Numerical Study on Soil Width in Quasi-Static Pushover Test of Soil-Underground Structure System

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Abstract: Based on the test results of series quasi-static tests carried out by JSCE Committee, the rationality of the numerical model for quasi-static test of soil-underground structure system was verified. Then a quasi-static pushover test scheme was introduced, the verified numerical model was adopted to study the reasonable range of soil width in the quasi-static pushover test of soil-underground structure system. The results indicated that for this quasi-static pushover test scheme, when \( \alpha \) (\( \alpha \) is the ratio of the distance from boundary to the model structure to the model structure’s width) is 0.5 to 1.2, error of the seismic capacity of the key structural components obtained by the test method is relatively small.

1. Introduction

Due to the constraint of surrounding soil, the seismic performance of underground structure is better than that of above-ground structure. However, there were still some underground structures damaged in recent earthquakes, this phenomenon indicates that underground structure may also be severely damaged under strong earthquakes, therefore, it is necessary to research seismic response characteristics and seismic performance of underground structures systematically[1-3].

Experimental method is an effective method to study seismic problems of underground structures[4-5]. Quasi-static pushover test of soil-underground structure can get seismic failure form and seismic failure mechanism of underground structures, and this test method has many advantages, such as large geometric scale, real materials, and can simulate initial ground stress and the soil-structure interactions. The first quasi-static test of soil-underground structure system was carried out by JSCE Committee [6]. In the test, the model box was composed by rigid walls, the object of the test was a two vents box culvert, vertical load was applied on the top surface of soil to increase soil stress, the top of the rigid wall was pushed to rotated for simulating the earthquake action, and the test results indicated that the soil-structure stiffness ratio has a great influence on the soil-structure interactions. Xu[7-8] carried out the quasi-static pushover test of soil, this test adopted rigid walls as the model box, the object of the test was free field, this test researched the attenuation law of soil strain and the relationship between soil pressure and soil displacement in the middle of soil. In the quasi-static pushover test of soil-underground structure, the model box composed of rigid walls cannot well reflect the shear deformation of soil under horizontal earthquake, therefore, Du et al. [9] developed laminar shear box for quasi-static pushover test of soil-underground structures, and it could impose different distributions of forced horizontal displacement on the soil-structure system[10].

However, the cost of this test method is high and test procedures are complex, the research work of this test method is still rare. Especially, in order to stabilize the test results and reduce test costs, the
soil width in quasi-static pushover test of soil-underground structure system needs to be in reasonable range. The numerical simulation method is used to research this question in this study.

2. Verification of the numerical models

The experiment of two vents box culvert carried out by JSCE Committee[6] is hereinafter referred to as Exp.S test, the experiment of soil-structure system(CASE A) carried out by JSCE Committee[6] is hereinafter referred to as Exp-SSI test. The Exp.S test and the Exp-SSI test are taken as verification tests in this research.

The Exp.S test is used to verify the numerical model of quasi-static test of structure. The model structure was a two vents box culvert, there was load point load at the middle and two supports at the edges, and the test scheme is shown in Fig. 1.

![Fig. 1 Diagram of the Exp.S test scheme](image)

The numerical analyses are carried out using the finite element software ABAQUS, a 2-D numerical model is built under the plane strain conditions. The material mechanical behaviour of concrete adopts the concrete damaged-plasticity constitutive model[11] to simulate and the material mechanical behaviour of steel adopts the steel ideal elastoplastic constitutive model to simulate. The structure is meshed with CPE4R elements and rebar is meshed with truss elements. Rebar and structural properties are the same as the parameters given in the test. Relationship between total load and the vertical displacement at point A is shown in Fig. 2, it can be seen that the vertical bearing capacity-displacement curve of the structure calculated by numerical simulation is close to the test results. So the numerical model of quasi-static test of structure in this paper is reliable.

![Fig. 2 Relationship between the total load and vertical displacement at point A in the Exp.S test](image)
A 2-D finite element model is built by the software ABAQUS. The soil-structure interfaces are defined as frictional contact in the tangential direction, and the friction coefficient is 0.4[12]. The rebar is planted into the concrete and the sliding between the steel and the concrete is not considered. The constitutive model of the soil adopts the Davidenkov constitutive model[13], the numerical model of structure adopts the previous verified numerical model. Select proper parameters of Davidenkov constitutive model for soil material in the numerical model of the Exp-SSI test, the relationship of horizontal force and displacement of soil-structure system is shown in Fig. 5. The load-displacement relationship obtained by the numerical method is similar to the test results, so the numerical model of quasi-static test of soil-structure system in this study is reliable.
3. Test Scheme and the numerical models

Fig. 6 shows a quasi-static pushover test scheme of soil-underground structure system. In this test, the model structure is a scaled model structure of Daikai subway station[14], the geometric scale ratio of model structure to prototype structure is 1/5, the width of the model structure is 3.4m and the height is 1.434m, the central column has a rectangular cross-section, the length and width are 0.2 m and 0.08 m respectively, the longitudinal clear distance between the adjacent columns of the model structure is 0.5m, the model structure’s cross-section is shown in Fig. 6. The reinforcement ratio of the model structure is the same as that of the Daikai station [14].

Numerical model of the test method and numerical model of the Pushover analysis method are established[15]. Diagram of the Pushover analysis method model for the test is shown in Fig. 7. The software ABAQUS is used to build a 2-D finite element model to analyse the Exp-SSI test. Previous verified numerical model is used to establish the numerical models. The concrete strength level is No.C30, its density is 2500kg/m³, elastic modulus is 30GPa, Poisson’s ration is 0.2, and the uniaxial tensile and compressive stress-strain curves of concrete are shown in Fig. 8. For a 2-D numerical model, the columns should be equivalent to a wall, in order to keep the same material properties in the numerical model, the equivalent elastic modulus of column should be 8.57 GPa, and the equivalent density should be 714 kg/m³[12]. The steel strength level is HRB400, and its density is 7800kg/m³, elastic modulus is 200GPa, Poisson’s ration is 0.3. The model soil is sand, and its density is 1800kg/m³, elastic modulus is 150MPa, Poisson’s ratio is 0.3, parameter A=1.1, parameter B=0.35, parameter $\gamma_0=0.00038[11]$. In numerical model of the test method, the horizontal displacement distribution on the lateral boundary of soil-structure system adopts inverted triangular distribution. In numerical model of the Pushover analysis method, the horizontal inertia force also adopts inverted triangular distribution. The horizontal displacement and the horizontal acceleration monotonically increasing until structure is damaged.

Fig. 6 Diagram of a quasi-static pushover test scheme.

Fig. 7 Numerical model of the pushover analysis method.
4. Influence of soil width
The numerical result of the Pushover analysis method is taken as the exact solution in this research. In the numerical model of the test method, the distances from boundary to the model structure are taken as 0.5B, 0.68B, 1B, 1.2B, 1.4B, 1.6B, 1.8B, 2.0B respectively for research (B is the model structure’s width), the numerical results of the test method with different $\alpha$ ($\alpha$ is the ratio of the distance from boundary to the model structure to the model structure’s width) can be obtained. By comparing numerical results of the test method with numerical results of the Pushover analysis method, the influence of soil width on errors of the test method is shown in Fig. 9. When the shear capacity of mid-column decreases to 85% of the peak value, the inter-storey drift is the limit inter-storey drift of the structure. For this test, the error of the seismic capacity of mid-column obtained by the test method increase slightly with the increase of $\alpha$, when $\alpha$ is about 0.7, the error of the test method is the smallest. In general, when $\alpha$ is 0.5 to 1.2, the error of the seismic capacity of mid-column is basically within 10%.

5. Conclusion
In order to improve the accuracy of the test results and reduce the test costs, the soil width in the quasi-static pushover test of soil-underground structure system should be in a reasonable range. This paper verified the validation of a numerical model of quasi-static pushover test based on the series tests carried out by JSCE Committee, and then the verified numerical model is used to study the reasonable range of soil width in a quasi-static pushover test of soil-underground structure system. For
this quasi-static pushover test scheme, the test method has good accuracy when $\alpha$ is 0.5 to 1.2. Therefore, numerical method can be used to research reasonable soil width before quasi-static pushover test of soil-underground structure is carried out.

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**References**

[1]. Youssef M.A. Hashash A, Jeffrey J. Hook A, Birger Schmidt B, John I-Chiang Yao A. (2001) Seismic design and analysis of underground structures. Tunnelling & Underground Space Technology Incorporating Trenchless Technology Research, 16: 247-293.

[2]. Li W, Chen Q. (2020) Effect of vertical ground motions and overburden depth on the seismic responses of large underground structures. Engineering Structures, 205: 110073.1-110073.18.

[3]. Chen G, Chen S, Du X, Lu D, Qi C. (2016) Review of seismic damage, Model test, Available design and Analysis methods of urban underground structures: Retrospect and Prospect. Journal of Disaster Prevention and Mitigation Engineering, 36: 1-23.

[4]. Zhuang H, Fu J, Chen S, Chen G, Wang X. (2019) Liquefaction and deformation of the soil foundation around a subway underground structure with a slight inclined ground surface by the shaking table test. Rock and Soil Mechanics, 40: 1263-1272.

[5]. Zheng Y, Yue C. (2020) Shaking table test study on the functionality of rubber isolation bearing used in underground structure subjected to earthquakes. Tunnelling and Underground Space Technology, 98: 103153.1-103153.18.

[6]. Shawky A. A. (1994) Nonlinear static and dynamic analysis for underground reinforced concrete. Doctoral Dissertation, University of Tokyo, Tokyo, Japan.

[7]. Xu K. (2019) Study on pseudo-static seismic analysis method of underground structures and pushover test. Master’s Thesis, Institute of Engineering Mechanics, China Earthquake Administration, China.

[8]. Xu K, Jing L, Bin J, Cheng X, Liang H. (2020) Experimental study on the coefficient value of subgrade reaction in seismic analysis of underground structures. Journal of Southwest Jiaotong University.

[9]. Du X, Xu Z, Xu C. (2020) A large quasi-static testing device and method for underground structures. https://d.wanfangdata.com.cn/patent/CN201710432131.0.

[10]. Han R, Xu C, Du X, Xu Z. (2021) Optimization of model box type in quasi-static pushover test of soil-underground structure system. Rock and Soil Mechanics, 42: 462-470.

[11]. Zhuang H, Hu Z, Wang X, Chen G. (2015) Seismic responses of a large underground structure in liquefied soils by FEM numerical modelling. Bulletin of Earthquake Engineering, 13:3645-3668.

[12]. Xu Z, Du X, Xu C, Hao H, Bi K, Jiang J. (2019) Numerical research on seismic response characteristics of shallow buried rectangular underground structure. Soil dynamics and earthquake engineering -Southampton-, 116:242-252.

[13]. Zhuang H. (2006) Study on nonlinear dynamic soil-underground structure interaction and its large-size shaking table test. Doctoral Dissertation, Nanjing university of technology, Nanjing, China.

[14]. Nakamura S. (1995) Investigation, analysis and restoration of collapsed daikai subway station during the 1995 hyogoken nanbu earthquake. Geotechnical engineering in recovery from urban earthquake disaster, 97:367–76.

[15]. Liu J, Liu X, Li B. (2008) A pushover analysis method for seismic analysis and design of underground structures. China civil engineering journal, 04:73-80.