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Research progress and prospects of seismic performance on underground structure embedded in soft soil foundation

Xuelei Cheng[1,2]✉, Qiqi Li[1], Ran Hai[1,3], Shuoshuo Guo[1] & Xiaofan Xing[1]

For the complexity and difficulty of seismic research on subway station structure system embedded in soft soil foundation, the seismic research method is quite different from the ground structure. The methods of seismic research on subway station structures in soft soil were summarized, and relevant literature on this field in recent years were sorted out. The advanced progress of theoretical analysis and quasi-static simplification analysis, model test (shaking table test, centrifuge test), numerical simulation (the total stress method, the effective stress method), and dynamic reliability of underground structures were mainly introduced for seismic analysis of subway station embedded in the soft foundation. The advantages and disadvantages of each method and the development direction of this field were proposed briefly in order to better understand seismic analysis of underground structure engineering in soft soil.

Keywords Soft soil ground, Subway station structure, Seismic analysis, Research progress, Research prospect

Underground structure refers to the structure of the underground part of a building, such as basements, underground garages, underground passages, etc[1–3]. Since the beginning of the twenty-first century, China's urbanization process has been continuously advancing, causing the urban population, scale and living space to encounter tremendous pressure. Therefore, the development and utilization of underground space have become an effective means to alleviate traffic congestion and improve the pressure of the living environment. The subway, which is a fast, efficient and environmentally friendly means of transportation, gradually plays an irreplaceable role in modern urban passenger transport. Many underground railways have been built in big cities such as Beijing and Shanghai, thus forming an efficient and fast transportation network. Still, some cities are building (or preparing for) underground rail transit. In the new era, there is great potential for constructing underground space structures, which will be developed to a greater extent[1,4,5].

During an earthquake, underground structures often face significant seismic forces and therefore must have a certain level of seismic resistance. The large-scale construction of subway stations in high-intensity regions started in the past 30 years, and most of them have not been tested by strong earthquakes. Meanwhile, due to the constraints of objective factors such as the difficulty of underground structure observation, there haven't been many records of earthquake damage examples[6]. Before the 1995 Kobe Earthquake in Japan, it was generally believed that the seismic capacity of an underground structure was 1 to 3 intensity levels higher than that of a ground structure under the same conditions, and the underground structure would not be damaged by the earthquake or even did not need seismic design[7]. However, several major earthquakes (the 1987 Miyamoto Earthquake in Japan; the 1995 Kobe Earthquake in Japan; the 1997 Chi-Chi Earthquake in Taiwan; the 1999 Kocaeli Earthquake in Turkey; the 2007 Malaga Earthquake in Portugal) caused serious damage to subway station structures in the earthquake area, which has attracted the attention of scholars all over the world. Therefore, the seismic resistance of underground structures has increasingly become a cross-hot issue of concern in the fields such as earthquake engineering, geotechnical engineering, and disaster prevention, mitigation and protection engineering[8–10].

Currently, most of the subways that have been built or are newly built are concentrated in coastal, riverside and lakeside areas (developed areas), where deep soft and poor foundation soil layers are widely distributed.

[1]School of Architectural and Civil Engineering, Zhongyuan University of Technology, Zhengzhou 450007, Henan, China. [2]School of Traffic and Transportation Engineering, Dalian Maritime University, Dalian 116026, Liaoning, China. [3]School of Materials Science and Engineering, Henan University of Science and Technology, Luoyang 471023, Henan, China. ✉email: xueleic@163.com

It is known that there is a complex genesis of marine, delta, river and lake muddy sedimentary soft soil[11,12]. It belongs to the late Quaternary soil, including fine-grained muddy soil, peaty soil and a small amount of humus. Existing underground buildings (structures) have been damaged due to large deformation of soft soil (Xinxie Earthquake, 1964; Tangshan Earthquake, 1976; Taiwan Chi-Chi Earthquake, 1999). Especially in the 1995 Kobe Earthquake in Japan, the Dakai Station was severely damaged by the earthquake: the middle column was bent and collapsed, resulting in the collapse of the roof, which led to the large-scale settlement of the overlying soil layer of the subway, and the settlement depth of some sections even reached 2.5 to 4.0m. The earthquake damage site is shown in Fig. 1. The underground structure of the subway was expensive, and it was difficult to repair and costly due to the concealment of the damage. The cost of repairing the Dakai station alone was as much as 10 billion Yen[13–16].

The basic principle of seismic design for underground structures is to increase the seismic capacity of the structure, reduce the impact of earthquake action on the structure, and ensure that the underground structure will not collapse or suffer serious damage during an earthquake. Generally, the seismic design of underground structures needs to meet the following basic principles: increasing the stiffness of the structure, controlling structural deformation, increasing the energy dissipation capacity of the structure, and adopting seismic isolation structures. The seismic design of underground structures needs to consider both seismic design parameters and structural design parameters. The seismic design methods for underground structures mainly include strength design methods, displacement design methods, and capacity design methods[17,18].

The seismic damage of subway station structure is a complex process with high nonlinearity and continuous accumulation and development of damage, which involves complex problems such as multi-phase coupling nonlinearity, soil-structure contact nonlinearity, as well as strength and deformation nonlinearity of soil-structure system. Saturated sand or silt liquefaction and large deformation of soft soil are two typical catastrophic instability phenomena of foundation under an earthquake. Domestic and foreign scholars have studied more on the dynamic strength deformation of liquefiable sites and had a more comprehensive and in-depth understanding of its mechanism[19,20]. *Survey Procedure for Geotechnical Engineering in Soft Soil Areas JGJ83-2011* divides the main distribution areas of soft soil in China into three areas: Area I: the northern area, Area II: the central area, and Area III: the southern area. The unique complex physical (dynamic) and mechanical properties of soft soil, such as high sensitivity, weak permeability, low strength, high compressibility, long consolidation, etc., make the seismic research of underground structures on soft foundation sites more complicated. Besides, the research in this field started late, increasing the difficulty in seismic research of underground structures, and resulting in a lag in comprehensive and in-depth systematic research results[21]. Therefore, China has not yet stipulated a special seismic design code for underground structures. Currently, due to the limited understanding of the dynamic disaster mechanism of the interaction system of underground structures in soft soil sites, the current relevant seismic code design is not mature enough, and it is relatively rough when especially compared with the liquefiable sand foundation site. Moreover, it only provides some qualitative and general provisions, but there is still a lack of more in-depth and comprehensive systematic studies that can improve the seismic code design. Therefore, it is difficult to adapt to the rapid development of subway construction in China and meet the new requirements for the seismic design of underground structures.

Therefore, based on the requirements for urban underground space development and underground transportation hub construction, it is necessary to study the dynamics and seismic failure mechanism of underground structure system in soft soil sites to solve the unavoidable practical possibility of potential seismic threat of underground structures in deep soft soil sites. In this way, it can not only offer an important reference for the location of urban subway transportation hubs and lines but also provide an important basis for the seismic design of urban underground structures.

Research status of seismic analysis of underground structures at home and abroad

The current seismic analysis methods of subway station structures mainly include theoretical analysis (analytical and quasi-static simplified methods), model test (ordinary shaking table and centrifugal shaking table), and

(a) Pillar failure (b) Surface subsidence

Fig. 1. Earthquake damages of Dakai subway station.

numerical simulation (dynamic total stress and effective stress)[22–24]. In this paper, the existing research results in the field of seismic research of underground structures in soft soil sites in the past ten years were summarized and analyzed, and the limitations and future development trends of various methods were pointed out, aiming to make the seismic design research of underground structures in soft soil site standardized, systematic and practical.

Theoretical analytical method and pseudo-static simplification method

Before entering the twenty-first century, limited by computer hardware and technology, the seismic design calculation of underground structures is mainly based on simplified methods. The analytical method is mostly proposed for the foundation vibration problem and the dynamic response analysis of underground structures, and it can only solve limited problems, but it can still play an important role when coupled with other numerical methods. The calculation parameters of the quasi-static simplified method are easy to determine, with a small calculation workload, so it is easy to accept. Therefore, it is mainly suitable for the study of plane linear elastic problems and qualitatively analyzes the impact of different factors on the dynamic response of underground structures. After decades of research and development, analytical or quasi-static simplified methods mainly include a series of seismic calculation methods represented by response displacement method, surrounding rock strain method, ST. John method, Shukla method, BART method, response acceleration method, underground structure Push-over seismic analysis method, and Fujerva method[25,26].

Pure theoretical analysis method

Theoretical analysis is the result obtained by extremely simplifying the on-site model, so the results obtained cannot be directly used to guide engineering practice. For example, simplifying the structure into beams or shells, assuming the soil layer as a homogeneous soil layer, using normal and tangential springs to simulate the contact interaction between the stratum and the structure, etc. These assumptions differ significantly from the real situation. The analytical method of theoretical derivation cannot consider the nonlinear dynamic characteristics of soil due to the limitation of its own conditions, but it is helpful to understand the failure modes of underground structures in soft soil sites, so some conclusions and significance obtained are not lose generality[27–48].

The existing analytical or semi-analytical methods for seismic research of underground structures mostly aim at the linear characteristics of underground structures in elastic or viscoelastic media, mainly because the theoretical analysis cannot consider the impact of complex factors such as the strength and deformation nonlinearity of sites and underground structures, the contact nonlinearity of soil-structure interface, and the soil–water coupling (dynamic pore pressure) effect.

Quasi-static simplified method + numerical (or experimental) verification

Since the beginning of the twenty-first century, with the development of computer technology and software functions, the numerical analysis method of seismic dynamic calculation of underground structures has made rapid progress. As the analytical method is based on certain assumptions, the real validity of its solution remains to be verified by numerical calculation and model tests. In particular, after fully absorbing the advantages of the existing theoretically analytical methods, the quasi-static semi-analytical method, which effectively combines the analytical method with the numerical (or experimental) method, is one of the development directions of the practical seismic calculation method of underground structures[37,49–63].

Due to climatic conditions and sedimentary environments, the middle and lower reaches of the Yangtze River are widely distributed with floodplain soft soil. Due to the poor engineering properties of soft soil, it has brought many problems to the seismic design and construction of subway stations. A two-dimensional finite element model of soil structure interaction was established based on the ABAQUS. Nonlinear dynamic time history analysis method and underground structure Pushover analysis method were used to analyze the seismic resistance of subway stations in different soil stiffness layers Based on the results of nonlinear dynamic time history analysis, the influence of soil stiffness on the calculation accuracy of Pushover analysis method for underground structures was studied using peak inter story displacement angle and peak internal force[64]. To study the accuracy of simplified method for seismic analysis of underground structures under shallow bedrock conditions, the accuracy of the response acceleration method and the response spectrum method for the seismic analysis of underground structures under the conditions of homogeneous site and shallow bedrock site are compared and analyzed by taking the two storey two span and two storey three span subway station structures as examples[23]. The seismic resilience of underground structures is generally based on the results of the seismic fragility analysis and the damage of all the structural components comprehensively. Whereas, the seismic behavior of underground structures is greatly influenced by the vertical ground motions. Therefore, a new method was proposed to study the seismic fragility of underground structures subjected to both horizontal and vertical ground motions, and by considering the damage weight coefficients of the structural components to the overall structure. Pushover/pseudo-gravity analyses were conducted to determine the demand measures and seismic performance levels of all the structural components[65]. The seismic performances of underground structures with either transverse traditional rigid layout or sliding interior columns are numerically evaluated by pushover analyses; both the horizontal and vertical components of the seismic ground motion are taken into account[66].

The quasi-static simplified method is characterized by simplicity, easy mastering, small calculation workload and good calculation accuracy. Meanwhile, it can further consider the nonlinear behavior of strength and deformation of underground structures and the nonlinear behavior of interface contact. However, there is a lack of consideration of the impact of saturated porous media site coupling (effect) dynamic nonlinearity and other factors. The theoretical analysis method has limitations in considering the nonlinear effects of complex factors such as strength deformation of the site and underground structures, soil structure interface contact nonlinearity, and soil water coupling (dynamic pore pressure) effects. However, research can help to understand the failure modes of subway station structures in soft soil sites, and some conclusions and significance obtained from it are also general.

Model test method

Based on the difference in the gravity field environment of the structural system, the model test can be divided into the ordinary shaking table test (Fig. 2a) and the centrifuge shaking table test (Fig. 2b). The model test can better grasp the seismic response characteristics of underground structures and the dynamic interaction characteristics between the foundation and the underground structure, and the cost is relatively low, which supplements the insufficiency of prototype observation data to a certain extent.

Ordinary shaking table test

There are many ordinary shaking tables in China, which are the mainstream of experimental research on seismic problems of underground structures in soft soil sites. Scholars at home and abroad have carried out comprehensively studied on model similarity design, test material selection, and counterweight application in this field, and many mature research results have been achieved.

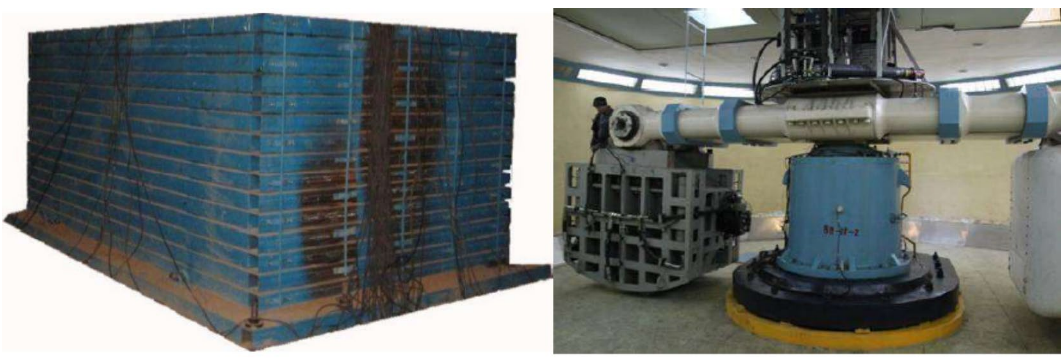
Yang, et al.[67,68] carried out the shaking table model test of railway stations in soft soil foundations in China for the first time, analyzed the seismic characteristics of the model structure under the action of ground motion, and then performed a numerical verification on the test results. In particular, the test puts forward effective solutions one by one for the form of the model box, the configuration of model soil, the determination of similarity ratio, the type selection and layout of sensors, etc., and summarizes them in detail. The research results and experience lay a solid foundation for the follow-up scholars to carry out the model test of underground structures in soft soil sites.

Some scholars have also compared the results of shaking table tests with the numerical simulation results or the (semi) analytical solutions of the analytical simplified method. The correctness of numerical simulation and analytical/simplified method was calibrated by shaking table tests[69–73]. The ordinary shaking table model test was carried out when there was a gravity acceleration of 1g. According to the similarity theory, the stress level caused by the self-weight of the soil is reduced by n times when the geotechnical structure is reduced by n times. Due to the strong nonlinearity of the soil, the soil parameters are correlated with the confining pressure. Therefore, the ordinary shaking table scale model test has a gravity distortion effect, and there are some differences between the test results and the real results. Although it is impossible for the ordinary shaking table test to completely simulate the real seismic response of the underground structures in the prototype sites, the test can not only qualitatively study the vibration law of the dynamic interaction system by controlling the ground motion characteristics, selecting the test materials and measuring the changes of various physical quantities in the vibration process, but also be used as an effective means of numerical verification[74–77].

The ordinary vibration table is tested under a gravitational acceleration of 1g. At present, in the field of seismic testing research on underground structures, ordinary vibration tables have a wider range of testing platforms and have gained rich and mature experience. Ordinary vibration table model testing is still the mainstream of seismic testing research on underground structures in soft soil sites. Although it is impossible to fully simulate the actual seismic response of the underground structure in the prototype site due to the gravity distortion effect of ordinary vibration table tests, and the test results may differ from the real results to some extent, the test can qualitatively study the vibration laws of the dynamic interaction system by controlling the seismic characteristics, selecting the test materials, and measuring the changes in various physical quantities during the vibration process. It can also be used as an effective means of verifying numerical simulation methods.

Centrifuge shaking table test

After the 1960s, the United States, Europe and Japan have successively established centrifugal equipment for model tests, and the geotechnical centrifuge equipment in China has gradually increased. In the ng gravity



(a) 1g (b) *n*g

Fig. 2. Shaking table test.

acceleration field provided by the centrifuge shaking table scale test, the stress state of any point is the same as that of the corresponding point in the prototype, so it can be considered that the displacement response, pore pressure response, failure mode and failure mechanism of the model are similar to those of the prototype. At present, centrifuges have been widely used in the study of soil-structure dynamic interaction, and many achievements have been made[78–92].

Currently, the research on centrifuge shaking table tests is mainly carried out on the seismic performance of underground structures in sandy soil foundations, and there are few experimental studies on the seismic response characteristics of underground structures in (saturated) soft soil foundations.

Although the centrifuge shaking table has outstanding advantages, due to the large cross-section size of the underground structures, it is difficult for the geometric similarity relationship design of the centrifuge shaking table to meet the requirements of the same stress level of the prototype and the model. Besides, using the centrifuge tests to study the soil-structure interaction of the site also involves complex factors such as soil particle size and permeability similarity, pore water viscosity similarity ratio, sensor layout, data test accuracy, gravity field effect, and softening soil fluidity along the centrifuge radius surface. In particular, silicone oil and other materials are commonly used to replace water in the test, but silicone oil only changes the permeability of soil in a limited range. However, when the centrifugal acceleration is large, it is difficult for silicone oil to be consistent with the real soil's permeability coefficient, and the use of silicone oil and other materials may change the soil's dynamic characteristics. As centrifuge shaking table equipment is very expensive, there are few in China. Currently, only a few units such as Tsinghua University, Zhejiang University, Tongji University, China Institute of Water Resources and Hydropower Research and Hong Kong University of Science and Technology have owned it. Meanwhile, the centrifuge shaking table has the Coriolis effect caused by the conversion of the inertial coordinate system and the rotating coordinate system, and it is not enough to install sufficient measuring equipment due to the limitation of the model ratio. In this way, it is difficult to embody the internal characteristics of the structure and the foundation soil.

However, it is very important to design and analyze the test for both ordinary shaking table tests and centrifuge vibration tests. If the dynamic principle is not properly understood, there will be serious error results.

Numerical analysis

The above analytical and quasi-static simplification methods are mainly applicable to linear viscoelastic problems, while the soft soil foundation and underground structure show obvious elastic–plastic strong nonlinear mechanical behavior under earthquake. At this time, the dynamic numerical simulation method can more truly simulate the dynamic nonlinear interaction of the underground structure-foundation system under earthquake action. With the rapid development of computational theory and hardware (software) conditions, numerical simulation technologies with lower cost than model tests are more and more applied to the study of the seismic performance of underground structures in soft soil sites. As shown in Fig. 3, the finite element calculation model of the soft soil foundation of the Hanshin earthquake Daikai Station is presented. As shown in Fig. 4, the finite element calculation model of the underground structure of the Daikai Station is presented[93,94].

Numerical analysis method of dynamic total stress

Some scholars have simplified the seismic resistance of underground structures into a plane assumption research[95–99].

It is necessary to consider the spatial effect of sites and structures to study the seismic response laws of underground structures and analyze the comprehensive influence of different ground motion fields for the underground structures under complex geological and topographic conditions or large underground space structures with complex forms. Meanwhile, it is also necessary to adopt the three-dimensional integral model of underground structures[100].

The above studies are carried out on the seismic performance of typical underground structures (subway tunnels/stations) in soft soil sites. With the development of rail transit and the maturity of subway construction technology, more and more subway lines are interspersed with each other, and the number of transfer stations is increasing. Meanwhile, the spatial cross structure of stations is becoming more and more common, so the inevitable trend of subway development in the future is the diversification of subway structures and the combination of spatial structures. Facing the current situation of large-scale construction of subway underground engineering, some scholars have also studied the ground motion response of composite underground structure systems[101–105].

As the displacement distribution of the intersection of the underground structure of the subway, which represents the future trend, is different from that of the surrounding area, it is more likely to produce large uneven deformation and significant interaction than the general underground structure, and the deformation

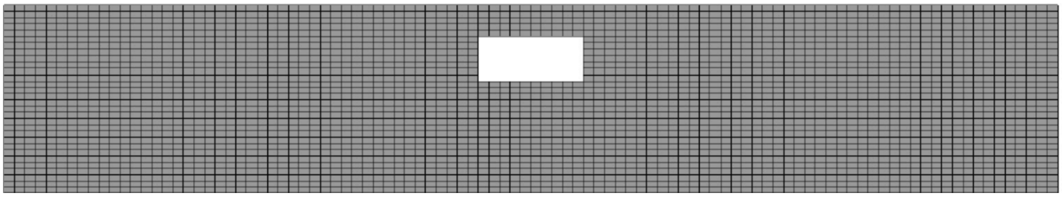


Fig. 3. Numerical calculation model.

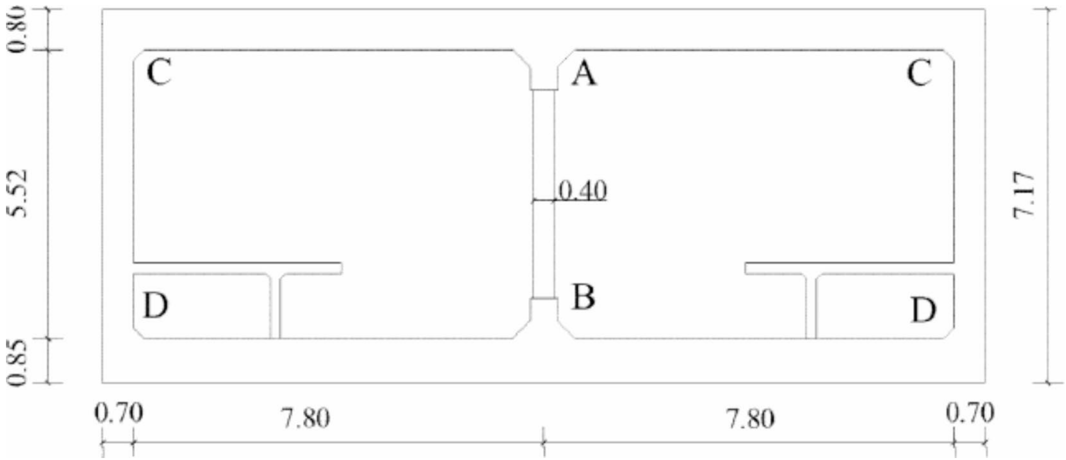


Fig. 4. Subway station structures.

and stress state are more complicated and the damage consequence is more serious. Moreover, the transverse shear deformation caused by seismic waves in one tunnel will cause another tunnel to be in a complex stress state of longitudinal tension and compression or bending and even cause the two to be separated. In particular, the cross-close structure changes the site conditions of the existing subway tunnel, and there is an inevitable interaction between the tunnels, which will significantly affect the seismic response characteristics of the existing tunnel[106–115].

Since the twenty-first century, with the rapid development of economy, national defense and other undertakings, more and more large-span and large section underground space structures have emerged, and such projects are gradually developing towards ultra long spans. Conducting seismic response analysis of ultra large span underground space structures is of great significance. For large-span underground structures, due to the significant traveling wave effect, partial coherence effect, attenuation effect, and local site effect caused by seismic waves in the process of propagation and incidence to structures, the earthquake motion has obvious differences in spatial distribution. If the consistent seismic input is still used, there will be obvious differences in the actual situation. Therefore, the seismic response analysis of large-scale structures also needs to consider the spatial non-uniform characteristics. In this way, the seismic response analysis of large-span underground structures considering non-uniform excitation input is more in line with the actual situation and more reasonable, and scholars have also carried out relevant studies in this field[116–130].

Currently, most dynamic constitutive models are established in the framework of continuum mechanics, so they are constrained by the assumption of continuum mechanics that does not conform to the actual structure of the soil. To deeply understand the seismic mechanical response mechanism of underground structures in soft soil sites, there have been many studies on the dynamic response indexes such as internal force, deformation and displacement of underground structures under seismic excitation. It is known that the underground structure system in soft soil sites may have a large deformation under seismic excitation, and at this time, the theory based on the small deformation assumption is no longer applicable. Therefore, it is necessary to study the interaction between the foundation and the underground structure by employing numerical calculation under a large deformation assumption or multi-element mixed (coupling) method[131,132].

The numerical solution method of dynamic total stress is extensively used in the seismic field of underground structures in soft soil sites in diversified forms. The dynamic total stress analysis method can consider the nonlinearity and hysteresis characteristics of the soil, but it cannot consider the growth, diffusion and dissipation process of the excess pore pressure during the vibration process as well as its impact on the dynamic stress–strain characteristics of the soil. Therefore, the excess pore pressure generated during the vibration process and the permanent deformation after the dissipation of the excess pore pressure cannot be directly obtained. Compared with the quasi-static simplified method, the dynamic total stress calculation method can further consider the inertial effect of the underground structure interaction system, the nonlinearity of dynamic strength and deformation, as well as the nonlinear behavior of the soil-structure contact interface in complex condition sites, but it cannot take into account the impact of the coupling effect of soil skeleton and pore water on the mechanical behavior of large deformation seismic damage in saturated porous media sites. Currently, the research on the dynamic problem of single-phase medium is relatively mature. For saturated soil, the problem becomes more complicated due to the coupling effect of soil skeleton and pore water. However, after several years of efforts, people have made some progress in the study of saturated soil dynamics and proposed corresponding analysis methods for different geotechnical dynamic problems[133–139].

Numerical analysis method of dynamic effective stress

Under the action of seismic excitation, there is a strong coupling between soil particles and water in soft soil layers, and the excess pore pressure is higher due to the lack of drainage, which reduces the force between soil particles and degrades the stiffness of soil, eventually resulting in soil softening and strength degradation. As the numerical solution method of dynamic total stress cannot take into account the impact of the distribution change of dynamic excess pore water pressure and the foundation soil is a porous medium, the coupling effect of pore water and soil skeleton stress and deformation should be further considered in the seismic dynamic response analysis of underground structures in saturated sites. The fluid–solid coupling two-phase medium dynamic model considers the coupling relationship between solid phase and fluid dynamic response in saturated soil, which is a relatively perfect calculation model in terms of strength. Therefore, the method based on the fluid–solid coupling two-phase medium dynamic model has a solid theoretical foundation and is a more accurate calculation and analysis method. The dynamic effective stress analysis method can be divided into simplified decoupled effective stress (quasi-effective stress) and real effective stress method based on fluid–solid coupling two-phase medium dynamic model. At present, there is no deep research on the dynamic problem of underground structures in saturated soil based on the dynamic model of fluid–solid coupling two-phase medium.

(1) Quasi-effective stress method.

The quasi-effective stress analysis method quantitatively solves the generation, diffusion or dissipation process of pore pressure through coupling of the pore pressure development model under dynamic load under undrained conditions and Terzaghi consolidation theory or Biot consolidation theory based on the equivalent linear dynamic response analysis.

The existing dynamic numerical analysis is mostly performed by the decoupling effective stress solution method based on the pore pressure mode, and the constitutive model employed is mainly the viscoelastic model and the static Mohr–Coulomb elastoplastic constitutive model. The dynamic viscoelastic constitutive model has some limitations when considering the impact of dynamic residual deformation in applying the soft soil's large deformation. Meanwhile, the Mohr–Coulomb constitutive model also has inherent defects and deficiencies in reasonably reflecting the dynamic deformation behavior of soil under cyclic loading. The decoupled effective stress dynamic calculation method carries out the "coupling of "pore pressure" based on the pore pressure stress model or the pore pressure strain model. The pore pressure stress model is established basd on the constant amplitude stress condition in the laboratory, while the site stress condition is more complex and can neither solve the shape residual deformation under undrained conditions nor reflect the reverse shear shrinkage characteristics of the soil. The pore pressure strain model solves the contradictions in the pore pressure stress model to a certain extent, but in principle, it is only suitable for the soil in the static compression state and the dynamic shear or pure shear state but cannot describe the real change mechanism. In this way, the decoupled effective stress dynamic calculation method based on the pore pressure model has some limitations when describing the coupled stress and deformation characteristics of pore water and soil skeletons under complex stress states. The fully coupled real effective stress dynamic numerical solution method can better reflect the coupled stress and deformation behavior of soil skeleton and pore water under dynamic cyclic loading[140].

(2) Coupled effective stress method.

On this basis, Zienkiewicz et al. established a real effective stress dynamic calculation method that can couple the diffusion and dissipation of pore water pressure with the dynamic reflection analysis by combining the dynamic Biot theory. In the framework of the dynamic consolidation equation, the generation, dissipation and diffusion of pore pressure are completely coupled with the deformation of the soil. The fully coupled analysis methods, represented by Biot's dynamic consolidation theory, can consider the nonlinear, large deformation and elastic–plastic behavior of soil skeletons. The fully coupled numerical method based on the dynamic consolidation equation is the current mainstream and development direction, and many scholars have developed fully coupled dynamic calculation programs according to the needs and successfully applied them to solve the dynamic problems caused by earthquakes[95,96,141,142].

The fully coupled effective stress dynamic numerical analysis method can better describe the coupled stress deformation behavior of soil skeleton and pore water in saturated soil under dynamic cyclic loading. It is a relatively complete calculation model in terms of strength and an accurate calculation method. Compared with the dynamic total stress analysis and the decoupled effective stress dynamic analysis method based on pore pressure mode, due to the complexity of numerical implementation and solution, it is less applied in seismic research of underground structures in soft soil sites.

However, due to the complexity of the seismic research of underground structures, until now, there has been no means that can fully explain the dynamic response mechanism of underground structures in soft soil sites. Usually, the actual phenomenon is partially or qualitatively reproduced by the model test, and the physical mechanism can be explained, the change process can be inferred, the characteristic law can be summarized, and the disaster consequences can be analyzed. On this basis, a reasonable mathematical analysis model that can reflect the actual soil-structure dynamic interaction law is established, forming the corresponding numerical analysis method, which is then compared with the model test or prototype observation results. Later, the different seismic design schemes are calculated and analyzed to reproduce and simulate the actual dynamic response as much as possible, study the seismic performance, and further put forward the corresponding seismic countermeasures. This is a reasonable and effective way to study and evaluate the seismic performance of underground structures.

Dynamic reliability evaluation method and prefabricated underground structure

The dynamic reliability of underground structures refers to the probability that the underground structures complete the predetermined function within the specified conditions and time under the action of random dynamic load. Seismic excitation is an accidental random load, and it is an inevitable trend to adopt the reliability optimization method in the seismic design of underground structures. As we know, due to the characteristics of earthquake source and wave propagation, the complexity of engineering geological conditions, the variability of underground structure resistance, and the error of response analysis model, there are more uncertain factors in the dynamic stability analysis and design of underground structure system than that of ground structure, making the dynamic reliability analysis of the engineering more difficult. Therefore, it can only be described by the probability that the underground structure may be in a certain state[143–151]. Using theoretical analysis, numerical simulation and model tests, many scholars both at home and abroad have studied the seismic performance of subway station structures and achieved many valuable scientific research results. While acquiring the dynamic response characteristics of subway station structures, at present, how to evaluate the dynamic reliability of subway station structures under earthquakes is a difficult problem when studying subway stations[152–156].

Dynamic reliability is one of the complex problems in reliability theory, which will become completely complicated especially when considering both the randomness of seismic load and the randomness of structural material parameters. In particular, for complex geotechnical engineering structures, it is often difficult to write an explicit expression of the performance function, and there is a large workload when directly using the Monte Carlo method for numerical simulation. Generally, the dynamic reliability problem can be studied by the frequency domain analysis method and time domain analysis method, but the research in the time domain is more complicated than that in the frequency domain. The frequency domain analysis method for earthquake vulnerability analysis is to establish a frequency domain transfer function for controlling multi degree of freedom systems through the concept of substructures, which is used to evaluate the overall seismic performance of multi degree of freedom systems. Seismic resistant system for underground structures on soft soil foundation are established based on the finite element platform. The frequency domain method in elastic half-space theory is used to obtain ground motion rotation through three-way translational ground motion components. The incremental dynamic analysis of near-field and multi-dimensional ground motions is performed on the example, and the probabilistic seismic demand analysis method is used to draw the seismic vulnerability curves. When taking into account the randomness of structural materials, if the stochastic finite element is simply used in the time domain, the structure will diverge after one cycle, and the degree of divergence becomes more and more serious with time. The study of analyzing and calculating the random dynamic response of multi-degree-of-freedom large-scale structures in the time domain is still in the exploratory stage in the world[157–163].

The lifecycle of tunnel structures includes construction phase, usage phase, and aging phase. Numerous theoretical studies and engineering practices have shown that the reliability of engineering structures is relatively low during the construction and aging stages throughout their entire lifecycle. At present, the research on reliability of both ground and underground structures mainly focuses on the usage stage of the structure. The combination of BIM technology and GIS technology, which has been rapidly promoted in recent years, has become the application trend of urban underground structures. BIM + GIS technology can play a dynamic simulation and decision support role in underground structures, and has an irreplaceable role in resource sharing, monitoring and management. Therefore, its application in the field of underground structures has been increasing year by year. The collaborative application of BIM + GIS technology can integrate comprehensive professional models throughout the entire lifecycle of pipe galleries, and use them as a carrier to correlate multidimensional information such as cost, quality, contract, and schedule at different stages of pipe galleries, providing comprehensive data support for pipe gallery projects, achieving the goals of deepening design, optimizing progress, and reducing construction changes. The collaborative application of BIM + GIS and other new technologies has broad prospects in future engineering, which will inevitably promote China's construction industry to enter a more intelligent era[164–168].

With the deep popularization and development of the Internet and the deep integration with mobile communication technology, the application mode of BIM and GIS technology will be completely changed, and various concepts such as "GIS sharing and switching cloud platform" and "BIM + " will emerge. The deep integration of these emerging technologies will enable convenient and rapid information exchange between macro and micro fields, and bring new opportunities for the development of various industries.

.In the past two decades, many scholars have systematically studied the seismic performance of general cast-in-place concrete underground structures using different research methods from different perspectives. They have basically explored the seismic response law and seismic damage mechanism of such underground structures, providing important scientific basis and practical analysis methods for the seismic design of underground structures at present. Prefabricated underground structures adopt modular design and production, which can ensure construction quality and reduce environmental pollution, and have incomparable advantages over traditional cast-in-place stations. At present, the seismic research on prefabricated underground structures is still in its infancy, and there are no relevant specifications for seismic design of prefabricated tunnels. There is insufficient systematic research on their seismic design and analysis. However, ensuring the seismic safety of the structure helps to save social resources, protect the ecological environment, and meets the strategic requirements of contemporary sustainable development[169–186].

Urban subway stations are typical representatives of large-scale underground engineering. Since 2012, Changchun Metro Line 2 has been the first to carry out research and application of prefabricated construction technology for open cut subway stations, paving the way for the construction of prefabricated subway stations. As of now, Changchun Metro has successfully built 8 prefabricated stations, and 10 more are under construction. The successful construction of prefabricated subway stations in Changchun has played a good demonstration role. According to preliminary statistics, as of now, 9 cities in China, including Changchun, Beijing, Jinan, Shanghai, Guangzhou, Harbin, Qingdao, Shenzhen, and Wuxi, have conducted research and application of prefabricated station construction technology from different perspectives, with nearly 40 stations implemented.

Prefabricated subway stations have grown from scratch, from a single construction mode to the coexistence of multiple modes, forming a cluster of nearly 40 prefabricated station constructions in China. The construction technology of prefabricated stations is gradually moving towards an industrialized construction concept and mode centered on design standardization, factory production, construction machinery automation, and management informatization.

Conclusion

In summary, the seismic research of underground structures in soft soil sites has developed from linear to nonlinear, from frequency domain to time domain, from quasi-static to time history analysis, from two-dimensional to three-dimensional, from single structure to complex composite structure system, from total stress to effective stress, from continuous medium to discontinuous medium and failure theory, from single theory to hybrid method, as well as from the arisen dynamic reliability evaluation method to the life cycle design method.

Currently, the research on the seismic response of underground structures in soft soil sites is still in the preliminary stage. The existing studies roughly consider the dynamic characteristics of the soil and don't systematically study the seismic performance of underground structures under complex soft site conditions. The relevant research results are far from enough to guide the comparison and selection of engineering schemes and seismic design of underground structures in complex soft sites. Therefore, the author suggests that the following aspects should be emphasized to study the frontiers of disciplines and key scientific and technological research issues.

(1) It is worthy of studying the consolidation time effect of underground structures in soft soil foundations after earthquakes. Under the action of earthquakes, the generation of excess pore pressure in the soil results in the destruction of some soil skeletons, and the shear strength and stiffness of the softened soil are reduced, which weakens the overall strength and stiffness of the soil. After the earthquake, the stress in the soil is redistributed, and the pore water pressure is also redistributed, which finally makes more soil softened. After the soil is softened, the shear strength and stiffness will decrease, which will affect the internal force and deformation of the underground structure of the subway. After the earthquake, the saturated soft soil will produce consolidation deformation due to the dissipation of excess pore water pressure in the soil, which will further destroy the engineering structure located in the soft soil site. The pore water pressure of saturated soft soil foundation dissipates after the post-earthquake consolidation seismic action stops. The dissipation of pore water pressure will be accompanied by the volume compression deformation of the soil, and the redistribution of pore water pressure in the site may still cause damage to the soil.

(2) It is more urgent to study the seismic response characteristics of underground cross structures close to subways, which is not only of great theoretical value and practical significance but also an urgent problem to be solved in the seismic research and design of subways. In the limited urban underground space, the construction of necessary projects such as urban underground transportation networks and underground pipelines will inevitably increase the engineering amount of underground structures crossing each other, and the spatial staggered structure between tunnels and stations, between tunnels, and between stations will become more and more common. For subway transfer stations or transportation hubs, coupled with the connection channels between each other, the subway station structure forms such as wide column spacing, large span and special-shaped columns will appear in future subway stations to constitute an intricate and interactive underground space structure. The traditional design method of subway crossing is to retain 2–10 m interlayer soil between the two tunnels to reduce the deformation of the upper tunnel, but this method produces very large structural deformation, so it can no longer meet the development needs of subways. However, at present, there is no clear seismic response of subway structures under the condition of spatial intersection and interaction between the upper and lower structures, which cannot guide the seismic design.

(3) How to reproduce the interaction response between these complex foundations and underground structures in the shaking table test is a key issue in the vibration model test of large-span underground structures. Currently, the test is still challenging due to some factors such as the oblique incidence of earthquake motion and complex geological conditions. However, numerical simulation and theoretical analysis can be employed to systematically analyze the dynamic response of underground structures considering single-point, multi-point and non-uniform earthquake motion input as well as complex geological conditions. At present, most of the shaking table tests treat foundation soils simply and do not reproduce the interaction between complex foundations and structures, especially the actual complex foundation conditions such as faults, soft soil interlayers, and uneven-layered foundations, which are often encountered in practical engineering.

(4) Most of the previous studies have focused on the seismic performance of underground structures in soft soil sites, while there are few studies concentrate on its mechanism. Based on the shaking table test, the damage degree, state and mechanism of underground structures in horizontal soft soil sites under strong earthquakes are reproduced. Further, through combining numerical simulation with tests, some important understandings of the main characteristics, basic process, mechanism and general laws of the dynamic characteristics of foundation-structure under strong earthquakes are acquired, which can not only accumulate data for the numerical platform of future shaking table test and finally make technical preparations for the application of the shaking table test to the actual site, but also provide a reliable basis for the seismic design of underground structures in horizontal soft soil sites and is of great significance to ensure the seismic stability and safety of underground structures in soft soil sites.

(5) However, there are still many problems that need to be solved urgently. The construction technology of prefabricated stations in China has just begun, the technical system needs to be improved, and the technical standards need to be formed; The technical route and engineering plan need to be decided according to the characteristics of underground engineering and tailored to local conditions; In terms of improving standardization and industrialization, increasing structural assembly rate, developing high-end construction equipment, enhancing construction efficiency and social benefits, the advantages of prefabricated assembly

construction technology should be fully utilized. Moreover, the cost of prefabricated subway stations is relatively high, and it is necessary to effectively reduce the project cost through reducing some taxes and fees, optimizing technical solutions and engineering design, maximizing the number of engineering applications, and reducing cost amortization fees. Although the government is actively advocating for the assembly of buildings, we are all aware that the process of assembly still needs to overcome many obstacles and barriers, including traditional concepts, extensive construction models, construction costs, new issues, and new talents. In short, the development of prefabricated assembly technology has a long way to go and requires the entire industry and society to face it together and continuously strive and contribute to it.

Studying and resolving the above issues have great scientific significance and engineering application value for improving the seismic theoretical analysis method and experimental research technology of underground structures in soft soil sites and obtaining the seismic response law and disaster mechanism and failure mode and mechanism of large underground structures in soft soil sites.

Data availability
The data used to support the findings of this study are available from the corresponding author upon request.

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References
1. Argyroudis, S. A. & Pitilakis, K. D. Seismic fragility curves of shallow tunnels in alluvial deposits. *Soil Dyn. Earthq. Eng.* **35**, 1–12 (2011).
2. Vanuvamalai, A., Jaya, K. P. & Balachandran, V. Seismic performance of tunnel structures: A case study. *Natl. Hazards* **93**(1), 453–468 (2018).
3. Amandi, K. U., Diemuodeke, E. O. & Briggs, T. A. Model for remaining strength estimation of a corroded pipeline with interacting defects for oil and gas operations. *Cogent Eng.* **6**(1), 1–9 (2019).
4. Xu, Z. *et al.* Numerical research on seismic response characteristics of shallow buried rectangular underground structure. *Soil Dyn. Earthq. Eng.* **116**, 242–252 (2019).
5. Zheng, G. *et al.* Resilient evaluation and control of geotechnical and underground engineering structures. *Chin. Civil Eng. J.* **55**(7), 1–38 (2022).
6. Arumugam, T., Karuppanan, S. & Ovinis, M. Finite element analyses of corroded pipeline with single defect subjected to internal pressure and axial compressive stress. *Mar. Struct.* **72**(C), 1–21 (2020).
7. Zhu, T., Wang, R. & Zhang, J. M. Effect of nearby ground structures on the seismic response of underground structures in saturated sand. *Soil Dyn. Earthq. Eng.* **146**, 106756 (2021).
8. Du, X. *et al.* Collapse simulation and failure mechanism analysis of the Daikai subway station under seismic loads. *Chin. Civil Eng. J.* **50**(1), 53–63 (2017).
9. Du, X. *et al.* Review on damage causes and disaster mechanism of Daikai subway station during 1995 Osaka-Kobe Earthquake. *Chin. J. Geotech. Eng.* **40**(2), 223–236 (2018).
10. Du, X. *et al.* Research status and prospects of quasi-static test for seismic research of underground structures. *J. Disaster Prev. Mitig. Eng.* **41**(4), 850–859 (2021).
11. Liu, J., Wang, D. & Bao, X. Longitudinal integral response deformation method for the seismic analysis of a tunnel structure. *Earthq. Eng. Eng. Vib.* **20**(4), 887–904 (2021).
12. Wang, Y., Zhang, P. & Qin, G. Reliability assessment of pitting corrosion of pipeline under spatiotemporal earthquake including spatial-dependent corrosion growth. *Process Saf. Environ. Prot.* **148**, 166–178 (2021).
13. Terzic, V. & Villanueva, P. K. Method for probabilistic evaluation of post-earthquake functionality of building systems. *Eng. Struct.* **241**, 112370 (2021).
14. Mohsen, A. & Reza, B. M. A new approach for finite element based reliability evaluation of offshore corroded pipelines. *Int. J. Press. Vessels Pip.* **193**, 1–13 (2021).
15. Salado, C., Bruneau, M. & Elhami-khorasanin, N. Functionality measures for quantification of building seismic resilience index. *Eng. Struct.* **253**, 113800 (2022).
16. Lu, D. *et al.* Earthquake resilience of urban underground structures: state of the art. *Sci. Sin. (Technol.).* **52**(10), 1469–1483 (2021).
17. Zhao, G. *et al.* Probabilistic seismic demand models for circular tunnels subjected to transversal seismic load. *Tunn. Undergr. Space Technol.* **125**, 104527 (2022).
18. Zhang, G. *et al.* Seismic intensity measures and fragility analysis for subway stations subjected to near-fault ground motions with velocity pulses. *J. Earthq. Eng.* **26**(16), 8724–8750 (2022).
19. Zhong, Z. *et al.* Seismic performance evaluation of two-story and three-span subway station in different engineering sites. *J. Earthq. Eng.* **26**(14), 7505–7535 (2022).
20. Zhuang, H. *et al.* Review and Prospect of Earthquake Resistance and Seismic Isolation of Underground Structures. *Technol. Earthq. Disaster Prev.* **18**(1), 1–12 (2023).
21. Hang, X. *et al.* New progress in seismic resilience assessment of urban structures. *World Earthq. Eng.* **40**(1), 34–48 (2024).
22. Zhu, J. *Research on Methods for Seismic Analysis of Underground Structures in Saturated Soft Soil* (Tianjin University, 2019).
23. Shi, W., Wang, R. & Wang, Q. Research review of the response displacement method for aseismic design of underground structures. *Sci. Technol. Eng.* **24**(1), 61–71 (2024).
24. Han, J. *et al.* Seismic vulnerability assessment of buried corroded steel pipes under different site conditions. *Chin. J. Geotech. Eng.* **46**(4), 774–783 (2024).
25. Yu, H. *et al.* Damage observation and assessment of the Longxi Tunnel during the Wenchuan Earthquake. *Tunn. Undergr. Space Technol.* **54**, 102–116 (2016).
26. Mayoral, J. M., Argyroudis, S. & Castañon, E. Vulnerability of floating tunnel shafts for increasing earthquake loading. *Soil Dyn. Earthq. Eng.* **80**, 1–10 (2016).
27. Debiasi, E., Gajo, A. & Zonta, D. On the seismic response of shallow-buried rectangular structures. *Tunn. Undergr. Space Technol.* **38**, 99–113 (2013).
28. Kouretzis, G. P. *et al.* Analysis of circular tunnels due to seismic P-wave propagation, with emphasis on unreinforced concrete liners. *Comput. Geotech.* **55**, 187–194 (2014).
29. Liu, S. & Yang, B. A closed-form analytical solution method for vibration analysis of elastically connected double-beam systems. *Compos. Struct.* **212**, 598–608 (2019).
30. Zhang, J. *et al.* Analytical solutions for seismic responses of the tunnel in a shafttunnel junction under transverse excitations. *Soil Dyn. Earthq. Eng.* **127**, 105826 (2019).

31. Zhang, J. *et al.* Analytical solution for dynamic responses of the vertical shaft in a shaft-tunnel junction under transverse loads. *Soil Dyn. Earthq. Eng.* **126**, 105779 (2019).
32. Zhang, B. & Chen, Z. Effects of nominal flexibility ratio and shaft dimensionless parameters on the seismic response characteristics of deep shafts. *Soil Dyn. Earthq. Eng.* **120**, 257–261 (2019).
33. Zhang, B. & Chen, Z. General winkler model for kinematic responses of shafts in linear soil. *Int. J. Comput. Methods* **17**(5), 1940004 (2020).
34. Wang, X. *et al.* Seismic response of tunnel lining structure in a thick expansive soil stratum. *Tunn. Undergr. Space Technol.* **88**, 250–259 (2019).
35. Zhao, M. *et al.* Numerical Validation of siplified analytical method for seismic response of circular tunnels. *Eng. Mech.* **37**(9), 84–93 (2020).
36. Dai, D. *et al.* Kinematic response of an end-bearing pile subjected to vertical P-wave considering the three-dimensional waves cattering. *Comput. Geotech.* **120**(7), 103368 (2020).
37. Kim, Y., Lim, H. & Jeong, S. Seismic response of vertical shafts in multi-layered soil using dynamic and pseudo-static analyses. *Geomech. Eng.* **21**(3), 269–277 (2020).
38. Yu, H., Wang, Q. & Liu, T. Analytical solution for longitudinal seismic response of long tunnels in homogeneous stratum. *Hazard Control Tunn. Undergr. Eng.* **2**(1), 34–41 (2020).
39. Yu, H. & Chen, G. Analytical solution for seismic response of deep tunnels with arbitrary cross-section shapes. *Chin. J. Geotech. Eng.* **43**(7), 1331–1337 (2021).
40. Zhong, Z. *et al.* Structural damage assessment of mountain tunnels in fault fracture zone subjected to multiples trike-slip fault movement. *Tunn. Undergr. Space Technol.* **104**, 103527 (2020).
41. Yang, B., Chen, J. & Xiao, M. Seismic response and damage mechanism of lining structures for underground tunnels across fault. *Chin. J. Geotech. Eng.* **42**(11), 2078–2087 (2020).
42. Dong, R. *et al.* Seismic deformation mode transformation of rectangular underground structure caused by component failure. *Tunn. Undergr. Space Technol.* **98**, 103–298 (2020).
43. Zhang, J. *et al.* Analytical solutions for seismic responses of shaft-tunnel junction under longitudinal excitations. *Soil Dyn. Earthq. Eng.* **131**, 106033 (2020).
44. Zhang, J. *et al.* Analytical solutions for seismic responses of shaft tunnel junction under travelling SH-wave. *Tunn. Undergr. Space Technol.* **112**, 103910 (2021).
45. Guerra, C., Labaki, J. & Barros, P. Dynamic response of large diameter, concrete-line dvertical shafts under external and seismi cexcitation. *Int. J. Numer. Anal. Methods Geomech.* **8**, 46 (2022).
46. Zhao, M. *et al.* Analytical solution for water-pile-soil interaction under horizontal dynamic loads on pile head. *Chin. J. Geotech. Eng.* **44**(5), 907–915 (2022).
47. Zhao, M. *et al.* Analytical solutions for circular composite-lined tunnels under obliquely incident seismic SV and P waves. *Comput. Geotech.* **151**, 104939 (2022).
48. Zhang, B. *et al.* Analytical solution of vertical seismic response of primary lining and secondary lining of shaft structure. *J. Xi'an Univ. Archit. Technol. (Nat. Sci. Ed.)* **55**(2), 196–204 (2023).
49. Wang, P. *et al.* Analytical solution for water-pile-soil interaction system under SV waves considering elastic half-space of soil. *Chin. J. Geotech. Eng.* **45**(11), 2248–2257 (2023).
50. Dianeva, P., Wuttke, F. & Manolis, G. Elastic wave scattering and stress concentration effects in non-homogeneous poroelastic geological media with discontinuities. *Soil Dyn. Earthq. Eng.* **41**, 102–118 (2012).
51. Do, N. A. *et al.* 2D numerical investigation of segmental tunnel lining under seismic loading. *Soil Dyn. Earthq. Eng.* **72**, 66–76 (2015).
52. Chen, Z., Li, W. & Yang, L. Simplified seismic design method for Shanghai underground structures in soft soil. *Indian Geotech. J.* **44**(2), 149–155 (2014).
53. Kumar, J. & Sahoo, J. P. Stability of a circular tunnel in presence of pseudostatic seismic body forces. *Tunn. Undergr. Space Technol.* **42**, 264–276 (2014).
54. Song, E. & Li, P. Three-dimensional numerical analysis for the longitudinal seismic response of tunnels under an asynchronous wave input. *Comput Geotech.* **63**, 229–243 (2015).
55. Chen, Z., Liu, W. & Chen, W. Performance experiment of a multi-story subway station. *J. Tongji Univ. (Nat. Sci.)* **48**(6), 811–820 (2020).
56. Ko, Y. Y. & Chen, C. H. On the variation of mechanical properties of saturated sand during liquefaction observed in shaking table tests. *Soil Dyn. Earthq. Eng.* **129**, 105946 (2020).
57. He, C. & Geng, P. Research on practical seismic analysis methods of shield tunnel. *China J. Highw. Transp.* **33**(12), 15–25 (2020).
58. Xu, K. *et al.* Experimental study on coefficient value of subgrade reaction in seismic analysis of underground structures. *J. Southwest Jiaotong Univ.* **56**(5), 1035–1042 (2021).
59. Xu, Z. *et al.* Research on seismic damage of Dakai station and tunnel based on quasi-static pushover analysis. *Chin. J. Geotech. Eng.* **43**(7), 1182–1191 (2021).
60. Jiang, J. *et al.* improved pushover method for seismic analysis of shallow buried underground rectangular frame structure. *Soil Dyn. Earthq. Eng.* **140**, 106–363 (2021).
61. Huang, J. *et al.* Simplified analytical solution for circular tunnel under obliquely incident SV wave. *Soil Dyn. Earthq. Eng.* **140**, 106–429 (2021).
62. Dong, Z. *et al.* study on seismic resilience quantitative framework of subway stations and resilience improvement strategy. *Front. Earth Sci.* **10**, 869–965 (2022).
63. Cheng, X. *et al.* Seismic performance and damping measures of shear keys for immersed tunnel joints. *J. Southwest Jiaotong Univ.* **57**(6), 1208–1216 (2022).
64. Cheng, X. *et al.* A method for calculating subgrade reaction coefficient and itsapplication in reaction displacement method. *Chin. J. Ceotech. Eng.* **45**(12), 2604–2613 (2023).
65. Yao, R. *et al.* Pushover method based seismic analysis for subway station built in the floodplain soft soil areap. *Technol. Earthq. Disaster Prev.* **18**(3), 614–619 (2023).
66. Zhao, M. *et al.* Study on the accuracy of simplified method for seismic analysis of underground structures under the condition of shallow bedrock site. *Technol. Earthq. Disaster Prev.* **18**(1), 13–19 (2023).
67. Ma, C. *et al.* Seismic fragility analysis of underground structures subjected to bi-directional ground motions based on the damage weight coefficients of components. *Soil Dyn. Earthq. Eng.* **178**(3), 1–14 (2024).
68. Bu, X., Xu, Z. & Lopez-Almansa, L. F. Seismic target drifts for underground railway stations. Cases of traditional rigid connections and sliding interior columns. *Tunn. Undergr. Space Technol.* **144**(2), 105555.1-105555.17 (2024).
69. Yang, L. *et al.* Shaking table test on metro station structures in soft soil. *Modern Tunn. Technol.* **40**(1), 7–11 (2003).
70. Yang, L. *et al.* Shaking table test on metro station structure and 3D numerical simulation of seismic response. *Chin. J. Rock Mech. Eng.* **26**(8), 1538–1545 (2007).
71. Yuan, Y., Huang, W. & Yu, H. Status of model container applications in shaking table test for underground structures. *Struct. Eng.* **30**(1), 38–45 (2014).
72. Chen, G. *et al.* shaking-table tests and numerical simulations on a subway structure in soft soil. *Soil Dyn. Earthq. Eng.* **76**, 13–28 (2015).

73. Yue, C., Zheng, Y. & Deng, S. Shaking table test study on seismic performance improvement for under-ground structures with center column enhancement. *J. Earthq. Tsunami* **13**(2), 1950009 (2019).
74. Chen, Z., Huang, P. & Chen, W. Seismic response characteristics of multi-story subway station through shaking table test. *Adv. Struct. Eng.* **24**(10), 136943322199329 (2021).
75. Han, J. *et al.* Longitudinal response of buried pipeline under non-uniform seismic excitation from multi-point shaking table tests. *Soil Dyn. Earthq. Eng.* **140**(2), 106440 (2021).
76. Cheng, X. *et al.* Shaking table test and numerical verification for free ground seismic response of saturated soft soil. *Math. Probl. Eng.* **2018**, 3416315 (2018).
77. Xu, C. *et al.* Study on solid-ligquid phase transition characteristics of saturated sand based on large shaking table test on free field. *Rock Soil Mech.* **41**(7), 2189–2198 (2020).
78. Chen, S. *et al.* Experimental investigation of the seismic response of shallow-buried subway station in liquefied soil. *Soil Dyn. Earthq. Eng.* **136**, 106–153 (2020).
79. Yu, Z. *et al.* Shaking table tests for cross subway station structure. *J. Vib. Shock* **40**(9), 142–151 (2021).
80. Chen, Z. & Shen, H. Dynamic centrifuge tests on isolation mechanism of tunnels subjected to seismic shaking. *Tunn. Undergr. Space Technol.* **42**, 66–77 (2014).
81. Baziar, M. H. *et al.* Effect of underground tunnel on the ground surface acceleration. *Tunn. Undergr. Space Technol.* **44**, 10–22 (2014).
82. Wang, J. *et al.* Centrifuge model study on the seismic responses of shield tunnel. *Tunn. Undergr. Space Technol.* **92**, 103036 (2019).
83. Xu, C. *et al.* validation of a numerical model based on dynamic centrifuge tests and studies on the earthquake damage mechanism of underground frame structures. *Tunn. Undergr. Space Technol.* **104**, 103–538 (2020).
84. Xu, C. *et al.* Seismic response and failure mechanism of underground frame structures based on dynamic centrifuge tests. *Earthq. Eng. Struct. Dyn.* **50**(7), 2031–2048 (2021).
85. Xu, C. *et al.* The influences of different deformation capacity of structure roof and middle columns on earthquake damage responses of subway station structure. *J. Build. Struct.* **43**(4), 26–35 (2022).
86. Qu, S., Chen, Y. & Lv, Y. Centrifuge shaking table tests on a friction pendulum bearing isolated structure with a pile foundation in soft soil. *Earthq. Struct. Int. J. Earthq. Eng. Earthq. Eff. Struct.* **23**(6), 517–526 (2022).
87. Liang, W. *et al.* Nonlinear numerical simulation of dynamic response of pile site and pile foundation under earthquake. *Nonlinear Eng.* **11**, 485–493 (2022).
88. Yan, Z. *et al.* Centrifugal experimental study on seismic response of bridge pile group foundation in saturated sand field overlain by water. *Rock Soil Mech.* **44**(3), 861–872 (2023).
89. Zhuang, H. *et al.* Quasi-static model test and numerical simulation of a single-story double-span underground subway station. *Soil Dyn. Earthq. Eng.* **173**(10), 108099.1-108099.17 (2023).
90. Yan, G. *et al.* Centrifuge shaking table tests on a subway station structure in liquefiable interlayer site. *Acta Geotech.* **19**(4), 1687–1706 (2023).
91. Fan, C. *et al.* Centrifuge shaking table tests on tiered reinforced soil retaining walls subjected to the excitations of near-field ground motions. *Geotext. Geomembr.* **52**(4), 343–354 (2024).
92. Cui, Z., Sui, T. & Yuan, W. Seismic response of subway station subjected to mainshock-aftershock sequences by centrifuge shaking table tests. *Soil Dyn. Earthq. Eng.* **176**(2), 1083271–10832716 (2024).
93. Wang, X., Xu, C. & Zhang, Z. A three-dimensional numerical simulation method for seismic nonlinear response of underground structure in liquefiable site and analysis of structural damage. *Comput. Geotech.* **165**(2), 105895.1-105895.15 (2024).
94. Zeng, J. *et al.* Research progress on seismic resistance of large-span spatial structures considering soil–structure interaction. *J. Archit. Civil Eng.* **41**(1), 69–82 (2024).
95. Cheng, X. & Sun, Z. Effects of burial depth on the seismic response of subway station structure embedded in saturated soft soil. *Adv. Civil Eng.* **2018**, 8978467 (2018).
96. Cheng, X. *et al.* Study on seismic vulnerability analysis of the interaction system between saturated soft soil and subway station structures. *Sci. Rep.* **13**, 7410 (2023).
97. Pitilakis, K. *et al.* Seismic behaviour of circular tunnels accounting for above ground structures interaction effects. *Soil Dyn. Earthq. Eng.* **67**, 1–15 (2014).
98. Zhuang, H. *et al.* Seismic responses of underground subway station built in different sites. *J. Nanjing TECH Univ. (Nat. Sci. Ed.)* **37**(4), 70–76 (2015).
99. Zhuang, H., Hu, Z. & Chen, G. Numerical modeling on the seismic responses of a large underground structure in soft ground. *J. Vibroeng.* **17**(2), 802–815 (2015).
100. Xia, C. *et al.* A study on affecting factors of seismically induced drift of subway station. *China Civil Eng. J.* **48**(S1), 132–136 (2015).
101. Yu, H. *et al.* Optimal design of seismic reduction and isolation of central column in a tyical metro station in soft soils. *Struct. Eng.* **32**(6), 86–91 (2016).
102. Lu, D. *et al.* Analysis of the three-dimensional seismic performance of underground structure. *J. Beijing Univ. Technol.* **42**(1), 87–94 (2016).
103. Wang, H. *et al.* Structure–soilstructure interaction between underground structure and ground structure. *Soil Dyn. Earthq. Eng.* **54**(11), 31–38 (2013).
104. Li, J. *et al.* 3 D dynamic response analysis of the closely-attached intersecting underground subway under strong earthquake. *J. Railw. Sci. Eng.* **10**(6), 64–68 (2013).
105. Li, J. *et al.* Analysis of 3D dynamic response of closely overlapping tunnels during a strong earthquake. *Modern Tunn. Technol.* **51**(1), 26–31 (2014).
106. Li, J. *et al.* Seismic response analysis of large closely-attached intersecting combination of subway station. *J. Beijing Univ. Technol.* **40**(3), 361–367 (2014).
107. Tao, L. *et al.* Analysis on seismic response of long-distance and closely-attached subway station to existing tunnel structure. *J. Heilongjiang Univ. Sci. Technol.* **24**(3), 301–305 (2014).
108. Xu, Y. *et al.* Upheaval deformation induced by newly-built metro tunnel upcrossing existing tunnel. *China Railw. Sci.* **35**(6), 48–54 (2014).
109. An, J. *et al.* Nonlinear seismic response of double-decked intersecting metro tunnel. *China Railw. Sci.* **36**(3), 66–72 (2015).
110. Li, J. *et al.* Shaking table test of the closely-attached intersecting subway station under far-field and near-field ground motion. *China Civil Eng. J.* **48**(10), 30–37 (2015).
111. Tao, L. *et al.* Research status and tendency of closely-attached intersecting underground structures. *J. Beijing Univ. Technol.* **42**(10), 1482–1489 (2016).
112. Li, J. *et al.* Study of seismic response of different clear-distance vertical intersecting combination subway station structures. *Chin. J. Rock Mech. Eng.* **35**(S2), 3890–3897 (2016).
113. Hamid, R. T. Development of synthetic soil mixture for experimental shaking table tests on building frames resting onsoft soils. *Geomech. Geoeng. Int. J.* **12**(1), 28–35 (2017).
114. Zhong, Z. *et al.* Structural damage assessment of mountain tunnels in fault fracture zone subjected to multiple strike-slip fault movement. *Tunn. Undergr. Space Technol.* **104**, 103527 (2020).
115. Han, X. *et al.* Seismic response analysis on subway station structures undergoing surface buildings. *Chin. J. Undergr. Space Eng.* **17**(2), 488–495 (2021).

116. An, S. *et al.* Application of two-level design method on subway tunnel crossing active fault: A case study on Urumqi subway tunnel intersected by reverse fault dislocation. *Bull. Eng. Geol. Environ.* **80**, 3871–3884 (2021).
117. An, J. *et al.* A shaking table-based experimental study of seismic response of shield-enlarge-dig type's underground subway station in liquefiable ground. *Soil Dyn. Earthq. Eng.* **147**, 106621 (2021).
118. Han, X. *et al.* Shaking table test of subway station structure passing through above-ground building. *Chin. J. Rock Mech. Eng.* **20**(1), 143–151 (2024).
119. Zhuang, H., Hu, Z. & Chen, G. Numerical modelingon the seismic responses of a large underground structurein soft ground. *J. Vibroeng.* **17**(2), 802–815 (2015).
120. Zhuang, H. *et al.* Seismic responses of a large underground structure in liquefied soilsby FEM numerical modelling. *Bull. Earthq. Eng.* **13**(12), 3645–3668 (2015).
121. Li, G. & Meng, X. A seismic analysis of a shallow-buried large-span single-arch station with no column. *Modern Tunn. Technol.* **54**(6), 158–165 (2017).
122. Chen, S. *et al.* Shaking table test on the seismic response of large-scale subway station in a loess site: A case study. *Soil Dyn. Earthq. Eng.* **123**(8), 173–184 (2019).
123. Wang, J. *et al.* Influence of diaphragm wall on seismic responses of large unequal-span subway station in liquefiable soils. *Tunn. Undergr. Space Technol. Inc. Trenchless Technol. Res.* **91**, 102988–102988 (2019).
124. Tao, L. *et al.* Comparative study of the seismic performance of prefabricated and cast-in-place subway station structures by shaking table test. *Tunn. Undergr. Space Technol.* **105**, 103583 (2020).
125. Li, J. *et al.* Shaking table tests on the seismic response of a columnless subway station with asymmetric load under bidirectional seismic action. *Int. J. Saf. Secur. Eng.* **10**(4), 559–566 (2020).
126. Qin, X. *et al.* Influence of multiple system transformation on the mechanical behavior oflong-span non-column underground spatial structure. *J. Railw. Sci. Eng.* **18**(10), 2703–2714 (2021).
127. Razzakov, S. R. Seismic resistance of nonlinearly deformable large-span spatial structures, taking into account changing dynamic stiffness. *Key Eng. Mater.* **887**, 672–679 (2021).
128. Zhang, N. *et al.* Lateral seismic response analys of super-large span flat underground cavern with different in-situ stress. *Sci. Technol. Eng.* **22**(9), 3716–3711 (2022).
129. Xiang, B., Sun, J. & Zhou, N. Seismic analysis of single-arch and large-span subway station structure under bidirectional ground motion. *Technol. Earthq. Disaster Prev.* **18**(2), 369–379 (2023).
130. Zhang, C. Research on structural system of super large span underground atrium of Shenzhen Gangxia North transportation hub. *Build. Struct.* **53**(22), 72–78, 59 (2023).
131. Xu, Z., Li, C. & Xia, Z. Influence of diaphragm wall on seismic response of column-freelarge-span subway station. *J. East China Jiaotong Univ.* **40**(4), 16–23 (2023).
132. Ye, D., Zhou, J. & Jin, X. Stayed buckle cable recycling for seismic upgrading of super-long-span concrete filled steel tube arch bridges. *KSCE J. Civil Eng.* **28**(2), 777–786 (2024).
133. Zhang, Y. *et al.* Experimental and numerical investigation on the response characteristic of the crane-wharf structure in liquefiable site. *Ocean Eng.* **299**, 117312 (2024).
134. Wang, C. Seismic racking of a dual-wall subway station box embedded in soft soil strata. *Tunn. Undergr. Space Technol.* **26**(1), 83–91 (2011).
135. Zhuang, H. *et al.* Seismic performance of underground subway station with sliding between column and longitudinal beam. *Tunn. Undergr. Space Technol.* **102**, 103–439 (2020).
136. Xu, Z. *et al.* Numerical analyses of seismic performance of underground and aboveground structures with friction pendulum bearings. *Soil Dyn. Earthq. Eng.* **130**, 105–967 (2020).
137. Lu, D. *et al.* A novel segmental cored column for upgrading the seismic performance of underground frame structures. *Soil Dyn. Earthq. Eng.* **131**, 106–11 (2020).
138. Yu, Z. *et al.* Neighboring underground structure-soil interaction characteristics under seismic aclion. *China Earthq. Eng. J.* **42**(2), 481–489 (2020).
139. Li, S. *et al.* Seismic performance of single-story subway station structures with different types of column. *Chin. J. Geotech. Eng.* **43**(10), 1905–1914 (2021).
140. Zhang, G. *et al.* Seismic performance of two-story and three-span underground subway station structure under different foundation isolation cases. *J. Vib. Shock* **42**(11), 27–33+41 (2023).
141. Zhang, J. *et al.* Influence of overburden load on seismic performance of shallow buried underground structures. *J. Vib. Shock* **42**(10), 263–272 (2023).
142. Zhuang, H. *et al.* Comparative analysis on seismic performance of two-story subwayunderground station structures with different isolating systems. *J. Vib. Eng.* **36**(02), 379–388 (2023).
143. Chen, G. *et al.* A new effective stress method for nonlinear site response analyses. *Earthq. Eng. Struct. Dyn.* **50**(6), 1595–1611 (2021).
144. Amorosi, A. B. D. Numerical modelling of the transverse dynamic behaviour of circular tunnels in clayey soils. *Soil Dyn. Earthq. Eng.* **29**(6), 1059–1072 (2009).
145. Cui, P. *et al.* Model test of soil arching effect in unsaturated sand tunnel and particle flow numerical simulation. *Rock Soil Mech.* **42**(12), 3451–3466 (2021).
146. Zhang, L. *Geotechnical Reliability Theory* (Tongji University Press, 2011).
147. Kwon, S. Y., Yoo, M. & Hong, S. Earthquake risk assessment of underground railway station by fragility analysis based on numerical simulation. *Geomech. Eng.* **21**(2), 143–152 (2020).
148. Huang, Z. *et al.* Seismic vulnerability of circular tunnels in soft soil deposits: the case of Shanghai metropolitan system. *Tunn. Undergr. Space Technol.* **98**, 103341 (2020).
149. Huang, Z. & Zhang, D. Recent advance in seismic fragility research of underground structures. *J. Tongji Univ. (Nat. Sci.)* **49**(01), 49–59+115 (2021).
150. Ghosh, S., Ghosh, S. & Chakraborty, S. Seismic fragility analysis in the probabilistic performance-based earthquake engineering framework: An overview. *Int. J. Adv. Eng. Sci. Appl. Math.* **13**(1), 122–135 (2021).
151. Jalayer, F., Ebrahimian, H. & Miano, A. Record-to-record variability and code-compatible seismic safety-checking with limited number of records. *Bull. Earthq. Eng.* **19**(15), 6361–6396 (2021).
152. Zhong, Z. *et al.* Seismic performance evaluation of station structures based on IDA method. *J. Beijing Univ. Technol.* **47**(7), 680–690 (2021).
153. Jiang, J. *et al.* Effect of ground motion characteristics on seismic fragility of subway station. *Soil Dyn. Earthq. Eng.* **143**, 106–618 (2021).
154. Zhuang, H. *et al.* Statistical numerical method for determining seismic performance and fragility of shallow-buried underground structure. *Tunn. Undergr. Space Technol.* **116**, 104090 (2021).
155. Gu, Q. Performance and risk assessment of soil–structure interaction systems based on finite element reliability methods. *Math. Probl. Eng.* **3**, 1–16 (2014).
156. Du, X. *et al.* Interstory drift ratio associated with performance objectives for shallow-buried multistory and span subway stations in inhomogeneous soil profiles. *Earthq. Eng. Struct. Dyn.* **50**(2), 655–672 (2020).

157. Wang, J. *et al.* Performance levels and evaluation method for seismic behaviors of a large-scale underground subway station with unequal-span frame. *J. Vib. Shock* **39**(10), 92–100 (2020).
158. Huamg, Z. K. *et al.* Selection of optimal intensity measures for fragility assessment of circular tunnels in soft soil deposits. *Soil Dyn. Earthq. Eng.* **145**, 106–724 (2021).
159. Jiang, J. *et al.* Selection of earthquake records ensembles based on cloud method applied in vulnerability of underground structures. *J. Build. Struct.* **44**(11), 208–215 (2023).
160. Zhong, Z. *et al.* Seismic performance evaluation of underground structures usingendurance time analysis. *Chin. J. Geotech. Eng.* **42**(8), 1482–1490 (2020).
161. Yang, J. *et al.* Seismic performance levels of frame-type subway underground station withthree layers and three spans. *Chin. J. Geotech. Eng.* **42**(12), 2240–2248 (2020).
162. Ma, C. *et al.* Seismic damage evaluation of CFRP-strengthened columns in subway stations. *Chin. J. Geotech. Eng.* **42**(12), 2249–2256 (2020).
163. Xu, M. *et al.* Seismic vulnerability analysis of subway station embedded in saturated sand layers. *Eng. Mech.* **38**(S1), 251–258 (2021).
164. Zhang, C. *et al.* Seismic intensity measures for the damage evaluation of circular tunnels. *Eng. Mech.* **38**(1), 100–108 (2021).
165. Zhuang, H. *et al.* Statistical numerical method for determining seismic performance and fragility of shallow buried underground structure. *Tunn. Undergr. Space Technol.* **116**, 104090 (2021).
166. Chen, J. N. *et al.* Seismic vulnerability evaluation of rectangular prefabricated subway station structure based on IDA method. *J. Build. Struct.* **44**(7), 37–46 (2023).
167. Yuan, S. *et al.* Providing self-healing ability for wireless sensor node by using reconfigurable hardware. *Sensors* **12**(11), 14570–14591 (2012).
168. Perminov, N. Simulation of a defectless lifecycle of unique underground structures of the sewage system at the stage of their construction in difficult soil conditions. *Int. J. Comput. Civil Struct. Eng.* **15**(1), 119–130 (2019).
169. Liu, S., Shi, Y. & Feng, M. Routing design and experimental analysis of wireless sensor monitoring network for mine environment. *J. Comput. Methods Sci. Eng.* **20**(7), 1–12 (2019).
170. Shahrour, I. *et al.* Smart technology applications for the optimal management of underground facilities. *Undergr. Space* **6**(5), 551–559 (2020).
171. Yu, L. *et al.* Durability performance of BFRP-confined coal gangue concrete exposed to the sulfate-rich mine environment. *Structures* **65**, 106716 (2024).
172. Su, H. *et al.* Experiment study on the grouting material for the fabricated metro station′s joint with tenon and mortise. *Sci. Adv. Mater.* **9**(9), 1644 (2017).
173. Du, X. *et al.* Study on seismic performance of sidewall joints in assembled monolithic subway station. *China Civil Eng. J.* **50**(4), 38–47 (2017).
174. Tao, L. *et al.* Research on mechanical behavior of prefabricated metro station structure after assembling into ringbased on ABAQUS. *Modern Tunn. Technol.* **55**(5), 115–123 (2018).
175. Ding, P. *et al.* Three-dimensional dynamic response analysis of a single-ring structure in a prefabricated subway station. *Sustain. Cities Soc.* **45**, 271–286 (2019).
176. Yang, X., Shi, Z. & Lin, F. Influence of geometrical parameters on performance of mortise and tenon joint with grout for application in prefabricated underground structures. *Adv. Civil Eng.* **6**, 1–14 (2019).
177. Yang, X., Lin, F. & Huang, M. Experimental research on flexural rigidity of grouted single mortise-tenon joints for prefabricated metro station structures. *China Civil Eng. J.* **53**(3), 38–43 (2020).
178. Liu, W. & Wu, Q. Comparison between the seismic performance of buried piples and pipes in a utility tunnel. *Comput. Model. Eng. Sci.* **123**(2), 661–690 (2020).
179. Ding, L. *et al.* 3-D numerical modelling on the seismic responses of an underground subway station with some sectional prefabricated members. *World Earthq. Eng.* **37**(4), 157–166 (2021).
180. Li, S. *et al.* Seismic performance of single-story subway station structures with different types of columns. *Chin. J. Geotech. Eng.* **43**(10), 1905–1914 (2021).
181. Yang, X. Development and prospect of construction technology for prefabricated metro station in China. *Tunnel Constr.* **41**(11), 1849–1870 (2021).
182. Yang, X. *et al.* Prefabrication technology for underground metro station structure. *Tunn. Undergr. Space Technol.* **108**, 103717 (2021).
183. Peng, Z. *et al.* Mechanical behavior of prefabricated underground station structure in construction stage. *Tunnel Constr.* **42**(3), 398 (2022).
184. Wang, C. *et al.* Lateral seismic analysis of discontinuous pipes in underground precast utility tunnel. *Spec. Struct.* **40**(2), 50–55 (2023).
185. Ou, F. Numerical study on seismic performance of prefabricated metro station. *Modern Urban Transit* **9**, 81–88 (2023).
186. Qiu, T. *et al.* Data-driven adaptive assembled joints decision-making model for prefabricated underground stations. *Tunn. Undergr. Space Technol.* **140**(10), 105284.1-105284.19 (2023).
187. Qiu, T. *et al.* Experimental investigation and modeling for assembled precast hollow components in full-assembled underground station application. *Tunn. Undergr. Space Technol.* **144**(2), 105543.1-105543.18 (2024).
188. He, H. *et al.* Effect of strata restraint on seismic performance of prefabricated sidewall joints in fabricated subway stations. *Front. Struct. Civil Eng.* **17**(5), 763–779 (2023).
189. Hong, C. *et al.* Monitoring and assessment of mechanical response of large-scale prefabricated structures in underground subway stations during construction process. *Measurement* **235**, 115015 (2024).

Author contributions

All authors contributed to the study conception and design. Data collection and analysis were performed by [Xuelei Cheng], [Qiqi Li] . The first draft of the manuscript was written by [Xiaofan Xing], [Ran Hai] [Shuoshuo Guo] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests
The authors declare that there are no conflicts of interest regarding the publication of this paper.

Additional information
Correspondence and requests for materials should be addressed to X.C.