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Shaking-table tests and numerical simulations on a subway structure in soft soil

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ABSTRACT

Shaking table tests were performed to investigate the damage mechanisms of a subway structure in soft soil while experiencing strong ground motions. The seismic responses of the structure and soil were found to be more sensitive to input motions with richer low-frequency components. The excess pore pressure ratio of soil increased slightly, and the distribution of the excess pore pressure surrounding the structure showed clear spatial effects. The frequency spectrum characteristics of input ground motions clearly influenced the lateral displacement of the structure. In addition, the structure was most severely damaged at the top or the bottom of the interior columns. Finite element analyses were conducted by using the modified Martin–Seed–Davidenkov viscoelastic and the rate-independent plastic-damage constitutive models for soil and concrete, respectively. Satisfactory agreement was observed between the simulation and test results, the difference between these results was discussed in detail. The results provide insight into how the characteristics of strong ground motion might influence and present a simplified analysis method to quantitatively evaluate the damage of subway structures in soft soil.

1. Introduction

With the rapid development and urbanization happening in China, urban spatial spread and traffic congestion have become major concerns. In particular, in the Yangtze River Delta and Pearl River Delta regions, rail transit systems are being increasingly built. However, many subway stations are located in soft soil. And thus, the seismic safety of the subway structures is a major concern. For example, in the Hyogoken–Nanbu earthquake in Japan on January 17, 1995, different types of damages such as longitudinal and transverse cracks, concrete spalling, and joint movement were observed in the areas affected by the earthquake, most notably, the collapse of the Daikai subway station [1,2]. Experience from major earthquake events has shown that slope instability, soil liquefaction, fault displacement, and earthquake propagation can cause severe damage to underground structures [3]. Hence, it is important to a thorough understanding the dynamic response of soil and the damage mechanism of subway structures experiencing strong ground motions.

In the literatures, the limited number of centrifuge/shaking table test investigations regarding subway structures and the limited field observations provide empirical data that may be used to calibrate dynamic analytical models and also provide very promising results with regard to modeling complicated nonlinear phenomena. Popescu et al. studied the dynamic interaction between liquefying soil and a structure under strong ground shaking [4]. Pronounced soil-structure interaction (SSI) effects were observed within the centrifuge as the test soil liquefied [5,6]. Pitilakis et al. carried out a series of tests in order to validate numerical simulations of SSI effects using a centrifuge model structure and non-liquefiable soil [7]. Liu et al., Han, and Ling et al. performed a series of centrifuge shaking table tests on one-story and three-span subway stations, a circular tunnel, and one-story and two-span subway stations, respectively [8–10]. Because shaking-table models are generally much larger than centrifuge models, the space available for instrumentation and actuators is greater, and loading, control, and observation can be carried out with greater sensitivity. Chen et al. had conducted a series of large-scale shaking table tests on subway structures with various cross sections in a liquefiable soil [9-13]. These works could expand our knowledge on seismic performance of different types of cross section subway structures. In terms of numerical simulations, several methods are available in the literature for the evaluation of the seismic response of underground structures [15–24]. For instance, Huo et al. used dynamic numerical nonlinear analyses to investigate the load transfer mechanisms between the

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Fig. 1. Laminar shear soil box used in the shaking table model tests.

Table 1
Similitude ratios of the model structure and soil.

Type	Physical quantity	Similitude relation	Similitude ratio	
			Model structure	Model soil
Geometry property	Length	S_l	1/30	1/4
	Linear displacement	$S_l = S_l$	1/30	1/4
Material property	Equivalent density	$S_\rho = S_E/S_l S_\alpha$	15/2	1
	Elastic modulus	S_E	1/4	–
Dynamic property	Mass	$S_m = S_\rho \cdot S_l^3$	2.8×10^{-4}	–
	Frequency	$S_\omega = 1/S_t$	5.4794	2
	Acceleration	S_α	1	1
	Duration	$S_t = \sqrt{S_1}/S_a$	0.1825	1/2

Table 2
Material properties of model soil.

Material	Unit weight (kN/m^3)	Liquid limit (LL)	Plastic limit (PL)	Soil moisture content (%)	Permeability (cm/s)	Specific gravity	Void ratio
Clay	16.6	36.84	18.75	15.6	–	–	–
Silt clay	17.6	29.5	17.0	25.9	0.47×10^{-6}	2.72	0.73

underground structure and the surrounding soil and to identify the causes for different behaviors of similar sections of the Daikai station subjected to the same seismic loading [15]. Abate et al. described the results of a shaking table test performed on a scaled physical model consisting of a 3D steel frame resting on dry sand, and the test results were compared with the FEM analysis ones obtained using a sophisticated but easy-to-use elasto-plastic constitutive model [18]. Shahrour et al. carried out elasto-plastic FEM analysis of the seismic response of tunnels in soft soils, the soil behavior was described using an advanced elasto-plastic cyclic constitutive relation involving both isotropic and kinematic hardening [19]. More recently, Gomes described the numerical simulation of a Plane-strain model tunnel centrifuge tests embedded in dry uniform fine sand with dynamic loading with an elasto-plastic model [24].

However, the above mentioned shaking/centrifuge table tests and numerical simulations were mainly performed in liquefied soil, dry sand or unsaturated soft soil. In view of this, in order to mitigate the risk of earthquake damage, a better understanding the seismic response of subway structure in saturated soft soil is needed, so a series of shaking table tests and numerical simulations were performed on a scaled model subway structure to investigate the seismic damage characteristics in saturated soft soil.

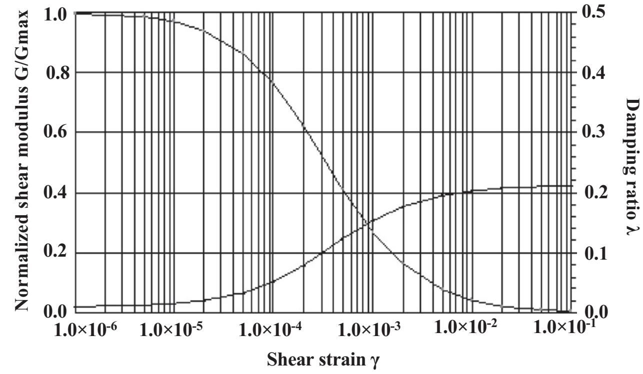

Fig. 2. Normalized shear modulus and damping ratio curves of silt clay.

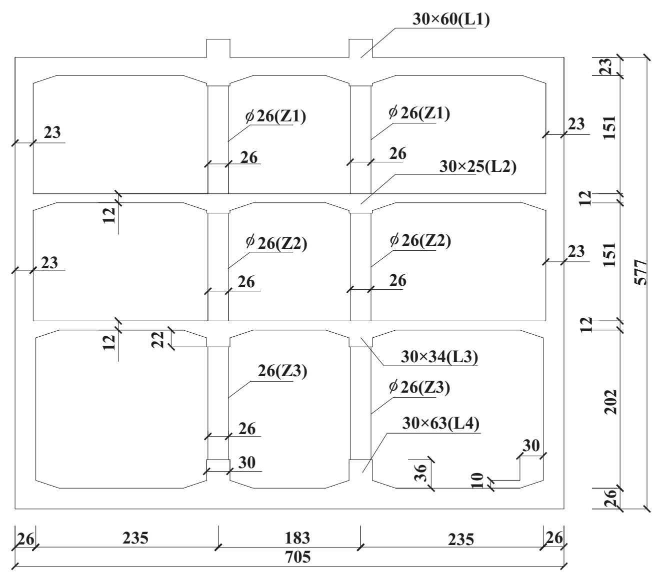

Fig. 3. Dimensions of the model structure (unit: mm).

2. Shaking table tests

2.1. Test apparatus and similitude ratio design

The seismic response characteristics of a subway station structure were studied with the help of the shaking table at Nanjing Tech University. The dimension of the shaking table was 4.86 m (length) × 3.36 m (width) in plane, which can produce 1-D horizontal motion along the length direction. The maximum permissible acceleration of the shaking table was 1g with the maximum proof mass of 25 t, where *g* is the gravitational acceleration. The frequency of the input motion ranged from 0.1 to 50 Hz. Successful modeling of soil in a 1-g environment is very difficult endeavor due to the dependency of the behavior of soil on effective stress and permeability, Chen et al. and Han et al. developed a platform for shake table testing of subway structures in soils, the testing platform includes a flexible water proof laminar shear soil box and a real-time dynamic signal acquisition system for testing data [14,25,26]. The soil box consisting of 15 horizontal layers was made of steel tubes with internal net size of 3.5 m in length, 2.0 m in width, and 1.7 m height. Each layer has external dimension of $3.7 \times 2.2\ m^2$ in plane and 0.1 m in thickness; the layers can move relatively to one another along with the deformation of the soils inside. Four upright columns were installed on the two side faces parallel to the vibration direction, and several shaft bearings were installed on each column, all of which were in contact with the side face of the box. The soil box is illustrated in Fig. 1. Boundary effects were tested by measuring the peak