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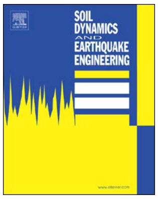

Multi-scale physical model of shield tunnels applied in shaking table test

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ABSTRACT

Experimental simulation of long-distance shield tunnels is difficult due to the enormous volumes of segments and complexity of joints. In this paper, a multi-scale method is proposed to simulate the test model of shield tunnels, which discretizes the entire model structure into the segmental equivalent ring portion (SER) and the equivalent uniform tube portion (EUT). The EUT model is employed to capture seismic response characteristics of the entire tunnel system, whereas the SER model is employed to describe in detail the deformation responses in lining segments and joints at positions of potential damage or interest. The proposed multi-scale physical model for shield tunnels is validated through shaking table tests, in which a full refined model is set as benchmark for comparison. Results show that: 1) the multi-scale physical model demonstrates the same macroscopic dynamic response, such as acceleration responses of model linings, as the full refined model; and 2) dynamic responses such as the extension of joints in the central zone of SER portion of the multi-scale model is consistent with those in the full refined model. The proposed multi-scale method provides an effective way for the design of complex segmental tunnel models applied in shaking table tests.

1. Introduction

As one of tunneling approaches, shield tunnels have taken an integral part in the constituents of modern transportation facilities or others. Usually, researchers considered that the lining structure of a shield tunnel would have better earthquake resistance than above-ground buildings because of their complete closure in soil or rock [1]. However, during recent strong earthquakes, such as the 1985 Mexico City earthquake in Mexico, the 1995 Kobe earthquake in Japan, and the 2008 Wenchuan earthquake in China, extensive damages were observed at local shield tunnels [2–4]. Those observed damages provide sufficient indications that comprehensive seismic design is critical for shield tunnels.

A number of researches have been done on the dynamic response of shield tunnels, yet most studies mainly focus on the dynamic behavior of shield tunnel's cross-section. Simplified static approaches, such as the free-field displacement method [5] and the seismic deformation method [6], are suggested to estimate the seismic action on tunnel linings. Recent studies have suggested that it is also critical to consider the longitudinal response of the shield tunnel, because the spatial variation of earthquake excitation has significant effects on long-span structures [7,8]. Until now, most studies on the tunnel's longitudinal seismic behavior are limited to analytical or numerical simulations. For example, Vanzi [9] has put forward an analytical solution for linear behavior of finite length tunnels under the longitudinal traveling earthquake excitation, which gives efforts to evaluate the crack or the joint's extension. Yu et al. [10] has established a full length model of a water conveyance tunnel subjected to non-uniform earthquake excitations, with the support of a powerful supercomputer.

Test through shaking-table is an alternative way to investigate the seismic performance of shield tunnels. Comparing with analytical and numerical methods, experimental investigations are hindered not only by lacking the facilities for input of earthquake, but also by the absence of methods to design and fabricate the complex physical model of shield tunnels. Until now, few shaking table test has been conducted for shield tunnel structures. Chen et al. [11] has performed a series of shaking table tests on subway shield tunnels, which mainly focus on the dynamic soil-tunnel interaction in liquefiable soil. Kawamata et al. [12] has carried out a group of large scale tests on shield tunnels using E-defense shaking table system. Although profound results have been achieved in these tests, the designed model linings cannot simulate real performance of actual tunnels very well. This is because most of the model linings are roughly simplified as uniform circular tubes, which are obviously not ideal representative for actual jointed tunnels. The

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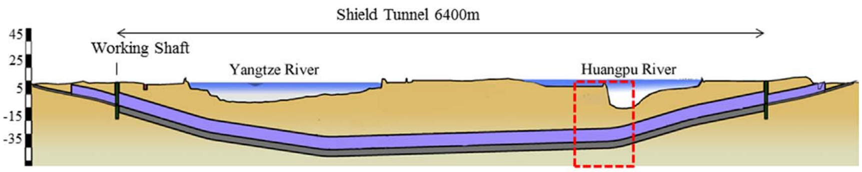
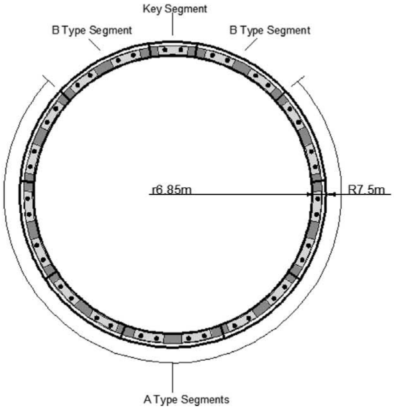


(a) Layout of the the shield tunnel (unit:m)



(b) Cross-section of the tunnel lining

Fig. 1. Prototype of the Riverine passage shield tunnel (a) layout of the shield tunnel (b) cross-section of the tunnel lining.

Table 1
Similitude relations.

Variables	Parameters	Similarity relations
Geometry	l, r	$S_l = S_r = 1/60$
Strain	γ	$S_r = 1$
Density	ρ	S_ρ
Dynamic shearing modulus	G, E	S_G, S_E
Shear wave	v	$S_v = S_G^{1/2} S_\rho^{-1/2}$
Frequency	f	$S_f = S_l^{-1} S_G^{1/2} S_\rho^{-1/2}$
Mass	m	$S_m = S_\rho S_l^3$
Acceleration	a	$S_a = S_G S_l^{-1} S_\rho^{-1}$

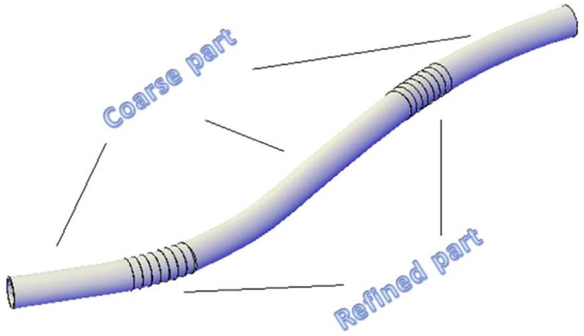


Fig. 2. Scheme design of the multi-scale physical model.

proposed physical lining model of shield tunnels can neither simulate the actual tunnel's long-span characteristic due to their very limited length.

Nevertheless, physical models applied in shaking table tests have already been established for other long-span underground structures. For example, a scaled model of an immersed tunnel (36.75 m) is applied in a series of multipoint shaking table tests [13,14], indicating that wave-passage effect of non-uniform excitation can add to the risk of tunnel's failure. Such tests are also desirable to be carried out to investigate the dynamic performance of long-span shield tunnels. In consideration of multipoint shaking table tests for shield tunnels, the main obstacle is how to design the model structure with enormous scale in longitudinal dimension and vast number of segment joints. An ideal physical model is supposed to describe not only the response of entire tunnel system, but also the extension of joints and the internal force of segments in location of potential damage or interests. The most relevant studies have been conducted by Yu et al. [15], who introduces multi-scale methods in numerical simulations of a full length shield tunnel. The numerical model involves discretization of entire domain with both coarse and fine scale finite element meshes. 'Bridging domain method' was used to couple the coarse part and the refined part. Cao et al. [16] also used the multi-scale method to evaluate the water hammer response of a full length water conveyance tunnel. A 'tie' interface was used between the coarse region and the refined region. Inspired by above studies, it is assumed that physical model of tunnel structure could also be designed in the multi-scale pattern.

In this study, we present a multi-scale physical modeling method for shield tunnels applied in shaking table tests. The multi-scale physical model of the tunnel structure is composed of the segmental equivalent ring (SER) portion and the equivalent uniform tube (EUT) portion. First, the design details are discussed for the SER portion and the EUT portion respectively. Then, the stiffness equivalences of proposed models are verified through a static test and a numerical simulation. This is followed by a series of shaking table tests to investigate the dynamic characteristic of the multi-scale model. During the tests, a full refined model is set as benchmark for comparison. Results from the tests are presented, which give evidence to the validity of the purposed multi-scale modeling method.

2. Multi-scale physical model of the shield tunnel

2.1. The prototype of a shield tunnel

The design of the multi-scale physical model is based on an actual shield tunnel, the Riverine Passage (under construction) in Shanghai, China. It is a large-diameter shield tunnel that connects the eastern and western banks of Huangpu river, as shown in Fig. 1(a). Part of the tunnel drills through beneath the Yangtze River. The total length of the shield tunnel section is 6400 m. The area of interest in this paper is highlighted in the Figure, where the depth of shield tunnel is 30–35 m.

Fig. 1(b) shows the typical circular cross-section of the tunnel's lining, with inner radius of 6.85 m and outer radius of 7.5 m