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Multi-point shaking table test for long tunnels subjected to non-uniform seismic loadings – Part I: Theory and validation

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ABSTRACT

The spatially varying ground motions can significantly influence the dynamic response of extended structures such as tunnels. However, current knowledge on the effects of non-uniform seismic excitations on long tunnels is limited to analytical or numerical methods and lack of experimental or field data. This paper presents a confirmatory experimental method for long tunnels subjected to non-uniform excitations, using four independent shaking tables worked in coordination as a large linear shaking table array. The discrete multi-point input mechanism is deemed critical to accomplish a continuous and coordinated excitation over a long tunnel. A 40 m-long segmental model container is developed to realize the equivalent transformation from the four independent shaking tables into continuous excitations. The dimension of the segmental model container as well as the connection between each of its components is determined after significant analytical and numerical simulations. A series of tests are conducted to investigate the wave passage effect along the length of the segmental model container. Results show that the wave passage effect is accurately reproduced with the test setup and the acceleration input scheme, and thus the validation of the design of the multi-point test system is approved.

1. Introduction

Underground facilities are an integral part of the infrastructure of modern society and are used for a wide range of applications. During recent strong earthquakes, especially during the 1995 Kobe Earthquake in Japan, 1999 Duzce Earthquake in Turkey, 1999 Chi-Chi Earthquake in Taiwan, 2003 Bam Earthquake in Iran and 2008 Wenchuan Earthquake in China, a number of underground structures experienced significant damage, some quite extensively [1]. The damage provides sufficient evidence to suggest that the safety of underground structures in seismically active areas is still an important issue, but not well understood yet, or at least not well considered during design.

Currently, seismic analyses of underground structures normally use uniform free-field motions at the bedrock interface as the seismic loading [2,3]. However, significant variations in amplitude or phase can occur along the interface if its spatial extent is large; this is certainly true for line-like structures [4–6]. It has been noted that appropriate considerations should be given to traveling waves [7], especially for extended or embedded structures with a large span or size such as tunnels, because spatial variation of earthquake motion has dramatic effects, which was already noted by a number of researchers [8–10]. It was believed that long tunnels would suffer more severe damage than normal ones if non-uniform excitation existed [11]. Three-dimensional numerical analysis of long tunnels conducted by Yu et al. [9] and Li and Song [10] also revealed that the excitation had a significant influence on the longitudinal seismic response of tunnels. Consequently, the influence of non-uniform excitations on the safety of long tunnels should be quantitatively evaluated and highly considered in seismic design.

Shaking table tests are always desirable to be carried out to learn the actual dynamic performance of long tunnels and to develop or validate design theories. However, current parallel research projects on tunnel response induced by non-uniform seismic loadings are limited to numerical approaches. Experimental investigation on the performance of long tunnels under non-uniform seismic excitation is still vacant due to limitations of testing facility. The most relative study conducted by Chen et al. [12] is a trial experiment on the dynamic response of a utility tunnel under non-uniform excitation. The scaled model tunnel was designed to be hold by two separate model boxes resting on two shaking tables. Obviously, it is not the practical case. What it would lead to is

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missing of continuous stratum between the two model boxes.

The objective of the present study is to initiate a confirmatory experiment for long tunnels subjected to non-uniform excitations. The test apparatus is provided by the State Key Laboratory of Disaster Reduction in Civil Engineering, located in Tongji University, Shanghai, China. It provides four independent shaking tables which can be organized as a linear shaking-table array. Obviously, the excitations for bridges can be easily realized by the four shaking tables due to the independent distribution of each of the bridge piers. For long tunnels, however, the seismic input is usually the continuous excitations from the bedrock or the base stratum. A critical issue is the equivalence between discrete inputs from scatter shaking tables and continuous seismic excitations through stratum, that is, how to use the four independent shaking tables to exhibit the continuous characteristics of a real non-uniform seismic excitation.

To fulfill the forward problem, a segmental model container is developed not only to hold the model soil and model tunnel but also to realize the equivalent transformation from discrete multi-point shaking of the tables into continuous excitations. The dimension of the segmental model container as well as the connection between each of its components is determined after significant analytical and numerical efforts. Validation tests on the arrayed-shaking-tables system are performed to investigate the wave passage effect along the length of the segmental model container, and furthermore to verify the feasibility of transferring the discrete seismic excitations from tables to the expected continuous excitations via the designed segmental model container.

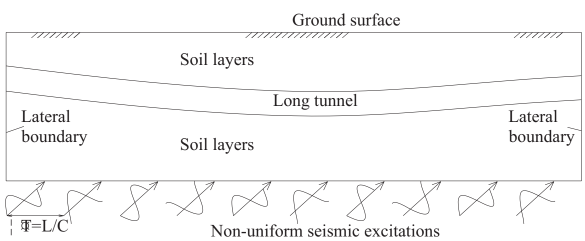

Fig. 1. Continuous non-uniform seismic input mode.

2. Problem description

Non-uniform ground motion is an important factor for seismic assessing of line-like structures. Due to inhomogeneity and anisotropy of soil layers, the motion caused by earthquake waves may differ from one tunnel element to another along the long tunnel structure. The wave passage effect, one of the most critical earthquake ground motions, is considered as the non-uniform seismic input mode in this paper. It is assumed that the tunnel response is solely due to the difference in arrival time at each point of a ground motion. The continuous non-uniform seismic excitation for long tunnels is illustrated in Fig. 1, in which the seismic wave propagates along the longitudinal direction of the tunnel with time delays at each point on the bedrock.

The shaking table test has become one of the most effective tools to study the seismic response of underground structures. Typically, a single shaking table supporting a model box that contains soil and structure is used to investigate a single structure such as a metro station [13], but two or more shaking tables are needed for a long tunnel. In particular, multi-point shaking table systems, together with accurate measuring devices, make it possible to observe in the laboratory the response of long tunnels under non-uniform loading.

The test apparatus used in this investigation consists of four multi-function shaking tables distributed along a 70-meter and a 30-meter long test trenches, as shown in Fig. 2. All the four tables have dimensions 4×6 m (4 m is along the length of the trench, while 6 m is perpendicular to the trench). Two of the tables have a 70-ton payload capacity and the other two, 30-ton. The four tables are movable along three-degrees-of freedom (transversal, longitudinal and rotational on a horizontal plane). The performance parameters of the multi-function shaking tables are listed in Table 1. The maximum shaking acceleration of each table is 1.5 g with frequency from 0.1 Hz to 50 Hz. Consequently, it can simulate harmonic vibration, earthquake excitation, and shock loading. All

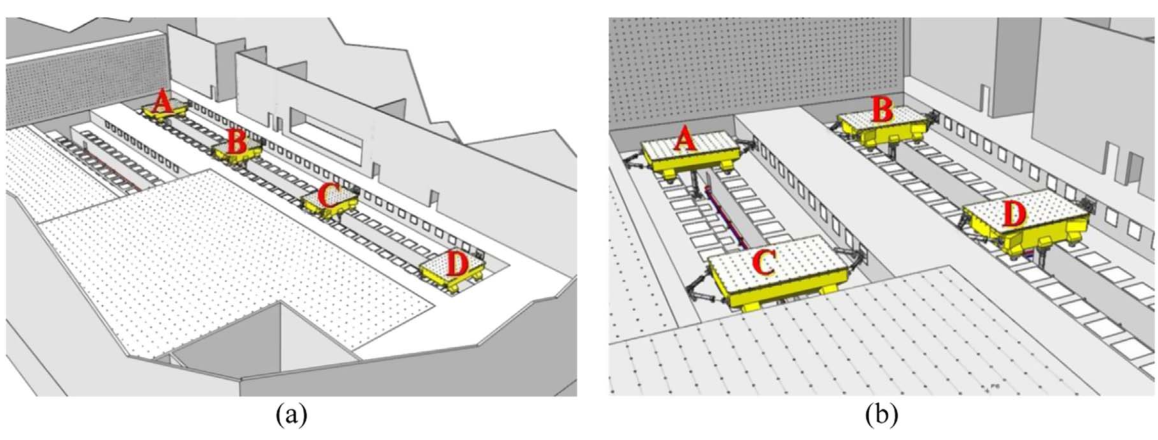

Fig. 2. The multi-point shaking table system: (a) linear-array and (b) rectangular-array.

Table 1
Parameters of the multi-point shaking tables.

Table	Payload (tons)	Size (m)	Frequency (Hz)	Displacement (mm)	Velocity (mm/s)	Acceleration (g)	Torque (ton · m)
A	30	4×6	0.1–50.0	500	1000	1.5	400
B	70						200
C	70						200
D	30						400

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