Seismic Response Analyses Method of Underground Structures in China

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Abstract: Seismic design of underground structures is an important part in earthquake engineering. Numerous simplified calculation methods have been raised in the seismic design of horizontal structures. According to the Chinese code in the seismic design of subway structure which was put forward 2014, it is crucial to take the practical demands of designers into consideration. This paper presents the calculation methods and procedures of seismic response analyses of underground structures that are commonly used in China. Comparisons are made to discuss the feasibility and reliability of existing methods, and some recommendations are proposed to provide a reference for designers.

Introduction

Along with the rapid development of urbanization in China, the amount of underground projects such as subways, underground garage, underground shopping malls and parking lots are increasing. Traditional knowledge indicates that underground structures would not suffer from catastrophe damages in earthquakes since they are adequately restrained by the surrounding soils. The opinions of engineers on underground structures seismic resistance performance have been changed due to damages on underground structures caused by recent earthquakes, especially in the 1995 Great Hanshin earthquake, in which the subway stations and interval tunnels are severely damaged. Meanwhile, underground structures have characterized by a high cost and a long term of usage. Thus, the seismic design of underground structures plays an important role in preventing the damages and hazards during an earthquake.

Development of seismic design theory in China

In recent years, a serious of researches on the earthquake resistance of underground structures have been conducted. Several methods of seismic response analyses are widely used in China, such as the inertial force method, equivalent horizontal acceleration method, response acceleration method, response deformation method, and time-history analysis method. Due to the different assumptions in selecting the seismic demand, different methods have been applied in different cases. Liu et al., [1] Tao et al.,[2] and Yu et al.,[3] made a comprehensive discussions on the index selection using different methods.

The seismic design methods of underground structures were developed relatively later in China than other countries. Shanghai firstly published a local seismic design code for underground structures in 2009, code for seismic design of underground structures and tunnels (DG/TJ08-2064-2009) [4] (noted as Shanghai Code in following part). This code provides four typical calculation methods of seismic responses of underground structures according to the theoretical research and model experiments: inertial force method, equivalent horizontal acceleration method, response deformation method and time-history analysis method.

In 2014, China officially announced a national seismic design code for underground structure, which is called *code for seismic design of urban tail transit structures* (GB 50909-2014) (noted as national code in following part). This code concludes the practical experience by referring some international advanced codes, and three kinds of methods are put

forward to calculate the earthquake response of frame structure: response acceleration method, time-history analysis method and response acceleration method

Calculation methods of seismic response

Five methods mentioned in the national code are discussed, which are inertial force method, equivalent horizontal acceleration method, response acceleration method, response deformation method, and time-history analysis method, associated with different assumptions and selections of index.

Inertial force method

As shown in figure 1, the inertial force method simplifies the structure into a frame with forces on the joints, and considers two parts of additional effects on the structure: the inertial force on the structure and the horizontal resistance force provided by the ground. The equivalent inertial force is expressed as:

$$F_{ij} = K_c \times Q_{ij} \qquad (1)$$

where K_c is the horizontal seismic resistant force index, and Q_{ij} is the concentrate mass of the joint. In most of methods, horizontal resistant force is derived according to the deformation of ground. In Shanghai code, the horizontal resistant force is assumed to be triangularly arranged, and the values can be derived through equivalent horizontal acceleration method, which is:

$$\sum P_k = \sum F_{ij} \qquad (2)$$

where $\sum P_k$ is the summation of horizontal resistant force on the ground which is arranged as triangle, and $\sum F_{ij}$ is the summation of inertial force of the structure.

In addition, Shanghai code added a maximum internal force correction coefficient, so that the results are more close to the result of time-history analysis method.

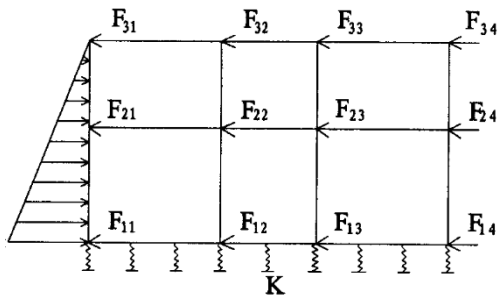

Figure 1 Diagram of the inertial force method

Equivalent horizontal acceleration method

This method is adopted only in shanghai code so far, and the basic principle of the method is to replace the horizontal acceleration time history by a static horizontal acceleration.

As shown in figure 2, H represents the thickness of soil; h_1, h_2 represent the depth of roof slab and baseboard, β_1, β_2 represent the accelerated velocity influence coefficient, 0.1g represents the designing value of basic earthquake accelerated velocity of buildings in seismic precaution area seven and with a return period of fifty years[4].

In this method, the basis of static acceleration distribution pattern is based on the experimental and time-history analysis results. Soft soils have an amplification effect on the earthquake acceleration and velocity [5]. The shear forces and axial

forces are determined by the introduction of a correction factor, by which the results is consistent with the dynamic time history method [6].

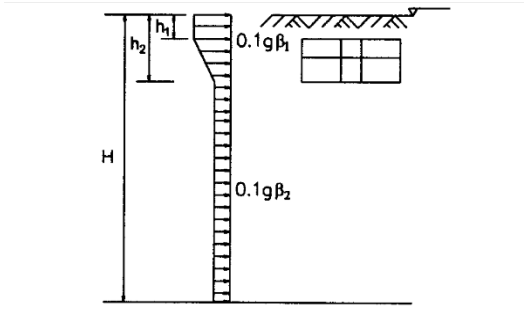

Figure 2 Diagram of equivalent horizontal acceleration method

Response acceleration method

This method is presented in the national cod. As shown in figure 3, elastic or elasto-plastic analysis can be made for the soil-structure system according to the position where the soil unit application imposed on the corresponding soil on, model structure also in accordance with the location of soil depth position level effective inertial acceleration and according to the requirements of the calculation, according to the static finite element method were linear elastic or elastic plastic analysis

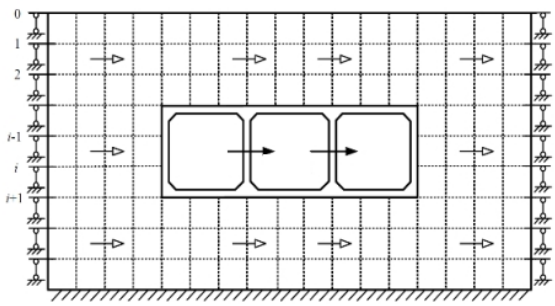

Figure 3 Response acceleration method calculation diagram

Soil underground structure at the position of occurrence time of maximum deformation into soil layer shear stress distribution can be through one-dimensional seismic response of soil layer calculation method for calculating, such as the use of equivalent linear program SHAKE91, eera, RSLNLM etc., or general finite element analysis software MSC. Marc and analysis. This method is based on the calculation of the effective inertia acceleration of the structure part, so the complex section structure can be calculated by using this method.

Response deformation method

This method is widely used all over the word due to its clear physical conception and its real simulation of the mechanics characteristic of structures [6]. What comes along is the complication of the coefficient selection. The coefficient selection method is different even between national code and Shanghai code. The main differences are as follows.

The arrangement of foundation spring

It can be seen from figure 4 and figure 5 that in national code, the calculation model has foundation springs in both tangential direction and normal direction, while in Shanghai code, no springs are settled on the top of the structure.

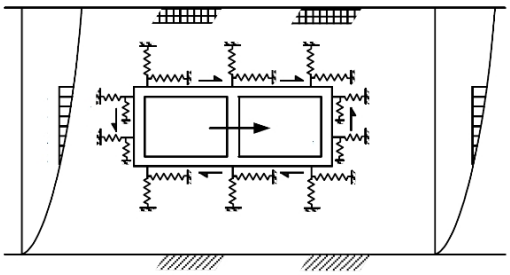

Figure 4 Response deformation method in national code

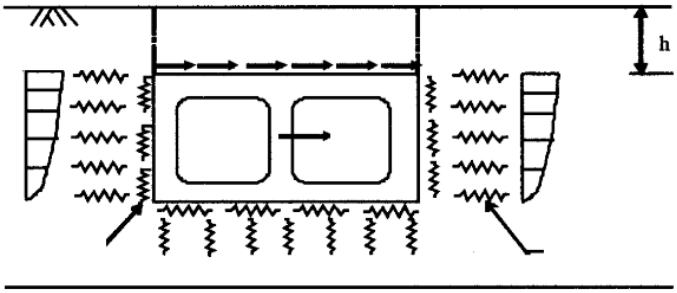

Figure 5 Response deformation method in Shanghai code

The method to determine dynamic shear modulus

Dynamic shear modulus G_m is an important coefficient in the dynamic analyses. In national code, the value of G_m is calculated using the flowing equation:

$$G_m = \rho_m \times C_S^2 \tag{3}$$

where ρ_m represents the soil density, and C_s represents shear wave velocity of soil. Shanghai code adopted the Davidenkov model, providing the evaluation equation as:

$$G_m = \alpha \times \frac{(2.97-e_0)^2}{1+e_0} \times (\sigma_v')^{\frac{1}{2}} \tag{4}$$

where α is decided by the type of soil, details are shown in figure 5.3.4 in Shanghai code; e_0 is the initial void ratio of soil; σ_v' is the effective overlying soil pressure .

The shear force on structure surface

It can be seen from figure 4 and figure 5 that the national code adds the shear force on all around the structure. The value of shear force can be determined by the finite-element method or response spectrum method, that is, determine the strain through soil deformation differential. Finally, calculate the shear force in soil:

$$\gamma(xz) = -\frac{\pi}{4H} \cdot u_{max} \cdot \sin\frac{\pi z}{2H} \tag{5}$$

$$\tau = G \cdot \gamma(xz) \tag{6}$$

where τ represents the shear force on the surface, G represent the dynamic shear modulus and $\gamma(xz)$ is the strain of soil (It can be assumed that deformation of soil changes along with depth in sinusoidal variation pattern)

In Shanghai code, the shear force is only added on the roof slab of structure, the shear force on side face and on bottom

slab was ignored. Shear spring is added on the side face and bottom slab to satisfy compatibility of deformation. Equation in Shanghai code is as follows:

$$\tau = \frac{G}{\pi h} S_V T_s \tag{7}$$

where G is the dynamic shear modulus, T_s is the natural period of soil above the roof slab, S_V is the velocity spectrum acting on the bottom boundary in calculation area[7], and h is the depth of soil above the roof slab.

The determination of foundation spring coefficient

Spring foundation coefficient of determination is a difficult point in response displacement method, parameter determination and the size of the coefficient of subgrade spring will also affect the equivalent load of lateral soil and constraints on the structure deformation. At present, the most reliable method for determining the spring coefficient of the foundation is static finite element method. The national code and Shanghai code use the method of static finite element, and the soil layer is modeled, and the soil of structural position is removed. The normal direction (horizontal direction) or tangential (vertical direction) units of the structural side surface are distributed load, so that the displacement can be obtained. The numerical value of the spring system can be obtained according to the force and displacement.

$$K=P/\delta \tag{8}$$

where K is the base spring coefficient, P is the unit uniform load, and δ is the displacement along the load direction.

Conclusion

Inertial force method is popular in Chinese codes due to the simplicity, and it can provide preliminary results of structural seismic response.

Equivalent horizontal acceleration method transforms the dynamic analyses into a static calculation process, so as to improve the computational efficiency.

The response acceleration method adopts an analysis model for soil and structure, and it can directly reflect the soil-structure interaction.

The response displacement method can truly reflect the underground structure stress characteristics.

Time history analysis method has a higher computation requirement. At the same time, this method can adequately reflect the soil-structure interaction during an earthquake. The application of this method is limited due to the unfriendliness to engineering designers。

Differences between the national code and Shanghai code in China are compared in terms of various methods in seismic response analysis.

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