Shaking table model test study on seismic performance of underground utility tunnel

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ABSTRACT

A series of shaking table model tests are designed and conducted to evaluate the seismic influence on underground utility tunnel and the soil. With reasonable similarity factors taken into consideration for the material properties and whole test models dimensions, varying input seismic spectrum are employed in the modeling tests for single and double storage utility tunnel. Due to soil-structure interaction, it is found that the maximum earth pressure at the top and bottom part of utility tunnel is greater. For low input PGA (Peak ground acceleration), like 0.2 g and 0.4 g, the maximum acceleration response next to utility tunnel will decrease along depth, while it will decrease firstly and become larger from mid-bottom part of utility tunnel to the bottom of test soil for high input PGA. The amplification factor usually ranges from 0.6 to 2.2, going down with an increasing PGA. Generally, there will be larger bending moment at the corners of utility tunnel when subjected to seismic loading. It is revealed that the seismic response is closely related to the location, structure type, soil-structure interaction, input PGA, and input seismic spectrum.

Keywords: Utility tunnel, Seismic response, Shaking table, Downscaled model test

1 INTRODUCTION

In recent years, some earthquakes, including the 1995 Kobe-Osaka earthquake, the 1999 Jiji earthquake in Taiwan, the 1999 Kocaeri earthquake, the 2008 Wenchuan earthquake, and the 2011 Tohoku earthquake and so on, heavily damaged underground structure, like subway station and utility tunnel (Patil et al. 2018). However, the research on mechanical property for underground utility tunnel is scarce, especially for its seismic response. Nishioka and Unjo (2002) put forward a simplified evaluation method for seismic performance of common utility boxes with rectangular cross section. Hu and Xue (2010) studied the mechanical property of prestress utility tunnel under static conditions, which lacks of dynamic analysis. Yue and Li (2009) investigated the seismic response of a utility tunnel through numerical simulation. Jiang et al. (2010) studied the seismic response by shaking table tests and finite element method, but the analysis of bending moment was not taken into consideration.

In this study, using the shaking table model test with different seismic spectrum, the seismic performances of both single and double storage utility tunnel under earthquake are revealed.

2 MODEL TEST DESIGN

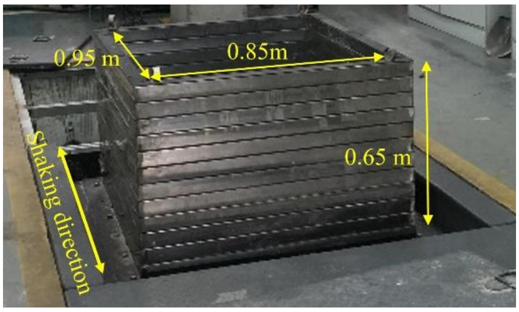
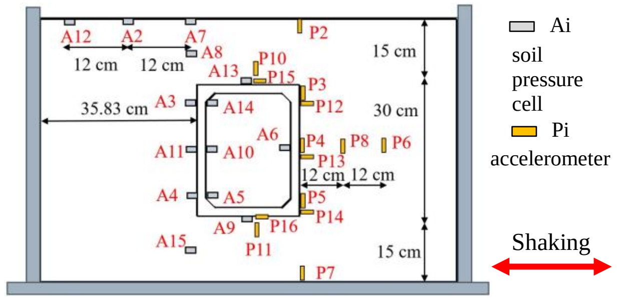


Fig. 1 Small scale shaking table test system

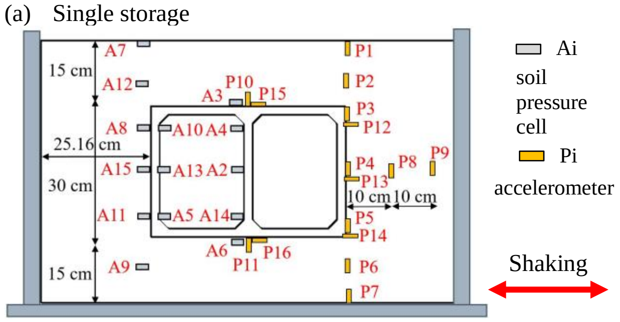
Fig. 1 shows a small scale shaking table test system, which equips a 0.95 × 0.85 × 0.65 m (length × width × height) shearing steel box to meet the boundary effect, allowing an input PGA from 0 to 1.2 g (g is the gravity acceleration). Accordingly, similarity factors are carefully considered (Iai (1989), Jiang et al. (2010), Zhou and Lv (2012)) as shown in Table 1. The structure has an elastic modulus of 6062.21MPa, and the soil has a dry density of 1730 kg / m^3. Taking the symmetry of structure into consideration, the recording instrumentation was arranged as shown in Fig. 2.

Table 1. Similarity factors of modeling utility tunnel

Parameter	Notation/Equation	Similarity factor
Length	S_l	1:15 (choosing)
Strain & Stress	S_ε & S_σ	1:1 & 1:3 (choosing)
Elastic modulus	$S_E=S_\sigma/S_\varepsilon$	1:3 (calculating)
Acceleration	S_a	5:1 (choosing)
Density	$S_\rho= S_E/(S_a\ S_l)$	1:1 (calculating)
Time	S_t	1:8.67 (calculating)



(a) Single storage



(b) Double storage

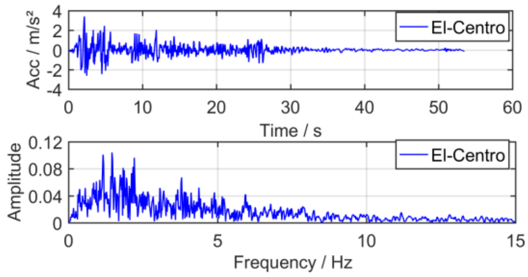
Fig. 2 Experimental model and soil

Xie and Zhai (2003) presented that El-Centro and Taft earthquake spectrum are suitable for II and III field. And El-Centro earthquake spectrum now is extensively used in civil engineering seismic research (Kojic et al. 1993). Based on above research, El-Centro and Taft earthquake finally are chosen for the present study, and their input acceleration time history and Fourier amplitude spectrum are given in Fig. 3. The two earthquakes spectrums are adjusted to have the PGA of 0.2 g, 0.4g, 0.8g, and 1.2 g, covering the range from 0.28 g to 0.54 g, suggested by Chowdhury (2015).

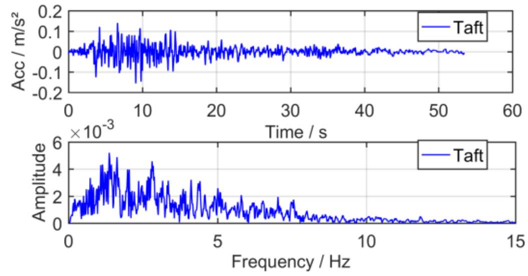
3 RESULTS AND DISCUSSION

3.1 Earth pressure responses

Fig. 4 shows the maximum horizontal earth pressure response (MHEPR) next to utility tunnel along depth at different seismic spectrum with varied input PGA.



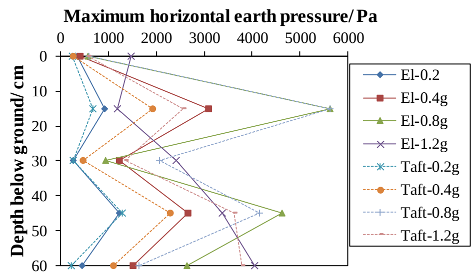
(a) El-Centro



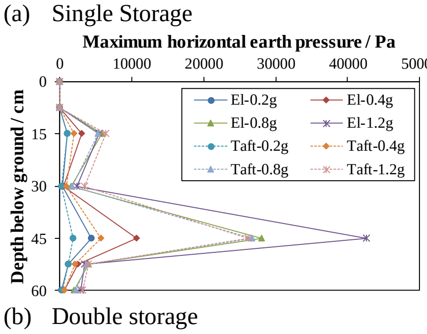
(b) Taft

Fig. 3 Fourier spectrum of input acceleration time history

From this figure, it is seen that MHEPR next to utility tunnel below ground has the distribution of reverse "W" for both single and double storage utility tunnel, which is due to the soil-structure interaction causing arch effect during continuous shaking. When PGA is 1.2 g under El-Centro earthquake, MHEPR at bottom is significantly larger than it with PGA at 0.8 g, while the value is very close to it under Taft earthquake, indicating that specific responses is related to seismic spectrum.



(a) Single Storage



(b) Double storage

Fig. 4 MHEPR next to utility tunnel along depth

Fig. 5 depicts the distribution of the maximum vertical earth pressure responses (MVEPR) next to utility tunnel at different seismic spectrum with varied PGA from 0.2 g to 1.2 g. Similarly, MVEPR always has the less value at the middle part of utility tunnel. Maybe it is the Poisson effect that lead to this phenomenon. In addition, it also increases as PGA is less than 0.8 g, then has the peak value at 0.8 g.

3.2 Acceleration responses

Fig. 6 shows the distribution of the maximum acceleration response (MAR) next to utility tunnel along depth under two earthquakes as PGA is 0.2 g, 0.4 g, 0.8 g, and 1.2 g respectively. Generally, the MAR becomes larger with increasing PGA, and decreases along depth at lower PGA (0.2 g and 0.4 g). For higher PGA (0.8 g and 1.2 g), MAR goes down along depth in the upper part and shows an increasing trend in the deeper part.

Fig. 7 describes the factures of amplification factor, varying from 0.6 to 2.2 and decreasing with an increasing PGA under El-Centro and Taft seismic spectrum for single and double storage utility tunnel. It can be seen that most of them are beyond 1.0, especially for lower PGA (0.2 g and 0.4 g). Obviously, the distribution along depth is similar to MAR in Fig. 6.

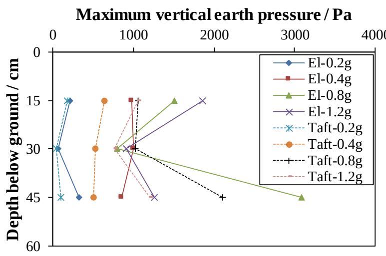
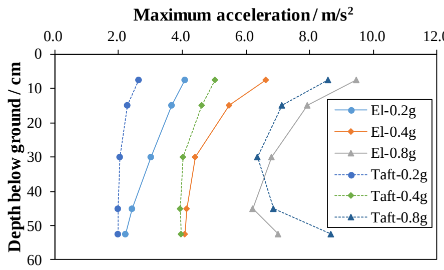
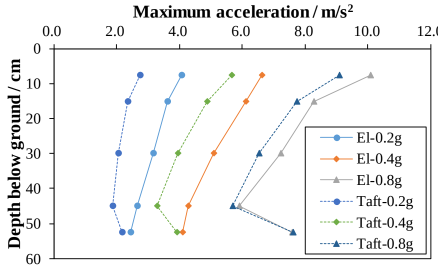


Fig. 5 MVEPR next to utility tunnel along depth



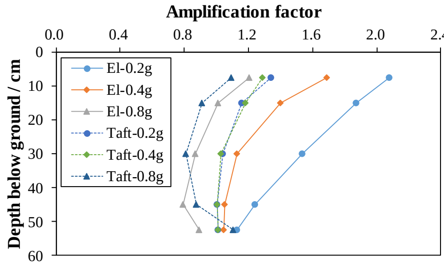
(a) Single Storage



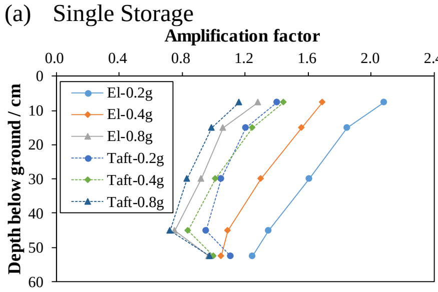
(b) Double storage

Fig. 6 MAR next to utility tunnel along depth

The acceleration time history to soil and structure is plotted for El-Centro for structure and the surrounding soil at same depth as shown in Fig. 8. It is seen that there is a slight difference for the acceleration response in the soil and on the structure at the same location, which suggests that the structure keep the same motion pattern with the surrounding soil next to the side wall.

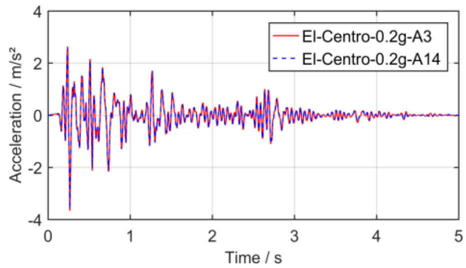


(a) Single Storage

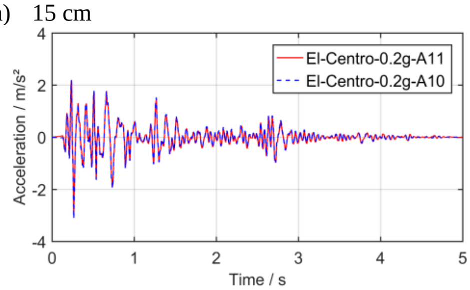


(b) Double storage

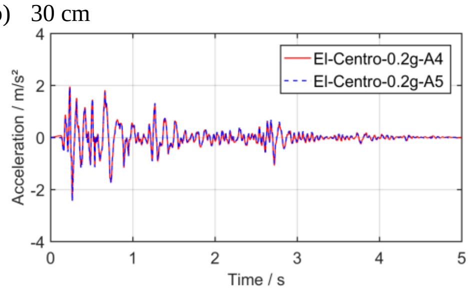
Fig. 7 Amplification response next to utility tunnel



(a) 15 cm



(b) 30 cm

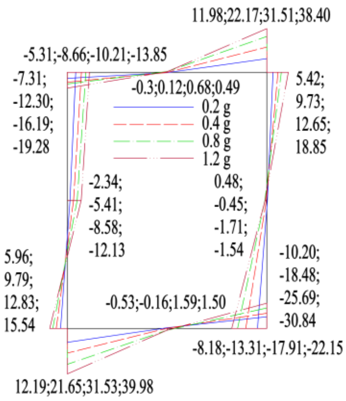


(c) 45 cm

Fig. 8 Acceleration time history of soil and structure

3.3 Bending moment responses

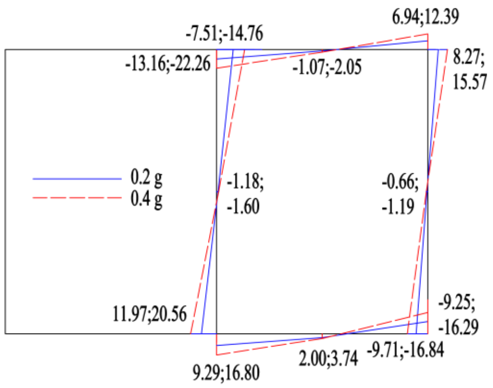
Fig. 9 and Fig. 10 show the bending moment response (BMR) on utility tunnel for El-Centro and Taft seismic spectrum respectively. It can be seen that there is the larger bending moment at the corner of utility tunnel structure, and the BMR becomes greater as input PGA increases. And, BMR under El-Centro earthquake is generally greater than it under Taft earthquake under same input PGA.



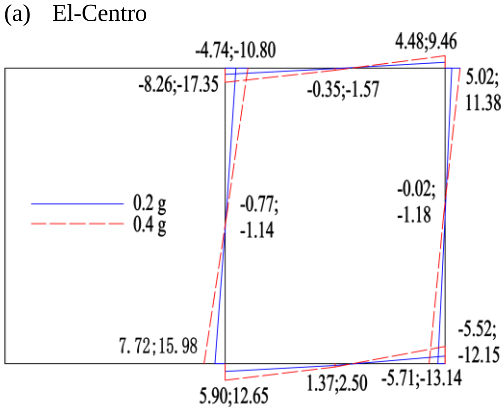
(a) El-Centro

(b) Taft

Fig. 9 BMR for single storage model / N • m



(a) El-Centro



(b) Taft

Fig. 10 BMR for double storage model / N • m

4 CONCLUSIONS

According to above analysis, some seismic responses about the structure and soil are revealed. MHEPR has a distribution of reverse "W" along depth. MAR decreases along depth under lower PGA, while for higher PGA, like 0.8 g, it decreases firstly, then increases from mid-bottom of utility tunnel to the bottom of test soil. The amplification factor for MAR, decreasing with an increasing PGA, ranges from 0.6 to 2.2 in this test. And there is a slight difference for acceleration responses between in the soil and on the structure at the same depth. The BMR increases with PGA, and the larger BMR happened at four corners on the utility tunnel, indicating that the strength at corners should be greatly reinforced in designing and construction. Finally, it is found that the specific seismic response is related to PGA, structure type, seismic spectrum, and soil-structure interaction.

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