

PAPER • OPEN ACCESS

Research Onquasi-Static Calculation for Seismic Response of Underground Rock and Soil

To cite this article: Leiyu Zhang *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **252** 052053

View the [article online](#) for updates and enhancements.

Research Onquasi-Static Calculation for Seismic Response of Underground Rock and Soil

Leiyu Zhang*, Xuejing Shen, Yanhong Wang, Yuxin Zhou

Army Military Transportation University, Tianjin, China

*Corresponding author e-mail: dzx0413@sina.com

Abstract. This paper analyzes the common quasi-static calculation error sources for seismic design of underground rock structure cross-section. For the current seismic underground rock response, the finite element reaction displacement method and the finite element reaction acceleration method are used for comparative calculation to a specific geological condition. The structure of the metro station changes the applicability of seismic wave, structural stiffness, coating stiffness and structural depth to the quasi-static actuarial. It is found that the finite element response stress method is the closest to the dynamic analysis results. It is a quasi-static calculation method with high precision and applicability, which can be used for seismic response analysis of underground geotechnical structures.

1. Introduction

The development and utilization of underground space is an inevitable choice and an important way for the sustainable development of urbanization in China [1]. At present, underground structures are widely used in urban construction, transportation and other fields [2]. In the recent large earthquakes, underground structures have produced varying degrees of damage, which has attracted researchers at home and abroad to pay attention to the seismic resistance of underground structures. Many scholars have proposed a variety of underground structures based on the reaction and destruction of underground structures in earthquakes. Seismic response calculation method.

The theoretical basis of the pseudo-static method is that the underground structure deforms with the deformation of the surrounding soil during the earthquake, and the dynamic characteristics of the structure itself cannot be reflected. The damage caused by the structure is mainly determined by the deformation and the extension performance of the structure itself [3]. In the late 1960s, American scholars conducted a more in-depth study on the seismic resistance of underground structures and proposed this design idea [4]. Later, Shukla, John and Zahrah applied the principle of elastic foundation beam and adopted the quasi-static method to consider the interaction between soil and structure and established a calculation model. In the 1970s and 1980s, Japanese scholars proposed various practical quasi-static methods based on seismic observations and model tests, combined with wave theory, to enrich and improve the seismic design theory of underground structures.



2. Error analysis of common quasi-static calculation method and quasi-static calculation method

2.1. Quasi-static calculation method

The seismic coefficient method is developed from the static theory, which equalizes the seismic load to a static load, assuming that the structure is subjected to inertial forces under the action of the earthquake, the active side pressure of one side of the soil, and the soil of the other side. Resistance, in order to calculate the structural seismic response.

The free field deformation method is based on the fact that the seismic response of the underground structure mainly depends on the deformation of the surrounding soil layer. The deformation of the free-soil layer under the action of the earthquake is applied to the structure as the structural deformation, and the seismic response of the structure is calculated by the loading method.

On the basis of the free-field deformation method, the soil-structure interaction coefficient method considers the mutual coordination effect caused by the difference of soil-structure stiffness. The deformation of the free-soil layer is multiplied by the interaction coefficient as the deformation of the underground structure, and the seismic response of the structure is calculated.

The reaction displacement method uses a foundation spring to reflect the interaction between the soil-structure due to the difference in stiffness. The method assumes that the underground structure is subjected to three earthquakes in the earthquake due to the relative displacement of the soil layer, the structural inertial force and the shear force around the structure [5].

The reaction acceleration method draws on the idea of the static elastoplastic method of the above-ground structure, and combines the seismic response characteristics of the underground structure to analyze the horizontal volume force in the soil-structure interaction model. In the specific implementation, the horizontal effective response acceleration is applied to the underground structure and the surrounding soil layer according to its position, that is, a horizontal effective inertial force is applied in the model to simulate the earthquake action and reflect the soil-structure interaction.

2.2. Error analysis of quasi-static calculation method

The error sources of the reaction displacement method are mainly as follows: First, it is difficult to accurately estimate the stiffness value of the soil spring whether it is through the load test or the seismic observation result, and the change of the stiffness value of the soil spring has a great calculation result for the internal force of the structure. Secondly, in the spring-beam model of the reaction displacement method, the equivalent springs of the soil are irrelevant, which makes the interaction of the soil itself not visible during the earthquake, causing the soil to surround the structure. The load distribution of the contact surface brings errors, which cannot truly reflect the dynamic force of the soil on the structure during the earthquake, especially the stress distortion of the corners of the structure connected with the soil is not well reflected.

The ground motion load input by the reaction acceleration method is converted from the reaction acceleration of the free-soil layer to determine the reaction displacement of the soil layer. In terms of kinetic theory, this is only a certain degree of approximation. If the soil layer reaction only has a first-order mode, the accuracy of the method is acceptable, and the error will increase when encountering complex soil layers [6]. Some scholars have used the method of forcing the reaction displacement of one-dimensional soil layer to the boundary of both sides of the finite element model, but this method does not have enough theoretical basis, and the soil at the boundary between the two sides develops in the horizontal normal stress, changing the state of the real stress field of the soil layer during the earthquake.

3. Quasi-reaction acceleration method for calculating quasi-static model of seismic response of underground rock and soil

For a multi-mass system, the dynamic equation expression is as follows.

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{P\} \quad (1)$$

In the formula, $[M]$ is the mass matrix, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix, $\{\ddot{u}\}$ is the acceleration vector of the particle system, $\{\dot{u}\}$ is the velocity vector, $\{u\}$ is the relative displacement vector, and $\{P\}$ is the applied force vector received by the particle.

Assuming a laterally uniform soil medium, the vibration can be expressed by dividing the soil layer vertically into a one-dimensional multi-mass point-spring system (string-shaped particle-spring system). The structure is buried in the soil, but only a part of the longitudinal depth of the entire soil layer, except for the bottom mass point being subjected to an external force due to the input of the forced acceleration, and the remaining area $\{P\} = \{0\}$. We are interested in the free vibration mode of the one-dimensional soil layer, which can be transformed into:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{0\} \quad (2)$$

$$\text{So, } [M]\{\ddot{u}\} + [C]\{\dot{u}\} = -[K]\{u\}.$$

Under the action of ground motion, when the free-soil layer at the upper and lower bottom positions of the structure has the largest relative displacement, since the whole vertical straight soil layer is a multi-mass system, the free-soil layer above the structural position is due to the high-order mode. The maximum value of the relative displacement is not reached at the same time, in other words, there is an expression:

$$[M]\{\ddot{u}\} \neq -[K]\{u\} \quad (3)$$

For the underground structure, the most unfavorable state of the structure is the maximum relative deformation of the structural roof and the bottom plate. The effective reaction acceleration is calculated by using the shear stress distribution of the free-soil layer at this moment, as shown in Fig. 1.

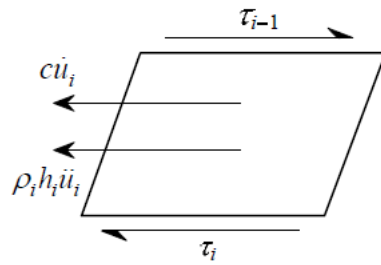


Fig. 1 Horizontal effective reaction acceleration solution method

At this moment, the equation of motion of the i -th layer soil unit is expressed as follows.

$$\tau_i - \tau_{i-1} + \rho_i h_i \ddot{u}_i + c_i \dot{u}_i = 0 \quad (4)$$

Where: τ_{i-1} and τ_i are the shear stresses at the top and bottom of the i -th layer soil unit when the underground structure is maximally deformed; ρ_i is the density of the i -th layer soil unit; h_i is the

thickness of the i -th layer soil unit; c_i is the medium damping Coefficient; \ddot{u}_i and \dot{u}_i are the acceleration and velocity of the i -th layer soil unit, respectively. There are expressions:

$$a_i = \frac{\tau_i - \tau_{i-1}}{\rho_i h_i} \quad (5)$$

Where a_i is the horizontal effective response acceleration of the i -th layer soil unit.

4. Case analysis

The subway underground station structure is a two-story three-span island structure with a cross-section width of 21.2m and a height of 13m. It adopts a circular center column with a longitudinal spacing of 9m and a diameter of 0.8m. It is converted into a thickness of 0.8 during calculation. For the longitudinal wall of m, the equivalent stiffness is calculated according to the longitudinal extension direction of the column. The concrete material is C30, the elastic modulus is 30GPa, the steel bar is HRB335, and the elastic modulus is 200GPa. The cross-sectional dimensions and reinforcement of the station are shown in Figure 2.

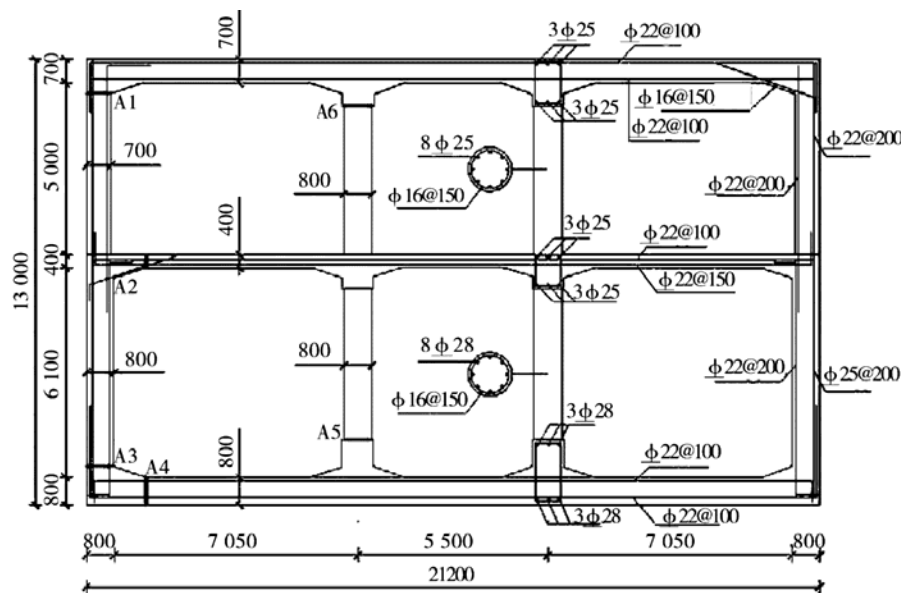


Fig. 2 Station model size and reinforcement map (unit: mm)

Assume: (1) The structure and soil of the station do not slip and separate during the ground motion; (2) The reinforced concrete does not consider nonlinearity, the elastic modulus adopts the composite modulus according to the reinforcement ratio; (3) The ground motion during the process, the soil is in an undrained state, and the Poisson's ratio is 0.49. The calculated depth of the soil layer is 60m, and the soil layer distribution is shown in Table 1. The bottom of the model constrains the vertical displacement, the side adopts the horizontal slip boundary, the soil adopts the reduction integral unit, and the station structure adopts the full integration unit.

Tab. 1 Soil layer profile and constitutive model parameters

Soil layer number	1	2	3	4	5	6
Coating description	Muddy silty clay	Fine sand	Fine sand	Silty clay	Silty clay	clay
Thickness (m)	4	15	7	15	6	13
Bottom depth (m)	4	19	26	41	47	60
Initial shear modulus (MPa)	25	47.9	89.5	127.3	168.1	242.6
Severe (kN/m ³)	19.2	18.7	19	20.2	20.7	19.8
Shear wave velocity v_s (m/s)	114	160	217	251	285	350
Reference shear strain ($\times 10^{-4}$)	3.2	3.5	4	3.4	3.8	4.1
Cohesion (kPa)	13.5	7	7	20	15	15.2
Internal friction angle ($^\circ$)	12.6	12	35	21	16	15.2

4.1. Finite element reaction displacement method

(1) Using the seismic response analysis software Proshake to extract the soil acceleration a , the displacement u and the strain-compatible shear modulus G at the maximum relative displacement of the top and bottom of the station structure; (2) using commercial software such as ABAQUS the free-field model is established on the platform, and the lateral and bottom boundaries are fixed. The displacement obtained in step 1 is applied to the soil boundary corresponding to the station structure, and the corresponding inertial force is applied to the interior of the soil. The node reaction force on the boundary; (3) the soil-structure interaction model is established based on commercial software such as ABAQUS. The fixed lateral and bottom boundaries are applied to the structure in the form of nodal forces generated in step 2, and a corresponding inertial force is applied to the structure to obtain the seismic response of the underground station structure.

4.2. Finite element reaction acceleration method

(1) Using the seismic response analysis software Proshake to extract the inter-layer shear stress, displacement and strain-dependent shear modulus of the top and bottom maximum relative displacement moments of the station structure; (2) Converting the inter-layer shear stress It is the horizontal effective acceleration of the soil layer a ; (3) The soil-structure interaction model is established by the finite element software ABAQUS. The bottom of the model is a fixed boundary and the side is a horizontal slip boundary. The seismic response of the underground station structure can be obtained by applying the horizontal effective acceleration calculated in step 2 to the entire system.

4.3. Earthquake input

The input ground motion is artificial wave, and the original ground motion time history is shown in Figure 5. In order to compare the effects of different ground motions on the calculation results of the reaction displacement method, the reaction acceleration method and the nonlinear dynamic time history method, the ground motion peak acceleration is taken as three levels of 0.05g, 0.1g and 0.2g, which closely represent small earthquakes. The role of medium earthquakes and large earthquakes.

4.4. Analysis of results

The stiffness of the underground structure is compared with the calculation of the bending moment. The stiffness of the underground structure has a significant effect on the seismic effect of the structure. For a specific structural section shape, the lateral stiffness is positively related to the elastic modulus of the material. At present, the concrete strength of underground structures ranges from C15 to C80, and the corresponding elastic modulus ranges from 22 GPa to 38 GPa. Considering the effect of

reinforcement on the composite elastic modulus of the structure, the underground structure is applied to the example in Section 2.1. The composite elastic modulus is assumed to be 22 GPa, 28 GPa, 34 GPa, 40 GPa, and 46 GPa, respectively. The bending moment output portion still takes the sections A1 to A6 in Fig. 1, and the calculation result is shown in Fig. 3. It can be seen that the bending moment values calculated by different methods increase with the increase of the stiffness of the underground structure. The bending moment growth of the two quasi-static methods is significantly higher than the dynamic time history method, and the structural composite elastic modulus is 22 GPa. The pseudo-static method and the dynamic time-course method are relatively close. When the structural composite elastic modulus is increased to 46 GPa, the error of the two pseudo-static methods relative to the dynamic time-course method is about 50%. The calculation results of the reaction displacement method and the reaction acceleration method are almost identical, and the degree of consistency is not affected by the stiffness of the underground structure.

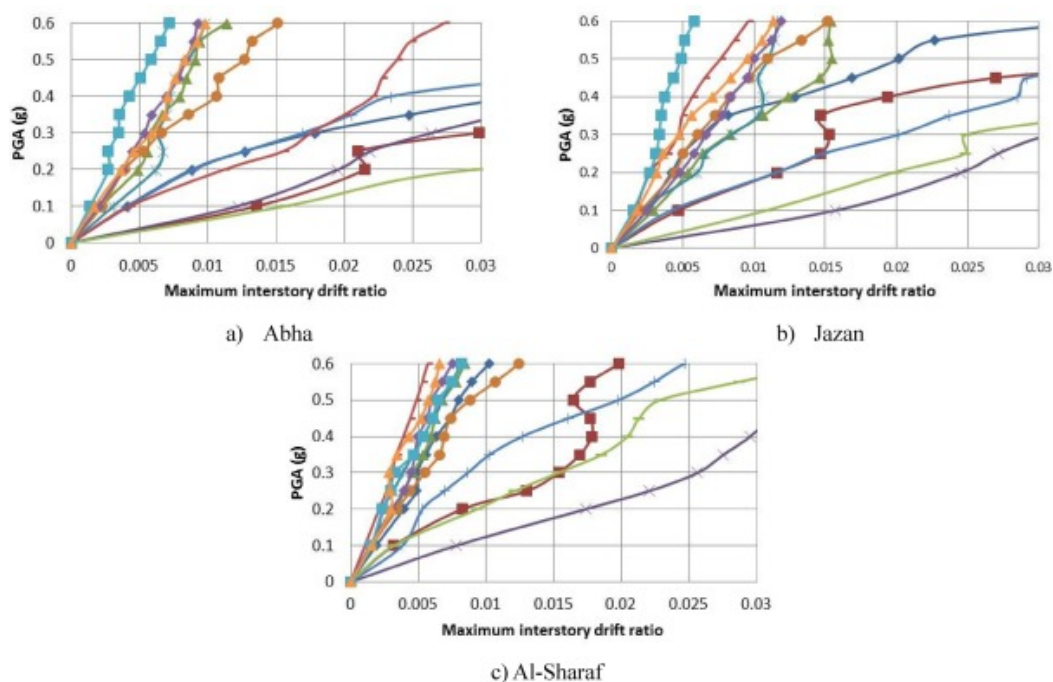


Fig. 3 Variation of the bending moment of different sections of the underground structure with the elastic modulus of the material

5. Conclusion

When the small earthquake is applied, the calculated bending moment of the reaction displacement method and the reaction acceleration method is slightly larger, and the error is less than 6%. When the medium earthquake is applied, the calculated bending moments of the two quasi-static methods are large, and the error is up to 20%. In the case of large earthquakes, the calculated bending moment deviations of the two quasi-static methods are too large, and the error can exceed 50%. From the economic point of view, it is unacceptable that the difference between the calculation results of the reaction displacement method and the reaction acceleration method is small, and the difference is similar. The degree is basically not affected by factors such as ground motion strength, structural rigidity, and buried depth of the structure.

References

- [1] YAN Mao-tian, LI Zhan, FAN Qinglai. Quasi-static seismic stability analysis of earth-rock dam and estimation of seismic slip of dam slope. *Rock and Soil Mechanics*, Vol.2 (2007) No.28, p.224-230.

- [2] LI Zhan, YAN Mao-tian. Strength reduction finite element method for quasi-static seismic stability analysis of earth-rock dam. *Rock and Soil Mechanics*, Vol.5 (2010) No.31, p.1503-1508.
- [3] Zhu Yuyu. Pseudo-static test study on seismic performance of reinforced concrete frame stairwell. *Beijing University of Technology*, Vol.4 (2012) No.28, p. 103-105.
- [4] ZHAO Jun, HOU Pengcheng, LIU Min, et al. Pseudo-static test study on seismic behavior of concrete frame stair structures. *Journal of Building Structures*, Vol.12 (2014) No.35, p.44-50.
- [5] Li Wei. Research on database structure of pseudo-static test for seismic performance of pier columns. *Chongqing Jiaotong University*, 2010. Vol.4 (2015) No.28, p. 103-105.
- [6] Cai Xinjiang, Gong Muhua, Jia Hongxing, et al. Quasi-static and hybrid experimental study on seismic behavior of solid-section steel-reinforced concrete cross-section columns. *Journal of Building Structures*, Vol.5 (2016) No.37, p.146-154.