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Damage analysis of the new Sanyi railway tunnel in the 1999 Chi-Chi earthquake: Necessity of second lining reinforcement

Chih-Chieh Lu[a,*], Jin-Hung Hwang[b]

[a] National Center for Research on Earthquake Engineering, No. 200, Sec. 3, Xinhai Rd., Taipei 10668, Taiwan, ROC
[b] Department of Civil Engineering, National Central University, No. 300, Jhongda Rd., Jhongli City, Taoyuan County 32001, Taiwan, ROC

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ABSTRACT

This study documented the case history of the new Sanyi railway tunnel. The New Austrian tunneling method (NATM)-built mountainous tunnel was seriously damaged during the 1999 Chi-Chi earthquake. In order to better understand the vulnerability and the deformation of the underground structure subject to strong ground motion, the modified cross-section racking deformation (MCSRD) method was used to evaluate the seismic performance of the tunnel. The analyses carefully took the nonlinear soil-structure interaction into account in order to derive damage pattern of the tunnel. Based on the analysis results, in addition to the extremely strong ground motion, numerical testing identified the causes of the disaster to include rectangle-like geometry at the refuge section, non-reinforcement of the second lining, and imperfect backfilling. The results also showed that the second lining of the NATM-built tunnel sustained substantial seismic loading and should be suitably reinforced in seismically active areas. The effect of the reinforcement of the second lining was demonstrated with a reinforcement example.

1. Introduction

The seismic performance of underground structures has become an important issue due to an increase in incidents of damaged tunnels caused by catastrophic earthquake events such as the 1923 Kanto earthquake, 1995 Kobe earthquake, 1999 Chi-Chi earthquake, and 2008 Wenchuan earthquake (Okamoto, 1973; Asakura and Sato, 1996; Wang et al., 2000; Hwang and Lu, 2007; Lu and Hwang, 2008; Wang and Zhang, 2013; Shen et al., 2014). As demonstrated by historical evidence, underground structures are still at a high risk of damage from compression by the surrounding ground, triggered by strong shaking. The documented case histories of damaged tunnels are valuable and worth further study for the practical engineer to take the lesson learned for future design work. In this study, the object of interest was the new Sanyi railway tunnel in central Taiwan. The NATM-built mountainous tunnel was seriously damaged by the 1999 Chi-Chi earthquake. Because of this event, the NATM concept that the second lining will not take any loading should be modified, and it is strongly recommended that the second lining in a seismically active area be reinforced. The purpose of this study was to determine the nonlinear seismic behavior of the studied mountainous tunnel subject to strong ground motion, and provide a guide to the reinforcement of a second lining according to the results of the parameter sensitive analysis.

To assess the seismic performance of underground structures, several references provide an overview of design work regarding seismic issues in underground structures; these include FHWA (2009), ISO 23469 (2005), and Hashash et al. (2001). According to these references, the seismic evaluation approach can be roughly divided into three categories, which are the CSRD (cross-section racking deformation) method, the MCSRD method, and full dynamic analysis. Of these, the pseudo-static CSRD and MCSRD methods prescribe a seismic ground deformation and consider the interaction between the underground structure and the surrounding ground using certain assumptions (Wang, 1993; Penzien, 2000; Nishioka and Unjoh, 2002; Gil et al., 2001; Huo et al, 2006; Kontoe et al., 2008, 2014; Park et al, 2009; Lu and Hwang, 2017). Note that the contribution of inertial force to the underground structure during an earthquake is ignored in these pseudo-static approaches. The CSRD and MCSRD methods are thought to be more applicable to the cases when the contribution of inertial force to the seismic performance of the concerned underground structure is small, i.e. mountainous tunnels. In contrast, the full dynamic analysis can consider the dynamic characteristics of an underground structure and the surrounding ground during dynamic loading without ignoring the inertial force, and it is believed that the comprehensive approach can better capture the seismic performance of an underground structure. To evaluate the performance of these methods, Tsinidis et al. (2016a,

* Corresponding author.
E-mail addresses: chchlu@ncree.narl.org.tw (C.-C. Lu), hwangjin@cc.ncu.edu.tw (J.-H. Hwang).

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2016b), and Tsinidis (2017) conducted a series of centrifuge tests that demonstrate better performance of the full dynamic analysis when compared with the test results. It is recommended to conduct a full dynamic analysis for the seismic performance of an underground structure if the target of concern is near the ground surface and confined by a soft medium, i.e. an urban shallow tunnel.

Since the rigorous dynamic analysis has a more complicated theoretical basis and is time consuming to use in comparison with the pseudo-static approaches, the CSRD and MCSRD methods are favored in practical design work if the inertial force does not obviously affect the seismic behavior of the studied case, such as a mountainous tunnel, like the old Sanyi railway tunnel and new Sanyi railway tunnel. Hwang and Lu (2007) documented the information for the old Sanyi railway tunnel and employed the MCSRD method to assess the seismic capacity of the mountainous railway tunnel in terms of peak ground velocity (PGV), seismic shear strain, and JMA intensity scale. The evaluated seismic capacity of the tunnel by the MCSRD method agreed well with the field observation during 1935 Hsinchu-Taichung and 1999 Chi-Chi earthquakes. Also, the MCSRD method can capture the seismic mechanism of the tunnel in comparison with the results by dynamic analysis. Contrary to the old Sanyi railway tunnel safely coming through the 1999 Chi-Chi earthquake, it is surprising that the “new” Sanyi railway tunnel, which is near the old ones, was seriously damaged by the shaking of the earthquake. To figure out the failure mechanism of the tunnel, a preliminary study of the seismic performance for the new Sanyi railway tunnel during the 1999 Chi-Chi earthquake was conducted by Lu and Hwang (2008) using the MCSRD method. In order to simulate the damage pattern of the tunnel, the strength of the second lining was reduced to 10% of its initial strength when the loading condition is over the corresponding P-M strength curve. The simplified approach, which gave a reduction in the strength factor of the yielding structural member to model the nonlinear mechanism of structural elements, was improved in 2017. Lu and Hwang (2017) compiled the Axial force-Moment-Curvature (A-M-C) surface of the structural elements in FLAC2D using the program’s built-in FISH language to model the nonlinear behavior of the structure. When this model is combined with the FLAC built-in nonlinear constitutive model for the geotechnical material, the nonlinear interaction between the underground structure and the surrounding ground can be well understood. The framework of the MCSRD method was also modified accordingly.

To better reflect the seismic performance of the new Sanyi railway tunnel, the suggested implementation of the MCSRD method by Lu and Hwang (2017) was adopted to re-evaluate the failure mechanism of the most seriously damaged section at Sta. 161K + 300 and review the inferred damaging factors including excessive earthquake shaking, rectangle-like geometry at the refuge section, imperfect backfilling, non-reinforced second lining, and geological weak zone (Hsu and Weng, 2000). From the results of numerical analyses, the simulation results agreed well with the field damage pattern observed after the 1999 Chi-Chi earthquake. Besides the bad geological conditions, the results indicated that rectangle-like geometry at the refuge section and the unreinforced second lining were the main causes of damage to the tunnel during the earthquake. The results also showed that the second lining sustained substantial seismic loading and the seismic capacity of the lining could increase significantly when the amount of reinforcement of the second lining is over a threshold value. Thus, the second lining of the NATM tunnel should be suitably reinforced in a seismically active area.

2. New Sanyi railway tunnel

2.1. Basic information

The new Sanyi railway tunnel is in central Taiwan and passes through a series of small mountain ridges and terraces neighboring a small valley, as shown in the Digital Terrain Model (DTM) of Fig. 1. Its overburden depths range from 20 to 150 m. The ground formations that the tunnel passes through are the Miocene Kuantaoshan Sandstone, the Shihliufeng Shale, the Toukeshan Gravel, and the river gravel terrace. The tunnel crosses over two fault zones, Sanyi fault and Shihliufen fault. Based on engineering characteristics, the rock mass along the tunnel can be classified into 6 grades, as shown in Table 1, and the geological profile accompanying with construction conditions during tunneling are shown in Fig. 2. In addition, the geological investigation, conducted by United Geotech (1989), indicated that the ground formations can be roughly divided into eight kinds of formations. The physical and mechanical properties of these formations are summarized in Table 2.

Since the tunnel cross section was designed for an electric double-track railway system, waterproofing was installed to prevent leakage of ground water. Furthermore, to satisfy the demands of operation and maintenance, refuge spaces were excavated on the side wall at 20 m intervals for small refuges and 300 m intervals for large ones. The three types of cross-sections, including the standard one, of the tunnel are shown in Fig. 3. In general, the tunneling adopted the Drill and Blasting (D&B) method with bench excavation. When difficult ground conditions were encountered, ground treatment or special excavation methods were adopted. From the monitored records during construction, the horizontal convergence deformation ranged from 15 to 555 mm, and the crown settlement ranged from 2 to 155 mm in most typical sections. The problems encountered during excavation included (1) roof spalling due to fractured rock, (2) rock mass sliding along the planes of cleavage and join, and (3) rock softening owing to ground water leakage. The problematic locations are indicated in Fig. 2.

2.2. Seismic ground motions

On 21 September 1999, a strong quake with a magnitude of 7.3 on the Richter scale occurred near the town of Chi-Chi. A large earthquake like this had not been experienced in Taiwan for over 100 years. The maximum ground accelerations measured by the strong motion seismographic stations in the Nantou-Wufeng area were as high as 0.7–1.0 g. It caused significant damage in nearby areas in central Taiwan. Because the seismographic stations in that area are dense, the acceleration history records of the earthquake near the concerned area were available, which can be obtained from the nearby seismographic stations. The closest seismographic station, 5 km from the tunnel, is Jian-Jhong elementary school, and its recording acceleration history is used in the following analysis. Since the tunnel axis runs in a roughly South-North direction, the critical motion is supposed to be in the east-west direction which mainly provided the racking action on the concerned tunnel section. Fig. 4 shows the acceleration, velocity, and displacement histories in the E-W direction at that station. Note that although the maximum ground acceleration is only 0.14 g, the maximum velocity is 26.5 cm/s, which is a more important motion index than acceleration when using MCSRD method to assess the seismic capacity of the tunnel.

2.3. Field investigation after the 1999 Chi-Chi earthquake

The new Sanyi railway tunnel was one of the most seriously damaged tunnels after experiencing the strong shaking of the 1999 Chi-Chi earthquake. It is located in the western foothills of central Taiwan, which passes through the Sanyi fault zone, Shihliufen fault zone, and other weak ground. The new Sanyi railway tunnel was designed and excavated using NATM, the total length of the tunnel is 7261 m, and its overburden ranges from 20 to 150 m. The tunnel was completed and opened to vehicle traffic in 1998 to replace the old Sanyi railway tunnels built in 1908. Unfortunately, after operating for just one year, the tunnel was shaken by the 1999 Chi-Chi earthquake and severely damaged. Railway traffic was interrupted for several days by this catastrophic earthquake. After field investigation, eight main damaged