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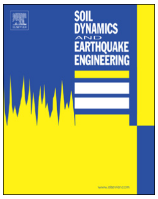

Dynamic centrifuge tests on effects of isolation layer and cross-section dimensions on shield tunnels

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ABSTRACT

An isolation layer, consisting of a rubber layer wrapped around the outside of a tunnel lining, acts as a countermeasure to enhance the safety of a tunnel during an earthquake. The main objective of the present paper is to verify the seismic efficiency of isolation layers in shield tunnels, and to study the influence of cross-section dimensions on seismic isolation effectiveness. Two sizes of shield tunnel model (with and without isolation layers) are prepared, and six groups of dynamic centrifuge tests are conducted. The test results show that the isolation layer effectively decreases dynamic bending moments in both large and small cross-section tunnels. The smaller cross-section tunnel with smaller ratio of tunnel diameter to isolation layer thickness has a greater reduction of structural response, because more soil deformation is absorbed.

1. Introduction

Tunnels are an important component of urban infrastructure. The damage information of recent earthquake events such as the Great Hanshin earthquake (Japan, 1995), the Chi-chi earthquake (Taiwan, 1999), the Düzce earthquake (Turkey, 1999), or the Wenchuan earthquake (China, 2008) show that tunnel structures are vulnerable to unrecoverable damage caused by earthquake [1,2]. Tunnels are difficult and expensive to repair if damaged in earthquake. Therefore, seismic analysis and structural control are key issues in engineering for disaster prevention and reduction.

So far, the seismic isolation, one of the structural control methods, has been used successfully in surface structures. However, this advanced concept is not well known for underground structures. It is mainly because underground structures are strongly constrained by surrounding soils. Therefore, differing from surface structures, the dynamic behaviors of underground structures are mainly controlled by deformations of surrounding soils rather than natural vibration characteristics. Hence, further researches of seismic isolation in underground structures are necessary. Isolation layers are a relatively new countermeasure to enhance tunnel safety during earthquakes, so few studies have investigated the dynamic behavior of a tunnel with an isolation layer. Yamada et al. [3] conducted a series of centrifuge model tests of a flat cross-section tunnel and ground system with three different countermeasures in the transverse direction, and the combination method (solidified ground and rubber membrane) was verified to be most effective. Kusakabe et al. [4] summarized physical modeling of the seismic response of tunnel structures, and emphasized the effectiveness of isolation layers and other countermeasures. These studies mainly concentrated on the influence of motion amplitude input on tunnel response, which takes isolation layers as countermeasures. The structural characteristics that influence the effectiveness of isolation layers, such as tunnel profile and dimensions, have not been investigated.

Seismic behavior of underground structures varies with structural design and structure stiffness [4]. Unlike cut and cover tunnels or immersed tunnels, the linings of shield tunnels are usually constructed in segments that are secured together using circumferential and longitudinal bolts. The seams of shield tunnel reduce the stiffness and strength of the structure and have significant influence on structural seismic responses [5]. Shield tunnels are widely employed for transportation and municipal works in urban areas, where the cross-section dimensions are of great variety. Previous theoretical studies [6–8] have shown that the stiffness of a tunnel relative to the surrounding soil is a key factor when conducting seismic analysis. The cross-section dimensions, such as tunnel diameter and thickness, are the determining factors in tunnel stiffness and thus have important effects on structural seismic response. Liu et al. [9] conducted a parametric study of shield tunnels without an isolation layer using the time-history method, focusing on tunnel diameter and thicknesses. Their results indicated that

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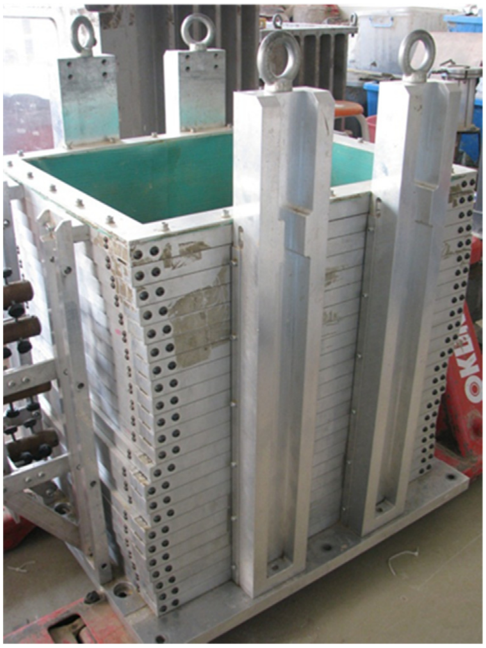

Fig. 1. Lamination box.

Table 1
Scaling factors for the centrifuge model.

Parameter	Scaling factories (model/prototype)	Dimensions
Length	1/n	L
Area	$1/n^2$	L^2
Volume	$1/n^3$	L^3
Stress	1	$ML^{-1}T^{-2}$
Strain	1	1
Mass	$1/n^3$	M
Time (Dynamic)	1/n	T
Velocity	1	LT^{-1}
Acceleration	n	LT^{-2}
Frequency	n	1/T

Table 2
Properties of prototype and model materials.

Material	Modulus (GPa)	Density (kg/m^3)	Possion's ratio υ	Yield stress (MPa)	Ultimate stress (MPa)
Prototype (Concrete)	35.5	2500	0.2	–	–
Model (Aluminum)	70	2700	0.33	500	600

Table 3
Physical properties of the model soil.

Parameter	Symbol	Value
Special gravity	G_s	2.67
Maximum void ratio	e_{max}	1.039
Minimum void ratio	e_{min}	0.682
Maximum unit weight	γ_{max}	1556 kN/m^3
Minimum unit weight	γ_{min}	1283 kN/m^3
Maximum particle	d_{max}	2 mm
Friction angle	φ	32°

the dynamic bending moment and shear forces of shield tunnels have a positive correlation with the stiffness ratio, and that axial forces have a positive correlation with thickness and diameter of the lining structure. Therefore, the cross-section dimensions of a shield tunnel are believed to influence the seismic isolation effectiveness; thus, further research is needed.

The main objective of the present paper is to verify the seismic efficiency of an isolation layer in a shield tunnel and to further study the influence of cross-section dimensions on seismic isolation effectiveness. For this purpose, two shield tunnel models with different cross-section dimensions (with and without an isolation layer) are prepared to conduct comparative dynamic centrifuge tests.

2. Dynamic centrifuge tests

2.1. Test facilities

2.1.1. Centrifuge machine and shaking table

A TLJ-50 geotechnical centrifuge machine and an electro-hydraulic shaking table in Tongji University are used in the tests, which were manufactured by the Overall Engineering Institute of Chinese Academy of Engineering Physics. This shaking table can provide concise vibration at 50*g* centrifugal acceleration with a maximum payload of 300 kg. It can reproduce sinusoidal and actual earthquake waves of maximum 20*g* shaking acceleration with a maximum duration of 1 s.

2.1.2. Model soil container

The design of container is the key factor in an effective centrifuge test. To minimize the boundary effect, a lamination box (Fig. 1) sized 500 mm × 400 mm × 550 mm was adopted in the tests. It is comprised of 22 rectangular cross-sectional aluminum frames. These frames can slide on the inner rail with little friction. The maximum slide displacement between two frames is 6 mm. A 1-mm-thick latex film is placed on the inner wall to prevent soil leakage from the gaps between the frames. The advantage of this kind of box is that it deforms together with the model soil in the shaking direction, reducing the reflection of P waves from the boundaries to a minimum level [10,11].

2.2. Scaling laws

Geotechnical centrifuges are widely used in underground structure model tests because they can reproduce the actual stress and strain states of soil and structures. To explain the test results rationally, the test data need to be converted. The scaling law can be derived from dimensional analysis [12], as shown in Table 1. The geometric scaling factor is set as $1/n$ ($n = 50$), thus the centrifugal acceleration applied in these tests is 50*g*.

The tunnel lining is an elastic shell structure, which bears both the bending moment and the axial force. According to different control equations, the bending deformation scaling law and axial deformation scaling law can be expressed in a different manner as Eq. (1) and Eq. (2), respectively.

The scaling law when bearing bending deformation is

$$\sigma_p = \frac{1-\nu_p^2}{1-\nu_m^2}\left(\frac{nh_m}{h_p}\right)^2\sigma_m \tag{1}$$

where σ is the stress of lining, ν is Poisson's ratio, n is the centrifugal acceleration level, h is the thickness, and subscript p and m denote the prototype and model parameters, respectively.

The scaling law when bearing axial deformation is

$$\sigma_p = \left(\frac{nh_m}{h_p}\right)\sigma_m \tag{2}$$

If the geometry was scaled by $h_p = n\ h_m$, and if the model and prototype had the same Poisson's ratio, then the bending and axial stresses in the model would equal the stresses in the prototype. Owing to material differences between the model tunnel and the prototype, these two equations cannot be satisfied simultaneously. Because