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Shaking table tests on seismic response and damage mode of tunnel linings in diverse tunnel-void interaction states

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ABSTRACT

The voids between the primary and the secondary linings for tunnel structures can be regarded as the worst contact state, which is deemed as serious tunnel quality defect. Recently, researchers have attempted to study tunnel linings behavior with the voids mostly in static state but these sort of defective tunnel linings are easier to destroy by earthquake. A shaking table-based method to determine the behavior of tunnels subject to the voids behind linings can be the ideal method to study their interaction in seismic dynamic states. This paper presents results from a series shaking table tests on scaled tunnel models with and without the void on the lining crown under increasing seismic intensities excitations. Details of experimental setup and procedures are described first and then the test results are presented. The test results are discussed based on the acceleration amplification factors, tension-compression strains, and damage patterns. The comparison shows that the peak acceleration on the outer surface of lining crown with a void is greater than without a void after inputting the peak ground acceleration (PGA) beyond 0.4 g regardless of the excitation directions. Each monitoring point on lining models without a void is mainly in the reasonable stress state and the most adverse strain state generates on the arch springing. There is nearly no strains difference between lining models in tight and loose contact states while the input PGA grows from 0.2 g to 0.4 g. However, plenty of tension strains appear and increase from the crown to the sidewall of lining model with a void with the input PGA increasing from 0.6 g to 1.0 g. Accordingly, multiple longitudinal cracks along axis of lining model are generated from the crown to the sidewall but three annular cracks on outer surface of lining crown should be focused attention. Finally, it is found that tunnel models behavior with and without voids behind the linings in the shaking table tests compared favorably with that in seismic damage instances.

1. Introduction

Recent series strong earthquakes in China, such as the 2008 Mw 8.0 Wenchuan earthquake, 2013 Mw 7.0 Lushan earthquake and 2017 Mw 7.0 Jiuzhaigou earthquake, had testified the vulnerability of tunnels (Baziar et al, 2014; Moghadam and Baziar, 2016), quite a substantial proportion of which were actually defective during construction or operation periods (Wang et al., 2001, 2009, 2013; Li, 2012; Yu et al., 2016a). One of quality defects is void between secondary lining and surrounding rock (Nie et al., 2015). In reality, void is one of the three types of contact states between secondary lining and surrounding rock for tunnel structures. The other two are tight and loose contact state respectively. Both the loose contact state and the voids behind the lining can be regarded as poor contacts, which are also deemed as typical inducements of other tunnel quality defects (Zhang et al., 2013). Due to the inherent characteristics of concealment and randomness, generally, voids do not directly lead to structural damage in static state but it is related to a large number of compound and secondary tunnel defects. Although voids defects are not difficult to detect, they are not easy to renovate perfectly (Wang et al., 2010). Hence, this type of defects has received minimal attention from the design, construction and operation communities, and much more the earthquake engineering community (Meguid and Dang, 2009; Oreste, 2014). Whereas in seismic state, this lack of attention may stem from the fact that tunnel structures with voids have generally been considered to perform well in small to moderate earthquakes due to their lower constraining forces that lead to limited seismic inertia forces (Leung and Meguid, 2011). However, what has been underestimated is that the constrain effects from surrounding rock, which is directly related to complicate and potential hazards of tunnel structures in earthquakes (Yu and Rowe,

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1999; Fraldi and Guarracino, 2009; Jones and Hunt, 2011).

As mentioned above, relatively few studies conducted on seismic responses and damage modes of tunnel structures with voids but the performance of tunnel structures with void to withstand moderate to severe seismic events was still questionable. To address the tunnel-void interaction issue in static and seismic states, many geophysical scientists initiated voids position detection projects by using various non-destructive approaches and techniques (Fang et al., 2016). There was no doubt that the voids behind secondary linings and primary supports were very common especially which were on the outer surfaces of lining crowns, spandrels and sidewalls (Zhou et al., 2017). Furthermore, in many high intensity seismic areas, it is ordinary that the total length of voids between secondary lining and surrounding rock is more than 10% of railway tunnels length or even more than 50% of highway tunnels length (Zhang et al., 2016). Investigation has proven that three main reasons as construction methods, design mistakes and geological conditions can result in voids; meanwhile the results from voids have started to draw attention of researchers (Gao et al., 2014). There are three phases to describe the evolutionary process of void-inducing disasters. First, voids appearances have strong influence on worsening the constrain interaction of linings and rock, especially on squeezing lining structures and loosing surrounding rock (Balkaya et al., 2012). Second, voids expansion is effective in lining cracking or even spalling due to the seepage, unsymmetrical overloading of lining and absent counterforce of rock, thereby leading to reduction of reliability and durability (Huang et al., 2013). Third, voids shrink and collapse are highly beneficial for reducing carrying capacity and serviceable security owing to the superimposition of loose contact states behind primary supports and secondary linings (Wang et al., 2014). Thus, it is important to detect, backfill or grout the voids behind lining in time, especially which are on the tunnel lining crown.

To date, many transport tunnels have been unavoidably constructed in seismic fortification zones and voids concealing areas. Fig. 1 shows the damage patterns of tunnel structures with voids on its crown after Wenchuan Great Earthquake (Wang et al., 2015). Thus, it is of great significance to study the seismic damage mechanism of tunnel linings with voids defects, which is helpful to protect serviceability of transport tunnels under and after earthquake attack. Herein, this research aims to study the seismic response and damage patterns of tunnel linings in diverse tunnel-void interaction states. Thereby we had designed and conducted a series of shaking table tests on lining models with voids on lining crowns. Technical details of the tests including test facilities, experimental setup, soil and lining models, design and fabrication of the soil container and simulations of seismic excitations are presented in this paper. The results obtained in this study may provide useful references for researching the failure mechanism, preventing and repairing methods for void-inducing defects of tunnel structures.

2. Experimental setup and description

2.1. Tunnel prototype description

Taking the Longxi tunnel, which was serious damaged in Wenchuan Great Earthquake, as the prototype structure. The tunnel is a 3700 m long highway tunnel connecting the towns of Dujiangyan and Yingxiu, the stretching directions of which are from southeast to northwest. The tunnel has a horseshoe shape cross section with excavated dimensions of 11.2 m width and 7.9 m height. Since Longxi tunnel is located approximately 2–3 km away from the epicenter of Wenchuan Great Earthquake and built in weak and fractured surrounding rock, rock deformation and lining crushed phenomena were very common during the construction period (Yu et al., 2016b). Moreover, Longxi tunnel is a fault-crossing tunnel below the underground water table, no wander plenty of voids were detected behind the tunnel linings especially on the lining crown.

(a)

(b)

Fig. 1. Damage modes of Longxi tunnel with voids on its crown in Wenchuan Great Earthquake 2008, China. (a) Void-inducing lining crown collapse in constructing stage; (b) Void-inducing lining crown collapse in operating period.

2.2. Shaking table array

The shaking table at Institute of Engineering Mechanics, China Earthquake Administration is a three-direction with six-degree-of-freedom shaking table array that can be excited using either electrical actuator (for high frequency shaking) or hydraulic actuator (for low frequency shaking) controlled using a digital control module (Chen et al., 2010). The digital control module allows simulation of various types of dynamic displacement time-histories, including harmonic spectrum, band limited white noise spectrum and pre-stored earthquake records. Due to the experimental requirements, the electrical actuator was used in this series research. The shaking table can efficiently run in the range of 0.5–40 Hz, the dimension of which is 5 m × 5 m in plane (see Fig. 2(a)). The maximum acceleration of shaking table is 10 m/s^2 in horizontal directions and 7 m/s^2 in vertical directions with the maximum displacement of 50 mm and maximum proof model mass of 30 tons. The accessory facilities include loading controlling devices and data logging apparatus (see Fig. 2(b) and (c)). The data logging apparatus is directly able to obtain strains, displacements and accelerations from test models during excitations.

2.3. Model container design and manufacture

A model container is fabricated and installed on the shaking table in order to contain the surrounding rock and lining models. One of the