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Seismic damage assessment of mountain tunnel: A case study on the Tawarayama tunnel due to the 2016 Kumamoto Earthquake

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ABSTRACT

The Kumamoto Earthquake with magnitude of 7.3(Mj) on April 16 and 6.5(Mj) on April 14, 2016 have triggered numerous damages to the Tawarayama Tunnel in Kumamoto Prefecture, Japan. Distribution and characteristics of these seismic damages were investigated and summarized to assess potential influencing factors. Seismic damages are categorized into five patterns as follows: lining cracks, spalling and collapse of concrete lining, construction joint damage, pavement damage and groundwater leakage. Lining cracks can be further classified into ring crack, longitudinal crack, transverse crack and inclined crack. Site investigation showed the primary seismic damage was lining crack, especially ring crack. In special, an interesting phenomenon was observed that ring cracks occurred with an estimated average spacing of 10.0 m in 23.4% spans of the Tawarayama Tunnel. This results from the interaction between seismic wave and special geological conditions that dense Andesite and crushed Andesite around the Tawarayama Tunnel appear in tilt alternately with space between 10 m and 20 m. Following these analysis, some recommendations were proposed for future tunnel planning.

1. Introduction

Tunnel is generally divided into two types: shallow-buried urban tunnel and deep-buried mountain tunnel. It was widely accepted that mountain tunnel was assumed to be seismic resistant due to being situated deep with rock layers (Towhata et al., 2008). Therefore, studies of mountain tunnel damages by earthquakes were limited. Whereas, three strong earthquakes involving the 1995 Kobe Earthquake occurred in Japan, the 1999 Chi-Chi Earthquake in Taiwan and the 2008 Wenchuan Earthquake in Sichuan province of China have given strike on this tradition view. Among them, 12% of mountain tunnels in the epicentral area in the Kobe Earthquake were damaged severely (Yashiro et al., 2007), 26% of 50 tunnels located with 25 km of the earthquake fault in the Chi-Chi Earthquake damaged heavily and 22% moderately damaged (Wang et al., 2001), and 73% of 18 tunnels located in the Du (Du-jiang-yan)-Wen (Wen-chuan) highway in the Wenchuan Earthquake severely damaged and 22% damaged moderately (Wang et al., 2009). The damages to mountain tunnels by earthquakes occurred in recent years have attracted much higher attention on seismic effect of earthquake on mountain tunnels.

Thus, conspicuous efforts of collection and classification on seismic damages to mountain tunnels due to earthquakes have been taken by many researchers, such as Dowding and Rozan (1978), Asakura (1996), Wang et al. (2009), Li (2012), and Chen et al. (2012). Dowding and Rozan (1978) suggested three forms of the seismic damages: damage by earthquake-induced ground failure, damage from fault displacement and damage from ground shaking or vibration. After the Taiwan Chi-Chi Earthquake in 1999, Wang et al. (2001) classified the damages into six types: sheared off lining, slope failure induced tunnel collapse, lining cracks, pavement or bottom cracks, wall deformation and cracks that develop near opening. Li (2012) analyzed characteristics of tunnel failures following the Wenchuan Earthquake in 2008 and categorized them into six types: avalanches and sliding towards the tunnel portal, cracking of the tunnel portals, collapse of the liner and surrounding rock, failure and dislocation of the lining, uplift and cracking of the tunnel invert, deformation and cracking of the preliminary bracing. Chen et al. (2012) based on previous studies to summarize seven common damage characteristics according to manner of the structural damages: lining cracks, shear failure of lining, collapse caused by slope failure, portal cracking, leakage, wall deformation, and invert damage. In addition, database for seismic damages to tunnels due to earthquakes were developed to analyze main factors affecting stability of underground structures (Sharma and Judd, 1991) with case histories and remediation methods (Lanzano et al., 2008). Much more detailed site

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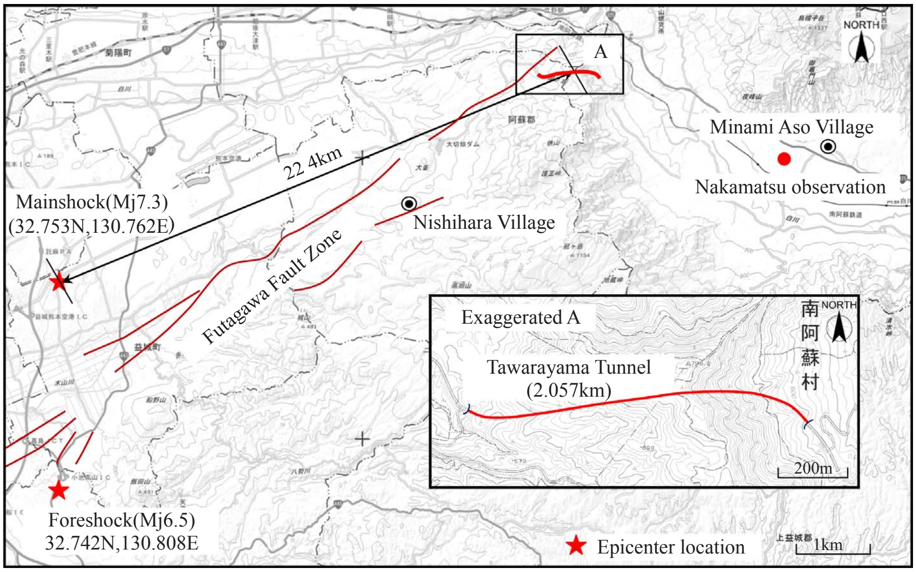

Fig. 1. Location of the Tawarayama Tunnel and epicenter of the Kumamoto Earthquakes.

investigation and analysis on tunnel seismic damage have been carried out by other researchers for the 1995 Great Hanshin Earthquake (Asakura and Sato, 1998), the 2004 Mid Niigata Prefecture Earthquake (Shimizu et al., 2005, 2007; Yashiro et al., 2007; Konagai et al., 2009; Jiang et al., 2010), the 2007 Niigata Prefecture Chuetsu Offshore Earthquake (Saito et al., 2007), the 2008 Wenchuan Earthquake (Wang et al., 2009; Shen et al., 2014; Yu et al., 2013a,b, 2016a,b).

In this study, distribution and characteristics of seismic damages to the Tawarayama Tunnel were investigated and summarized to assess potential influencing factors. Aimed at the axially regularly distributed ring cracks, preliminary discussion on its cause involving seismic wave and geological conditions were conducted. And some recommendations were proposed for future tunnel planning based on these analysis.

2. Kumamoto Earthquake's damages to the Tawarayama Tunnel

2.1. Project of the Tawarayama Tunnel

The Tawarayama Tunnel is located at a distance of about 22.4 km from the epicenter of the mainshock (Mj7.3) as shown in Fig. 1. The total length of the tunnel is 2057 m with horseshoe cross section. Fig. 2 shows the typical cross section of the tunnel. The typical cross section has a total width of 10.20 m and a maximum height of 7.97 m. Fig. 3 presents the geological profile of the tunnel. Its maximum overburden is about 300 m. The Tawarayama Tunnel runs through three different formations: the Quaternary Holocene, the Quaternary Pleistocene and the Tertiary Pliocene. The portal area is excavated in Talus and Early Stage Talus deposites composed of welded tuff, gravel, silt and clay. The tunnel is excavated in the Andesite lava. Based on the Japanese Technical Standard for Structure Design of Road Tunnel (JARA, 2003), rock mass along the tunnel (Fig. 3) is organized into four classes, involving C_{II}, D_I, D_{II} and D_{III}.

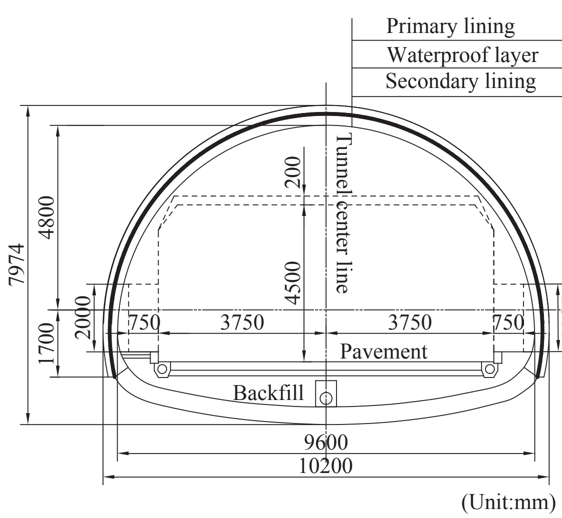

Fig. 2. Typical cross section of the Tawarayama Tunnel.

Excavation method of the Tawarayama Tunnel is New Austrian tunnelling method (NATM). NATM is assumed to be much better than the traditional method based on the conditions after earthquakes. This is because interaction between surrounding rock and tunnel using NATM performs better than that using traditonal method (Chen et al., 2012). Support systems of the tunnel consist of primary support, waterproof layer, and secondary support. The primary support include shotcrete (0.10 m, 0.15 m, 0.20 m and 0.25 m for rock calss C_{II}, D_I, D_{II} and D_{III}, respectively) and rockbolt. For rock class D_I, D_{II} and D_{III}, the rockbolts are distributed on a grid of 1.2 m × 1.0 m and have a length of 4.0 m. For rock class C_{II}, the rockbolts are distributed on a grid of 1.5 m × 1.2 m and have a length of 3.0 m. Besides, for rock class D_{III}, forepoling is conducted, especially at the portals. The rockbolts are spaced on a grid of 0.60 m × 1.0 m with length of 3.0 m. The secondary lining is reinforced concrete with a thickness of 0.30 m.

2.2. Overview of the Kumamoto Earthquake and seismic damages to the Tawarayama Tunnel

The 2016 Kumamoto Earthquakes were a series of earthquakes, including a foreshock (the epicenter located at 32.742N, 130.808E) with a magnitude 6.5(Mj) at 21:26 JST on April 14, 2016, at a depth of about 11 km, and a magnitude 7.3(Mj) mainshock (the epicenter located at 32.753N, 130.762E) which struck at 01:25 JST on April 16, 2016 at a depth of about 12 km (Asian Disaster Reduction Center, 2016) beneath Kumamoto City of Kumamoto Prefecture in Kyushu Region, Japan. Fig. 4 illustrates distribution of peak acceleration of both the foreshock and mainshock according to the National Research Institute for Earth Science and Disaster Prevention of Japan. The acceleration waves measured at the Nakamatsu observation site (Fig. 1) during the mainshock on April 16, 2016 are depicted in Fig. 5. The Nakamatsu observation site is located at the northeast of epicenter with a distance of 32.3 km. Acceleration of the mainshock from time of 15 s to 30 s at Nakamatsu observation site is shown in Fig. 5b. The seismic