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Experimental study on seismic response of underground tunnel-soil-surface structure interaction system

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ABSTRACT

More and more projects of underground structures undercrossing adjacent surface structures have emerged in recent years. The existence of underground structure influences the propagation of seismic wave, and the inertia effect of the surface structure affects both the seismic response of surrounding site and that of underground structures. Thus, the underground structure and near surface structure can be deem as an interaction system. In this paper, in order to investigate the law of seismic response of underground structure-soil-surface structure interaction system, a shaking table model test was designed and implemented. Based on the experimental results, the law of seismic response of such complex system was analyzed. Note that to overcome the limitation of the bearing capacity of shaking table and eliminate the distortion of soil-structure rigidity ratio, the sawdust soil was chosen to model the surrounding site soil. Test results showed that using sawdust soil as a model soil is feasible. Regarding the law of seismic response of interaction system, it was found that the existence of the tunnel structure has weakened the rigidity of the whole model, and therefore, the seismic response of surrounding soil was amplified. However, it was observed that the existence of the tunnel impeded the propagation of seismic wave to some extent and thus reduced the seismic response of the surface structure, especially for lower and medium floors. The existence of surface structure suppressed the seismic response of soil and underground structures. By comparing the test results under different earthquake excitations, it was shown that the seismic response of the system was affected by the type of seismic wave significantly.

1. Introduction

The aseismic ability of underground structures has drawn wide attention especially after Kobe earthquake, in which a few of underground structures, including subway stations and tunnels, were severely damaged. Many researchers have conducted the study of seismic response of underground structures in the last two decades (Stamos and Beskos, 1996; Tateishi, 2005; Gil et al., 2001; Hashash et al., 2001). Nowadays, in China, numerous adjacent underground and surface structures, such as shield tunnels undercrossing surface buildings from closed range, have arisen with the rapid development of metro construction. The reflection and refraction of earthquake wave may occur at the interfaces of underground structures, which influence the propagation of seismic wave and then the seismic response of surface structure. The wave field and additional stress field caused by the inertia effect of surface structures will cause the disturbance of soil stress history and then affect the seismic response of underground structures. Thus, surface and underground structures can be seen as an interaction system. In the current building seismic design code of China, the design methods of surface and underground structures disregard the influence of dynamic interaction.

The interaction system of underground structure-soil-surface structure consists of four subsystems: free field, surface structure-soil, underground structure-soil and underground structure-soil-surface structure. Studies about the former two subsystems have been preceded thoroughly, so herein the advancement on these two subsystems was not described.

Because of that the Dakai subway station was severe damaged in Kobe earthquake, most of the early studies concentrated on the seismic response of underground structures (subway station and tunnel) to evaluate their aseismic ability (Amorosi and Boldini, 2009; Bao et al., 2017; Tsinidis, 2017; Debiasi et al., 2013; Chen et al., 2015; Yan et al., 2016). The results showed that as the underground structures became large scale; that to say its dimension can match or even exceed the wavelength of earthquake wave, the existence of underground structure will affect the propagation of seismic wave. Hence, the influence of

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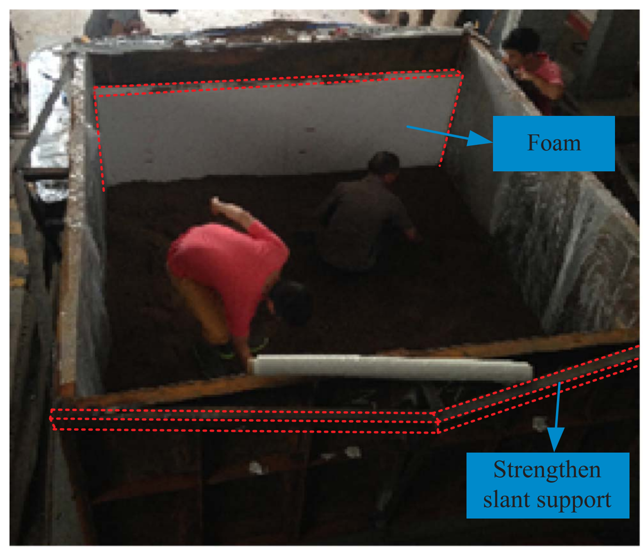
underground structure on the characteristic of surrounding soil had attracted public attention. Baziar et al. (2014) and Moghadam and Baziar (2016) studied the influence of tunnel on the surface acceleration by using shaking table test, fitting analysis, and parameter analysis. Results showed that the existence of underground tunnel reduced the system period, weakened the short-period response, and amplified the response in long period. The amplification effect of underground structure on the surrounding soil mainly depends on the dimensionless period, dimensionless depth, and flexibility, and the impact degree mainly depends on the dimension of the underground structure, buried depth, and the relative flexibility. Yiouta-Mitra et al. (2007) studied the effect of a single circular tunnel on the seismic responses of surface structure through finite difference method, considering elastic half space and SV wave incidence. Numerical computation results showed that the presence of an underground structure should be considered in the design of a surface structure. Based on the Rayleigh method, Smerzini et al. (2009) analyzed the effect of underground circular cavities in visco-elastic half-space subjected to the incidence of both plane and cylindrical waves on surface earthquake ground motion and discussed the influence of cavity dimension, buried depth and characteristic of incident wave. Alielahi et al. (2015) studied the influence of tunnel dimension, buried depth and tunnel shape on the seismic ground amplification, using a robust numerical algorithm working based on the boundary element method. The results showed that the amplification of the ground surface underlain by a tunnel is increased in long periods.

Normally, the seismic load in free field is used to conduct tunnel design. However, in urban area, tunnels are near or beneath the foundation of surface structure, which leads to a complex interaction between surface structure and tunnels, and thus may change the seismic response of tunnels. Pitilakis et al. (2014) studied the impact of single and multiple adjacent surface structures on the seismic response of underground tunnel; and found that the existence of surface structure affected the shear wave and pressure fields of surrounding soil and then changed the seismic response of the underground tunnel. It was also observed that the influence was more significant for shallow-buried tunnel. Tzarmados (2011) investigated the interaction effect between single and multiple adjacent surface structures and rectangular shallow-buried tunnel. It was found that the small-scale underground structure relative to earthquake wavelength had a limited influence on the seismic response of surface structure. Azadi and Hosseini (2007) analyzed the influence of seismic wave type on the interaction of double tunnels-surface structure system; and found that the horizontal displacement and bending moment responses of the surface structure and surface embedded structure highly depended on the type of structure and the frequency components of earthquake. Wang et al. (2013) established a numerical model of underground structure-soil-surface structure to study the seismic response rule of the interaction system. It was shown that the main factors influencing the seismic response of the system were the layout of the surface structure, seismic wave incident direction, distance between underground and surface structures, soil shear wave velocity, buried depth of underground structure, and quantity of underground structures, among which the arrangement of surface structure and the incident direction of seismic wave were the most important factors. Gao et al. (2013) analyzed the impact of spacing distance between underground and surface structures on the interstory drift ratio of surface structure by using the interlayer displacement spectrum method. Results showed that the period of surface structure and spacing distance were the key factors influencing the seismic response of the surface structure. In addition, the existence of underground structure could increase the bending deformation of the structure in short period and the shear deformation in long period. Based on a case study, Glenda (Abate and Massimino, 2017) analyzed the interaction between tunnel and surface structure subjected to seismic load, and it was observed that the seismic response of the whole system was significantly different from that of any single sub-system.

(a) Model container without strengthen slant support



(b) Model container with strengthen slant support

Fig. 1. Model soil container.

Although numerous theoretical analyses and numerical simulation studies on the interaction of underground and surface structures have been conducted, however, the model tests about the interaction system are very rare. In this paper, based on the numerical simulation results (Wang et al., 2017), a series of shaking table tests were conducted on tunnel-soil-surface structure (TSF) system. Experimental details were discussed, which may be of interest for researchers. In particular, the focus is on design of model soil and devices for measuring. The experiments were conducted in four phases. Phase 1 was free field test (FF). For comparison, phases 2 and 3 were the model tests for tunnel-soil (TS) and soil structure (SF) systems, respectively. Phase 4 was the model test concludes tunnel, soil and surface structure (TSF) to study the dynamic interaction of the complicated system.

2. Experimental setup

2.1. Shaking table

The shaking table tests were conducted using the shaking table facility at the Hubei Key Laboratory of Roadway Bridge and Structure Engineering, Wuhan University of Technology. The table could be input