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Seismic damage mechanism and dynamic deformation characteristic analysis of mountain tunnel after Wenchuan earthquake

Yusheng Shen [a,*], Bo Gao [a], Xiaoming Yang [b], Shuangjiang Tao [a]

[a] Key Laboratory of Transportation Tunnel Engineering, Ministry of Education, Southwest Jiaotong University, Chengdu 610031, China
[b] School of Civil and Environmental Engineering, Oklahoma State University, Stillwater, OK 74078, USA

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ABSTRACT

After the 2008 Wenchuan earthquake (Mw = 8.3), many mountain highway tunnels in the affected area were severely damaged. In order to improve the current knowledge about the seismic performance of mountain tunnels under strong earthquakes, a forensic investigation was conducted on 52 tunnels after the earthquake. Based on the seismic damage data, the damage level of the inspected tunnels was classified using a new damage evaluation criterion. Subsequently, typical seismic damage characteristics and mechanisms of mountain tunnels were analyzed based on three different damage patterns: damage to shallow tunnel, damage to deep-buried tunnel structure and damage to pavement. Finally, based on the relative displacement (RD) method, a three-dimensional numerical model was developed to investigate the deformation characteristics of the portal structure under a strong earthquake. The numerical results showed that the tunnel lining cross section exhibited an alternate tension–compression deformation at the diagonal directions, and the relative displacement value of the upper-structure (above the sidewall) was generally more than that of the lower-structure (under the sidewall). Three stress states of the lining were deduced from the numerical model, which provided a good interpretation for the seismic tunnel damages observed after the Wenchuan earthquake.

1. Introduction

In seismically active mountainous areas, tunnels are generally thought to be less susceptible to the earthquake damage compared to above-ground structures due to its strong seismic-resistance by nature (He et al., 2009). Nevertheless such a traditional viewpoint has been challenged by several recent strong earthquakes (Asakura et al., 2000; Lin et al., 2007). The 1995 Kobe earthquake (Mw = 6.9) and the 1999 Chi-Chi earthquake (Mw = 7.6) both caused considerable tunnel damages (Li, 2008). After the 2008 Wenchuan earthquake (Mw = 8.3 with a duration of 120 s), some tunnel portals suffered severe damage and needed remedial measures or even reconstruction (Gao et al., 2009; Cui et al., 2011). Understanding the potential damages to the tunnel during strong earthquakes is an emerging problem in engineering geology especially for sites with poor geological conditions (Alija et al., 2013). In order to improve the current knowledge about the seismic performance of mountain tunnels under strong earthquakes, it is necessary to carry out a forensic investigation on the tunnels damaged during the Wenchuan earthquake.

The forensic investigation is a traditional practice in tunnel engineering and has been carried out by many researchers. Asakura et al. (2000) studied the damage mechanism of mountain tunnels by collecting damage information from several tunnels in Japan. Lanzano et al. (2008) developed a tunnel damage database with case histories and remediation methods. Konagai et al. (2005) collected tunnel damage information from the 2004 Chuetsu earthquake. After the Wenchuan earthquake, many researchers have investigated the general damage mechanism of tunnels and the influence factors of seismic damages (Li, 2008; Gao et al., 2009; Qian et al., 2009; Shen et al., 2009, 2011; Sun et al., 2010; Cui et al., 2011; and Wang et al., 2012). However, little effort was made to classify and summarize the damage characteristics of the tunnels in the region.

In this study, seismic damage data were collected from 52 tunnels in the region after the Wenchuan earthquake. The structural damage of each tunnel was classified based on a new severity evaluation criterion. Typical characteristics and mechanisms of seismic damage of the investigated tunnels were analyzed based on different locations, i.e., damage to shallow tunnel, damage to deep-buried tunnel at poor geological conditions and damage to tunnel pavement. Finally, based on a real tunnel case, the typical seismic damage characteristics for the portal structure were modeled numerically. The deformation characteristics of the portal structure were analyzed during the seismic motion by the relative displacement (RD) method, which explained the seismic damage

* Corresponding author. Tel.: +86 13550187393; fax: +86 2887600612.
E-mail addresses: sys1997@163.com (Y. Shen), prgaobo@vip.sina.com (B. Gao), xmyang@okstate.edu (X. Yang), 35140999@qq.com (S. Tao).

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characteristics of the tunnel portal structures under a strong earthquake action.

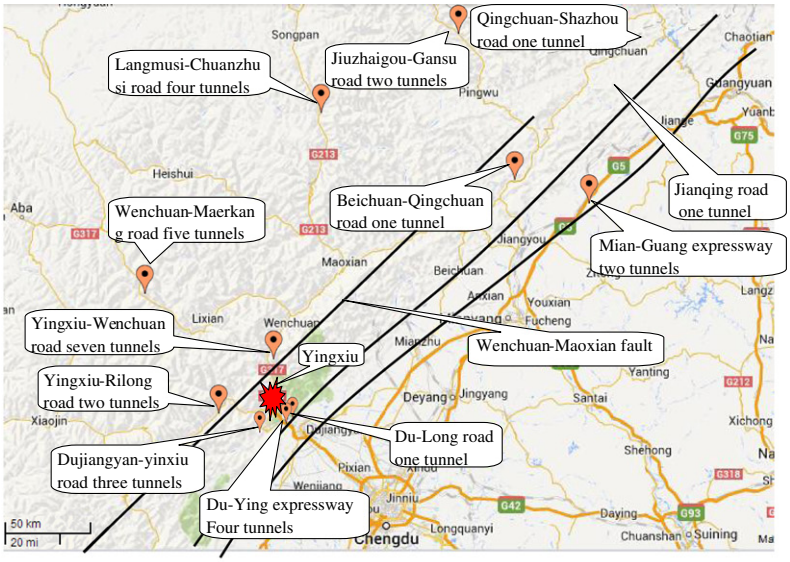
2. Field investigation of tunnel damage

The 2008 Wenchuan earthquake occurred in Wenchuan County, Sichuan, China. The epicenter was at Yingxiu town with a depth 14 km. The maximum peak ground acceleration (PGA) exceeded 1.0 g. The earthquake caused about 320 km rupture along the Longmenshan Fault Zone by thrusting with a dextral component (Li, 2008).

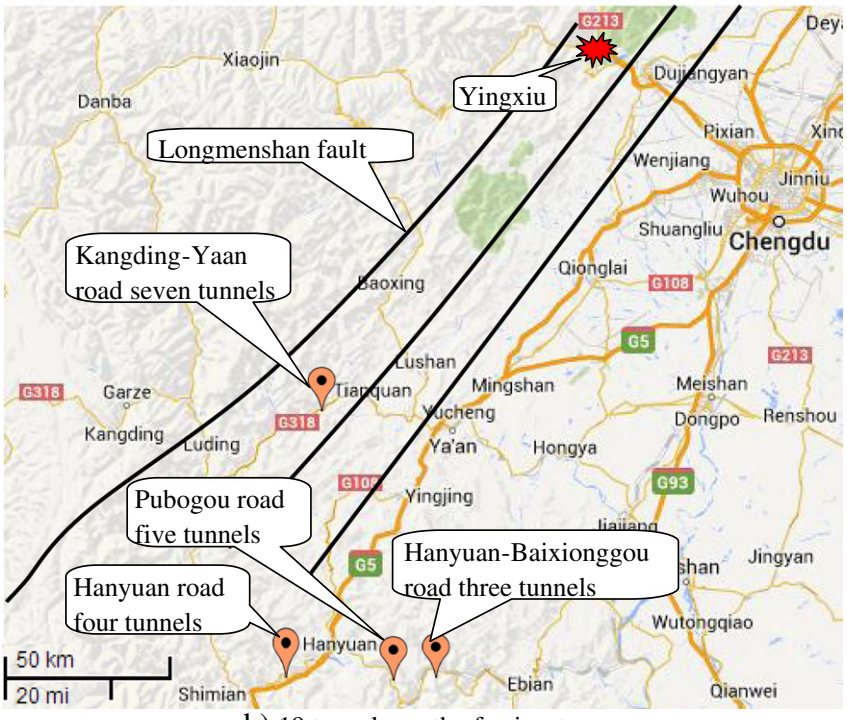
After the earthquake, 52 tunnels in the affected area (Figure 1) were inspected of which 35 tunnels were in operation and 17 tunnels were under construction when the earthquake happened. Most tunnel portals within 20 km from the epicenter were buried or damaged due to slope failure or landslide, but some tunnels being in operation also were damaged to some extent even though those were more than 150 km from the epicenter, as shown in Table 1.

Fig. 2 presents the typical cross section of a tunnel structure in the different region. The support systems of tunnels for provincial highways usually consist of primary liner, mesh, piper roof, waterproof layer, and secondary lining (Figure 2a). For local highways, the support systems only consist of primary lining, waterproof layer and secondary lining (Figure 2b).

Currently, no standard tunnel damage classification is available, although some criteria were introduced in literatures. Dowding and Rozen (1978) considered three damage classes (i.e., no damage, minor



a) 33 tunnels near or north of the epicenter



b) 19 tunnels south of epicenter

Fig. 1. Location of the 52 tunnels investigated (map snapshots were from https://maps.google.com). a) 33 tunnels near or north of the epicenter. b) 19 tunnels south of epicenter.