Method Article

A Review of Seismic Response Analysis Methods for Underground Structures

ABSTRACT: The seismic safety of underground structures is crucial. This paper reviews the current research status of seismic response analysis methods for underground structures, focusing on the basic principles, advantages, disadvantages, and applicability of the pseudo-static method and dynamic time-history analysis method. It analyzes their engineering applications. The study indicates that the seismic coefficient method is simple but may have relatively large calculation errors due to excessive simplifications. Other pseudo-static methods consider soil-structure interaction but are still based on simplified assumptions. Dynamic time-history analysis method is accurate but computationally intensive. Future research trends involve integrating prototype observations, model tests, and numerical simulations to develop sophisticated constitutive models and efficient computational methods. Consideration of non-uniform seismic input and multi-factor coupling effects aims to predict underground structure seismic responses more accurately, providing reliable guidance for seismic design.

Keywords: Underground Structures; Seismic Response; Pseudo-Static Method; Dynamic Time-History Analysis Method.

1. Introduction

As an important part of urban infrastructure, underground structures play an irreplaceable role in transportation, energy, water conservancy, national defense and other fields. In recent years, with the acceleration of urbanization and the increase in the scale and number of underground structures, the problem of seismic safety of underground structures has become more and more prominent. In particular, seismic events in recent years have shown that underground structures also suffer from different degrees of damage. the 1995 Hanshin earthquake in Japan [1] and the 2008 Wenchuan earthquake in China [2] caused a large number of underground tunnels to suffer from severe damage, resulting in significant casualties and economic losses. Therefore, the method of analyzing the seismic response of underground structures is a topic worth exploring.

In order to improve the seismic performance of underground structures and ensure their safety under seismic action. This paper will focus on reviewing the current research status of seismic response analysis methods for underground structures and comparing and analyzing the basic theories, advantages and disadvantages, and the scope of application of different methods. The research method mainly adopts the literature review method, through collecting, organizing and analyzing relevant literature at home and abroad, to summarize the research results and provide reference for the seismic design of shield tunnels.

2. Seismic Response Analysis Method for Underground Structures

The seismic response analysis method of underground structures consists of three methods: prototype observation, model experiment and theoretical analysis. Through prototype observation, the real seismic response data of the structure can be obtained to reveal its laws and characteristics. In the model experiment, the artificial seismic source test is limited by the model size and seismic wave intensity. Theoretical analysis mainly relies on numerical simulation to restore the disaster process and analyze the cause of the disaster through parameter adjustment. The future research trend is to combine the three methods organically, complement each other's advantages, and improve the accuracy and reliability of the analysis. This paper focuses on the theoretical analysis of seismic response of underground structures, which can be divided into dynamic time course analysis method and proposed static analysis method [3].

2.1 Proposed static analysis method

(1) Seismic coefficient method: The seismic coefficient method is based on the static theory, which simplifies the dynamic seismic force into an equivalent static load, and then adopts the static calculation method to analyze the seismic performance of the structure. In the calculation model of the seismic coefficient method, there are two values that need to be focused on, one of which is the earth pressure, for the calculation of the active lateral earth pressure increment of the soil body on one side of the structure, the most widely used is the Mononobe-Okabe seismic earth pressure calculation method [4], and then Zhang et al. [5] proposed a calculation method that can evaluate the seismic earth pressure of the retaining wall under the condition of arbitrary lateral displacement; the other one is the calculation method of the overburden pressure; and the other one is the calculation method of the upper cover. Another calculation method of overburden height, Geng Ping et al [6] modified the conventional seismic coefficient method, and then analyzed the problem of reasonable calculation height for the overburden column of the tunnel in the seismic coefficient method, and gave a reasonable calculation height [7].

The seismic coefficient method is relatively simple in form, easy to calculate, easy to understand and suitable for general structural design. However, the oversimplification of this method leads to a relatively large calculation error. Since the distribution of seismic acceleration in the height direction of the structure is not consistent with the ground surface, it is unreasonable to use the ground surface acceleration value directly for calculation, because the structure is not subject to the inertia force of all the overlying soil, and the actual loads borne are less than this value. In addition, the seismic coefficient method ignores the influence of the stiffness of the surrounding soil on the deformation of the structure.

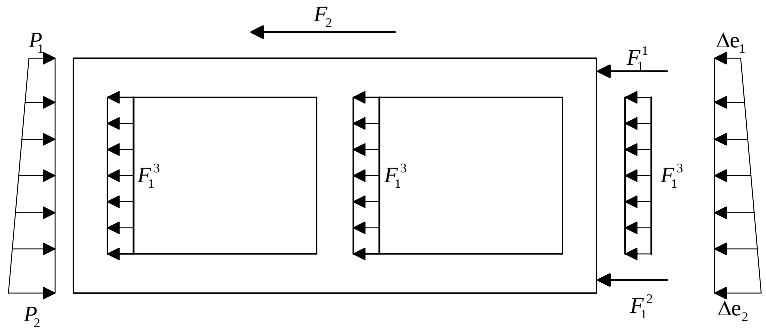

Fig. 1. Seismic coefficient method calculation model

(2) Free-field deformation method: Newmark et al [8] considered that the seismic response of underground structures is mainly affected by the deformation of the surrounding soil. Based on this theory, Wang et al [9] proposed the free-field deformation method. In this method, the deformation of the structure adopts the deformation of the soil at the location, which does not take into account the effect of foundation excavation or underground structure on the deformation of the soil around the structure, and the difference in stiffness between the structure and the surrounding soil.Wang et al [9] proposed the method of applying seismic load as shown in Fig. 2, where the bottom of the structure is simply supported and a horizontal load is applied in the analysis process. The specific method is as follows: ① Apply horizontal concentrated load at the top of the structure. ② Apply horizontal inverted triangle distributed loads on the side walls of the structure. Then, the structure is loaded step by step until the lateral deformation reaches the same value as the relative deformation obtained from the free-field seismic response calculation. At this point, the response of the structure can be considered as the response under seismic action.

The basic idea of this method is that the key factor of the seismic response of underground structures is the deformation of the soil around the underground structure, which is consistent with the viewpoint of the current understanding of the seismic response of underground structures. The free-field deformation method can be conveniently applied to different site conditions and ground vibration inputs for solving and analyzing, which is easy to be applied in engineering practice. However, since the calculation model of this method only adopts the constraint of simple support, it is difficult to accurately reflect the constraint effect between the underground structure and the surrounding soil layer. The deformation forms of the actual seismic response of underground structures are complicated and diverse, and it is difficult to accurately reflect the force characteristics of the simple centralized or distributed loads, so the method has certain limitations.

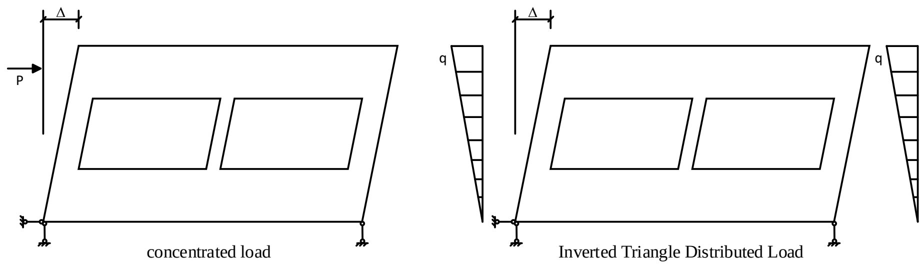

Fig. 2. Free-field deformation calculation model

(3) Flexibility coefficient method: The flexibility coefficient method (also known as the soil-structure interaction coefficient method) is based on seismic fluctuation field analysis and seismic observation of underground structures. It takes into account the interaction between the structure and the soil brought about by the difference in shear stiffness. When it calculates the relative lateral deformation of underground structures under seismic action, the maximum value of relative lateral deformation generated by the free-field soil body under seismic action at the corresponding position of the structure is multiplied by the soil-structure interaction coefficient to obtain the structural deformation. Subsequently, the structural internal force calculation is carried out after the loading method proposed by Wang et al [9].

$$\Delta_{structure} = \beta \Delta_{free-field} \tag{1}$$

Where, $\Delta_{structure}$ is the structural deformation of underground structure under seismic action; β is the soil-structure interaction coefficient; $\Delta_{free-field}$ is the free-field deformation.

Soil-structure interaction coefficients are obtained from the structure-soil flexibility ratio F. The structure-soil flexibility ratio F is calculated as the ratio of the deformation of the structure to an equivalent soil unit of the same form factor under equivalent loading:

$$F = \Delta_S / \Delta_M = G_f W / S_1 H \tag{2}$$

where, Δ_S is the deformation under structural load; Δ_M is the deformation of the equivalent soil unit under load; G_f is the shear modulus of the foundation soil; W is the width of the structure; S_1 is the unit shear stiffness of the structure; and H is the height of the structure.

The flexibility coefficient method introduces the soil-structure interaction coefficient on the basis of the free-field deformation method, which can better reflect the deformation coordination relationship between the underground structure and the surrounding soil, and it takes into account the influence of the difference in lateral stiffness. When calculating the structure-soil flexibility ratio, the method does not consider the influence of structure size and burial depth, which leads to the deviation of the results. In addition, the method inherits some of the defects of the free-field deformation method because it follows the calculation model of the method.

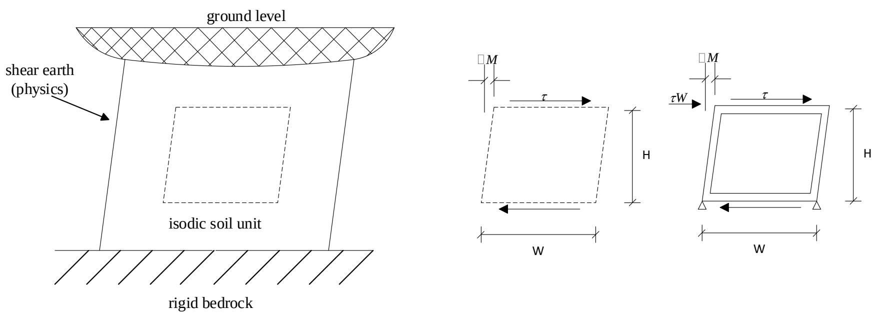

Fig. 3. Structure-soil flexibility ratio F

(4) Reaction displacement method: The theoretical basis of the reaction displacement method is that the seismic response of underground structures is related to the deformation of the surrounding medium [11]. On the basis of this theory, in order to consider the interaction between the structure and the soil, foundation springs are introduced as a way to minimize the effect of the difference in lateral stiffness between the soil-structure. This method is essentially based on the deformation of the soil body when analyzing earthquakes, simplifying the interaction between the structure and the soil into a foundation spring system, and simulating the response of the structure under seismic action by adjusting the spring stiffness to reflect the difference in stiffness between the two. When using the reaction displacement method for seismic analysis of underground structures, three parts of loads need to be considered: the relative displacement of the soil layer, the horizontal inertia force of the structure, and the shear force of the soil layer around the structure. The soil relative displacement should be determined based on the soil displacement distribution at the moment of maximum relative horizontal displacement of the free field at the location of the top and bottom slabs of the underground structure, and applied to the compression springs on both sides of the structure and the upper shear springs away from the end of the structure. The horizontal inertia force of the structure is calculated by multiplying the mass of the structure with the maximum acceleration and then acting on the center of the structure or calculating the inertia force of each part separately, and applying the obtained inertia force on each part of the structure. The shear force of the soil layer around the structure can be calculated in the following ways: ① Using the shear force of the soil on the upper surface of the structural model and the soil on the lower surface. ② Calculate the displacement response of the soil layer by the reaction spectrum method to obtain the displacement values of the soil layer at different frequencies, then, calculate the strain of the soil layer by using differential operations, i.e., the velocity and acceleration of the soil layer are obtained by differentiating the displacements, next, according to the physical relationship of the soil body and the adopted intrinsic model, the strain of the soil layer is converted into the shear stress of the soil layer, and lastly, according to the shear stress of the soil layer and the soil layer's geometric characteristics of the soil layer, the shear force of the soil layer is calculated.

The reaction displacement method is widely used in the seismic response analysis of underground structures because of its more comprehensive consideration. However, due to the selection of foundation spring parameters and the different forms of seismic action, this method has some errors.

(5) Reaction acceleration method: the reaction acceleration method uses two-dimensional plane strain finite element to simulate the soil body, and the beam unit to simulate the structure, and the two are connected with each other to form a calculation model. The computational model of the reaction acceleration method is shown in Figure 4 [12]. The method first performs a one-dimensional soil reaction analysis to determine the moment when the maximum relative displacement occurs at the location of the top and bottom plates of the underground structure. Then, the horizontal acceleration value corresponding to the depth of the soil layer at that moment is converted into a nodal force, which is applied to the corresponding node of the finite element model, in order to calculate the effect of seismic loading on the structure.

Horizontal effective response acceleration is the key parameter of the method, which is calculated by inverting the corresponding effective response acceleration based on the shear stress distribution under the maximum relative deformation of the soil layer at the top and bottom positions of the structure. As shown in Fig. 5, the shear stress distribution of the layered soil can be obtained by analyzing the free-field one-dimensional soil seismic response. The equation of motion of the soil unit in layer i:

$$\tau_i - \tau_{i-1} + m\ddot{u} + c\dot{u} = 0 \qquad 3$$

Considering the dynamic characteristics of the soil body under seismic action, the finite reaction acceleration calculation method based on the deformation of the soil unit can more accurately reflect the actual stress situation of the soil body, and the effective reaction acceleration rate is calculated by the stress term in Eq. 3:

$$\alpha_i = \frac{\tau_i - \tau_{i-1}}{\rho_i h_i} \qquad 4$$

Where: α_i is the effective reaction acceleration of the soil unit in layer i; ρ_i is the density; and h_i is the height of the soil unit.

The reaction acceleration method adopts an overall analysis model of soil-structure, which can more realistically simulate the interaction between soil and structure under seismic action, and there is no need to determine the foundation spring stiffness as in the reaction displacement method, which avoids the resulting error. The advantage of this method is that it takes into account the effect of damping force and has a better theoretical foundation. However, there are some errors in the way the method handles the conversion of the reaction acceleration of the free soil layer to the structural ground vibration load. Especially for underground structures with large dimensions and obvious influence on the free-field seismic response, the load calculation error of this method is large, which affects the calculation accuracy.

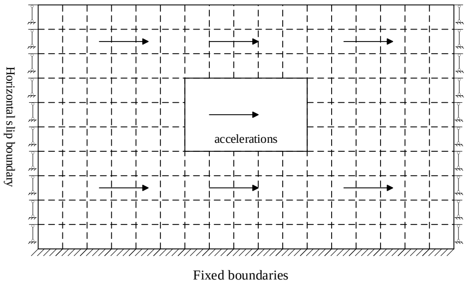

Fig. 4. Reaction acceleration method calculation model

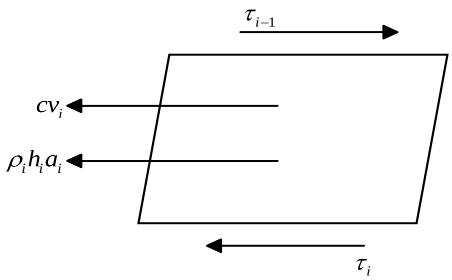

Fig. 5. Horizontal effective inertial acceleration solution

(6) Dynamic time-course analysis: Dynamic time-course analysis treats the structure and the surrounding soil as an interacting system, and solves the process of the dynamic response of the structure in the time domain through numerical computation methods. This method is a more accurate method of seismic response analysis, which uses real or artificially simulated seismic waves as inputs to calculate the dynamic response of the structure throughout the seismic duration, including displacements, velocities, accelerations, internal forces, and so on. The method needs to address key issues such as artificial boundaries, ground shaking inputs, material nonlinearities, and soil-structure dynamic contact. The initial exploratory phase of the dynamic time-course analysis method mainly focuses on simple subsurface structural forms analysis methods are relatively simplified, often using two-dimensional models and linear elastic material assumptions, and the treatment of soil-structure interactions is relatively simple, for example, simulated using a spring-damper model.Jennings [13] analyzed the effects of the San Fernando earthquake on subsurface structures, which facilitated the use of the time-course analysis method in the application in this field. With the application of numerical computation methods such as finite element method and boundary element method, the fineness and computational efficiency of the time-range analysis model of subsurface structures have been improved, and the effects of soil-structure interaction and nonlinear material properties on the seismic response of subsurface structures have begun to be considered.Wolf et al. [14] systematically elaborated the theory of soil-structure interaction, which provided the theoretical basis for the time-range analysis of subsurface structures. Since the development of dynamic time-course analysis method, with the rapid development of computer technology and the increasing maturity of large-scale commercial finite element software, the method has developed in a more refined direction. When analyzing soil-structure interaction, in order to effectively simulate semi-infinite foundations, an artificial boundary is often used at this stage at the model truncation. Currently, the research on artificial boundaries is continuously deepening [15], and Lysmer [16] firstly proposed the viscous boundary conditions. Then Deeks [17] developed viscoelastic boundary conditions. On this basis, Liu Jingbo et al[18] proposed the concepts of consistent viscoelastic boundary and viscoelastic artificial boundary unit, and realized the two-dimensional viscoelastic boundary unit software simulation. Subsequently, a three-dimensional consistent viscoelastic artificial boundary cell was derived at the two-dimensional viscoelastic boundary [19]. In

addition also [20] proposed a method to develop a unified static-dynamic artificial boundary and established a three-dimensional viscoelastic static-dynamic unified artificial boundary. And a method for transforming the ground vibration input into a wave source problem is proposed, i.e., the seismic acceleration is transformed into an equivalent load applied to the artificial boundary. This method has now been widely applied to nonuniform ground shaking and layered nonlinear foundation problems [21,22].

The dynamic time-course analysis method can take into account the randomness of ground shaking and the nonlinear characteristics of the site and structure, with strong applicability, and can obtain a more accurate structural seismic response. However, this method requires a large number of calculations, and the results are sensitive to the model parameters, intrinsic relationship, boundary conditions, etc. Professional knowledge and experience are needed to analyze and interpret the results reasonably. The future of underground structural dynamic time-course analysis method will be developed in the direction of high efficiency, precision, intelligence and multidisciplinary cross-discipline. On the one hand, with the help of high-performance computing, refined modeling and artificial intelligence, the computational efficiency and accuracy of the results will be improved; on the other hand, the integration of methods such as multi-physical field coupling and multi-scale analysis, and close integration with monitoring technology, will realize a more comprehensive assessment of the seismic response of underground structures, and provide a more reliable technical support for the earthquake-resistant design and safety assessment [23].

3. Conclusion

At present, combining prototype observation, model test and numerical simulation is the main way to study the seismic performance of underground structures, and it is also the future development trend of seismic response analysis of underground structures. However, there are some problems that need to be studied in depth. Firstly, in terms of the model test, there are differences in the structural stresses between the model and the prototype of the ordinary shaking table test, which will have an impact on the simulation effect, so it is necessary to pay more attention to the design of the model and the selection of the model material to make up for the shortcomings of the existing research. Centrifuge shaker tests have obvious advantages and can make up for the shortcomings of ordinary shakers. Centrifuge shaker tests can take into account the size effect, simulate real scenarios, accurately control the test conditions, and obtain a wealth of observational data, thus providing more accurate and reliable research results. However, the lack of domestic equipment limits the application and promotion. In terms of numerical simulation , further in-depth study of the ontological model of the underground structure, the surrounding soil and the contact surface is needed in order to more accurately describe the dynamic response of the soil-structure interaction system. In addition, the seismic response analysis of underground structures mostly adopts consistent ground shaking excitation, but for long and large structures, non-uniform ground shaking excitation should be adopted due to the time-varying and spatially-varying characteristics of ground shaking, which makes the ground shaking load at each point of the structure different. In addition to the analytical methods need to be continuously studied in depth, it is also necessary to improve the relevant normative standards to make them more scientific and reasonable. In the future, the seismic response analysis method of underground structure will pay more attention to multidisciplinary cross-fertilization, and develop in the direction of more accurate, efficient and intelligent, so as to provide more reliable guarantee for the seismic safety of underground structure.

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