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Review of Earthquake Resistance and Mitigation of Underground Structures

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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Review Article

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ABSTRACT

The rapid development of underground structural engineering in China has been accompanied by pressing issues in the research of earthquake resistance and mitigation. Typically, underground structures exhibit good seismic performance with relatively few disasters. However, once they are damaged by earthquakes, the consequences can be severe and difficult to repair. This paper first elaborates on the prototype observation, theoretical analysis, model testing, and numerical simulation involved in seismic response analysis of underground structures. It comprehensively analyzes the advantages, disadvantages, and applicability of different research methods. Finally, it summarizes the research achievements on technical measures to mitigate earthquake damage to underground structures in strong earthquake regions, both domestically and internationally.

Keywords: Underground structures; earthquake resistance research; mitigation measures; analysis methods.

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1. INTRODUCTION

Due to the strong confinement from surrounding soil, underground structures in cities have traditionally been considered to have excellent seismic performance compared to traditional ground structures. However, numerous seismic damage investigations and engineering seismic theory research have shown that site conditions significantly impact the degree of structural damage. With the construction of long tunnels, underground structures, and urban subways in complex geological strata, it is inevitable that they will traverse unfavorable geological zones such as weak geological belts, high-intensity seismic zones, and active faults. Therefore, there is an urgent need to conduct in-depth research and engineering practice on the earthquake resistance and mitigation of underground structures in strong earthquake zones or complex geological strata [1].

As an essential component of urban infrastructure, the seismic resistance and mitigation performance of underground structures directly relate to the safety and stability of cities. With the acceleration of urbanization, the development and utilization of underground space are becoming increasingly extensive. The number and scale of underground structures (such as tunnels, subways, underground complexes, etc.) continue to increase, making their seismic issues increasingly prominent. This paper provides a comprehensive review of the seismic response characteristics, failure mechanisms, seismic design methods, mitigation measures, and future research directions of underground structures.

2. SEISMIC RESPONSE CHARACTERISTICS OF UNDERGROUND STRUCTURES

When an earthquake occurs, the seismic response of ground buildings is primarily the dynamic response of the building itself, whereas underground structures undergo dynamic interactions with the surrounding soil due to soil constraints. When seismic waves propagate [2], they reach the structure via bedrock through soft soil layers, causing structural movement and deformation. Part of the seismic waves reflect back into the soil layers, producing a counteraction. The energy of waves on the model boundary radiates into a semi-infinite space, causing energy loss. Therefore, the seismic response characteristics of underground structures can be summarized as follows [3]:

1. The vibration and deformation of underground structures are significantly constrained by the surrounding soil, and the structural dynamic response generally does not exhibit apparent natural vibration characteristics.
2. The influence of underground structures on the surrounding soil vibration is generally small (in cases where the size of the underground structure is relatively small compared to the seismic wavelength).
3. The vibration pattern of underground structures is greatly influenced by the incident direction of seismic waves. Small changes in the incident direction can lead to significant changes in deformation and stress at various points of the structure.
4. The phase differences among points in the vibration of underground structures are highly pronounced, whereas they are less noticeable for ground structures.
5. The strain in underground structures during vibration is generally not strongly correlated with seismic acceleration.
6. The seismic response of underground structures does not vary significantly with depth.
7. The interaction between underground and ground structures with the foundation soil significantly impacts their dynamic response, but the mode and extent of influence differ.

3. ANALYSIS METHODS OF SEISMIC RESISTANCE FOR UNDERGROUND STRUCTURES

Currently, the primary analysis methods applied to underground structures' seismic resistance are theoretical research, numerical research, and experimental research.

3.1 Theoretical Research

The theoretical basis of the analytical method is relatively complete, but due to numerous assumptions in its establishment, it is generally only applicable to underground structures with regular cross-sections such as circles and rectangles. Domestic scholars, such as Liang Jianwen et al. [4], have successively provided analytical and numerical solutions to the scattering of SH, SV, P, and Rayleigh waves by circular lined tunnels based on the wave function expansion method. Subsequently, they also provided the series solution for ground motion when underground tunnel groups are subjected to P and SH waves [5]. Li Weihua et al. [6] also presented a wave function expansion method to solve the scattering problem of plane P waves by cylindrical holes in saturated half-space soil. In terms of seismic analysis and calculation methods, Yu Haitao et al. [7] simplified the variable stiffness tunnel into an infinitely long elastic foundation beam, derived the analytical expression for the longitudinal response of the tunnel, introduced the displacement phase angle, and obtained a pseudo-static method for longitudinal seismic analysis of variable stiffness tunnels. Cheng Kaishu et al. [8] studied the applicability of seismic calculation methods for shallow-buried large-diameter shield tunnel linings. Liu Xueshan et al. [9] simplified the longitudinal seismic problem of tunnels into a vibration problem of elastic rods in viscoelastic foundations, used joint elements to simulate the longitudinal joints of tunnels, and conducted dynamic finite element analysis on the internal forces and deformations of tunnels. Jiang Jianqun et al. [10] employed a nonlinear dynamic finite element method with equivalent stiffness considering both axial force and bending moment to analyze the longitudinal nonlinear response characteristics of shield tunnels under seismic loads. Zhao Boming and Su Yan [11] established a longitudinal equivalent continuous model for shield tunnels and conducted seismic analysis of shield tunnels using both the response displacement method and the finite element method. Yan Qixiang et al. [12] introduced the basic theory and calculation method of the longitudinal response displacement method for shield tunnels, combined with a subway shield tunnel project.

With the introduction of these series of simplified design methods, the theory of seismic analysis for underground structures has gradually matured.

3.2 Numerical Studies

Numerical methods have emerged as one of the crucial approaches for investigating the seismic resistance of underground structures, enabling the consideration of complex cross-sectional geometries by treating the foundation and the structure as an integrated whole. This comprehensive approach takes into account the dynamic characteristics such as soil-structure interaction, material nonlinearity, and contact nonlinearity.

Wang Wenhui [13] conducted numerical research on the longitudinal response of tunnel structures under seismic excitation. Combining the calculation method of the free field under oblique incident seismic waves, he proposed the integrated reaction displacement method for seismic studies of tunnel structures. Li Peng [14] investigated the longitudinal dynamic response of an infinitely long tunnel embedded in a saturated foundation under earthquake action. He examined the longitudinal response patterns of tunnels when P-waves and SV-waves are incident at different angles and conducted a systematic analysis of the dynamic response of the Hong Kong-Zhuhai-Macao immersed tube tunnel under seismic excitation. Zhou Yundong et al. [15] utilized multi-point acceleration time histories as seismic inputs and separately considered the effects of uniform seismic input, wave passage effect, coherence effect, and their superposition on the dynamic response of tunnels. Li et al. [16] established a three-dimensional soil-tunnel structure interaction model to study the influence of different seismic waves and oblique incident angles and directions on the longitudinal seismic response of tunnels. Based on the laws and characteristics of longitudinal seismic response of large-space tunnel structures, Wang Dongyang et al. [17] carried out research on longitudinal excitation, combining the Timoshenko beam theory. They ultimately determined the method to obtain the most unfavorable moment of longitudinal seismic response for large-space tunnel structures through free-field seismic response, thereby developing an applicable approach. Shi et al. [18], based on the theory of structural viscoelastic boundaries, considered the geological variations in soil layers and tunnel penetration depths to conduct a dynamic time-history analysis of the structural response of defective lined tunnel segments under seismic excitation. This analysis revealed the stress and deformation patterns of the overall tunnel structure and its defective segments. Yuan Mingzhi [19] combined multi-point non-uniform input methods with seismic resistance of underground structures to separately investigate the seismic response states of soil and underground structures under the action of uniform and non-uniform waves. By comparing the influence of various factors of seismic spatial effects on structural responses, he summarized the seismic response laws of underground structures and site soils under non-uniform seismic excitation. Huang et al. [20], utilizing the equivalent nodal force method in conjunction with viscoelastic artificial boundaries, studied the three-dimensional input methods for SV and SH waves at arbitrary incident angles. The numerical results indicated that the nonlinear seismic response of long-lined tunnels is significantly influenced by the incident angle of S-waves.

The aforementioned numerical studies indicate that significant changes in internal forces and displacements occur in underground structures under seismic actions, posing a considerable threat to tunnel seismic resistance. To ensure the seismic safety of tunnel structures, it is imperative to conduct dynamic response analyses of tunnel structures under seismic input.

3.3 Experimental Research

Model experiments are research methods utilizing vibration testing to investigate the seismic response characteristics of underground structures such as tunnels. They are broadly classified into two types: conventional shaking table tests and centrifuge shaking table tests. Due to the limited and random availability of actual earthquake records, scientific research based on these records faces significant constraints. As a result, model tests with seismic excitations have emerged and gradually become essential avenues for studying the seismic response and seismic performance of underground structures.

Recent years have witnessed abundant research achievements in conventional shaking table tests. Han Junyan [21] established a continuous model box shaking table test platform for studying the seismic response of underground structures and conducted shaking table model tests on buried pipeline structures. It was found that the nonlinearity of foundation soil increases under seismic effects, accompanied by significant spatial effects, leading to a certain degree of bending deformation in the underground pipeline structures. Li Liyun et al. studied the shaking table model tests of underground pipelines under multi-point seismic inputs and various site conditions, revealing that seismic actions enhance the relative displacement of site soil [22].

Conventional shaking table tests are conducted under normal gravity conditions. However, due to technical limitations, the geometric dimensions of the models used are typically fractions of the actual structures, making it impossible to simulate the actual stress field and accurately reflect the actual damage characteristics of underground structures. The observed experimental results mainly focus on structural deformation characteristics. To simulate stress levels equal to or similar to the prototype and restore the physical properties of the prototype structure more accurately, centrifuge shaking table tests are sometimes necessary.

Currently, centrifuge testing technology has been widely applied in the field of seismic resistance of underground engineering, and fruitful research results have been achieved. Yang et al. [23] conducted centrifuge shaking table tests to investigate the seismic dynamic response of an immersed tube tunnel and the influence of foundation liquefaction on the tunnel. Han Chao et al. [24] performed two sets of centrifuge shaking table tests on saturated sandy soil free fields and circular tunnel structures in saturated sandy soil foundations under various seismic wave excitations. They separately studied the pore water pressure and acceleration response laws in free fields and the dynamic response laws of internal forces and deformations of circular tunnel structures under seismic actions. Furthermore, they analyzed the influence of tunnel structures on site responses.

Centrifuge shaking table tests can reflect the stress of underground structures under actual gravity conditions, accurately capturing their seismic dynamic characteristics, and demonstrating a more significant advantage in studying seismic failure modes of underground structures. However, current centrifuge shaking table model tests are mostly focused on small-sized simple structures, and the similarity materials used in models cannot fully reflect actual conditions. Therefore, the combination of experimental and numerical methods will make the research more accurate. Han Junyan et al. [25] found that the numerical simulation calculation and the shaking table test results are in good agreement in terms of acceleration time history, acceleration amplification factor, and strain peak curve along the pipeline axis, reflecting similar patterns and mutually verifying the correctness of the numerical model and shaking table test results.

4. SEISMIC MITIGATION MEASURES FOR UNDERGROUND STRUCTURES

Seismic energy transmitted to underground structures is typically dissipated through plastic deformation of components and structures, which can be damaging to underground structures or components [26]. Therefore, seismic mitigation technologies that limit or isolate seismic energy from entering underground structures, protecting them from damage or reducing damage, have become significant technological demands for underground engineering construction and vital pathways to achieving resilient cities. Current research on seismic mitigation measures for underground structures can be categorized into reinforcing the surrounding rock of underground structures, installing seismic isolation layers between underground structures and soil, improving the inherent properties of underground structures, and installing seismic mitigation devices.

(1) Reinforcing the Surrounding Rock
By grouting the surrounding rock and other methods, the integrity and strength of the rock are enhanced, causing changes in its stiffness relative to that of the lining, thereby reducing the seismic response of the lining [27]. Reinforcing the surrounding rock in areas with poor geological conditions is also a commonly used engineering measure in conventional design. In future research, specific design parameters and construction methods for surrounding rock reinforcement, primary support, and secondary lining should be adjusted in conjunction with conventional design to mitigate the seismic response of underground structures [28].

(2) Altering the Properties of the Underground Structure Itself
The impact of earthquakes on underground structures is mitigated by altering their dynamic characteristics, including stiffness, mass, strength, and damping. Key measures include: reducing the overall mass of the underground structure; enhancing the ductility and damping of the structure through the use of flexible segment joints and reinforced concrete materials; adopting smooth structural shapes to avoid sharp corners or incorporating seismic joints, inverted arches, and other structural measures [29]; and reducing structural stiffness to increase ductility, allowing the structure to deform with the surrounding rock under normal use conditions [30].

(3) Installing Shock Absorption Systems
A shock absorption system applies structural control to the structure itself, with the control mechanism and structure jointly withstanding seismic forces to coordinate and reduce the seismic response [31]. While structural control has been applied to high-rise buildings with practical results, it has seen limited widespread application in current underground structural engineering.

5. CONCLUSION

The analysis of seismic response in underground structures primarily relies on prototype observations, theoretical analysis, model testing, and numerical simulations. This paper summarizes the advantages and disadvantages of each method. Due to the constraints of highly nonlinear surrounding soil, the lack of cases of seismic damage to underground structures, the complexity of soil-structure dynamic interactions, and limitations in experimental equipment, these methods need to be combined to obtain a more realistic seismic response pattern of underground structures and achieve seismic-resistant design.

Research on seismic resistance and shock isolation/mitigation engineering measures for underground structures has yielded certain results, including reinforcing the surrounding rock of underground structures, installing seismic isolation layers between underground structures and soil, improving the inherent properties of underground structures, and installing shock absorbers. However, the proposed measures are primarily based on theoretical analysis and numerical simulations, lacking experimental data for verification and support. Furthermore, their practical application in engineering projects is limited, especially in terms of shock absorption devices for underground structures.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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