns (Kitazume and Maruyama, 2007; Han et al. 2004; Navin and Filz 2006; Zhang et al. 2014; Yapage et al. 2015a; 2015b). Kitazuma and Maruyama (2017) conducted a series of centrifuge tests and concluded that the cement mixing columns below the embankment suffered bending failure rather than shear failure. The columns at different positions failed progressively rather than simultaneously destroyed. The bending failure of the columns will not directly lead to the instability of the embankment which will lose its stability only after a certain range of progressive failure. Han et al. (2004), Navin and Filz (2006), and Zhang et al. (2014) found through numerical simulations that the failure modes of cement mixing columns, i.e., bending failure or overturning failure, heavily depends on the column strength. The Bishop's arc sliding method will heavily overestimate the stability of the embankment. Yapage et al. (2015a, 2015b) found that the column has an obvious softening behavior after failure. After bending failure of the columns, their cohesion and dilatation angles are reduced to a certain extent. The columns failed progressively at different positions.

The rigid columns, such as plain concrete columns, reinforced concrete columns, and prestressed pipe columns, are mainly suffered from bending failure with obvious brittle and progressive characteristics (Zheng et al. 2010, 2012, 2017). Zheng et al. (2017) proposed a model for considering the post-failure behavior of rigid columns. They observed the phenomenon of progressive failure and analyzed its influence on the stability of the embankment. The influence of one-column failure on the adjacent columns had been analyzed, and the key factors that control the overall stability of the embankments had been clarified. The results from the centrifuge and numerical studies showed that the columns below the embankment shoulder suffered a bending failure. This process made the tensile stresses and bending moments of the columns at the failure position. In the embankment failure cases, the bending failure phenomenon was also confirmed by the excavated columns as shown in Fig. 35(a) (Zheng et al. 2018; Yu et al. 2021). The analysis shows that, after the localized bending failure, the column and soil stresses redistribute within a certain range which will increase

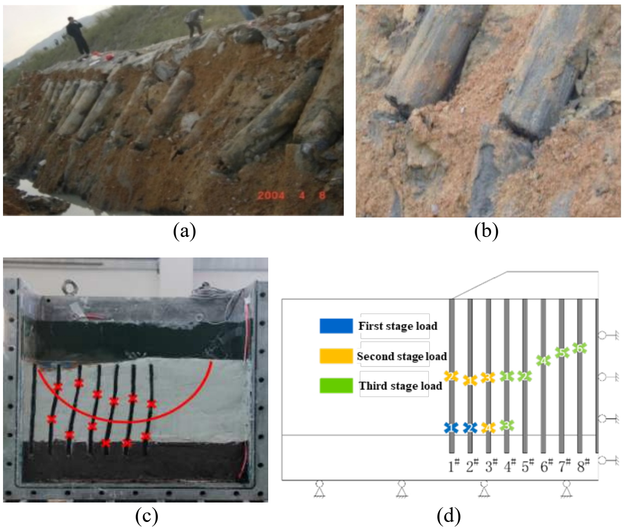


Figure 35. Progressive failure of rigid column (a) and (b) photos of the excavated columns, (c) failure points of the column after centrifuge test (d) failure points of the column after numerical simulations.

the tensile stress and the bending moment of the adjacent columns and finally may lead to the progressive failure, see Fig. 35(b) to 35(d). With an increase in the embankment height, the columns below the embankment shoulder undergo secondary bending failure at a shallow position. Due to the large deformation of the soil in between the columns after damage, the low confining pressure induced by the soil was hard to confine the column. The secondary bending failure at these positions is more likely to induce the progressive failure of the adjacent columns and finally the instability of the embankment. At this time, a plastic sliding surface will be formed along with the bending failure position of the columns.

In the above failure modes of rigid columns, the stability of the embankment was determined by the strength of the columns after the shear failure and bending failure. However, in some other conditions, the instability of the embankment is not related to the strength of the column. Kitazume (2007, 2006) observed through centrifuge tests that the column bodies undergo bending failure when their tensile strength is small but undergo overturning failure when it is large. The centrifuge and numerical studies conducted by Toshinari et al. (2017) showed that the stability of the deep mixing column didn't depend on the column strength no matter whether it failed in shear failure or soil flow between columns. The deep mixing column was even under overturning failure when the underlying soil layer is inclined. Zheng et al. (2021) and Zhou et al. (2019) found that rigid columns easily undergo overturned failure when they are inserted into the inclined hard soil layer at a conventional embedded depth. Terashi et al. (1983) found through the centrifuge tests that the soft soil was easily flowing around the columns if the column spacing was large and the soil between them was very weak.

Based on whether the stability of the embankment is determined by the column strength, the failure modes of the embankment on the columns can be divided into the following two categories: (1) internal failure due to the loss of the strength of the column materials with their failure modes of shear failure, compression bulging failure, and bending failure; (2) external failure due to the loss of some contributions to the stability of embankment in a certain form with their failure modes of the soil flowing failure, overturning failure and horizontal slipping failure. The stability of the embankment mainly depends on the strength of the soil and the column-soil frictions.

6.3 *Resilience design methods*

6.3.1 *Case of embankment failure*

Even if various types of rigid columns are used to support the embankment on soft soil, landslide accidents of the embankment were still happened from time to time. On April 4, 2004, a large-scale landslide accident occurred in a section of a Luochang Expressway in Fujian Province, China, although the cemented fly ash gravel (CFG) columns are used to form the reinforcement in the deep silty clay. More than 70 m of the expressway were destroyed with the lateral influence distance of approximately 100 m, and the collapse depth of approximately 10 m, as shown in Fig. 36(a). The Tai-Hua Expressway used dry vibrating gravel columns for soft soil treatment. The supported embankment slipped during the filling process (Cao and Chen 2007). On a highway in the coastal area of Zhejiang province, the subgrade slipped in a road section during the filling process although the foundation was treated using granular columns because the soft soil foundation accounts for one-third of its total length. (Zhang et al. 2007). Although the soft soil foundation of a railway line was reinforced using cement mixing columns, the embankment suddenly collapsed when it was filled to a height of 5.2 m during the construction process (Qin and Wang 2007). A soft soil under the highway in the Pearl River Delta was treated using pipe columns and two layers of geogrids in the cushion on the surface of the pipe columns. When the subgrade was filled to 7 m, the subgrade collapsed with the pipe columns overturned and slid off the subgrade as shown in Fig. 36(b). Although the designs of the above cases satisfied the standards with their factor of safety being greater than 2.0, serious accidents still occurred because the current design standards cannot satisfy the resilience requirements.

Figure 36. Photo of the embankment failure in (a) Luochang highway and (b) Railway subgrade.

6.3.2 *Stability analyses of column-supported embankments considering resilience*

The most widely used stability design method for embankments is based on the limit equilibrium theory. For a homogeneous soil slope, it is assumed that the sliding surface is cylindrical and the soil above that is rigid. The stability factor of safety is defined as the ratio of the average shear strength to the average shear stress acting on the entire sliding surface.

For the stability analyses of column-supported embankments, the traditional design method adapts the global safety factor to provide the safety reserve. The factor of safety of the subgrade slope is usually calculated using the Swedish method, the Janbu method, and the Bishop method. However, these design methods cannot quantitatively consider the random variations of load effects, geotechnical parameters, and soil resistance. The design parameters heavily depend on engineering statistics, laboratory tests, or engineering experience.

For the stability analysis of the embankment on the soft soil foundation treated by rigid column, it is usually calculated using the method for the granular column, i.e. circular arc sliding method, see Fig. 37. The shear strength on the sliding surface S_{sp} is calculated as:

$$S_{sp} = (1 - m)c_u + mS_p \cos\alpha \qquad (2)$$

where S_p is the shear strength of the rigid column, α is the angle between the tangent direction on the sliding arc and the horizontal directions, c_u is the undrained shear strength of the soil, m is the area replacement ratio of the rigid column.

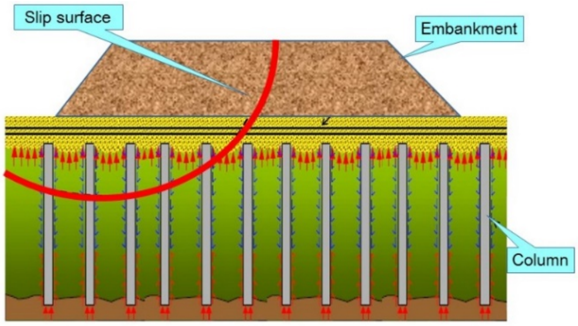
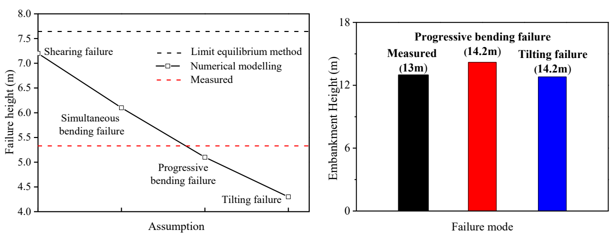


Figure 37. Slip surface of the column-supported embankments.

There are following three basic assumptions in this design method: (1) only shear failure happens in the column without considering the possibility of other failure modes; (2) the columns are simultaneously failed without considering the possibility of progressive failure; (3) the column is uniform and play a role without considering the possibility of external damage. Therefore, the circular arc sliding method for stability analysis may be seriously inconsistent with the failure characteristics of the actual project. The failure cases investigated by Cao et al. (2007), Zhang et al. (2007), and Qin and Wang (2007) showed that the design methods may make the engineering project unsafe or even induce failure accidents. It is necessary to analyze the real failure modes of different reinforcement methods, especially for rigid columns and high embankments constructed on the flexible columns in soft soil. The numerical and experimental studies have to be conducted to simulate the real failure modes and estimate the overall stabilities of the subgrade and embankment.

The three basic assumptions of the most commonly used arc sliding methods ignore the possibilities of the internal shear failure, progressive failure, and external failure of the column bodies. The calculation results overestimate the safety of the embankment to a varying degree. For the internal failure mode, the ultimate filling height of the embankment calculated using the potential shear failure mode is very close to that calculated using the arc sliding method but significantly larger than that calculated using the simultaneous bending failure. The smallest limit filling height of the embankment is obtained based on the progressive bending failure, which is almost consistent with the actual buckling height, as shown in Fig. 38(a). For the external failure mode, the embankment filling height based on the progressive bending failure mode is significantly larger than that based on the overturning failure mode, which is almost identical to the actual buckling height, as shown in Fig. 38(b).

The above studies show that the two cases are the progressive bending failure and overall overturning failure modes induced by the localized failure of a column. The traditional stability



(a) (b)

Figure 38. The failure modes of the embankment (a) Internal failure, (b) external failure.

analyses cannot guarantee resilience against the failure risks of the embankments. It is suggested to evaluate the stability of the embankment using different calculation methods based on its potential failure modes, establish the characterization of the failure evolution, identify the key factors and their thresholds, and finally propose analytical methods and technologies to improve the resilience of the embankment engineering. However, there are limited studies on the robustness and recoverability design methods of the embankment under extreme conditions.

The above studies show that the failure modes of the two engineering projects are progressive bending and overturning failures induced by the local failure of the first column. The traditional stability analytical methods could not guarantee the disaster resilience of the embankment which has potential instability risk.

It is therefore required to focus on the resilience of the embankment, realize the characteristic of its failure evolution process, identify the key influencing parameters and thresholds, and finally propose the evaluation methods according to the real failure modes of the embankment. Based on the progressive failure mechanism of the embankment, Zheng et al. (2020) defined the evaluation of the resilience against progressive failure, that is, the ability of the system to resist external disturbances during the progressive failure procedure. The sensitivity coefficient S_{ij} of each stage of progressive failure could be used to evaluate the resistance of the system, see Eq. (3). It can be found from Fig. 39 that the larger sensitivity coefficient S_{ij} represents the more serious column damage, i.e. $S_{ij} \leq 0.2$ for slight damage, $S_{ij} \leq 0.4$ for moderate damage, and $S_{ij} \leq 0.6$ for severe damage.

$$S_{ij} = \frac{\sigma'_{ij} - \sigma_{ij}}{\sigma_t - \sigma_{ij}} \tag{3}$$

where σ_t is the ultimate tensile strength, and σ_{ij}, σ'_{ij} are the tensile stresses of adjacent columns before and after local column damage, respectively.

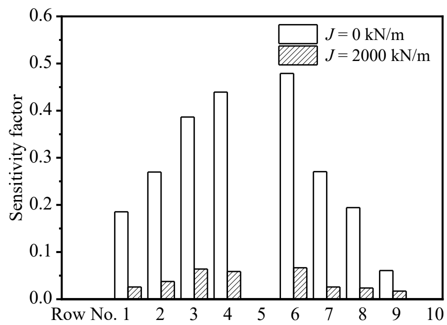


Figure 39. Sensitivity factor of resilient evaluation.

6.4 *Measures with resilience design methods*

For the granular column with a relatively lower strength, bearing capacity, and stability, Chen et al. (2015) proposed a design method for this type of composition foundation reinforced by geosynthetics. The stability of the column body is greatly improved because the geosynthetics reinforcement can coordinate the deformation of the system and prevent the column body from bulging. Zhao et al. (2014) conducted the laboratory model tests to analyze the bearing capacity and stability of the gravel column enclosed by geosynthetic within a certain depth from the ground surface and concluded that the geosynthetic enclosed gravel column has a better engineering performance. Zhao et al. (2016) proposed a two-way reinforced composite foundation using geocell and gravel columns to improve the deformation capacity of gravel columns. They found that geocells can effectively increase the bulge range and volume of the gravel columns with their maximum bulging position moving up to give full play of the bearing capacity. Wen et al. (2010) poured cement slurry into gravel columns to form slurry-solid gravel columns which have higher strength and rigidity to heavily improve the bearing and deformation performance of the embankment. The column body still keeps its characteristics of construction and environmental friendliness performance.

For the semi-rigid column, Broms (1991) installed the continuous column wall in the position where the column body is prone to be bending failed, such as under the embankment shoulder, to improve the bending resistance of columns. Han and Gabr (2002) analyzed the effect of horizontal reinforcement on the settlement characteristics of columns and concluded that horizontal reinforcements can effectively reduce their total and uneven settlements. The numerical study conducted by Navin (2005) showed that the installation of installing continuous column wall under the embankment shoulder could greatly improve the stability of the columns with the same replacement ratio, and maintain high-level reliability considering the spatial variability of materials, and optimize the safety performance of the embankment. Jamswang et al. (2015) found through engineering measurement and numerical simulations that the column body at the toe of the embankment is prone to bending damage which may lead to excessive lateral deformation. Installing grouting columns and continuous column walls on both sides of the embankment can significantly improve its deformation and stability performances.

For the rigid composite foundation, the column-net composite foundation, column-slab composite foundation, and column-raft composite foundation are widely used in engineering practices (Liu and Zhao 2016). Increasing the column-soil stress ratio could make the forces between the column groups more coordinated and thus improve the stability of the embankment. After the embankment is internally damaged, the rigid columns may suffer from local brittle bending failure and then a significant progressive failure. The rigid column may also experience external damage, such as overturning damage. When analyzing the stability of rigid columns under the embankment, the traditional overall stability analysis method assumes that the columns are sheared at the same time (Jamsawang et al. 2015). According to the loading characteristics of the rigid columns at different positions under the embankment, Zheng et al. (2010) divided the columns beneath embankments into four different areas, such as tension-bending area, and bending-shearing area, compression-bending area, and pressure-bearing area. There are significant differences in the anti-slipping mechanism of rigid columns in different areas. The performance requirements should be considered to optimize and improve the resilience of the embankment. The resilience design method could make the embankment on columns have a higher structural economy and safety with a reasonable spatial layout.

Zheng et al. (2018) proposed a model to simulate the post-failure behavior of rigid columns considering the characteristics. Their studies reflected the generation of tensile cracks and the weakening of the shear bearing capacity during the bending failure process of the rigid column. According to the column positions and their influences on the stability of the embankment, an unequal strengthen method was proposed to prevent the internal failure of the embankment on rigid columns. Reinforcing the key columns in the bending and shearing areas can effectively prevent the progressive failure of the rigid columns and improve the stability of the embankment.

Zhou et al. (2021) proposed a design method to consider the bending performance and post-failure of the rigid column. The numbers of strengthening columns versus ultimate bearing capacity curves are shown in Fig. 40. It can be seen that strengthening the three key columns can greatly improve the stability of the embankment with an effect similar to strengthening all columns. Since the steel reinforcements of the column determine the cost of the column, the number of columns used under the embankment is hugely reduced especially then the method was adapted for a long highway. Therefore, using the performance-based design method with key columns strengthened can significantly improve the embankment stability and save engineering costs.

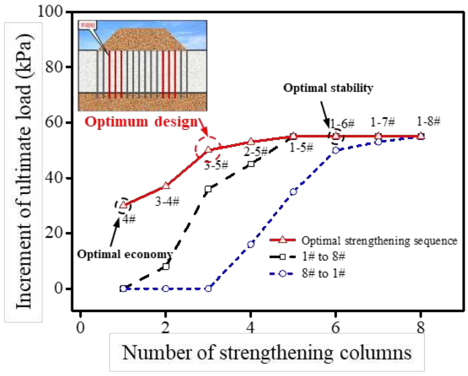


Figure 40. The numbers of strengthening columns versus ultimate bearing capacity curves (Zheng et al. 2018).

In the current stability studies of the embankment on the rigid column, the horizontal embedded layer is mostly considered. The rigid column is often designed to be embedded 0-2 times the column diameter into the hard soil layer. Zhou et al. (2019) conducted centrifuge tests and numerical studies and concluded that the rigid column body may suffer from overturning damage when a substratum is inclined. With the increase of the embedded depth of rigid columns, the failure modes change from the overturning failure to the bending failure. The mechanical characteristics of the columns below different positions of the embankment have different ways to influence the stability of the columns. A non-isometric performance-based design method was proposed based on the external failure of rigid columns. The surcharge loading versus the number of strengthened column curves is shown in Fig. 41. By increasing the spatial layout strategy of the embedding depth of the columns at key positions to fully use the characteristics of columns at different positions, the stability and resilience of the embankment can be economically and effectively improved.

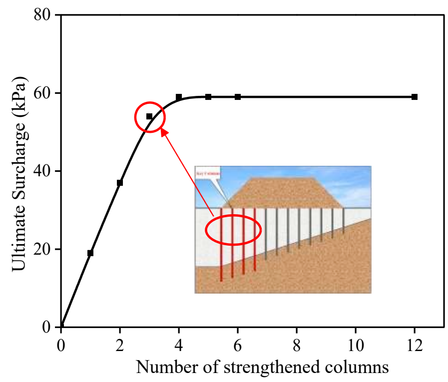


Figure 41. The surcharge loading versus the number of strengthened column curves.

7 CONCLUSIONS

The safeties of urban and major infrastructures in geotechnical and underground engineering are of great importance. To realize the design and construction of resilient underground infractions and cities, some major problems in geotechnical and underground engineering have to be solved to resist natural disasters or human-induced serious disasters, maintain their functions to the greatest extent, and restore their functions as soon as possible after disasters. This paper summarized the connotation and development of resilience and pointed out that the evaluation and control of resilience can be divided into the following four levels: permissible stress design method, reliability-based design method, robustness method, and recoverable performance method. Through this study, the following conclusions can be drawn:

(1) The factor of safety and reliability-based design theories have been fully developed and played important roles in ensuring the safety of infrastructures in geotechnical and underground engineering. However, the two methods are often adapted together in design which is required to be further developed.

(2) Based on traditional reliability-based design theories, the robustness design method has been proposed to consider the uncertainty of the geotechnical parameters, evaluate the sensitivity of system performance to the parameter variabilities and assess the failure probability of geotechnical engineering, which has deepened the traditional reliability design theories. More efficient and convenient methods for applying robustness design method to engineering and incorporating it into design specifications have to be developed.

(3) In geotechnical and underground engineering, large-scale progressive failure accidents often happened due to the local failures of soil and structures. Studies in the field of excavation engineering, shield tunnel engineering, and column-supported embankments have been reviewed to illustrate the mechanism, evaluation, and design theories of resilience against progressive failure. The evaluation and design methods of resilience against progressive failure in geotechnical and underground engineering still need further studies in various fields.

(4) The self-healing and rapid recoverability of engineering structures are very important for the improvement of their resilience. Because the infrastructures in geotechnical and underground engineering are deeply buried in the ground, it is difficult to repair once damaged. There are relatively few studies on the recoverability analyses of infrastructures in geotechnical and underground engineering. The cost of improving their recoverability is relatively high to rapidly recover the damaged underground structures. How to rapidly, economically, and effectively improve the recoverability of the geotechnical infrastructures after earthquakes and other accidents are required further in-depth studies.

(5) Resilience evaluation methods and indicators are the basis to establish systematic resilience design theories in geotechnical and underground engineering. Due to the uncertainties in geotechnical and underground engineering, the complex interactions between soil-water-structures, and the difficulties in repairing once damaged, the reasonable and convenient resilience evaluation indicators that can comprehensively consider the robustness (resilience against progressive failure), resources, rapidity, and redundancy of structures in geotechnical and underground engineering are required.

8 REFERENCES

Abusharar S.W. and Han J. Two-dimensional deep-seated slope stability analysis of embankments over stone column-improved soft clay, *Engineering Geology*, 2011, 120(1):103-110.

Alonso E.E. Risk analysis of slopes and its application to slopes in Canadian sensitive clays. *Géotechnique*, 1977, 26(26): 453-472.

Anastasopoulos I, Gazetas G, Loli M, et al. Soil failure can be used for seismic protection of structures. *Bulletin of Earthquake Engineering*, 2010, 8(2): 309–326.

Artola J. A solution to the braced excavation collapse in Singapore (Master thesis). Boston: Massachusetts Institute of Technology, 2005.

Asaoka A, Agrivas D. Spatial variability of the undrained strength of clays. *ASTM Geotechnical Testing Journal*, 1981, 108.

Babu G L S, Murthy D S. Reliability Analysis of Unsaturated Soil Slopes. Journal of Geotechnical and Geoenvironmental Engineering, 2005, 131(11): 1423-1428.

Breen J.E. Research Workshop on Progressive Collapse: Regulatory Approached to the Problem. National Bureau of Standards, Washington D.C., 1975.

Broms B.B. Stabilization of Soil with Lime Columns. *Ground Engineering*, 1991, 12(4): 833-855.

Bruneau M, Chang S E, Eguchi R T, et al. 2003, A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*, 19(4): 733 - 752.

Bruneau M., Reinhorn A., 2006, Overview of the resilience concept, Proceedings of the 8th US National Conference on Earthquake Engineering, 2006, pp. 18-22.

Cao Weiping, Chen Yunmin. Analysis of sliding failure mechanism and treatment for Taihua Highway embankment slope over soft soils, *Chinese Journal of Rock Mechanics and Engineering*, 2007, 26(7) : 1504-1510. (In Chinese)

Casagrande A. Role of calculated risk in earthwork and foundation engineering. *Journal of the Soil Mechanics & Foundations Division*, 1966, 91: 1-40.

Chang M. Basal stability analysis of braced cuts in clay. *Journal of Geotechnical and Geoenvironmental Engineering*, 2000, 126 (3) : 276-279.

Chen Fei, Wu Kaixing, He Shu. Field tests on load transfer performances of squeezed branch piles. *Journal of Geotechnical Engineering*, 2013, 35(s2): 990-993(In Chinese)

Chen J F, Li L Y, Xue J F, et al. Failure mechanism of geosynthetic-encased stone columns in soft soils under embankment. *Geotextiles and Geomembranes*, 2015, 43(5):424-431.

Chen, J. S., & Mo, H. H. Numerical study on crack problems in segments of shield tunnel using finite element method. *Tunnelling and Underground Space Technology*, 2009, 24, 91–102.

Cheng X.S., Zheng G., Diao Y. et al. Experimental study of the progressive collapse mechanism of excavations retained by cantilever piles. *Canadian Geotechnical Journal*, 54: 574–587 (2017).

Cheng Xue-song, Zheng Gang, Deng Chu-han et al. Study of the mechanism of progressive collapse induced by partial failure of cantilever contiguous retaining piles. *Chinese Journal of Geotechnical Engineering*, 2015, 37(7): 1249–1263. (In Chinese)

Cheng Xue-song, Zheng Gang, Huang Tiam-ming et al. Experimental study on mechanism of progressive collapse along length of excavation retained by cantilever contiguous piles. *Chinese Journal of Geotechnical Engineering*, 2016, 38(9): 1640–1649. (In Chinese)

Cheng, X. S., Zheng, G., Diao, Y., Huang, T. M., Deng, C. H., Lei, Y. W., and Zhou, H. Z. (2016). Study of the progressive collapse mechanism of excavations retained by cantilever contiguous piles. *Engineering Failure Analysis*, 71.

Cherubini C, Christian J T, Baecher G B, et al. Factor of Safety and Reliability in Geotechnical Engineering. *Journal of Geotechnical and Geoenvironmental Engineering*, 2001, 127(8): 700-721.

Choosrithong K , Schweiger H F . Numerical Investigation of Sequential Strut Failure on Performance of Deep Excavations in Soft Soil. *International Journal of Geomechanics*, 2020, 20(6):1-12.

Deng Jian, Zhu Hehua. Finite Element Monte- Carlo Method Using Neural Networks for Geotechnical Reliability Analysis. *Journal of Tongji University (Natural Science)*, 2002, (03): 269-272. (In Chinese)

Duncan J M. Factors of safety and reliability in geotechnical engineering. *Journal of Geotechnical and Geoenvironmental Engineering*, 2000, 126(4): 307-316.

Ellingwood, B. and Leyendecker, E.V. (1978), Approaches for Design Against Progressive Collapse, *Journal of the Structural Division*, Vol. 104, No. 3, pp. 413–423.

Fang JH, Zhang ZH, Zhang JY, 2009. Application of artificial freezing to recovering a collapsed tunnel in Shanghai Metro No. 4 Line. *China Civil Engineering Journal*, 42(8):124-128 (In Chinese)).

Finn W. D. L (2015). 1st Ishihara Lecture: An overview of the behavior of pile foundations in liquefiable and non-liquefiable soils during earthquake excitation. *Soil Dynamics and Earthquake Engineering*, 68(2015) 69–77.

Fu Qiang, Ding Xuanming, Liu Hanlong, et al. Dynamic analysis of PCC pile composite foundation under train vibration load. *Rock and Soil Mechanics*, 2013, 34(s2): 413-420 (In Chinese)

Goh A. and Wong K. S. Three-dimensional analysis of strut failure for braced excavation in clay. *Southeast Asian Geotech, Soc.* 2009, 40(2), 137–143.

Guan Z., Yang B., Dong K., Li J., Experiment on Hysteretic Properties of Bridges with Pile-group Foundations Allowing Rocking and Uplift of Pile Cap, *China Journal of Highway and Transport*, 2017, 30(10), 62-68.

Guan Z, Chen X, Li J. Experimental investigation of the seismic performance of bridge models with conventional and rocking pile group foundations. *Engineering Structures*, 2018, 168:889-902.

Ge Hong. Comparison of immune algorithm with genetic algorithm. *Journal of Jinan University*, 2003, (01): 22-25. (In Chinese)

Goh A. T. C., Fan Z., Liu H., Zhang W., Dong Z. Numerical Analysis on Strut Responses Due to One-Strut Failure for Braced Excavation in Clays. 2018

Gong W P, Khoshnevisan S, Juang C H. Gradient-based design robustness measure for robust geotechnical design. *Canadian Geotechnical Journal*, 2014, 51(11): 1331-1342.

Gong Xiao-nan. Generalized composite foundation theory and engineering application. *Chinese Journal of Geotechnical Engineering*, 2007, 29(1): 1–13. (In Chinese)

Haack I A. Construction of the North-South-Metro Line in Cologne and the accident on March 3rd, 2009. *International Symposium on Social Management Systems (SSMS)*, 2009

Han J, Chai J C, Leshchinsky D, Shen S L. Evaluation of deep-seated slope stability of embankments over deep mixed foundations. *ASCE Geo-Support*, 2004.

Han J, Gabr M A. Numerical Analysis of Geosynthetic-Reinforced and Pile-Supported Earth Platforms Over Soft Soil. *Journal of Geotechnical & Geoenvironmental Engineering*, 2002, 128(1):44-53.

Han J. Recent research and development of ground column technologies, *Proceedings of the Institution of Civil Engineers Ground Improvement*, 2015, 168(4):1-19.

Han Jianyong, Zhao Wen, Jia Pengjiao et al. Mechanical Response of Anchored Pile Supporting Deep Excavation Influenced by Local Anchor Failure, *Journal of Northeastern University (Natural Science)*, 2018, 39(03): 426-430.

Ha J G , Kim D S . Evaluation of seismic behavior of soils under nuclear containment structures via dynamic centrifuge test. *Nuclear Engineering and Design*, 2014, 277(1):64–75.

Hao Yiwen, Xu Jiang, 2015. Understanding Urban Resilience: A Conceptual Analysis Based on Integrated International Literature Review. *Urban Planning International*, 30(02): 48-54. (In Chinese)

Holling C.S. Resilience and stability of ecological systems. Annual *Review of Ecology and Systematics*, 1973 (4):1-23.

Hsien P G, Ou C Y, Liu H T. Basal heave analysis of excavations with consideration of anisotropic undrained strength of clay, *Can. Geotech. J.*, 2008, 45:788-799.

Hu Lei. Seismic dynamic response research on steel fiber reinforced concrete in tunnel lining structure, Master thesis, 2015, Southwest Jiaotong University. (in Chinese)

Huang Hongwei, Gong Wenping, Zhuang Chuanxian, Zhang Jie. Robust Geotechnical Design of Gravity Retaining Wall, *Journal of Tongji University (Natural Science)*, 2014, 42(3): 377-385.

Huang Hongwei, Gu Leiyu, State-of-the-art of researches on risk management of foundation pit engineering, *Chinese Journal of Geotechnical Engineering*, 2008, (S1), 651-656 (In Chinese)

Huang Hongwei, Huang Xi, Schweiger F. H. 2012, Numerical analysis of the influence of deep excavation on underneath existing road tunnel. *China Civil Engineering Journal*, 45(03):182-189. (In Chinese)

Huang Hongwei, Shen Xianda, Wang Fei, Zhang Dongming, Vulnerability Analysis and Assessment of Segment Joints in Shield Tunnel 2016,44(02):198-206+219. (In Chinese)

Huang H., Gong W., Zhuang C., et al Robust design of gravity retaining wall. *Journal of Tongji University*, 2014, 42 (3):377- 385 (in Chinese)

Huang Juan, Peng limin, Li Xinglong, Transverse seismic response of Shiziyang shield tunnel in liquefiable soil and its shock absorption measures, *Chinese Journal of Geotechnical Engineering*, 2009, (10):1539-1546. (in Chinese)

Huang Mao-song, Song Xiao-yu, Qin Hui-lai. Basal stability of braced excavations in K0-consolidated soft clay by upper bound method. *Chinese Journal of Geotechnical Engineering*, 2008, 30(2):250-255. (In Chinese)

Huang Yu, Shu Xiang, Ye Weimin et al. Recent studies on seismic resistance of pile foundation, *Industrial Construction*, 2002, 32(7). 50-53,61 (In Chinese)

Huang H W, Zhang D M. Resilience analysis of shield tunnel lining under extreme surcharge: Characterization and field application.

ISSMGE. Joint TC205/TC304 Working Group on "Discussion of statistical/reliability methods for Eurocodes"– Final Report, 2017.

Itoh, K., Kikkawa, N., Toyosawa, Y., Suemasa, N., and Katada, T. Failure Mechanism of Anchored Retaining Wall due to the Anchor Head Itself Being Broken. *Proc., TC302 Symposium Osaka: International Symposium on Backwards Problem in Geotechnical Engineering & Monitoring of Geo-construction*. 2016.

Jamsawang P, Voottipruex P, Boathong P, et al. Three-dimensional numerical investigation on lateral movement and factor of safety of slopes stabilized with deep cement mixing column rows. *Engineering Geology*, 2015, 188:159-167.

Jiang Li-hong, Kong Ling-gang, Lin Gang, Chen Yun-min, Simplified method of laterally loaded single piles with partial pile head fixity, *Engineering Mechanics*, 2014, 31(11), 63-69

Juang C H, Wang L, Atamturktur S, et al. Reliability-based robust and optimal design of shallow foundations in cohesionless soil in the face of uncertainty. *Journal of Geoengineering*, 2012, 7(3): 75-87.

Juang C H, Wang L, Liu Z F, et al. Robust Geotechnical Design of Drilled Shafts in Sand: New Design Perspective. *Journal of Geotechnical and Geoenvironmental Engineering*, 2013, 139(12): 2007-2019.

Khoshnevisan S, Gong W P, Juang C H, et al. Efficient Robust Geotechnical Design of Drilled Shafts in Clay Using a Spreadsheet. *Journal of Geotechnical and Geoenvironmental Engineering*, 2015, 141(2).

Kitazume M, Kenji M. External stability of group column type deep mixing improved ground under embankment loading. *Soils and Foundations* 2006, 46(3): 323-340.

Kitazume M, Maruyama K. Internal stability of group column type deep mixing improved ground under embankment loading, *Soils and Foundations*, 2007, 47(3): 437–455.

Ko K W, Ha J G, Park H J, et al. Centrifuge modeling of improved design for rocking foundation using short piles. *Journal of Geotechnical and Geoenvironmental Engineering*, 2019, 145(8): 04019031.

Kong Gangqiang, Zhou Hang. Theoretical analysis of soil compaction effect of belled wedge pile China, *Journal of Highway and Transport*, 2014, 27(2): 9-16 (In Chinese)

Larosche A, Ziehl P, ElBatanouny M K, Caicedo J, Plain pile embedment for exterior bent cap connections in seismic regions. *Journal of Bridge Engineering*, 2014, 19(4), 04013016

Lehman D E, Roeder C, Stringer S J and Jellin A, Seismic performance of improved pile-to-wharf deck connections, PCI Journal, 2013: 62-80

Li Guang-xin, Li Xue-mei. The shear strength in stability analysis of subway pit in soft clay. *Geotechnical Investigation and Surveying*, 2010, 1: 1-4. (In Chinese)

Li Siming, Yu Haitao,Xue Guangqiao, Xu Lei, Analysis on seismic response of shield tunnels passing through soil-rock strata, *Modern Tunnelling Technology*, 2021, 58(5):65-72. (in Chinese)

Li X. Study on the load transfer mechanism induced by the failure of anchors in excavations retained by pile-anchor structure. Master thesis, Tianjin University, 2018. (In Chinese)

Liao D. Experiments and finite element analysis of underwater shield tunnel damping joints based on SMA, Master thesis, 2019. Guangzhou University. (in Chinese)

Liu G., Wang W. *Excavations Engineering Manual* (The second edition). Beijing: China Architecture and Building Press, 2009: 121-146. (In Chinese)

Liu Hanlong, Ren Lianwei, Zheng Hao, et al. Full-scale model test on load transfer mechanism for jet grouting soil-cement-pile strengthened pile. *Rock and Soil Mechanics*, 2010, 31(5): 1395-1401(In Chinese)

Liu Hanlong, Zhao Minghua. Review of ground improvement technical and its application in China, *China Civil Engineering Journal*, 2016, 49(1):96-115. (In Chinese)

Liu J., Hou X. *Excavations Engineering Manual*. Beijing: China Architecture and Building Press, 1997. (In Chinese))

Liu S., Yi Y., Zhu Z. Comparison tests on field bidirectional mixing column for soft ground improvement in expressway. *Chinese Journal of Rock Mechanics and Engineering*, 2008, 27(11): 2272-2280 (In Chinese)

Liu X., Huang X. Experimental study of collapse capacity of straight joint segmental tunnel lining structure. *Chinese Journal of Rock Mechanics and Engineering*, 2015(S2):3703-3714. (In Chinese)

Liu Xian, Sun Qihao. Case analysis on progressive collapse of shield tunnel linings. *Hazard Control in Tunnelling and Underground Engineering*, 2020, 2(2): 21-30. (In Chinese)

Lu Y, Tan Y. Overview of Typical Excavation Failures in China. *Eighth International Conference on Case Histories in Geotechnical Engineering*. 2019

Lu X., Chen Y., Mao Y., New Concept of Structural Seismic Design : *Earthquake Resilient Structures*, 2011, 39(7):941-948. (In Chinese)

Lumb P. Safety factors and the probability distribution of soil strength. *Canadian Geotechnical Journal*, 1970, 7(3): 225-242.

Lumb P. The Variability of Natural Soils. *Canadian Geotechnical Journal*, 1966, 3(2): 74-97.

Lv Xilin, Quan Liumeng, Jiang Huanjun. Research trend of earthquake resilient structures seen from 16WCEE, Earthquake Engineering and

Engineering Vibration, 2017, 01(3):1-9. (In Chinese)
Mo, H. H., Chen, J. S. Study on inner force and dislocation of segments caused by shield machine attitude. *Tunnelling and Underground Space Technology*, 2008, 23, 281–291.
Navin M P, Filz G M. Numerical stability of embankments supported on deep mixed columns. ASCE GSP 152, *Ground Modification and Seismic Mitigation*, 2006.
Navin M P. *Stability of Embankments Founded on Soft Soil Improved with Deep-Mixing-Method Columns*. 2005.
Nees / E-defense. Report of the seventh joint planning meeting of NEES / E-defense collaborative research on earthquake engineering. PEER 2010 /109. Berkeley: University of California, Berkeley, 2010.
Olsson A M J, Sandberg G E. Latin hypercube sampling for stochastic finite element analysis. *Journal of Engineering Mechanics-ASCE*, 2002, 128(1): 121-125.
Peng X, Li D Q, Cao Z J, et al. Reliability-based robust geotechnical design using Monte Carlo simulation. *Bulletin of Engineering Geology and the Environment*, 2017, 76(3): 1217-1227.
Pong, K. F., Foo, S. L., Chinnaswamy, C. G., Ng, C. C. D., and Chow, W. L. (2012). Design considerations for one-strut failure according to TR26 – A practical approach for practising engineers. *The IES Journal Part A: Civil & Structural Engineering*, 5(3), 166-180
Qin L., Wang Z. Fall into Unstable Analysis of a Certain Embankment on Soft Soil Ground in Railway, *Subgrade Engineering*, 2007(2) : 42-44.
Qingdao Kazuki, Yasuda Satoshi, Sadayuki Ishizaki, Hiroshi Shimada, Tsutomu Komuro, Ichizo Kawabata, Development of pile head semi-rigid junction construction method (F.T.Pile construction method), Taisei Construction Technology Center report, 2004, 37, 1~8
Ser, C., Sayin, B. Geotechnical assessment and rehabilitation of retaining structures collapsed partially due to environmental effects. *Eng Fail Anal* 119. 2020.
Shadabfar S, Mahsuli. M, Zhang Y., et al. Resilience-Based Design of Infrastructure: Review of Models, Methodologies, and Computational Tools. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, 2022, 8(1): 03121004.
Sivandran C. Probabilistic analysis of stability and settlement of structure on soft Bankok clay. Ph.D. Dissertafion of Asian Institute of Technology.1979: 56-58P
Taguchi G. Introduction to quality engineering: Designing quality into products and processes. Asian productivity organization, Tokyo, 1986.
Tang Liang, P-Y model of dynamic pile-soil interaction in liquefying ground, PhD thesis, Harbin institute of technology, 2010. (In Chinese)
Terashi M, Tanaka H, Kitazume M. Extrusion failure of ground improved by the deep mixing method, *Proc. 7th Asian Regional Conference on Soil Mechanics and Foundation Engineering*, Haifa, Israel. 1983, 1: 313-318.
Tian Z., Xu Y., Study on the Law of Transverse Seismic Response of Two Paralleled Shield Tunnels, *Modern Tunnelling Technology*, 2019, (2):57-64. (in Chinese)
Tunnelling and Underground Space Technology, 2016, 51:301-312.
Toshinari Y, Matsuda S, Kitazume M, Nguyen B. Centrifuge Model Studies on External Stability of Column Type Deep Mixing Ground on Inclined Foundation. Grouting, 2017,227-23
Ukritchon B, Whittle A J, Sloan S W. Undrained stability of braced excavations in clay. ASCE, 2003, 8: 738-755.
Vanmarke E H. Probabilistic Modeling of Soil Profiles. *Journal of the Geotechnical Engineering Division ASCE*, 1977, 103(11): 1227-1246.
Wachi K., Asano S., Maeda N., Aoshima K., Nagai K., Mechanical characteristics of simplified connection of pile head for precast concrete pile, *Journal of Structure Concrete Engineering*, AIJ, 2003, 570, 85-91
Wang Qi, Yu Haitao, Dai Chunxiang, Wu Yongxin, Duan Keping, Seismic response analysis of ultra-shallow buried shield tunnel in soft soils, *Modern Tunnelling Technology*, 2018, 55(s2):493-500. (in Chinese)
Wang G., Wang Y., Yu H., Zheng N., Sun F. Shaking table tests on seismic response of rocking frame structure considering foundation uplift, *Chinese Journal of Geotechnical Engineering*, 2021,11(43):2064-2074. (In Chinese)
Wang Ruichuan. Prediction and analysis of shield boring parameters in a mixed ground based on BP neural network. Master thesis, Tongji University, 2019. (In Chinese)
Wang Xinquan, Chen Yonghui, Chen Long, et al. Comparative study on bearing characteristics of Y –section pile and common piles under embankment load. *Journal of Railway Engineering Society*, 2011(11): 46-52 (In Chinese)
Wen Shiqiang, Chen Yumin, Ding Xuanming, et al. Application of grouted gravel pile in soft subgrade improvement of expressway, *Rock and Soil Mechanics*, 2010, 31(5): 1559-1563. (In Chinese)
White D J, Pham H T V, Hoevelkamp K K. Support Mechanisms of Rammed Aggregate Piers. I: Experimental Results, *Journal of Geotechnical & Geoenvironmental Engineering*, 2007, 133(12):1503-1511.
Whittle A J, Davies R V. Nicoll Highway collapse: evaluation of geotechnical factors affecting design of excavation support system. *International Conference on Deep Excavations*, Singapore, 2006.
Wu B., Ou Y. Experimental study on tunnel lining joints temporarily strengthened by SMA bolts. *Smart Materials and Structures*, 2014, 23:1-10.
Wu T H, Kraft L M. Safety analysis of slopes. *Journal of the Soil Mechanics & Foundations Division*, 1970, 96(1):609-630. (In Chinese)
Xi Z. Research on longitudinal seismic performance of underwater shield tunnel and SMA flexible dissipation joint, Master thesis, 2017, Guangzhou University. (in Chinese)
Xia J., Gu J., Xu Y., You Y. Research on Foundation Pit Multiple Horizontal Bracing System Based on the Redundancy, *Bulletin of Science and Technology*. 2018, 34(08): 200-205. (In Chinese)
Xiang W., Liu S., JingFei, et al. Bearing capacity of composite foundation of soilcement deep mixing columns with different cross-section parts. *Journal of Southeast University: Natural Science Edition,* 2009, 39(2): 328-333(In Chinese)
Xiao X., Yuan J., Zhu Y\. Causation analysis of the collapse on Singapore MRT circle cine lotC824 (Part I)- Project background and process of collapse. *Modern Tunnelling Technology*, 2009, 46(05): 66-72. (In Chinese)
Xiao X., Yuan J., Zhu Y. Causation analysis of the collapse on Singapore MRT circle cine lot C824 (Part I)- Technically breaching back analysis and insufficient instrumentation. *Modern Tunnelling Technology*, 2010, 47(01): 22-28. (In Chinese)
Xu J., Shao J., Zheng Y. Application of genetic algorithm to reliability analysis of geotechnical engineering. *Chinese Journal of Geotechnical Engineering*, 2000, (05): 586-589. (In Chinese)
Yang Z. Research on seismic performance of prestressed high strength concrete pile, PhD thesis, Tianjin University, 2014.
Yapage N N S, Liyanapathirana D S, Kelly R B, et al. Numerical Modeling of an Embankment over Soft Ground Improved with Deep Cement Mixed Columns: Case History. *Journal of Geotechnical & Geoenvironmental Engineering*, 2015a, 140(11):04014062.
Yapage N N S, Liyanapathirana D S, Poulos H G, et al. Numerical Modeling of Geotextile-Reinforced Embankments over Deep Cement Mixed Columns Incorporating Strain-Softening Behavior of Columns. *International Journal of Geomechanics*, 2015b, 15(2):04014047.
Ye Lieping, Qu Zhe, Lu Xinzheng, Feng Peng. Collapse prevention of building structures: a lesson from the Wenchuan earthquake, *Journal of Building Structures*, 2008, (04): 42-50.
Ye Z, Liu H. Investigating the relationship between erosion-induced structural damage and lining displacement parameters in shield tunnelling. *Computers and Geotechnics*, 2021, 133, 104041.
Zhang D M, Zhai W Z, Huang H W, et al. Robust retrofitting design for rehabilitation of segmental tunnel linings: Using the example of steel plates. *Tunnelling and Underground Space Technology*, 2019, 83:231-242.
Zhang D., Gao C., Yin Z., Wang R., Yang T. Particle flow simulation of seepage erosion around shield tunnel, *Rock and Soil Mechanics*, 2017(S1): 435-444.
Zhang J., Wang W., Jiang D., Guan Z. Tests for aseismic performance of pile-to-pile cap joint of cast-in-place piles with steel casings, *Journal of Vibration and Shock*, 2018, 37(003):79-84. (In Chinese)
Zhang K., Li J. Accident analysis for '08.11.15' foundation pit collapse of Xianghu Station of Hangzhou metro. *Chinese Journal of Geotechnical Engineering*, 2010, 32(S1): 338–342. (In Chinese)
Zhang W., Ling S., Chen Y., Zhou M. Stability analysis of filled embankment laid on soft subsoil compacted with sand-stone pile, *Railway Engineering*, 2007(11): 46-49. (In Chinese)
Zhang Y., Chen X. Finite element analysis for slope stability with multi-braced retaining wall through reduction of strength parameters. *Chinese Journal of Geotechnical Engineering*, 2006, 28(11): 1952-1957.
Zhang Z, Han J, Ye G B. Numerical analysis of failure modes of deep mixed column-supported embankments on soft soils. *Ground Improvement and Geosynthetics*, 2014, 168: 78–87.
Zhang Z, Han J, Ye G. Numerical investigation on factors for deep-seated

slope stability of stone column-supported embankments over soft clay, *Engineering Geology*, 2014, 168(2):104-113.
Zhao M., Gu M., Zhang L., et al. Model tests on influence of vertical geosynthetic-encasement on performance of stone columns. *Journal of Geotechnical Engineering*, 2014, 36(9):1587-1593 (In Chinese)
Zhao M., Liu M., Ma B., Long J. Calculation for Stress Concentration Ratio and Settlement of Bidirectional Reinforced Composite Foundation Consisting of Geocell Mattress and Stone Column Under Embankment, *China Journal of Highway and Transport*, 2016, 29(05): 1-10. (In Chinese)
Zhao T, Liu W, Ye Z, et al. Effects of Water Inrush from Tunnel Excavation Face on the Deformation and Mechanical Performance of Shield Tunnel Segment Joints. *Advances in Civil Engineering*, 2017: 1-18.
Zhao W, Han J Y, Chen Y, et al. A numerical study on the influence of anchorage failure for a deep excavation retained by anchored pile walls. *Advances in Mechanical Engineering*. 2018,10(2):1-17.
Zheng G, Cheng X S, Diao Y, et al. Concept and design methodology of redundancy in braced excavation and case histories. *Geotechnical Engineering Journal of the SEAGS & AGSSEA*, 2011, 42(3): 13-21.
Zheng G, Cui T, Cheng X, et al. Study of the collapse mechanism of shield tunnels due to the failure of segments in sandy ground. *Engineering Failure Analysis*, 2017, 464-490.
Zheng G, Dai X, Diao Y, et al. Experimental and simplified model study of the development of ground settlement under hazards induced by loss of groundwater and sand. *Natural Hazards*, 2016, 82(3): 1869-1893.
Zheng G, Dai X, Diao Y, et al. Parameter analysis of water flow during EPBS tunnelling and an evaluation method of spewing failure based on a simplified model. *Engineering Failure Analysis*, 2015, 96-112.
Zheng G, Yang X., Zhou H, et al. Numerical modeling of progressive failure of rigid piles under an embankment, *Canadian Geotechnical Journal*, 2018(4).
Zheng G. Method and application of deformation control of excavations in soft ground. Chinese J. Geot. Eng., 2022, 44(1): 1-36. (in Chinese)
Zheng G., Cheng X., Diao Y. DEM simulation and redundancy analysis of excavation collapse. *Rock and Soil Mechanics*, 2014b, 35(2): 573-583. (In Chinese)
Zheng G., Cheng X., Zhang Y. Progressive collapse simulation and redundancy study of ring-beam supporting structures of excavations. *Chinese Journal of Geotechnical Engineering*, 2014a, 36(1): 105-117. (In Chinese)
Zheng G., Cui T., Cheng X., Diao Y. Transverse Deformation of Shield Tunnel Under Lateral Loosening Conditions, *Journal of Tianjin University*, 2017, 50(12): 1304-1313. (In Chinese)
Zheng Gang, Cui Tao, Cheng Xue-song, Sun Ji-bin, GE Long-bo, Introduction and analysis of an accident in a shield tunnel, *Chinese Journal of Geotechnical Engineering*, 2017, 39(z2): 132-135. (In Chinese)
Zheng G., Cui T., Cheng X., Zhang T. Safety situation investigation and analysis of the shield tunnels under the condition of the sandy ground leakage, *Journal of Safety and Environment*, 2018: 39-44. (In Chinese)
Zheng G., Cui T., Jiang X. Mechanism of progressive collapse induced by partial failure of shield tunnels in sandy soil, *Chinese Journal of Geotechnical Engineering*, 2015, 37(9): 1556-1571. (In Chinese)
Zheng G., Dai X., Zhang X.. Experimental study and numerical simulation of leaking process of sand and water in underground engineering., *Chinese Journal of Rock Mechanics and Engineering*, 2014, 33(12): 2458–2471. (In Chinese)
Zheng G., Deng C., Cheng X., Huang T., Lei Y. Influence of Space Effect on Progressive Collapse in Excavations Retained by Cantilever Piles, *Journal of Tianjin University*, 2016, 49(10): 1016-1026. (In Chinese)
Zheng G., Gong X., Xie Y., et al. State-of-the-art techniques for ground improvement in China, *China Civil Engineering Journal*, 2012, 45(2): 127–146. (In Chinese)
Zheng G., Lei Y., Cheng X., Li X., Wang R. Influences and mechanisms of anchor failure on anchored pile retaining system of deep excavations, *Chinese Journal of Geotechnical Engineering*, 2020a,42(03): 421-429. (In Chinese)
Zheng G., Lei Y., Cheng X., Li X., Yu D. Experimental study on influences of local failure on steel-strutted pile retaining system of deep excavations, *Chinese Journal of Geotechnical Engineering*, 2020b, 41(08): 1390-1399. (In Chinese)
Zheng G., Li S., Diao Y. Centrifugal model tests on failure mechanisms of embankments on soft ground reinforced by rigid piles. *Chinese Journal of Geotechnical Engineering*, 2012, 34(11): 1977–1989. (In Chinese)
Zheng G., Liu J., Han J. Stability of embankment on soft subgrade reinforced by rigid piles (I)—background and single pile analysis. *Chinese Journal of Geotechnical Engineering*, 2010, 32(11): 1648–1657. (In Chinese)
Zheng G., Liu J., Han J. Stability of embankment on soft subgrade reinforced by rigid inclusions (II) - group piles analysis. *Chinese Journal of Geotechnical Engineering*, 2010, 32(12): 1811–1820. (In Chinese)
Zheng G., Liu S., Chen R. State of advancement of column-type reinforcement element and its application in China. *Proceedings of the US-China Workshop on Ground*
Zheng G., Yang X., Zhou H., Sun J. Researches on stability and control strategy of embankments reinforced by rigid piles based on the concept of progressive failure, *Chinese Journal of Geotechnical Engineering*, 2017, 39(4): 581–591. (In Chinese)
Zheng G., Yi F., Huang T., Cheng X., Yu D., Lei Y., Wang R. Mechanism of overturning progressive collapse of excavations retained by double-row piles induced by over-excavation, *Chinese Journal of Geotechnical Engineering*, 2020b, 43(08): 1373-1381. (In Chinese)
Zheng G., Yu X., Zhou H., Yang X., Guo W., Yang P. Influence of geosynthetic reinforcement on the stability of an embankments with rigid columns embedded in an inclined underlying stratum. *Geotextiles and Geomembranes*, 2021, 49(1): 180-187.
Zheng G., Zhang N., Ba Z., Zhang T. Seismic performance of PHC pipe piles in layered soft soils, *Chinese Journal of Geotechnical Engineering*, 2013, 35(S2): 506-510. (In Chinese)
Zheng G., Zhao J., Zhou H., Yu X., Xiao B., Wang J. State-of-the-art review for techniques on ground improvement of highway and railway, *Chinese Journal of Ground Improvement*, 2021, 3(02): 91-99. (In Chinese)
Zheng G., Zhao J., Cheng X., Yu D., Wang R., Zhu X., Yi F. Mechanism and Control Measures of the Vertical Progressive Collapse of Deep Excavations Retained by a Multilayer Strutting System, *Journal of Tianjin University*, 2021, 54(10): 1025-1038. (In Chinese)
Zheng G., Zhou H. State-of-the-Art Review of Ultimate Bearing Capacity and Stability of Composite Foundations, *Journal of Tianjin University*, 2020, 53(07): 661-673. (In Chinese)
Zheng G., Zhu X., Cheng X., Lei Y., Wang R., Zhao J., Yi F. Study on the control theory and design method of progressive collapse in excavations retained by cantilever piles, *Chinese Journal of Geotechnical Engineering*, 2021, 43(06): 981-990. (In Chinese)
Zheng G., Yu X., Zhou H., Wang S., Zhao J., He X., Yang X. Stability analysis of stone column-supported and geosynthetic-reinforced embankments on soft ground. *Geotextiles and Geomembranes*, 2020, 48(3): 349-356.
Zheng J., Guo J., Lee F. Immune algorithm for reliability analysis of geotechnical engineering, *Chinese Journal of Geotechnical Engineering*, 2007, (05): 785-788. (In Chinese)
Zheng Y. *Engineering Treatment of Slope & Landslide*. China Communications Press, 2007. P817. (In Chinese)
Zheng, Y., Hu, Z., Ren, X., Wang, R., Zhang, E. The influence of partial pile cutting on the pile-anchor retaining system of deep foundation pit in loess area. *Arabian Journal of Geosciences*, 2021, 14(13), 1-12.
Zhou L.. Resilient City: Risk Management and Its Indicators. *Journal of Beijing Administrative College*. 2016(02): 13-20. (In Chinese)
Zhou H, Zheng G, Liu J, et al. Performance of embankments with rigid columns embedded in an inclined underlying stratum: centrifuge and numerical modelling. *Acta Geotechnica*. 2019, 14: 1571–1584
Zuo Y., Zhu H., Li X. An ANN-based four order moments method for geotechnical engineering reliability analysis. *Rock and Soil Mechanics*, 2013, 34(2): 513-518. (In Chinese)