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Comparative numerical analysis on dynamic effects of underground large scale frame structures under seismic waves

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ABSTRACT

In this paper, dynamic effects of the underground large scale frame structure (ULSFS) with large scales along both two horizontal directions are investigated by 3-D numerical analyses. To guarantee the accuracy of seismic inputs, seismic waves are transformed into equivalent forces adding on the truncated boundary nodes based on the viscous-spring artificial boundary. 3-D finite element models of 4-span, 8-span, and 20-span underground frame structures with surrounding foundation are proposed to simulate small, middle and large scale underground structures. For a comprehensive study of results, another two analyses of the ULSFS are proposed to evaluate the two dynamic effects of structures: structural inertial effects on inner structures, and effects of structural vibration on the whole soil-structure system, respectively. Furthermore, several soil conditions are employed to study influences of the relative stiffness between the structure and soil on the two mentioned dynamic effects of the ULSFS. The results demonstrate that dynamic effects of the ULSFS are much more significant compared with small scale underground structures which make the structural deformations and internal forces to be larger; and dynamic effects of the ULSFS would decrease with increasing elastic moduli of surrounding soils due to great soil constraints.

1. Introduction

The underground structures are the essential infrastructure systems of the modern society with a range of applications, such as pipelines, tunnels and subway stations widely used for the traffic and transport. Completely enclosed in surrounding foundation, underground structures are thought to be less vulnerable than aboveground structures (Gomez-Masso and Attala, 1984; Chen et al., 1990; Navarro, 1992; Penzien et al., 1993; Stamos and Beskos, 1995, 1996) However, the great damages of underground structures in recent great earthquakes aroused extensive attentions among researchers, showing the necessity of the seismic design of underground structures (Matsuda et al., 1996; Iida et al., 1997; An et al., 1997; Wang et al., 2001; Hashash et al., 2001; Gazetas et al., 2005). In the previous years, researchers focus on the small scale underground structures, such as subway stations, tunnels, and pipelines. Several excellent papers investigate the seismic responses of small scale underground structures and show the great influences of soil constraints on underground structures (Wang, 1993; Clough and Penzien, 1995; Penzien, 2000; Huo et al., 2006; Zlatanovic et al., 2015; Zhuang et al., 2015a,b; Abate et al., 2015; Abate and Massimino, 2017a,b). And in the analysis of underground structures, the 3-D finite element model is rarely employed due to large computational costs. The 3-D model of soil-underground structure system is advantageous to show the complex spatial features of underground structures. Not only the above papers (Stamos and Beskos, 1995, 1996), there are several outstanding papers employing the 3-D finite element model (Hatzigeorgiou et al., 2001, Hatzigeorgiou and Beskos, 2010; Chen et al., 2010; Gu et al., 2013; Chen et al., 2015; Li and Song, 2015). Through the analysis with 3-D models, researchers reveal the seismic influencing factors on tunnels and subway stations and present comprehensive and compellent conclusions of seismic responses of the soil-underground structure system. However, in order to increase the utilization of underground space, the structural scales of underground structures are much greater along two horizontal directions and the structural styles are designed to be much more innovative (Zhuang et al., 2015a,b; Li et al., 2015; Gao and Chen, 2016). The investigations on the new underground large scale frame structure (ULSFS) are rare, and the authors mainly focus on the distinctive seismic response of the ULSFS by 3-D finite element analyses in this work.

In the soil-underground structure system, the soil-structure interaction (SSI) is one of the most primary influences on seismic responses of underground structures. And there are two types of the SSI:

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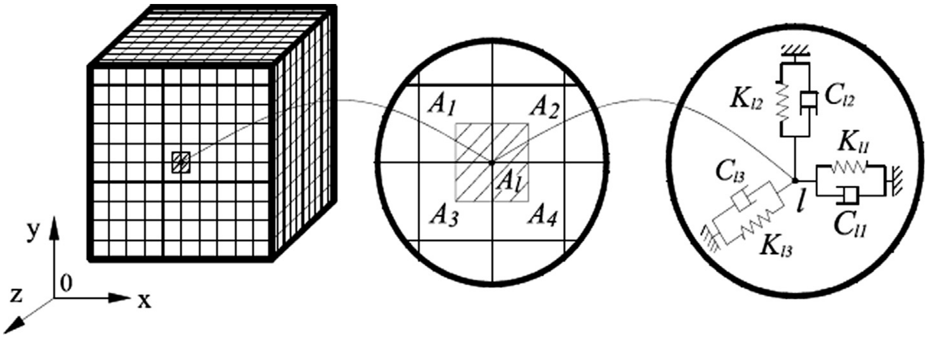

Fig. 1. Mechanical model for 3-D viscous-spring artificial boundary.

kinematic interaction-the ability of underground structures to match the foundation deformation, which is mainly influenced by the relative stiffness between the soil and underground structure (Huo et al., 2006); dynamic effect–the effect of structural vibration on the inner structure and the soil-structure system; it not only pushes the whole structure to deform the soil but also influences the deformation of the inner structure components. In the preceding discussion of underground structures, lots papers revealed that dynamic effects of underground structures generally had negligible effects on the inner components and the soil-structure system (Wang, 1993; Clough and Penzien, 1995; Penzien, 2000). Though the small cross section underground structures (such as pipelines, tunnels and subway stations) have the large scale along the axial direction, the soil constraints still have great effects on the whole structure because there are merely a few metres along the cross section. However, when the structural scales along both two horizontal directions are large enough, the complicated dynamic effects of underground structures would be shown up. Comparing with small scale underground structures, the ULSFS have larger spatial span which would make the soil constraints decrease from outside to inside structure. Additionally, the greater value of length to height ratio of the cross section would make the ULSFS to be flexible and structural dynamic effects to be obvious under seismic motions (Huo et al., 2006). The structural dynamic effects have two main influences: effects of structural inertial forces on the inner structure, and effects of the structural vibration on the soil-structure system. According to the distinctive structural characteristics, the authors focus on the following contents. Comparing with small and middle scale underground structures, seismic responses of the ULSFS is mainly investigated employing deformations and internal forces of a typical framework. And the mentioned two dynamic effects of the ULSFS are evaluated by comparisons of proposed analyses. Moreover, the different dynamic effects of the ULSFS with different soil conditions are compared to study influences of the relative stiffness between the structure and soil.

In this paper, the authors mainly focus on variation rules of dynamic effects of underground structures. Therefore, the following assumptions are put forward to make the investigation to be clear. First, the material of underground structures is assumed to be elastic. The employment of the elastic material is beneficial to compare different seismic responses of small and large scale underground structures proportionally and evaluate variation rules of different parts of the structure. Second, the foundation is assumed to be homogeneous and viscoelastic material. The dynamic behaviour of underground structure in soil is very complicated because of various uncertainties in stratigraphic details and the nonlinear cyclic behaviour of soil (Chen et al., 2015). The elastic model is advantageous to eliminate uncertain influences in different soil conditions. Third, a single horizontal seismic wave is inputted on the finite element model, which is clear to find out the variation rules of underground structures eliminating disadvantageous impacts. This paper mainly focuses on the distinctive dynamic effects of the ULSFS which are usually ignored before; and it is advantageous to explore variations of dynamic effects of underground structures with different structural scales and reveal influences of dynamic effects of the ULSFS.

2. 3-D finite element models and seismic input

2.1. 3-D viscous-spring artificial boundary

To guarantee the accuracy of the artificial boundary and seismic input, the 3-D viscous-spring boundary is employed in this work. The viscous-spring boundary has been used widely to simulate the elastic recovery of the infinite foundation, and it could also solve drift errors of the low-frequency in viscous boundary. Moreover, the viscous-spring boundary can be implemented by the general finite element program easily and the accuracy of it has been assured (Liu and Lv, 1998). According to paper (Liu et al., 2006), the coefficients of springs and dashpots are as fellows:

In the normal direction

$$K_n = \alpha_n G/R \quad C_n = \rho c_p \tag{1}$$

In the tangential direction

$$K_\tau = \alpha_\tau G/R \quad C_\tau = \rho c_s \tag{2}$$

where K_n and C_n are the coefficients of springs and dashpots in the normal direction, respectively; K_τ and C_τ are the coefficients of springs and dashpots in the tangential direction, respectively; α_n and α_τ are modified coefficients in the normal and the tangential directions with good values of 1.333 and 0.667, respectively (Liu et al., 2006); R is the distance between the load point and the boundary point; G is the shear modulus and ρ is the mass density of the medium, respectively; C_p and C_s are velocities of the compression wave and the shear wave propagating in the medium, respectively; and A_l is the total truncated boundary area of node l showing in Fig. 1. To achieve the 3-D artificial boundary in the general software, a Fortran program has been compiled by authors to impose the springs and dampers on every artificial boundary node precisely.

2.2. Wave input method

In the soil-underground structure system, the motions on the artificial boundary are combined with the scattered waves produced by underground structures and incident waves. The scattered waves should be absorbed by the artificial boundary and the incident waves should be transformed into equivalent forces adding on the artificial boundary nodes (Joyner and Chen, 1975). And in the paper (Liu and Lv, 1998), the authors propose a new method of the seismic input for the viscous-spring boundary. The motion of the free field is assumed to be $u_i(x_l, y_l, z_l, t)$. The displacements and stresses of every nodes on the artificial boundary generated by the equivalent forces, should be equal to them in the free field (Zhang et al., 2009):

$$u(x_l, y_l, z_l, t) = u_i(x_l, y_l, z_l, t) \tag{3}$$

$$\sigma(x_l, y_l, z_l, t) = \sigma_i(x_l, y_l, z_l, t) \tag{4}$$