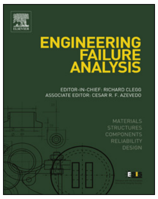
Engineering Failure Analysis 93 (2018) 44–54

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal



Short Communication

Seismic behaviour of damaged tunnel during aftershock

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ARTICLE INFO

Keywords:
Tunnel
Shake table
Bender element
Aftershock
Damage

ABSTRACT

This paper studies the seismic behaviour of tunnels that are damaged during aftershocks. The tunnels were made from three different materials that had different flexural rigidity. An undamaged tunnel was constructed out of one material, while the damaged tunnels were built with the other two materials. The seismic load was applied with a unidirectional shake table. The peak ground acceleration for various input motions varied from 0.1 g to 1.2 g. The dynamic earth pressure around the tunnel was measured using three soil pressure transducers. The tunnel was placed in the transverse direction of shake table motion. The properties of the surrounding soils were calculated from bender element. The peak dynamic stress generated in the soil was used to study the behaviour of the damaged tunnels. A hand-held vibration analyser was used to measure the motion of the shake table. The results show that the damaged tunnel is more vulnerable to low frequency seismic motion.

1. Introduction

The demand for underground spaces has increased with the increased population. The underground structures were constructed mostly in mountainous region with hard rock strata and with little or few human population. However, during the last few decades, underground structures have been constructed beneath cities with large human populations living in densely packed buildings. Comparatively shallow cover and soft ground conditions make such structures more vulnerable. Thus, any damage to the underground structure beneath the city can cause severe damage to the surrounding structures and human lives. Therefore, the underground structures constructed beneath the city need greater safety and functionality during main shocks (MS) and aftershocks (AS). Aftershocks (AS) are very common phenomena observed after the MS and are believed to follow the Gutenberg-Richter Law. The randomness and large magnitude of AS have the potential to collapse structures damaged during MS. Most often, the larger MS are followed by larger AS [1–6]. Hence, this research focuses on the seismic behaviour of the damaged tunnel during AS.

The severity of earthquakes to underground structures can be seen from the results of the Kanto earthquake, which occurred in year 1923 and damaged about ninety-three tunnels. Twenty-five out of ninety-three tunnels damaged in the Kanto earthquake had to be reconstructed. Also, the ground collapse resulted from lining damage. The Izu-Oshima-Kinkai earthquake damaged nine tunnels that crossed the fault line. The Kobe earthquake in 1995 caused the tunnel lining to fail under shear and compression. In a more recent Niigataken-Chuetsu earthquake in 2004, twenty-four tunnels were damaged. The tunnels near the epicentre (within 10 km radius) sustained heavy damage. Spalling of concrete lining was observed along with a reduction in the tunnel's diameters [7]. The tunnels passing through rock were also damaged during the Niigataken-Chuetsu earthquake [8]. Dowding (1978) collected data about seventy-one (71) tunnels and found that the tunnels are vulnerable to damage only if the peak ground acceleration (PGA) exceeds 0.19 g. Furthermore, PGAs of 0.19 to 0.5 g are moderately damaging and PGAs of 0.5 g or more are heavily damaging [8].

Many researchers have reported that the sections damaged occurred during MS become more vulnerable during AS [9–12].

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https://doi.org/10.1016/j.engfailanal.2018.06.028
Received 20 March 2018; Received in revised form 19 June 2018; Accepted 28 June 2018

However, most studies on structural damage during AS were carried out on buildings [10, 11, 13, 14], bridge piers or reinforced columns [9, 15], and gravity dams [16]. Very few investigated tunnel damage [12]. Soil liquefaction due to AS has also been studied [17]. The effect of frequency of AS on the seismic response of reinforced concrete columns has also been reported [9]. Damage and ductility-based reduction factors have also been used by researchers to quantify the extent of damage to buildings [18]. However, tunnels are confined by surrounding soil, therefore such parameters may not be suitable to quantify the damage of tunnels during AS. In addition, repetitive earthquake loading causes deterioration in mechanical properties of surrounding rock. AS should not be ignored because they can cause further failure of tunnels in soft rock. Moreover, considering AS in the design of the tunnel is important when the tunnel is situated in the Meizoseismal area [12]. Still, no significant work has studied the behaviour of underground structures during AS. Parameter like shear force and bending moment reduction in damaged tunnel, fault movement and change in alignment due to bending of tunnel can affect the behaviour of damaged tunnel. However, shear force and bending moment reduction will have major effect on seismic behaviour of damaged tunnel and this parameter is considered for the present analysis.

Therefore, an experimental investigation to study the seismic behaviour of tunnels during AS is presented in this paper. The experiment was carried out on a tunnel of 15 cm diameter with varying thicknesses. As the tunnel is damaged during main shocks (MS), its shear force and bending moment carrying capacity are reduced. This reduction is simulated by varying the thickness of the tunnel, which changes the flexibility ratio, which is an important criterion governing the seismic behaviour of the tunnel. The tunnel with thickness 1.6 mm ($T_{(t=1.6)}$) and 1.0 mm ($T_{(t=1.0)}$) is 22 and 95 times more flexible compared to a tunnel with thickness 3.0 mm (($T_{(t=3.0)}$)), respectively. The input motion was generated with a shake table, and the tunnel was placed along the transverse direction of the motion. Three soil pressure transducers were used to measure peak dynamic soil pressure. It was found that AS of low frequency has a significant effect on the extent of damage in the tunnel.

2. Methodology

2.1. Shake table test

The experimental work was done on a unidirectional shake table. The size of the shake table top is 1.5 m × 1.5 m. It has a maximum load carrying capacity of 2000 kg. The maximum theoretical frequency is 10 Hz and maximum displacement is ± 50 mm. A rigid container of 18 mm thick perplex glass measuring 1.0 × 1.0 × 1.0 m was mounted on top of the shake table (Fig. 1). The tank is additionally supported by using angle and flat steel sections. The tank base was made rough by gluing sand to it to avoid slippage between the tank and the soil. The vertical boundaries were made absorbent by sticking expanded polyethylene (EPE) foam to them.

2.2. Sensors arrangement

Two types of sensors were used to measure the seismic response of the tunnel. Three soil pressure transducers were used to measure the peak dynamic pressure in the soil. The data were recorded on the dynamic data acquisition module. Fig. 2 shows the arrangements of sensors. The hand-held vibration analyser was used to capture the actual motion of the shake table. The hand-held

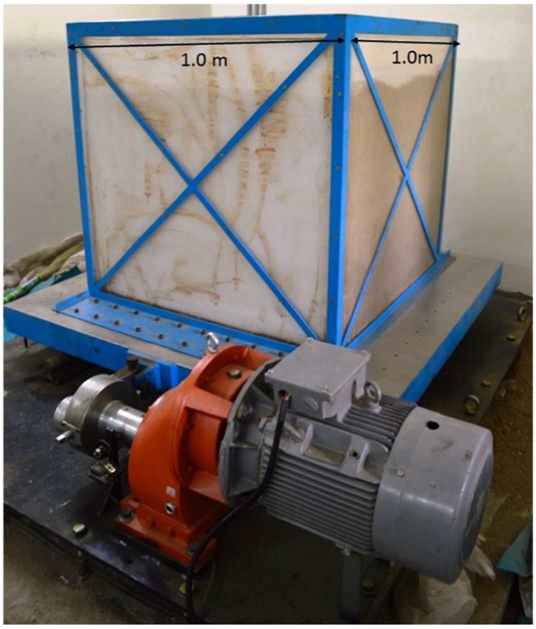

Fig. 1. Shake table with container.