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Shaking table test of a multi-story subway station under pulse-like ground motions

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ABSTRACT

A series of shaking table tests were conducted to investigate the effect of pulse-like ground motion on a multi-story subway station. Dynamic response data, including internal forces, column drift, and settlement and deformation of the soil were obtained and analyzed. Results show that the pulse-like ground motion increases dynamic responses of the subway station and surrounding soils mainly owing to its inherent rich low-frequency component and high energy. In terms of the structure, central columns, especially central columns on a floor with large story height, are vulnerable components of a multi-story subway station. Both the dynamic earth pressure and the deformation mode of the side wall were analyzed.

1. Introduction

With the rapid development of the economy and society in China, modern underground transportation, represented by the subway, is continuously developing towards having a deeper and multilevel structural form. Huaihai Road Station on metro line 13 in Shanghai, for example, is a six-story island-platform station having height of nearly 30 m and diaphragm walls that are 71 m deep [1]. More problems tend to arise for a deeper structural form that has multiple layers and a larger story height. First, the water and earth pressures imposed on side walls of the structure increase with an increase in depth. Second, owing to the accumulation of load transferred from top to bottom, the axial compression ratio of central columns increases. Third, the structural configuration tends to be more complicated so as to provide multiple functions, which increases the number of latent vulnerable points. Finally, a large story height greatly reduces the lateral stiffness of central columns and side walls. Hence, the seismic performance of such an underground structure is worthy of attention.

In recent years, centrifuge and shaking table tests have been conducted for subway stations to study the seismic performance and failure mechanism of their underground structures [2–5]. Results show that underground structures may suffer severe damage during a strong earthquake. It is commonly believed that the centrifuge test is an attractive way for seismic performance evaluations due to its ability of reproducing the in-site stress state of soils. Researches have been conducted by using a centrifuge, and good results were obtained [6,7]. In addition, shaking table is subtlety in loading, control and observation [8]. Hence, shaking table test is also a common way for studying seismic performance of underground structures [6,9,10]. These studies are of great help to understand soil–structure interaction or responses of structures.

In studies of superstructures, it is also found that pulse-like ground motions may induce more severe damage to structures compared with other ground motions, such as far-field ground motions. Pulse-like ground motion is defined as ground motion whose PGV/PGA (the ratio of peak ground velocity to peak ground acceleration) is greater than 0.2 while ordinary ground motion has a ratio smaller than 0.15 [11]. If the rupture propagates in the direction of the recording station, coherently traveling long-period waves produce high ground velocities and large displacements in the fault-normal direction [12], and most of the seismic energy in ground motion is concentrated in the pulse [13]. Many studies have verified the effects of pulse-like ground motion on the superstructure. Bertero et al. [14] showed that pulse-like ground motion can induce a dramatically strong response in fixed-base buildings. Anderson and Bertero [15], in their study of the nonlinear dynamic response of a 10-story steel frame, revealed that the lower floors of buildings with such structure can suffer great damage if subjected to pulse-like ground motion. Makris and Black [16] found that local, distinguishable acceleration pulses result in unusual demands of structures. Sehhati et al. [17] stated that

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pulse-like ground motions impose a larger ductility demand on a structure compared with ordinary ground motions. Additionally, studies have been conducted on the effect of pulse-like ground motions on isolated structures and bridges [18–22]. With regard to underground structures, Chen and Wei [23] studied the effect of pulse-like ground motion on mountain tunnels and concluded that the velocity pulses are the main factor determining damage to tunnel linings. However, from the perspective of the structural form, the subway station has a framed structure. Hence, the subway station and tunnel differ in terms of their mechanical and vibration characteristics. Furthermore, the framed structure configuration does not transmit static loads as effectively as a circular lining. As a result, the high-energy impulse of pulse-like ground motion poses a great threat to the structural members of a framed structure, doing damage to the undetected vulnerable spots and even to the whole structure. Additionally, the impulse may increase the shear deformation of soil notably and thus enlarge the story drift of the station and cause further damage.

In this paper, shaking table tests of a multi-story subway station under pulse-like ground motions are conducted. On the basis of the elastic response of a subway station under different ground motions, the effects of pulse-like ground motion on the internal force and deformation of structural members are discussed. The dynamic earth pressure and deformation pattern of the side wall are investigated. Moreover, the seismic performance of a deep subway station under different levels of ground motion are evaluated.

2. Experimental setup

2.1. Shaking table

The shaking table test was carried out using the MTS Company shaking table facility at the State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University. The table can be input with three-dimensional and six-degree-of-freedom motions. The dimensions of the table are 4 m × 4 m. The working frequency ranges from 0.1 to 50 Hz. The shaking table vibrates with two maximum horizontal direction accelerations of 1.2 g and 0.8 g, and a maximum acceleration of 0.7 g vertically.

2.2. Model soil container

To minimize the box effect, a flexible container was used in the test. The cylindrical soil container was 3000 mm in diameter, see Fig. 1. Its lateral rubber membrane was 5 mm thick, and reinforcement bars having a diameter of 4 mm and spacing of 60 mm were used to strengthen the outside of the box. The membrane was fixed with an upper ring plate and a base plate by bolts. A height-adjustable screw rod was installed to adjust the cylinder to a proper state. A universal joint was set on the top of the columns,

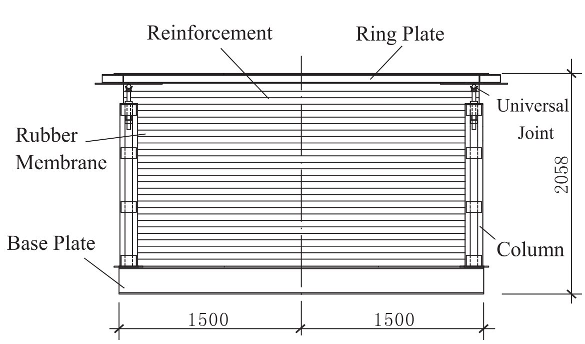

Fig. 1. Schematic diagram of the soil container.

which supported the upper ring plate, to allow the ring plate to deform laterally. To minimize the relative slip between the soil and the container on the base surface, crushed rock was bonded to the base steel plate to roughen the surface. In Ref. [24], Lu et al. conducted three free field-shaking table tests to verify the boundary effect of the flexible container, which was the same one used herein. They indicated that the boundary effect can be ignored when the distance between the structure and the boundary was more than 600 mm. The distance in this paper's tests was more than 1.2 m. Hence, the effect of boundary on dynamic responses of the structure could be ignored.

2.3. Sensors and data acquisition system

To study the dynamic response of the model structure and the dynamic soil–structure interaction, accelerometers, strain gauges, displacement meters, laser displacement meters and soil pressure gauges were used. The strain gauge was an FLA-3-11 produced by the Japanese company TML. The gauge backing was made of epoxy resin with thickness of 0.03 mm, and the length, width, backing length and backing width of the gauge were 0.3, 1.4, 3 and 2 mm, respectively. The laser displacement meter was a CP08MHT80 produced by the German company Wenglor and had dimensions of 50 mm × 50 mm × 20 mm, a measuring range of 50 mm, resolution finer than 8 μm, and response time less than 660 μs. The soil pressure gauge had an outside diameter of 30 mm, capacity of 200 kPa, and precision of 0.5% of full scale. The data acquisition system with 128 channels was produced by MTS Company, and the sampling rate used in the test was 512 Hz.

3. Test design

3.1. Scale factor design

The prototype design of the model structure is a modern subway station with height of 28.3 m. The station was designed originally to be a six-story island platform station, and then because of the need for parking, the first to third floors underground were merged into one layer to function as a stereo garage. The second floor is the lobby floor, the third is a floor that houses equipment, and the fourth is an island platform. The total length of the station is 155 m, and the width varies from 23.6 to 28.35 m. The prototype structure was made of reinforcement concrete. Concrete of Grade C45 was used for central columns and C35 for the rest parts of the station [25]. Steel rebar of HRB400 was used in central columns and HRB335 for the other parts [25].

The scale factors of the model structure are listed in Table 1. According to similarity theory, three aspects of the simulation of the soil–structure interaction should be considered primarily: geometric similarity, physical similarity and mechanical similarity. On account of the differences in dimensions between a modern subway station and typical one, the scale factor design should be based on the size and bearing capacity of the shaking table, size of the soil container, boundary effect, and convenience of model manufacturing. The length scale factor is set to 0.02. Fig. 2 presents the dimensions of the model structure. Then scale factors of displacement and area can be determined.

In the shaking table test, organic glass was chosen as the material of the model structure owing to its good homogeneity, high strength and low elastic modulus, providing flexibility to the design of the scale factor. This material is also suited to accurate manufacturing. Thus elastic modulus and density scale factors can be determined according to material tests of the organic glass.

After the scale factor of geometry, elastic modulus and density are decided, scale factors among the physical quantities can be