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Seismic Analysis of Urban Underground Engineering Structures Based on Sensitivity Analysis

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Abstract: Dynamic response analysis of underground structures is a key research topic in structural dynamic analysis in recent years, which plays a very important role in engineering construction. Three-dimensional dynamic model is established by large-scale finite element program, and the structure is modified by design parameter model modification method based on sensitivity analysis. The basic finite element model of the structure is established, and the deformation and internal force response of the structure are obtained. The inter-story displacement difference, inter-story displacement angle and static and dynamic mechanical characteristics of the structure are analyzed. Explore the use of elastic boundary element between soil and structure to carry out seismic analysis of structures; Compared with the same structure without elastic boundary element, it is very necessary to calculate the earthquake resistance of underground structure.

1. Introduction

Because the soil around the underground structure has a restraining effect on the structure, the movement of the underground structure is the result of the interaction between the soil and the structure during the earthquake, which is obviously different from the ground structure [1]. Therefore, the study on the interaction between soil and underground structure is one of the important contents in the seismic design and seismic response analysis of underground structures [2]. In the design of urban rail transit engineering, checking the seismic performance of underground structures is an essential work [3], but at present, there is little experience in the research and engineering design of seismic performance of large underground space structures in China.

The purpose of structural dynamic model modification is to require the structural dynamic characteristics to meet certain standards. However, different engineering structures require different goals, and the characteristic goals are various. They can be: natural frequency requirements. This requirement is the most common, and most of it is to make the structure avoid possible resonance under actual working conditions. Requirements of vibration modes. When the natural frequency of the structure cannot be removed from the main frequency area of dynamic load, if the natural frequency of a certain order cannot fall within the working frequency, the response of a certain point is required to be as small as possible, or the relative displacement of two points is as small as possible [5]. Requirements for frequency response function or response. The frequency response function reflects the ability of the structure to transfer dynamic load to make it a response. Requirements for response power spectrum. Most of these requirements are encountered in the dynamic modification of seismic structures or vehicles [6]. The modified structural dynamic model can correctly reflect the dynamic characteristics of the structure, accurately predict the dynamic response of the structure, and carry out damage detection and residual life assessment of the structure by combining the measured results.

In this paper, the numerical analysis of seismic response of site and underground structure will be carried out. Based on sensitivity analysis, a reasonable calculation model is established by using appropriate boundary conditions, and the finite element method is used to analyze the seismic response of underground structures and discuss its dynamic response law.

2. Three-Dimensional Finite Element Dynamic Model

In this paper, MIDAS/GTS NX software is used for three-dimensional numerical simulation analysis, and the seismic response characteristics of underground spatial structures are discussed.

2.1 Models and Parameters

According to the analysis needs, the size of the model is x × y × z = 650m × 430m × 120m, with 119 000 nodes and 515 000 units. In the model, the soil is divided into four layers from the surface, which are simulated by tetrahedral element, and the strata are distributed horizontally in layers. The main body of the station is simulated by plate element, and the beams, columns and piles of the station are simulated by beam element. In the model, the upper boundary is the free surface, the lateral surface limits the horizontal movement, and the bottom limits the vertical movement.

2.2 Calculation of Stiffness of Soil Spring

The stiffness of soil spring is determined by the "M" method commonly used in the field of highway bridges in China, and its definition is shown in the following formula:

$$k_s = \frac{P_s}{x_z} = \frac{1}{x_z} A\sigma_{zx} = \frac{1}{x_z}(ab_p)(mzx_z) = ab_p mz \tag{1}$$

In which, k_s --Stiffness of soil spring;

P_s --Is the lateral pressure of soil;

σ_{zx} --Transverse resistance of soil to structure;

a --Thickness of soil layer;

b_p --Width of the pile;

z --Depth of soil layer;

x_z --The displacement of the structure at z (that is, the lateral displacement value of the soil there);

m --Proportional coefficient of foundation soil / $\mathrm{kN/m^4}$ can be determined according to test. If there is no measured data, it can be selected by referring to relevant data or consulting relevant experienced experts [7].

According to the engineering geological conditions of the construction site, take

m=15MN/m^4, b_p=1m, a as the length of each subdivision unit, and calculate the k_s at each node according to formula (1).

2.3 Loading and Solving

Structural dynamics analysis is used to solve the influence of time-varying loads on structures or components. Different from static analysis, dynamic analysis should consider the force load changing with time and its influence on damping and inertia. The types of structural dynamic analysis that can be performed include transient dynamic analysis, modal analysis, harmonic response analysis and random vibration response analysis.

The load types in ANSYS can be divided into:

(1)Degree of freedom, namely displacement constraint in structural analysis;

(2)Concentrated load, point load in structural analysis, such as concentrated force and moment;

(3)Surface load, distributed load such as pressure acting on the surface;

(4)Volume load, which acts in volume or field, such as electromagnetic force;

(5)Inertial load, load caused by structural mass or inertia, such as gravity and moment; Acceleration, etc.

In order to truly reflect the stress and deformation of soil and structure, this paper incorporates gravity as a dynamic load into dynamic calculation, that is, applies gravity as a vertical acceleration field to the system for transient analysis [8].

In an actual earthquake, the bedrock movement occurs first, and then the soil layer moves under the excitation of bedrock movement. According to the principle of relative motion, in dynamic calculation, the bedrock can be fixed, and the soil layer (and underground structure in it) can generate reverse acceleration relative to the bedrock at each moment, so as to calculate the motion of the soil layer and underground structure relative to the bedrock.

3. Modification of Structural Parametric Finite Element Model Based on Sensitivity Analysis

3.1 Fundamental Principle

In the process of model modification based on sensitivity analysis, the objective function combining structural frequency and mode shape can be expressed as [10 ~12]:

$$J(r)=\sum_i W_{\lambda i}^2\left[\lambda_i(\{r\})^A-\lambda_i^E\right]^2+\sum_i W_{\varphi i}^2\sum_j\left[\varphi_{ij}(\{r\})^A-\varphi_i^E\right]^2 \qquad (2)$$

In which:

r --Design parameters of initial finite element model;

λ_i^A --Represents the i-th eigenvalue of the finite element model, and $\lambda_i^A=\left(\omega_i^A\right)^2=\left(2\pi f_i{}^A\right)^2$ is the square of the frequency of the structure circle;

φ_{ij}^A --The value of the i th feature vector corresponding to the j th degree of freedom;

$\lambda_i^A,\varphi_{ij}^A$ --;The function of design parameter $\{r\}$;

λ_i^E,φ_i^E --Representing the eigenvalues and vibration modes of structural test modes respectively;

$W_{\lambda i},W_{\varphi i}$ --The weight coefficient of structural test frequency and vibration mode under different measurement accuracy conditions, and the weight matrix of frequency and vibration mode is to normalize the structural eigenvalue and vibration mode value.

3.2 Optimization Method of Ansys for Model Modification

In fact, model modification of structure is a kind of optimization, which modifies the structure by optimizing various parameters of the structure. In order to facilitate engineering application, this paper comprehensively adopts the first-order optimization and random search methods provided by ANSYS software to solve the problem of model modification.The first-order method transforms constrained problems into unconstrained ones by adding penalty functions to objective functions. It uses the partial derivative of the dependent variable to the design variable t, determines the search direction by gradient calculation in each generation, and minimizes the unconstrained problem by line search method.

Using the first-order analysis method, the above-mentioned constrained multivariable nonlinear programming problem is changed into unconstrained nonlinear programming problem, that is, the original objective function $F(a)$ is extended to a new function $Q(a,q)$:

$$Q(a,q)=\frac{F}{F_0}+\sum_{j=1}^{n}P_a(a_j)+q\left[\sum_{i=1}^{l_1}p_g(g_i)+\sum_{i=1}^{l_2}p_h(h_i)\right] \quad (3)$$

In which Q is an unconstrained objective function, F_0 is a reference objective function, and q is a parameter of control constraint. P_a is the external penalty function of design variables, and p_g, P is the mixed penalty function of state variables. For example, for a state variable g_i with an upper bound, its penalty function can be written as:

$$P_g(g_i)=\left(\frac{g_i}{g_i+a_i}\right)^{2\lambda} \quad (4)$$

In the formula, λ is a very large integer when the value of g_i exceeds the constraint; λ is a very small integer when the value of g_i is within the constraint range; a is the allowable error of g_i.

Gradient method is applied to solve unconstrained problems. The convergence criterion of optimization calculation adopts:

$$\left|F^{(j)}-F^{(j-1)}\right|\le\tau,\left|F^{(j)}-F^{(b)}\right|\le\tau \quad (5)$$

In, $F^{(j)},F^{(j-1)},F^{(b)}$ represents the objective function value of step j, step $j-1$ iteration and optimal step respectively, and τ is the allowable error of the objective function.

The first-order method may converge on the unreasonable design variable sequence, that is, fall into the unreasonable design space of “local optimum”. Therefore, it is necessary to run the random search method to determine the reasonable design space first, and then re-run the first-order method starting from the reasonable design sequence.

4. Result Analysis

ANSYS has powerful post-processing ability, which can not only display the unknown quantities of nodes under specific loads in various forms, such as node displacement, node stress, strain, etc., but also give the change of the unknown quantities of specified nodes with load (or time) in the whole process.

There are two post-processors in ANSYS: general post-processor and time-history processor. In the general post-processor processor, you can view the calculation result of the whole model at a certain moment; Time-history processor is generally used for dynamic analysis and multi-load step solution, and can watch the time history changes of the model. The post-processing module can display the calculation results in the form of color isoline display, gradient display and vector display, and can also display or output the calculation results in the form of charts and curves.

The model described in this chapter is calculated by ANSYS program, and the following results are obtained after analysis and arrangement:

4.1 Vibration Characteristic Analysis

The modal analysis of the initial equivalent simplified finite element model in 100 m tunnel area is carried out by using matlab platform. Table 1 shows the first five natural frequencies of tunnel structure, and Figure 1 shows the first four vibration modes of tunnel structure.

Table 1 the First Five Natural Frequencies of Tunnel Structure

Order	Self-vibration frequency/ Hz
1	2.3025
2	6.6387
3	12.0245
4	21.5096
5	33.7014

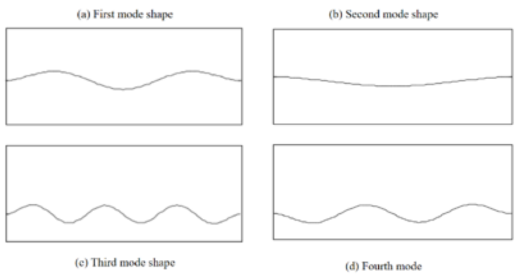

Fig.1 The First Four Modes of Tunnel

4.2 Internal Force of Middle Column

By analyzing the axial force nephogram of the center column, it is found that the maximum axial force of the center column occurs at the edge of the opening of the sinking square and the junction between the station and the roundabout. Statistics and calculations are made on the maximum axial force, axial compression ratio, maximum shear force and maximum shear bearing capacity of the middle column, as shown in Table 2. It can be seen from the table that the maximum axial force of reinforced concrete frame columns is 2117 kN, the axial compression ratio is 0.47, and the maximum shear force is 1128 kN, which is less than the maximum shear bearing capacity of 2 663 kN.

Table 2 Internal Force Of Middle Column

Load condition	Maximum axial force/kN	Axial compression ratio	Maximum shear force/kN	Maximum shear capacity/kN
1	22303	0.44	1027	2117
2	22570	0.47	1128	
3	22529	0.51	8963	

4.3 Seismic Response of Foundation Soil

It can be seen from Figure 2 that due to the uneven distribution of soil layers in the site, the horizontal ground motion displacement distribution of soil layers is unequal, and the displacement response changes with the change of soil layers. Among them, the displacement of upper backfill, silty clay and sand layer is remarkable. If the displacement acts on the station structure, it will cause large lateral deformation and even shear failure of the structure.

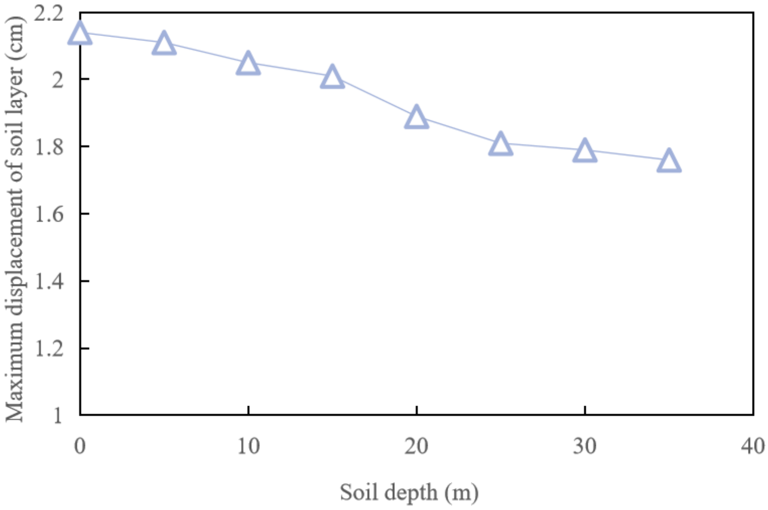

Fig.2 Variation Diagram of Maximum Displacement of Soil Layer with Depth

The inhomogeneity of site soil layer distribution has a great influence on soil layer displacement, especially in the shallow layer below the ground, and the horizontal displacement is obviously larger than that in the deep layer. The shearing effect of the relative displacement between soil layers on the structure can not be ignored. Considering the disturbance influence of construction on the foundation, the shearing force may be more obvious. Therefore, the underground structure itself should have enough ductility to bear the displacement of the soil layer to avoid shear failure. In addition, the large displacement of shallow soil will also affect the buildings on the ground.

Under the ground motion excitation assumed in this paper, due to the constraint of soil and the stiffness of the structure, the displacement of the station structure shows a strong integrity, and the maximum displacement at different points of the structure does not vary too much with different positions. However, due to the constraint difference of surrounding foundation soil, the structure will be deformed unevenly with the increase of vibration magnitude, resulting in torsion and shear, which should be paid enough attention to.

5. Conclusion

(1) Under the action of seismic fortification, the internal force of large underground space structure is larger than that of static calculation.

(2) Under different foundation cut-off ranges, the maximum displacement and acceleration response laws of each soil layer tend to be consistent. When the foundation range is taken as three times the bottom width of the structure, the dynamic calculation results are close to those of five times and ten times the bottom width. However, choosing a smaller ground interception range can save a lot of storage space and operation time. Therefore, the foundation range can be taken as three times the bottom width of the structure in the calculation.

(3) It is suggested that in the structural design of large underground space structures, besides static calculation conditions, seismic conditions should be comprehensively considered, and three-dimensional dynamic time-history analysis should be carried out in order to fully grasp its seismic

performance; At the same time, reinforcement measures should be taken at the opening in the design.

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