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Effect of buried depth on seismic response of rectangular underground structures considering the influence of ground loss

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ABSTRACT

Great efforts have been made in investigating the effect of buried depth influencing the seismic response of rectangular underground structures, however, a consensus hasn't been achieved yet. This paper presents numerical studies on seismic behaviors of rectangular underground structures at different buried depths, and aims to illustrate the rule that buried depth effects the seismic response of underground structures. Firstly, to describe the softening and over-consolidated propertied of soils, a 3D elastoplastic constitutive model was developed. Then the stress states of the underground structures and surrounding soils before earthquakes, which were one of the most important issues and generally ignored in the previous studies, were discussed detailedly. Afterwards, three-dimensional numerical models for nonlinear earthquake response simulations of underground structures were built, and the seismic responses of the rectangular structure at various buried depths and under multiple ground motions were simulated. And vertical and horizontal deformations of both the underground structures and surrounding soils were systematically studied. Consequently, a buried depth of the strongest seismic response for underground structures was proposed based on the exploration of the relations between the buried depth and the structural distortions of underground structures as well as the ground subsidence. Finally, pertinence suggestions were proposed for the seismic design of underground structures at different buried depths.

1. Introduction

Underground structures, especially subway stations are increasingly developed in worldwide and constitute an important part of the civil infrastructure. Recent events, the collapse of Daikai station in 1995 Japan Great Hanshin earthquake [23], and the damage of tunnels in 1999 Taiwan Chi-Chi earthquake [42], in 1999 Turkey Koceali earthquake [17], in 2008 China Wenchuan earthquake [44] demonstrated that these underground structures in seismic regions are under great earthquake induced risks. In recent years, due to the interference of existing underground structures, city area, location of densely populated districts and several other factors, the buried depth of underground structures was getting deeper and deeper. Therefore, more analyses about the seismic responses of underground structures at different depths are necessary.

Great efforts have focused on the analyses of underground structures at different depths subjected to earthquakes, experimental and numerical studies mainly focus on the circular and rectangular structures in homogeneous ground [1,10,12–14,27,49,7]. However, the understandings about buried depth affecting the seismic responses of underground structures were different, and could be divided into three categories. Part of analyses concluded that shallow buried underground structures were at greater risk than the deeper buried ones during an earthquake [1,14,20,27,39]. These findings were quite similarly with the seismic responses of the retaining walls [33,8]. On the contrary, seismic responses of both square and circle tunnels at shallow and deep buried depths studied by Cilingir and Madabhushi [12,13] demonstrated that, the compressive forces and bend moments of deep tunnels were larger than those of the shallow buried ones. Additionally, studies on the uplift of underground structures in liquefied soils [10] also presented that the resisting forces imposed on the structures were directly proportional to the buried depth. Small part of researches considered that the seismic responses of underground structures at both shallow and deep buried structures were not most serious. Such as, based on the behaviors of tunnels at various depths subjected to seismic excitations [7], it was found that the seismically induced stresses of tunnels were particularly pronounced when tunnels at a depth of one quarter of wavelength. Consequently, a consensus on the seismic responses of underground structures influenced by the buried depth hasn't been achieved yet.

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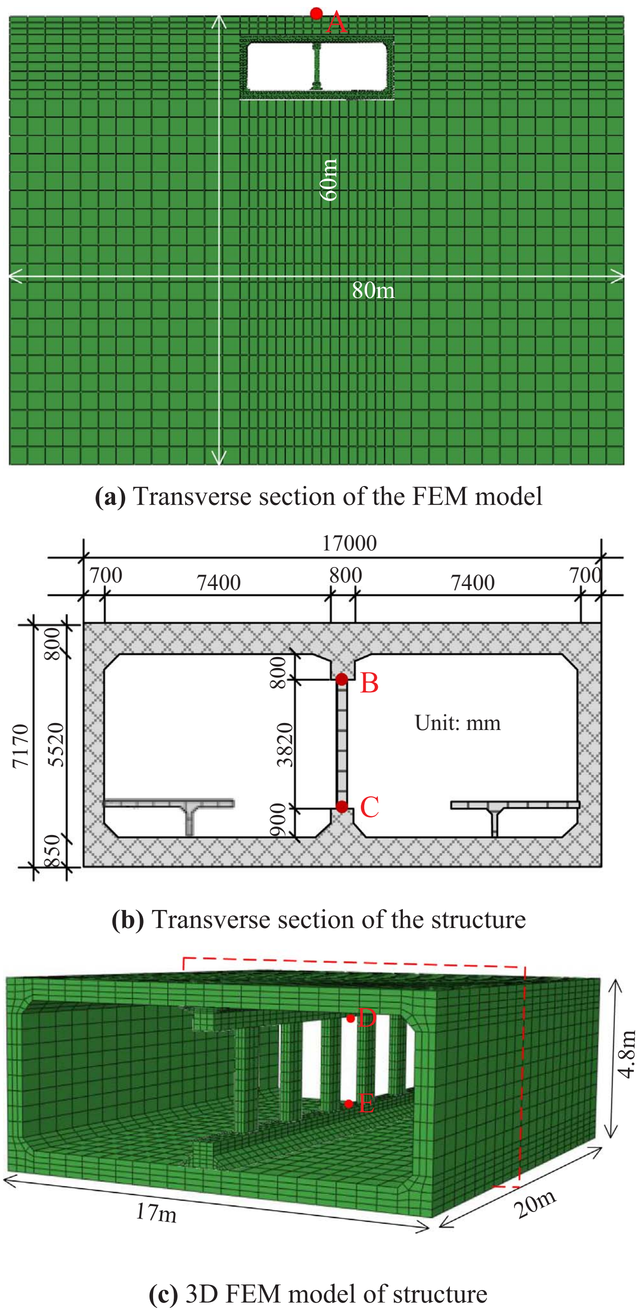

Fig. 1. FEM model for numerical simulation.

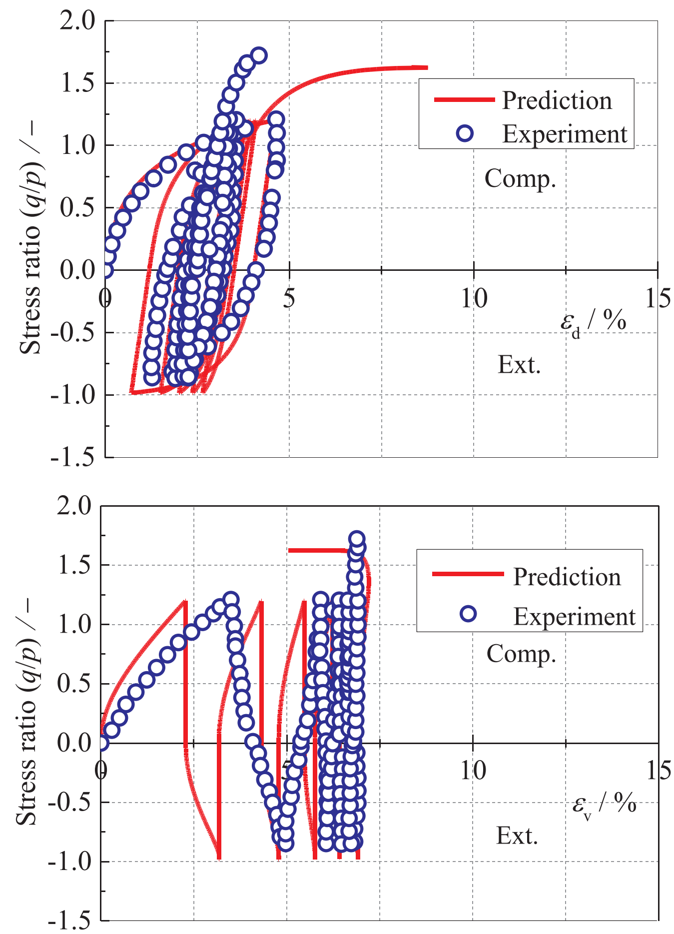

Fig. 2. Comparisons between established constitutive model and experimental results (data from Nakai and Hinokio [35]).

Table 1
Material parameters of the concrete.

Parameter	Value	Parameter	Value
Elastic modulus	30 GPa	Limited compression yield stress	26.8 MPa
Poisson's ratio	0.2	Initial tensile yield stress	2.4 MPa
Density	2500 kg/m^3	Compression stiffness recovery parameter	1.0
Dilatancy angle	35°	Tensile stiffness recovery parameter	0.0
Initial compression yield stress	18.8 MPa	Damage variable	(Table 2)

Prior to earthquakes hitting underground structures, the stress states of structures and surrounding soils are in a static equilibrate state. Any construction process of underground structures inevitably induces changes in stress in the ground [19] (Ng and Lu, 2014). Therefore, the stress states of surrounding soils are different from the geostress conditions of the free field. Geomaterials, including concrete, rocks and soils deform nonlinearly, thus, the initial stress states of geomaterials not only affect their deformation properties, but also affect their additional loading capacities [15,30,5]. Subsequently, the initial stress states of underground structures before earthquakes are very important for analyzing the seismic responses of underground structures influenced by the buried depth. For a shallow buried structure or structures constructed with cut-and-cover method, the vertical loads imposed on the structure before earthquakes might be approximately to the whole gravity of the overlying soils [21]. While, for deep buried underground structures, particularly for the bored underground structures, the vertical loads imposed on the structure should not be the gravities of the overlying soils due to the existence of ground losses during construction [38,48].

Nevertheless, the stress states of surrounding soils and underground structures with no ground loss were selected as the initial stress states in the seismic analyses of underground structures in previous studies [18,21,22,3,4,49], which seems unreasonable. This implies that, the deeper of the buried depth of structures, the higher stress states level of structures being at. Consequently, a structure at an enough buried depth would be damaged completely only under the geostress loads. Therefore, these studies about the seismic responses of underground structures with unreasonable stress states, especially about deep buried structures, were highly unacceptable.

This study aims to present numerical analyses to investigate the seismic behaviors of bored rectangular underground structures in homogeneous ground at various depths. Firstly, to examine the deformation and 3D strength properties of over-consolidated soils, an