ISSN: 2414-1895 DOI: 10.6919/ICJE.202609_12(9).0005

Theoretical and Technological Approaches to Seismic Design of Urban Underground Space Structures

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Abstract

With the acceleration of urbanization, the scale of urban underground space development is expanding day by day, and the seismic safety of underground structures such as subway stations and underground parking lots has become the focus of research in the field of civil engineering. Under the action of earthquakes, underground structures are faced with complex dynamic response and failure risks, and their seismic design needs to comprehensively consider the coupling effects of multiple factors such as seismic wave propagation characteristics, soil-structure interaction and structural form. Focusing on the theory, method and damping technology of seismic design of underground space structures, this paper provides theoretical support and practical reference for improving the seismic performance of underground structures by combing the research status at home and abroad, analyzing the technical limitations and looking forward to the development trend. Specifically, the content covers the force characteristics, design methods, seismic absorption measures and engineering cases, aiming to reveal the key scientific problems and technical challenges of seismic design of underground structures.

Keywords

Urban Underground Space Structure; Time History Analysis; Shock Absorption Technology; Main-Aftershock Sequence; Seismic Toughness.

1. Introduction

Performance-based seismic design theory is an important direction of seismic research of underground space structures, and its core lies in guiding design by quantifying the performance index of structures under earthquake action. The seismic time-history method proposed by Wang Guobo can be used as an efficient method to study the seismic performance of underground structures under the action of main and aftershock sequences. By constructing the input of main and aftershock sequences, the lateral deformation characteristics and damage laws of subway stations are analyzed. It is pointed out that the influence of peak strength ratio of main and aftershock sequences should be fully considered for lateral deformation of damaged structures after main earthquakes. Wang Jianning further studied the incremental damage of underground structure under the action of main aftershock, and found that the seismic damage degree of underground structure under the action of main aftershock is generally more serious than that under the action of main earthquake only, but its incremental amplitude and expansion range are closely related to the peak acceleration ratio of main aftershock sequence, ground motion characteristics and "polarity" factors of main aftershock. Wang Guobo constructed the input of main and aftershock sequence based on seismic resistance time history method, studied the lateral deformation characteristics and damage law of subway station under the action of main and aftershock sequence, and pointed out that seismic resistance time history method can be used as an efficient method to study the seismic performance of underground structure under the action of main and aftershock sequence. Zhong Zilan studied the effect of CFST center column on seismic performance of subway station structure. The results show that CFST center column significantly reduces the interstory displacement angle of subway station under frequent ground motion and earthquake protection. Moreover, CFST center column does not appear failure under extreme earthquake, showing good seismic performance. Lei Chong proposed a method for seismic toughness evaluation of subway stations based on vulnerability analysis, which considers not only structural components but also non-structural components, and provides decision-making basis for seismic toughness improvement of subway stations. Tian Guanfeng evaluated the seismic safety of subway tunnel structure in composite stratum by finite element time-history analysis method. It was found that the sensitivity of diameter deformation rate and shear force to seismic level was higher, and the lower the overall stiffness of stratum group and the more uniform the stratum distribution were, the better the seismic safety of tunnel was improved. These studies show that performance-based seismic design theory can effectively improve the seismic performance of underground space structures by quantifying the performance indexes of structures under earthquake action, and provides new ideas and methods for seismic design.

2. Mechanical Characteristics and Failure Mode of Underground Space Structures under Earthquake Action

2.1 Influence of Seismic Wave Propagation on Dynamic Response of Underground Structures

Seismic wave propagation has a significant influence on the dynamic response of underground structures, and the propagation characteristics of seismic waves in underground medium directly determine the mechanical state of structures [1]. Liu Ying studied the seismic response of subway station structures with near-vertical faults, and found that the hanging wall effect and damage concentration effect of faults are obvious, especially in the near-fault area, subway station structures are more likely to enter the plastic deformation development stage. The typical failure characteristics of different underground structures are also different. The post-earthquake failure probability of shallow-buried rectangular frame subway station structures is closely related to the average shear wave velocity of the site, and the deformation capacity of underground frame structures itself is also an important factor affecting the post-earthquake failure probability. Wang Guobo studied the lateral deformation characteristics and damage law of subway station under the action of main-aftershock sequence based on seismic time-history method, and pointed out that the influence of peak intensity ratio of main-aftershock sequence should be fully considered for lateral deformation of damaged structure after main-earthquake. The higher the main-earthquake level and damage state, the smaller the critical value intensity ratio of aftershock incremental damage, and the higher the risk of structure facing more serious damage. Wang Jianning further analyzed the incremental damage of underground structure under the action of main aftershock, and found that the seismic damage degree of underground structure under the action of main aftershock is generally more serious than that under the action of main earthquake only, but its incremental amplitude and expansion range are related to the peak acceleration ratio of main aftershock sequence, ground motion characteristics and "polarity" factors of main aftershock.

2.2 Influence of Soil-structure Interaction on Failure Mode of Underground Structures

Bao Xiaohua put forward a new method for seismic response of subway station structure in liquefied stratum, which is composed of clay replacement and unilateral drainage diaphragm wall. The results show that the combined method can effectively control the uplift displacement and shear force of subway station under moderate earthquake and giant earthquake. Especially under giant earthquake, the uplift displacement can be reduced by 95.2%. Tian Guanfeng evaluated the seismic safety of subway tunnel structure in composite stratum by finite element time-history analysis method. It was found that the sensitivity of diameter deformation rate and shear force to seismic level was higher, and the lower the overall stiffness of stratum group and the more uniform the stratum distribution were, the better the seismic safety of tunnel was improved. Lei Chong proposed a new seismic toughness evaluation method for subway stations based on vulnerability analysis, which considers

ISSN: 2414-1895 DOI: 10.6919/ICJE.202609_12(9).0005

not only structural components but also non-structural components. It is found that with the increase of span number of subway stations, the overrun probability under different damage states decreases, and the stations tend to be safe. However, with the decrease of stratum from Class I to Class III, the overrun probability under different damage states increases, and the stations tend to be dangerous.

2.3 Typical Failure Characteristics of Different Types of Underground Structures

Different types of underground structures (For example, subway station, underground parking lot) The typical failure characteristics vary according to the structural form, geological conditions and seismic characteristics. Ma Xiaoning pointed out that the shear wave and longitudinal wave in the seismic wave will lead to wall cracking and even collapse by analyzing the influence of seismic waves on the building structure. This failure characteristic is also significant in underground structures [2]. Li Shaofeng, aiming at the isolation design of subway roof buildings, found that the isolation arrangement scheme in areas with low seismic intensity and high wind pressure should comprehensively consider the synergy between wind-resistant devices and isolation layers to improve the overall seismic performance of the structure[3]. Li Xueting emphasized the influence of seismic intensity zoning and site type on the structural failure mode when discussing the seismic design principles of building structures, which is also applicable to the seismic design of underground structures [4]. To sum up, the typical failure characteristics of underground structures are not only closely related to seismic wave propagation and soil-structure interaction, but also affected by the comprehensive effects of structural form, site conditions and seismic characteristics. These factors jointly determine the failure mode and seismic performance of underground structures under earthquake action.

3. Practical Engineering Cases and Seismic Performance Evaluation

3.1 Seismic Performance Analysis of Subway Station in Near Fault Site

Seismic performance analysis of subway stations in near-fault sites is an important research direction in seismic design of underground space structures, and its core is to explore the influence of fault-site coupling effect on seismic response of structures. Liu Ying proposed an indirect boundary element-finite element joint solution analysis method. By establishing a two-dimensional global time-domain finite element model of nonlinear static-dynamic coupling of soil-diaphragm wall-main structure, the influence of fault-soft soil field coupling effect on seismic performance of subway stations was preliminarily explored. It was found that the structural damage of subway stations in the near fault region had typical fault hanging wall effect and damage concentration effect, and it was easier to enter the plastic deformation development stage. However, in the far fault region, Due to the fault-site effect coupling, the attenuation of seismic wave field in footwall is slow, and the overall damage of station structure in footwall is slightly larger than that in hanging-wall. The seismic response characteristics of subway station structure in soft soil layer near fault are systematically studied. The influence mechanism of fault-soft soil coupling effect on seismic performance of subway station is preliminarily explored. It provides guidance and reference for seismic performance and seismic safety evaluation of subway station structure in near field conditions. Under the effect of fault-soft soil coupling, the seismic damage of underground structures located on the hanging wall of fault is stronger in the near fault area, and the seismic damage of underground structures located on the footwall of fault is slightly larger than that of the hanging wall of fault in the far field area. The static-dynamic coupled time-history analysis method is used in this paper, which verifies the high reliability and strong operability of this method, and provides a new idea for the full-process seismic response analysis of underground structures. The research results provide guidance for the seismic performance of underground station structures under near-field site conditions. Evaluation provides guidance and is conducive to the safe operation and sustainable development of urban lifeline projects.

 Volume 12 Issue 9, 2026
DOI: 10.6919/ICJE.202609_12(9).0005

3.2 Study on Incremental Damage of Underground Structure under Main Aftershock Sequence

Research on incremental damage of underground structures subjected to main and aftershock sequences is a hot issue in seismic performance evaluation in recent years, and its core lies in exploring the additional effects of main and aftershocks on damaged structures and their failure mechanisms. Wang Guobo studied the lateral deformation characteristics and damage failure law of subway stations under the action of main and aftershock sequences based on seismic time-history method, and pointed out that the lateral deformation of damaged structures after main earthquake should fully consider the influence of peak intensity ratio of main and aftershock sequences. The higher the main earthquake level and failure state, the smaller the critical value intensity ratio of aftershock incremental damage, and the higher the risk of structure facing more serious damage [5]. The seismic behavior of underground structures subjected to main and aftershocks is studied based on the time history method (ETA). The randomness of earthquake motion and the dynamic interaction between site and structure are reasonably considered by nonlinear dynamic time history analysis[6]. The numerical simulation further verifies that the damage degree and failure risk of station structures under strong aftershocks increase significantly, especially the seismic behavior of columns in underground structures. The study also constructed a sequence of main aftershocks Finally, through the analysis of interlayer displacement angle θmax, the aggravating effect of main-aftershock sequence on structural damage is revealed, which provides a new efficient method for seismic design of underground structures. The values of interlayer displacement angle θmax considering aftershocks are larger than those of main shock alone, and the amplitude of θmax decreases with the increase of main shock intensity. ETA can reasonably consider the randomness of earthquake motion and the dynamic interaction between site and structure in nonlinear dynamic time history analysis. The ETA curve of long duration (0~30s) covers the ETA curve of short duration.(0~10s and 0~20s), which shows similarity and coverage. Under strong aftershocks, the damage degree of station structure is further aggravated, the distribution range of damage area is enlarged, and the main aftershock sequence obviously improves the damage degree and damage risk of structure. The acceleration response spectrum of seismic time-history curve is in good agreement with that of design code, and increases proportionally with time, indicating that the seismic time-history curve generated has high accuracy.

3.3 Practical Application of Seismic Toughness Evaluation Method for Subway Stations

The practical application of seismic toughness evaluation method for subway stations is an important guarantee for improving seismic performance of underground structures, and its core lies in considering seismic damage characteristics of structural and non-structural members comprehensively, which provides scientific basis for seismic design of subway stations. Lei Chong put forward a seismic toughness evaluation method of subway station based on vulnerability analysis, which not only considers the structural part, but also introduces the damage evaluation of non-structural members. It is found that with the increase of span number of subway station, the overrun probability under different damage states decreases, and the station tends to be safe. However, with the reduction of stratum from Class I site to Class III site, the overrun probability under different damage states increases, and the station tends to be dangerous [7]. A seismic toughness assessment method for subway stations based on vulnerability analysis is studied, which considers the seismic damage of structural and nonstructural members comprehensively, and calculates the transcendence probability under different damage states by analyzing the logarithmic linear relationship between seismic strength index (PGA) and damage metric (interlayer displacement angle θ). The seismic vulnerability curves of metro station structures are proposed, covering the situations of two stories with single span, two stories with double span and two stories with three spans on the sites of type I, II and III. It is pointed out that the stations tend to be safe with the increase of station spans and the improvement of stratum types.(single span, double span and three span). It is found that the station tends to be safe with the increase of the span number of the station, while the station tends to be

ISSN: 2414-1895 DOI: 10.6919/ICJE.202609_12(9).0005

dangerous with the decrease of the stratum type from I to III. The repair time and the classification standard of seismic toughness grade under different damage states are given. The seismic toughness grade of subway station is divided into one star, two stars and three stars. The evaluation process is divided into two stages: By calculating the toughness index, combining the damage probability and recovery time, the toughness rating of subway stations is completed.

4. A Review of Seismic Design

4.1 Limitations of Existing Seismic Design Methods

Abundant achievements have been accumulated in seismic design theory and technology of urban underground space structures, especially in the aspects of mechanical characteristics, failure modes, seismic design methods and damping measures under earthquake action. At the same time, isolation layer, concrete-filled steel tube column, clay replacement and unilateral drainage diaphragm wall show good application effect in practical engineering.[8] However, there are still some shortcomings and disputes in existing research. First, the existing seismic design methods are mostly based on single earthquake input, and the main aftershock sequence and multi-directional earthquake action are not considered enough, which may lead to the design results underestimating the actual earthquake risk. Secondly, the applicability of shock absorption measures under different geological conditions is not fully studied, especially for complex formation conditions In addition, the existing research focuses on the seismic performance of the structure itself, and the evaluation of the non-structural components and the overall toughness of the system is still weak, which is difficult to fully reflect the actual failure mode and functional recovery ability of underground space structures under earthquake action. Future research needs to further deepen the seismic design theory under complex ground motion, explore the seismic absorption technology suitable for different geological conditions, and strengthen the collaborative seismic performance research of structural and non-structural members, so as to comprehensively improve the seismic safety and toughness of urban underground space structures.

Seismic design of urban underground space structures is a key field to ensure urban safety and sustainable development. Its research involves multi-disciplinary intersection of seismic dynamics, soil-structure interaction, material performance optimization, etc.[9]. Through systematic sorting of domestic and foreign research status, it can be seen that remarkable progress has been made in the field of stress mechanism, design theory, shock absorption technology and engineering application, etc., but there are still some scientific and technical bottlenecks to be broken through. In the aspect of stress characteristics and failure modes, the existing achievements have revealed the propagation characteristics of seismic waves.(e.g. fault hanging wall effect, main aftershock sequence) and soil-structure interaction. For example, the seismic damage concentration effect and plastic deformation development law of subway stations near faults, and the critical characteristics of structural incremental damage varying with peak strength ratio under main and aftershocks provide basic theoretical support for seismic design. different structure types[10]. However, the existing researches focus on the structural response under single seismic input, and the fine analysis of the coupling effect of multi-directional seismic motion and main aftershock sequence is still insufficient, especially the systematic research on the failure mode under complex geological conditions (such as fault-liquefaction stratum interaction).

4.2 Applicability of Shock Absorption Measures under Different Geological Conditions

The existing research has accumulated abundant achievements in the development and application of seismic isolation measures, which show that isolation layer, concrete-filled steel tubular middle column, clay replacement and unilateral drainage diaphragm wall all show good seismic effect in different engineering scenarios. For example, the synergistic application of isolation layer and wind-resistant device effectively improves the seismic performance of the structure in areas with low seismic intensity and high wind pressure, while the CFST center column significantly reduces the inter-story displacement angle of subway stations and shows excellent stability under extreme seismic conditions [11]. In addition, the joint measures of clay replacement and unilateral drainage diaphragm wall for liquefied strata can effectively control the floating displacement and shear force of stations under moderate earthquake and giant earthquake, and the damping effect is remarkable. However, there are still obvious deficiencies in the applicability of seismic mitigation measures to geological conditions. Firstly, the performance verification of seismic mitigation measures under complex formation conditions is not sufficient, especially for fault areas and heterogeneous formation special geological environment. Secondly, the existing seismic mitigation technologies focus on the performance improvement under single geological conditions, while the research on seismic mitigation effect in transition areas between different geological conditions or under complex formation conditions is relatively scarce. Furthermore, the synergistic mechanism between seismic isolation measures and site conditions has not been fully revealed, especially the influence of seismic isolation measures on site seismic characteristics and its secondary effect on structural dynamic response. Future research needs to further deepen the applicability study of shock absorption measures under complex geological conditions, explore comprehensive shock absorption technologies suitable for multiple scenarios and conditions, and strengthen the research on the synergy mechanism between shock absorption measures and site conditions, so as to comprehensively improve the seismic performance of urban underground space structures under different geological conditions [12].

4.3 Development Trend of Seismic Design of Underground Space Structures in the Future

The research reveals the complex influence of seismic wave propagation, soil-structure interaction and structural form on the dynamic response of underground space structures, and proposes performance-based seismic design theory and advanced design method of time-history analysis method [13]. The seismic isolation layer, CFST column, clay replacement and unilateral drainage diaphragm wall have shown good application effect in practical engineering.[14] However, there are still some deficiencies and disputes in the existing research. Firstly, the existing seismic design methods are mostly based on single seismic input, and the main aftershock sequence and multi-directional seismic action are not considered enough, resulting in the design results may underestimate the actual seismic risk. Secondly, the applicability of damping measures under different geological conditions is not fully studied, especially for complex stratum conditions, such as liquefied stratum and fault area, the damping effect lacks systematic verification [15]. In addition, the existing research focuses on the seismic performance of the structure itself, and the evaluation of non-structural components and overall toughness of the system is still weak, which is difficult to fully reflect the actual failure mode and functional recovery capacity of underground space structures under earthquake action [16]. Future research needs to further deepen the seismic design theory under complex ground motion, explore the seismic absorption technology suitable for different geological conditions, and strengthen the collaborative seismic performance research of structural and non-structural members, so as to comprehensively improve the seismic safety and toughness of urban underground space structures.

Future research needs to achieve breakthroughs in the following aspects: deepening the multi-field coupling theory under complex ground motion, establishing a joint analysis framework for main and aftershock sequences, multi-directional ground motion and nonlinear soil-structure interaction [17], and developing a seismic design method based on probability risk; Develop a multi-dimensional adaptive seismic mitigation technology system of "geological conditions-structural form-functional requirements", focus on breaking through key technologies such as structural toughness design in fault areas and dynamic anti-floating of liquefied strata, and establish cross-scale seismic mitigation performance evaluation standards; expand the overall toughness research of non-structural components and systems, introduce Internet of Things monitoring and intelligent algorithms, and build a full-life-cycle seismic toughness system covering damage warning, function maintenance and rapid repair. Combining artificial intelligence and high-performance computing, developing intelligent simulation platform for seismic design of underground structures will become an important direction to improve design efficiency and reliability[18]. The research on seismic design of urban underground space structures needs to be promoted in theoretical depth, technical breadth and engineering adaptability. Through multidisciplinary and cross-scale research, it provides more solid theoretical and technical guarantee for the safe utilization of underground space.

5. Conclusion

The development of seismic design theory and method shows a trend of transformation from "strength control" to "performance quantification". The extensive application of time-history analysis method and finite element modeling technology, such as seismic time-history method to simulate the response of main aftershock sequence and three-dimensional refined model to analyze soil-structure dynamic coupling , significantly improves the accuracy of design methods. However, the existing methods do not fully consider the damage mechanism of non-structural members and the structure-nonstructure cooperative failure mode, resulting in the design results can not fully reflect the actual seismic risk. The application of concrete filled steel tubular (CFST) columns in subway stations near fault areas significantly improves the lateral displacement resistance of subway stations under extreme earthquakes. The performance-based seismic design theory and time-history analysis method provide scientific basis for quantifying structural damage. The proposed seismic time-history method can efficiently evaluate the cumulative damage law of structures under the action of main and aftershock sequences. For example, the combination of cohesive soil replacement and unilateral drainage diaphragm wall can reduce the floating displacement by 95.2% in liquefied stratum, while the coordination design of isolation layer and wind-resistant device can effectively consider the seismic requirements of low intensity and high wind pressure areas. Seismic design methods are mostly based on single earthquake input, and the simulation of complex earthquake actions such as main earthquake sequence and multi-directional earthquake is insufficient, which leads to deviation between design results and actual earthquake risk. The structural damage increment under main earthquake action may be far greater than that under single main earthquake action, but the existing codes have not fully incorporated such complex cases. The geological applicability of seismic mitigation measures is not systematic, especially in fault area and complex stratum. The results reveal that the stratum homogeneity has a positive effect on the seismic safety of tunnel, but the seismic optimization of transition stratum or heterogeneous stratum is still lacking. In addition, the existing research focuses on the seismic performance of the structure itself, and the evaluation of the overall toughness of non-structural components such as pipelines, equipment and systems is weak. Although the parameters of non-structural components are introduced into the toughness evaluation method, the study of functional recovery capacity and post-earthquake repair strategy still needs to be deepened.

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