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Research Article

Drift Ratio Limit for the Seismic Design of Underground Structures

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Abstract

The drift ratio of underground structures is an important seismic de-sign index in China's Seismic Design Code. However, existing elastic and elasto-plastic limit of drift ratio are adopted from ground structures, and those of under-ground structures have yet to be comprehensively studied. Based on the design practice of underground structures in China, a set of finite element pushover analysis is conducted on underground structures in this paper to investigate the seismic deformation of six common subway stations. A technique of combining beam elements with quadrilateral elements is utilized to capture the realistic elasto-plastic behavior of structural components. Computation results show that 1/550 and 1/1000 are appropriate elastic drift ratio limiting values for underground structures two stories or lower and underground structures three stories or high-er, respectively. The elasto-plastic drift ratio limit of 1/250 that is adopted from China's Code for Seismic Design of Building (CCSDB) is a conservative limit-ing value. The influence of buried depth and soil stiffness is also analyzed.

Keywords: Underground Structure; Drift Ratio; Elastic Limit; Elasto-Plastic Limit

Introduction

In the seismic design of underground structures, drift ratio θ is usually defined as:

$$\theta = \Delta/h \quad (1)$$

where Δ is the relative horizontal displacement between the top and the base while h is the height of the structure. Drift ratio is a practical index for evaluating the seismic deformation for underground structures, which is often used as a reference for the design of structural stiffness [1]. However, comprehensive studies on drift ratio have yet to be conducted for underground structures. In 2010, China's Code for Seismic Design of Buildings (CCSDB) adopts an elasto-plastic drift ratio limit of 1/250 for underground structures from the design code for ground structures. But for under-ground structures, there is little experimental or numerical validation of these limiting values in previous research. As a result, drift ratio, which plays an important role in quantifying the seismic performance, remains unclear for practical design.

In this paper, a set of pushover analysis is performed on six underground subway stations to obtain their elastic and elasto-plastic drift ratios [2]. The elastic drift ratio θe is the drift ratio at which the first plastic hinge occurs in the structure, the elasto-plastic drift ratio θp is the drift ratio at which the structure or part of the structure be-comes a mechanism.

Numerical Analysis Detail

Plane strain pushover analyses are performed on six station structures through the OpenSees finite element platform. Station 1, 2 and 3, which are box structures with reinforced concrete columns, are constructed using the cut-and-cover method at the burial depths of 2m and 4m. Station 4, 5 and 6, which have an arched crown and concrete-filled steel tube columns, are constructed using the undercutting method at the burial depths of 5m, 10m and 15m. Each structure has three spans apart from station 1, which has just two spans. Station 1, 2 and 4 has two stories, while station 3 and 5 are three-storied. Station 6 is a triple-arched structure with only one story. Be-sides, the dynamic Young's modulus of surrounding soil is set as 10, 150 and 300MPa in the analyses. These three values of dynamic Young's modulus represent the stiffness of soft clay, loose sand and dense sand in a strain range between 0.3% and 1.5% [3].

As shown in figure 1, the surrounding soil is considered elastic isotropic at a depth of 50m, discretized with the quadrilateral elements, while structural components are modelled using a technique of combining quadrilateral elements and beam elements with fibre section, in order to simulate the realistic elasto-plastic behaviour of rein-forced concrete structure [5]. The compressive strength of concrete is 16.7 MPa and the yield strength of steel is 335 MPa. The columns are modeled according to their geometric size, and the thickness of soil elements and structure elements is set up to be the same as the spacing of columns.

Figure 1: Mesh configuration of soil and structure for one station.

Analysis starts with a geostatic step to calculate the structure's initial internal force before pushover loading. After the initial step, an inverse-triangular horizontal dis-placement toward right is applied to both sides of soil boundary to perform pushover analysis [4]. The internal force and nodal displacement of the structures are recorded to determine the occurrence of plastic hinge and the failure of the structures.

Computation Results

Typically, plastic hinge first occurs at the left bottom of the lowest story's outer wall, and when plastic hinge occurs at the top of the same wall, the structure becomes a mechanism. At these two moments, the relative horizontal displacement between the top and the base is recorded to calculate the elastic and elasto-plastic drift ratio. Sta-tions 1 to 5 tend to end up with overall failure, that is to say, all of the walls and col-umns in the lowest story fail at their both ends. Station 6 ends up with local failure as the left side arch becomes a mechanism.

Figure 2 consists of three scatter plots which present the drift ratio values obtained from numerical analysis with a baseline indicating a limiting value on each plot. It shows that the higher an underground structure is, the lower its elastic and elasto-plastic drift ratio is. 1/460 and 1/612 are the minimum elastic drift ratio in under-ground structures two stories or lower and underground structures three stories or higher, respectively. 1/151 is the minimum elasto-plastic drift ratio in all these struc-tures. Therefore, 1/550 and 1/1000 are chosen to be the limiting values for underground structures two stories or lower and underground structures three stories or higher, respectively. Based on CCSDB, this paper conservatively takes 1/250 as the drift ratio's elasto-plastic limit.

Figure 2: Drift Ratio of different conditions. (a). elastic drift ratio for underground structures two stories or lower, (b). elastic drift ratio for underground structures three stories or higher, (c). elasto-plastic drift ratio underground structures.

Figure 3 (a) and (b) shows the effects of burial depth on the elastic and elasto-plastic drift ratio of station 6 at a certain Young's modulus. In most cases, the elastic and elasto-plastic drift ratio decrease with the increased burial depth. However, this trend reverses in extremely soft soil. On the one hand, as the burial depth increases, an underground structure will be usually designed stronger, which would lead to a higher drift ratio. On the other hand, the stiffness of the structure would usually increase as it is designed stronger, which would lead to a lower drift ratio. When the surrounding soil is extremely soft, the deformation of the underground structure is mainly controlled by its strength, but not the interaction between the surround soil and the structure, which is mainly controlled by their relative stiffness. Therefore, in extremely soft ground, the deeper an underground structure is buried, the higher its elastic and elasto-plastic drift ratio could be.

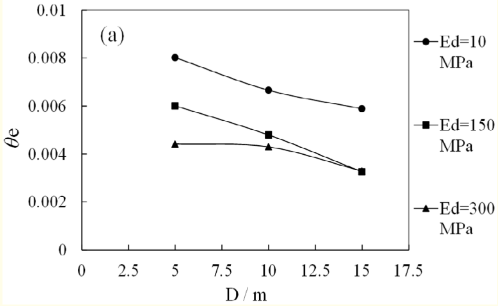

Figure 3: Effects of burial depth on drift ratio. (a). elastic drift ratio, (b). elasto-plastic drift ratio.

Figure 4 (a) and (b) shows the effects of dynamic Young's modulus of surrounding soil on the drift ratio of station 6 at a certain depth. It indicates that the larger dynamic Young's modulus usually results in lower elastic and elasto-plastic drift ratio. The reason is that at the same level of deformation, an underground structure buried in hard soil generally suffers from larger interaction force than that surrounded by soft soil. As a result, underground structures usually fail at a lower interlayer drift ratio when the dynamic Young's modulus of surrounding soil is larger.

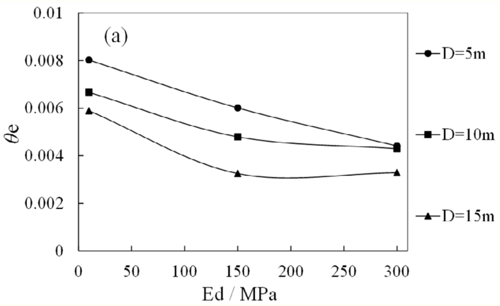

Figure 4: Effects of dynamic Young's modulus on drift ratio. (a). elastic drift ratio, (b). elasto-plastic drift ratio.

Concluding Remarks

In this research, for the six underground stations studied, numerical simulation shows that both ends of the lowest story walls are the weakest part under horizontal seismic load. Based on pushover analysis results, 1/550 and 1/1000 are appropriate elastic drift ratio limiting values for underground structures with two stories or lower and underground structures with three stories or higher, respectively. The elasto-plastic drift ratio limit of 1/250 that is adopted from China's Code for Seismic Design of Building is a conservative limiting value.

This study implements elastic constitutive model for soil material and a non-slip boundary condition at the soil-structure contact surface. Further study for drift ratio of underground structures under strong earthquake should take the non-linearity of soil and the slip at the soil-structure contact surface into account. Despite these limitations, numerical analyses still provide a credible validation for the elasto-plastic drift ratio limit in CCDBS and find appropriate limiting values for elastic drift ratio. The failure process of structures is also well simulated with the technique of mixed elements for structure modelling.

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