SEISMIC RESPONSE CHARACTERISTICS OF SHALLOW-BURIED UTILITY TUNNEL SYSTEMS

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ABSTRACT :

Utility tunnel(UT) is an integration system containing many sub-lifeline systems like water transmitting, power, telecommunication, gas-supply system, etc, so, UT is key factor to sustain the healthy development of society and economy. To improve its anti-seismic capacity, the paper studies the performance characteristics of utility tunnel system under seismic loads based on a shaking-table experiment. Herein, two models of two-span UT with rectangular section are set up, one is used to simulate the main utility tunnel, and the other is for branch utility tunnel. Three kinds of pipeline are installed in UT to model the water-supply system, cable and power-line system respectively. This research is used to identify and explore seismic performance of utility tunnel body and its inner pipeline. Anti-seismic performance of pipeline abutment and joints based on passive control device is also experimented to check their capacity of resisting earthquake damage. The experiment is done on the 3m X 3 m shaking-table; three selected seismic records are input. UT model with the scale of 1: 10 is built up based on statistics of the popular utilities system in China. Based on experiment results, a theoretical theory and simulation on the platform of ANSYS is done, some valuable conclusions have been got. The results had show that buried depth, wall thickness, steel amount and its distribution, and earthquake motion parameters have a big effect on earthquake damage of utility. These pipeline, cable and support contained in utility are also vulnerable to the earthquake in certain conditions.

KEYWORDS: Utility tunnel, Shaking table test, Seismic performance, Lifeline earthquake engineering

1. INTRODUCTION

Utility tunnel is designed to transport a known number and type of urban services. So, Utility tunnel is one of the most important lifeline systems, which often inside contains electrical power cables, water pipe, chilled water pipes, gas pipe, multimedia cables and telecommunication, etc. Because of urban rapidly development and the need for new facilities, but limited urban space, urban utilities tunnel are widely being used in China. From 1990s, 88.5 kilometers length of utility tunnel has been built in several big cities. Traditionally, the utility system was thought to own an excellent anti-seismic capacity like tunnel. However, in recent decades, in several great earthquakes, a lot of utility system earthquake damages have shown that utility is also vulnerable in earthquake. In Highline Community College, Washington, A single aging utility tunnel carrying water, gas, electric, sewer, and fiber optics was damaged as lateral ground movement ruptured the tunnel in the magnitude 6.8 Nisqually Earthquake on February 28, 2001. In 1997, a utility tunnel is damage in the Izimit, Turkey earthquake. In 2001, in Düzce earthquake, Turkey, an almost 400 m long stretch under construction of the Bolu tunnel collapsed. Collapses or heavy damages in tunnel. structures have been reported following to Kobe, Northridge and Loma Prieta earthquakes .In order to promote earthquake-proof capacities of utility tunnel, some measurements have been applied. To promote the urban utilities tunnel in France, a national research project was created. One of this plan’s goals is to develop a multi-criteria method integrating the following criteria for urban utility tunnel: safety, sustainable development, economy, maintenance, risk analysis and development facilities (Ludovic L., 2004). In USA, many utility tunnels in universities and colleges have already been retrofitted and are being retrofitted, such as Miami University, Morgan State University campus, Northern Arizona University, university of Washington, Wisconsin university、California state University,、Baylor university, Illinois university、Montana state university, New Jersey state university, Minnesota university and Notre Dame university, etc. In Europe, The Utility Tunnels European Research Group (U.T.E.R.G.), founded by the National Institute for Urban Engineering of France and the Polytechnic University of Valencia in Span, was established to serve as a focal point for research on utility tunnels in Europe(Cano-Hurtado J.1999).In Japan, from 1983 to 2003, all utility tunnel in urban area of Minato Mirai is retrofitted to resist earthquake（the length of main tunnel is 6.5 Km）. This paper aims to explore the earthquake damage mechanism of utility based on shaking-table test. The experiment is done on the 3m X 3 m shaking-table, three seismic records is input. The utility model is built up based on statistics of the popular utilities systems in China. Utility is a two-span structure with transect size of 6000 mm X 2500mm, one span is designed as comprehensive room containing the power and telecommunication cables, water-supply and sewage drainage pipelines, and heat-supply pipelines, the other is for gas-supply system. The buried depth of utility body is 2000mm. Some of important conclusions had been found based on this experiment.

2. SHAKING TABLE MODEL

This shaking-table test aims to explore the seismic response mechanism of utility tunnel and contains inside it. In this experiment, a utility tunnel model according to the popular structural and construction used in China was set up. Here are details of how to design the experiment model.

2.1. Experiment Apparatus and Design of the Experiment Box

This experiment was done on the 3m X 3m shaking table, which is managed by Key Laboratory of Earthquake Engineering and Structural Retrofit, Beijing University of Technology. The shaking self-weight is six thousand kilograms and is only to provide the horizontal direction load, its maximum bearing weight is ten thousands kilogram, only own horizontal exciting load. The providing maximum acceleration is ±1.0g and the maximum displacement is ± 127mm when the load is ten thousand kilogram. The frequency range is from 0.1 Hz to 50 Hz. The shaking experiment box of utility tunnel must be designed to satisfy the following requirements: 1) the box is strong enough to keep itself intact during the earthquake invading. 2) High reliability for simulation of boundary condition.3) the utility tunnel and its gatherings can be buried in suitable position to simulate their actual conditions, the experiment model of utility tunnel system are consistent with geometrical parameters, like the ratios of length to width, length to height, etc. 4) The box and the surrounding soil can't occur resonance during the earthquake, and 5) the total load including the box's and shaking table's weights is less than that of the limited bearing weight of shaking table. According to the most popular structure type of utility tunnel and their working condition in China and following the above requirements, a rectangle experiment box is selected. The longitudinal length (in the direction of earthquake propagation) of the utility tunnel is 3.0 meters, the transverse length is 2.4 meters, and the height is 1.2 meter. The structure is a steel-frame, which is made by welding angle iron. The box's bottom is an 8-mm- thickness steel plate, and its side-wall is wood plate with 60-mm-thickness polystyrene foam plate as inner liner. In order to simulate the boundary's coarseness, a layer soil is affixed to the inner liner with glue. The longitudinal length (L1) of the utility tunnel model box is calculated by the Eqn 2.1.

$$L_1 = 2 \bullet W + L \qquad (2.1)$$

Where, W is the width of utility tunnel, and the L is the length of utility tunnel between two joints, the transverse length (W1) of the experiment box is got by the ratio of L1/W1, the ratio is 3~5 in general.

2.2. Comparability of model and Design and manufacture of Model

Model comparability is important to simulate real structure in shaking table test. Comparability relation of model in shaking table test often includes these comparabilities in physical parameters, boundary conditions and geometric parameters. In this test, one of the important physical parameters is relationship of stress and strain. Geometric parameters include the ration of length, width, height between model and real utility tunnel. Boundary conditions include brace and constraint condition of these objects that are contained inside the tunnel, buried depth, mechanics condition. Herein, dimension analysis method is applied to set up the model comparability (Table 1).

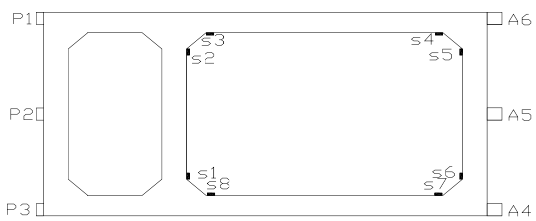
Table 2. 1. Model comparability of utility tunnel in shaking-table test

Parameter	Comparability	Parameter	Comparability
Strain	1	Displace	1/30
Length	1/5	Time	2/5
Density	1	Frequency	5/2
Elastic-mod.	1/4	Stress	1/5
Quality	1/125	Acceleration	1.25

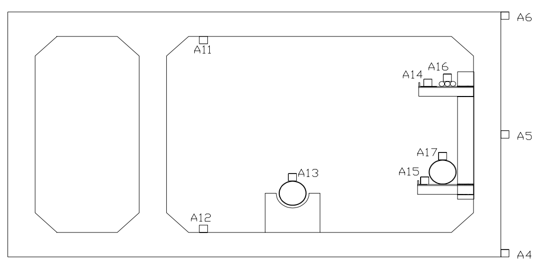
Popular UT in China is often constructed by manpower open-excavation, rather than shield excavation. So, the buried depth of utility tunnel is 2.0~2.5 meters underground, the width of tunnel is often 6 meters, and its height is 2.5 meters. Inside space is divided into two rooms, one is for gas-supply system, the other is for other lifeline systems, such as cable, pipeline of water supply and sewage, etc. In this experiment, the geometric parameters of the simulated utility tunnel are as following: 6000 mm width, 2500 mm height. It is a two-span structure, one room with 1950 mm net width is for gas-supply, and the other with 3300 mm net width is for pipeline of water transmission and electric-power cable, which is called integrative room. For the body of utility tunnel, its is reinforced concrete structure, its grade is C25 (E=2.8N/mm2), the type of steel is HPB235 (E=210 N/mm^2)and HRB335 (E=210,300N/mm^2).

2.2. Sensors Distribution and Model Soil Characteristics

In order to measure seismic response of the utility tunnel and pipelines and cables inside, three kinds of sensors are selected: acceleration seismograph (CA-YD), resistance strain gauge (BCL120-10AA) and resistance soil pressure gauge (DYB-2). 17 acceleration accelerometers are installed into the model soil, on the surface of utility tunnel, and to the pipeline and their braces. 5 pressure gauges are installed in soil, and 8-resistance strain gauges are installed on the interior surface of the tunnel. These installing-points are details shown in Figure.1.



Distribution of resistance strain gauges



Distribution of accelerometer

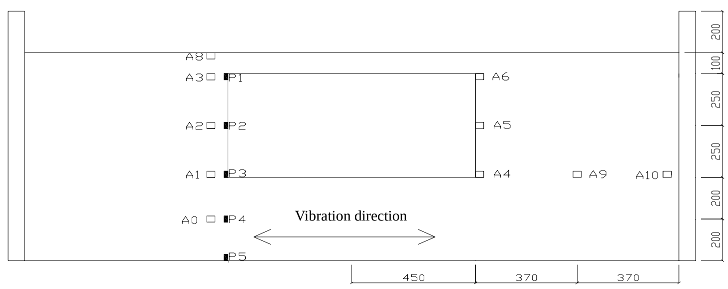


Figure. 1 Distribution of acceleration seismograph and pressure gauge inside soil
Note: S: resistance strain gauge, A: acceleration seismograph, P: resistance soil pressure gauge

Soil type is key factor to avoid the separation of utility tunnel and soil. Herein, viscid silt is selected as the surrounding soil media of utility tunnel. Before equipped into model box, a series of soil treatment have done, like sifting, water content control, density control, and other soil dynamics parameters test. In order to make the soil density uniformity, the soil layer is tamped into model box by layered-build method; every layer is controlled 10 cm thickness. Earth-tamp is applied to make the soil consolidation. During the consolidation, the water content is strictly controlled.

2.3 Seismic Wave Input

In this experiment, 4 seismic waves are selected; they are EL-Centro wave, Kobe wave, Hujialou wave and artificial wave. Because earthquake damage of metro and tunnel has been observed in Kobe earthquake 1995, Kobe earthquake is selected. Huijialou wave, recorded in Tangshan earthquake, 1976, is selected because some tunnels are intact during this earthquake. The artificial wave is composite based on the China Aseismic Design Code. All these seismic waves are adjusted according to model comparability. The seismic wave input is done based on the plan listed in Table 2.

Table 2. 2 Seismic input plan of shaking table test

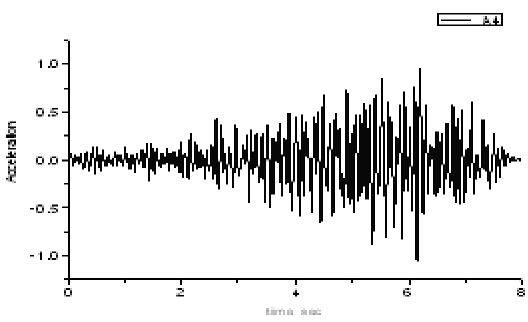
Seismic wave	Acceleration (g)											
	R. 1	R. 2	R. 3	R. 4	R. 5	R. 6	R. 7	R. 8	R. 9	R. 10	R. 12	R. 12
White-noise	0. 1	0. 1	0. 1	0. 1	0. 1	0. 1	0. 1	0. 1	0. 1	0. 1	0. 1	0. 1
Kobe	0. 1	0. 15	0. 2	0. 25	0. 3	0. 4	0. 5	0. 6	0. 8	1. 0	1. 2	1. 5
El-Centro	0. 1	0. 15	0. 2	0. 25	0. 3	0. 4	0. 5	0. 6	0. 8	1. 0	1. 2	
Hujialou	0. 1	0. 15	0. 2	0. 25	0. 3	0. 4	0. 5	0. 6	0. 8	1. 0		
A-Wave	0. 1	0. 15	0. 2	0. 25	0. 3	0. 4	0. 5	0. 6				

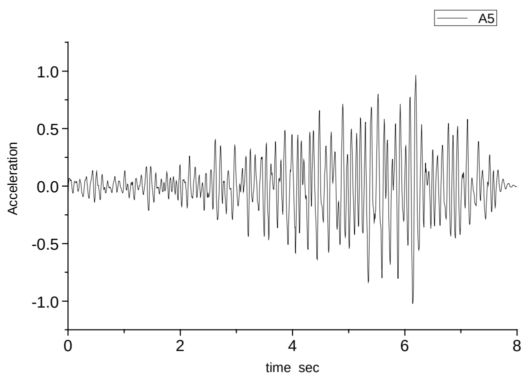
3. EXPERIMENT RESULTS AND ANALYSIS

3.1 Acceleration of Utility Tunnel

Three acceleration accelerometers (A4, A5, A6) are used to measure the seismic response of the utility tunnel in this test and the following results are obtained from observation of the data shown in Figure 2,3 and table 3.

1. There is the similar seismic response of the upper and bottom of utility tunnel, only difference exists in acceleration amplitude and the acceleration amplitude increases from the bottom to the upper of utility tunnel. This means that the seismic responses of the tested utility are mainly governed by first mode.





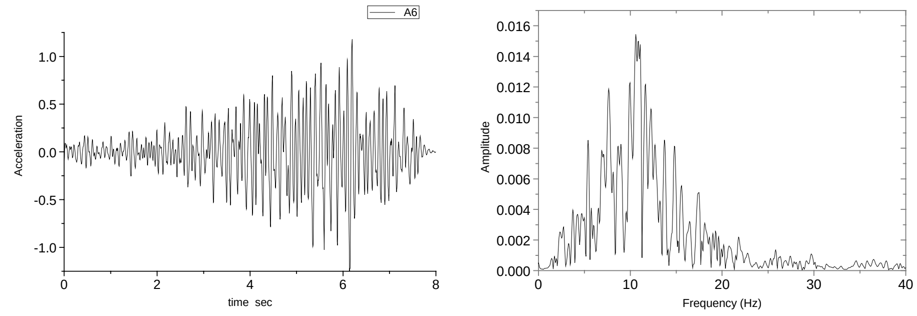


Figure 2. Acceleration time-history and Fourier spectrum (Hujialou record, a_{max}=0.6g)

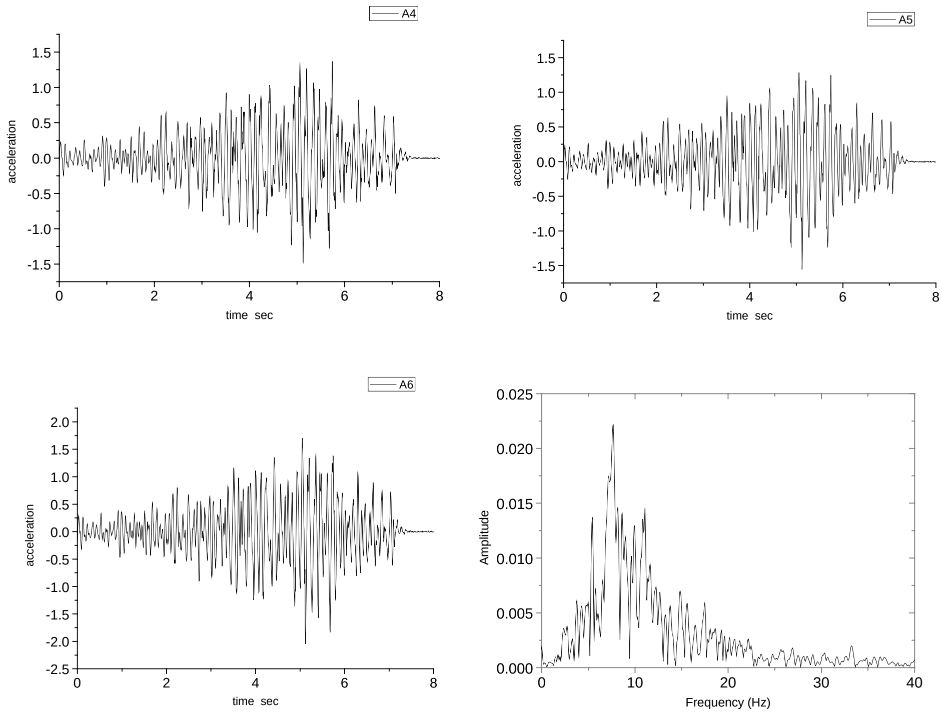


Figure 3. Acceleration time-history and Fourier spectrum of the model subjected to Hujialou record with amax=1.0g at measurement A4, A5 and A6 as shown in Fig. 1

Table 3.1 Acceleration and spectrum characteristics of the tested utility tunnel

Earthquake acceleration （g）	No. Accelerometer	Maximum-Acceleration （g）	Amplification coefficient	Spectrum characteristics	
				Predominate-frequency （Hz）	Amplitude
0.6	A1	0.974	1.623	10.596	0.0129
	A5	1.050	1.75	10.596	0.0127
	A6	1.260	2.1	11.133	0.0154
1.0	A1	-1.168	1.168	7.595	0.0170
	A5	-1.664	1.664	7.471	0.0174
	A6	-1.743	1.743	7.471	0.0221

2. It can be seen from the figures and data shown in Table 3 that the predominate frequencies of the seismic responses of the model decrease as increasing input acceleration and that means some kind of non-linearity is involved in seismic performance of the tested model.
3. The figures and data in Table 3 also indicate that general speaking the stronger the earthquake input the larger the earthquake response of the utility tunnel but the amplification coefficient decreases as increasing input the acceleration from 0.6g to 1.0 g. That implies a reduction factor depending on ductility of soil-structural system can be used into seismic design of utility tunnel as well as

3.2 Seismic Response of Pipeline inside Utility Tunnel

Three accelerometers are installed to the pipeline and cable in which A13 is installed to the pipeline supported by a concrete pier in the center of the integrative room; A16 is installed to the pipeline, which is supported by a steel cantilever beam brace; The seismic response results are listed in Figure 4, 5 and Table. 4.

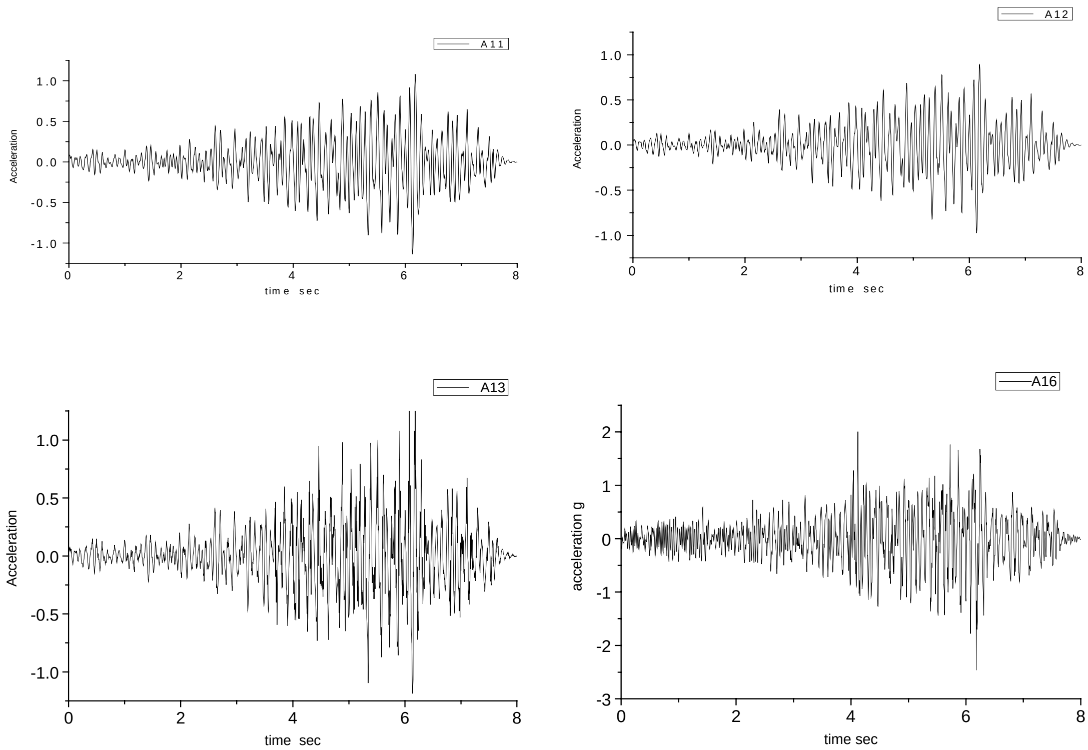
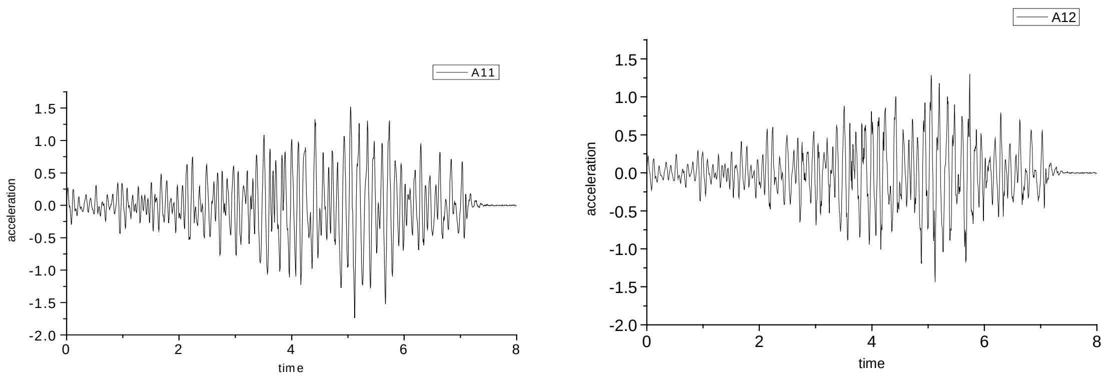


Figure 4. Acceleration time-history of pipeline and cable inside utility tunnel under excitation of Hujialou record with a_{max}=0.6g



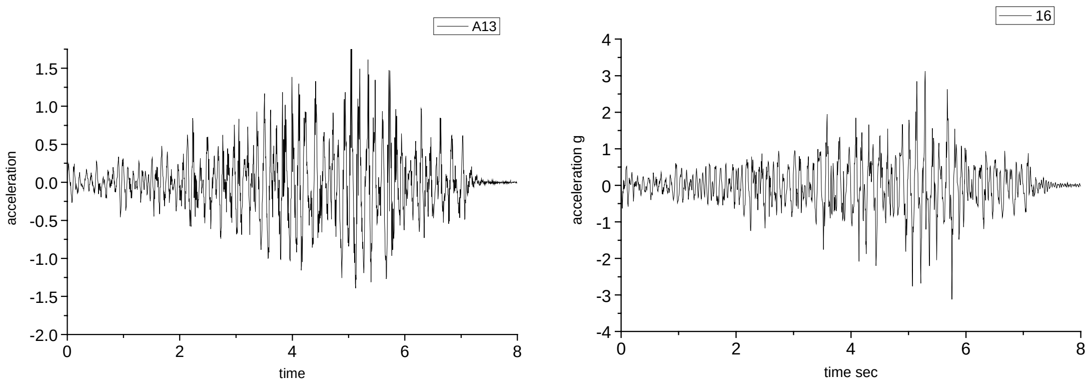


Figure 5. Acceleration time-history of pipeline and cable inside utility tunnel under excitation of Hujialou record with a_{max}=1.0g

Table 4. Acceleration and spectrum characteristics of pipeline and cable inside utility tunnel

Earthquake acceleration (g)	No. Accelerometer	Maximum-Acceleration (g)	Amplificatory coefficient	Spectrum characteristics	
				Predominate-frequency (Hz)	Amplitude
0.6	A11	-1.137	1.895	11.133	0.0142
	A12	-0.973	1.621	11.133	0.0120
	A13	-1.187	1.978	11.133	0.0129
	A16	-2.461		11.133	0.0113
1.0	A11	-1.738	1.738	7.520	0.0201
	A12	-1.439	1.439	7.520	0.0161
	A13	-1.951	1.951	7.471	0.0176
	A16	-3.122		7.452	0.028

From the figures shown in Fig. 4, Fig 5 and Table 4, these following test results can be observed.
1. Earthquake response of the cable supported by the steel cantilever beam brace (point A16) is biggest; that of the pipeline supported by a concrete pier in the center of the integrative room (point A13) is smallest, and that of the pipeline with a steel cantilever beam brace (point A17) is in between.
2.Under the same earthquake input, frequency contents, phase and amplitude in A11, 13 and A16 inside tunnel are obviously different. The amplitude of cable is biggest, that of the pipeline supported by a concrete pier in the center of the integrative room is smallest and that of the pipeline with a steel cantilever beam brace is in middle.

3.3 Strain of the Bottom and Top Slab of Utility tunnel

Four resistance strain gauges are installed inside utility tunnel to measure strain of the bottom and top slab of

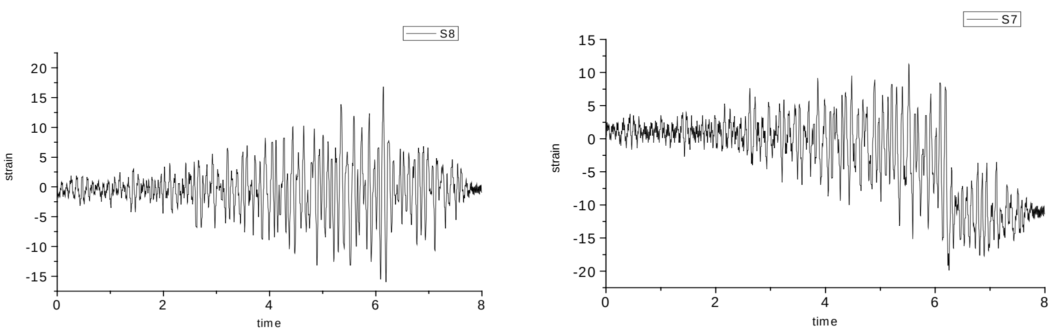


Figure 6. Acceleration time-histories of pipeline and cable inside utility tunnel under excitation of Hujialou record with a_{max}=0.6g

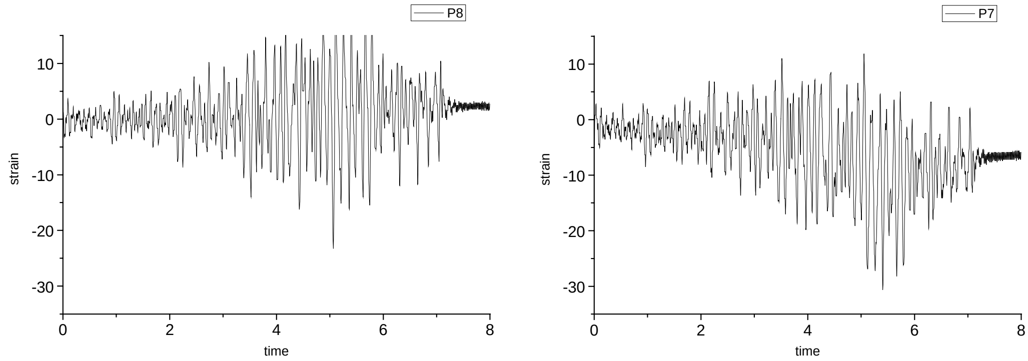


Figure 7. Acceleration time-histories of pipeline and cable inside utility tunnel under excitation of Hujialou record with a_{max}=1.0g

Utility tunnel. It aims to study the earthquake response of utility tunnel wall and slab. From the measured strain responses at point S3, S4, S7 and S8 shown in Fig.6 and Fig 7, it can be seen that the seismic response of the top slab is relatively bigger compared to that of lower part measurement points and furthermore the strain at joints of top slab and lateral wall is even bigger than that of top slab and central partition wall. These only are primary observation results and the further analyses will be done in near future.

4. CONCLUSION

From the above, some preliminary conclusions are summarized as following:
1. Utility tunnel system, including outside container and inside utility pipe and cable in shallow buried conditions is vulnerable to earthquake. General speaking the shallower the buried depth the bigger the earthquake vulnerability and the pipeline and cable with different type of brace, their earthquake response are different..
2. Acceleration amplitude increases from the bottom to the upper of utility tunnel and the upper of UT has a stronger seismic response than that of utility tunnel bottom. Primary observation also found that the response acceleration distribution along with height is almost retaining unchanged or time dependent during earthquake.
3.The predominant frequency and acceleration amplitude coefficient of the utility tunnel system decrease as input motion increases that means there issome what non-linearity involved in soil-structure system. As increasing input acceleration the accleration amplitude coefficient ahs tendency of decrease and it seems that for underground utility tunnel system we still can introduce a reduction factor in seismic design.

ACKNOWLEDGEMENT

Open foundation of Key Laboratory of Earthquake Engineering and Structural Retrofit, Education Ministry and Beijing University of Technology (No.EESR200605), Natural Science Foundation of China (No.50278028) and Scientific innovation research Foundation of Harbin Institute of Technology (HIT.MID 2003.03) support this project. The Authors give the great appreciated.

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