Seismic responses of tunnel and surrounding dense soil by centrifuge testing

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ABSTRACT

The seismic performances of a tunnel and surrounding soil were simulated by centrifuge technique. Earthquake input motions with different peak accelerations were adopted. Experimental results indicate that earthquake responses of tunnels are different from that of static state, and the dynamic responses of ground soil and tunnel distinctively depend on the excitation earthquake intensities. The seismic response of free field and non-free field will be significantly different, due to the tunnel's existence affecting the site responses (e.g. acceleration, lateral displacement and surface settlement) to some extent, which should not be neglected.

KEYWORDS: Centrifugal models; Seismic responses; Tunnel deformation; Earthquake

1. INTRODUCTION

Infrastructures such as tunnels and underground pipelines are often damaged by earthquakes. Theoretical analyses and numerical simulations have been done to study responses of underground structures to earthquakes. (Wang 1993; Penzien 2000; Hashash et al. 2001; Huo et al. 2006).

Centrifuge shaker can realistically simulate the stress conditions of the prototype stress field and accurately reproduce the real dynamic response of the prototype under actual stress conditions. It has been widely used in the fields of civil engineering and seismic engineering. Fiegel (1998) performed dynamic centrifuge tests to estimate the earthquake-induced settlement of a soft clay. The results illustrated that surface settlement depend on the intensity and frequency of the input motion. Zeng (1999) discussed some significant factors concerning physical modeling on liquefaction with centrifuge tests, and concluded that, it is desirable to avoid viscous fluid in centrifuge tests as the fluid may have an unwanted effect on permeability, strength, stiffness and damping characteristic of soils. Some studies mainly focused on free-field dynamic response for saturated sand (e.g. Arulanandan 1983; Hushmand 1988; Lee 1988). There have been very limited experiments concentrating on the response of large diameter tunnel during earthquakes. These scholars have carried out detailed research on sand liquefaction and its corresponding structural floating problems, and proposed corresponding measures, but the deformation of the structure and the interaction between soil and structure are not considered in these experiments.

In this paper, the seismic responses of the tunnel were simulated and compared with the static states. The deformation characteristics of the tunnel structure under seismic loading were studied. Meanwhile, compared with the results of the free-field model tests, the influence of the existence of the tunnel on the seismic responses of the site was discussed.

2. PREPARATION AND PROGRAM

Six sets of tests were performed at an acceleration of 50g centrifuge at Tongji University. A shaking table with maximum 20g acceleration capacity was used to provide basic earthquake motion. The model box used in the experiments was a laminar shear box with staked hollow aluminum rings, and the maximum relative displacement of adjacent two rings can reach 5mm. Its dimensions were 500mm x 440 mm x 550mm (length x width x height).

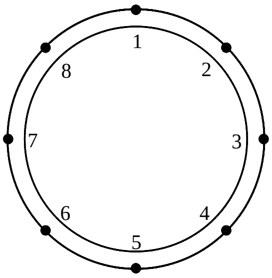

Fig. 1 Strain monitor points distribution

Tunnel material must satisfy: (1) The material should be easy to shape; (2) The tunnel's deformation must be significantly, which could be examined by strain gauges conveniently. Consequently, the tunnel model was manufactured from aluminum alloy with an outer diameter of 160 mm, an inner diameter of 138 mm and a length of 380 mm. Meanwhile, eight full-bridge strain gauges were attached at the outer wall of the model to monitor the seismic responses of the tunnel (Fig. 1).

The experimental material was sandy silt with a water content of 8% and an average unit weight of 16.55kN/m^3 . The main reasons of using unsaturated soil are: (1) Liquefaction is not the focus of present study. (2) The contradiction between the seepage scale(1/N^2) and the dynamic scale (1/N) may be avoided. (3) The dry soil sample can ensure the normal operation of the strain gauge.

Three earthquake waves were scaled version of middle Shanghai earthquake(MSE), small Shanghai earthquake(SSE, Fig.2) and Loma Prieta earthquake (LPE, Idriss&Sun 1991) .

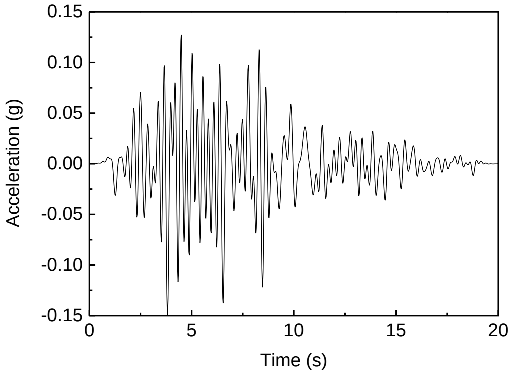

Fig. 2 Acceleration time history of SSE

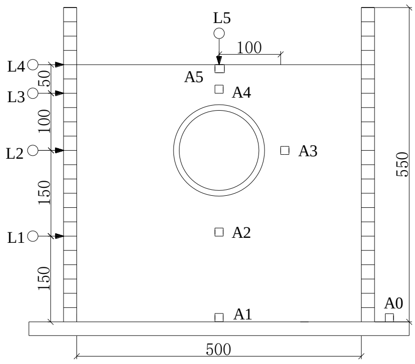

Fig. 3 Centrifugal model test instrument layout (model scale, mm)

In addition to the strain gauges, the sensors used in these tests include miniature accelerometers and linear variable differential transformers (LVDT) to record seismic acceleration and displacement, respectively. A schematic sketch of the experimental setup and instrumentation are shown in Fig. 3.

The formal experiments included six sets of tests which were summarized in Table1. The tunnel model will not exist for the free field tests (Test4~Test6), and the sensor A3 will be at the axis of the model box.

Table 1 Centrifuge testing program

No.	Earthquake motion	Peck acceleration	Model
1	LPE	0.10g	Tunnel-soil
2	SSE	0.15g	Tunnel-soil
3	MSE	0.40g	Tunnel-soil
4	LPE	0.10g	Soil only
5	SSE	0.15g	Soil only
6	MSE	0.40g	Soil only

3. ANALYSIS OF EXPERIMENT RESULTS

3.1 Site Acceleration Responses

The ground responses at corresponding locations for Test 2 were plotted in Fig.4. The input wave was in good agreement with the feedback wave (A0) at the base of the model box. It can be seen that the seismic wave was obviously enlarged from the bottom to the ground surface.

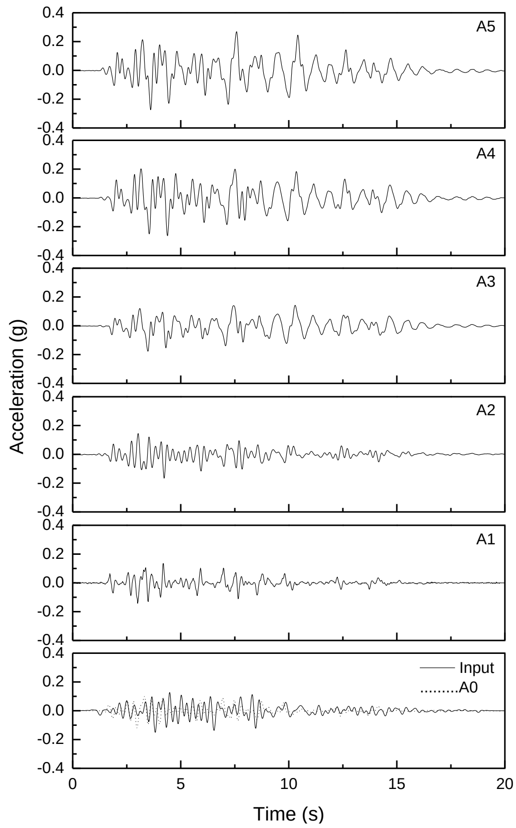

Fig. 4 Acceleration responses of soil in Test2

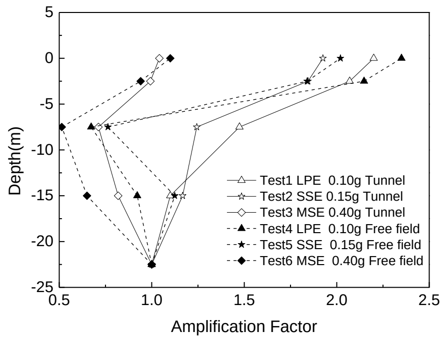

Fig. 5 Site responses of free and non free fields

The relationship between the acceleration amplification factors and the depths were plotted in Fig.5 (Test1~Test3). The amplification effect of Test1 was the most obvious, the amplification factor was 2.2 at the ground surface, but the peak acceleration of the base seismic wave was only 0.1g. Conversely, the surface amplification factor of Test 3 was 1.05, and the peak value of the input base motion was 0.4g (MSE). Therefore, a smaller peak acceleration of base motion will result in a more obvious amplification effect. The acceleration amplification coefficient of the ground surface decreases as the peak acceleration of the bedrock input increases. This may be due to the increase in seismic intensity results in an increase of the shear strain level and a decrease of the shear modulus.

Meanwhile, the amplification curves of free field (Test 4~ Test 6) were also plotted in Fig. 5. In the free field tests, the seismic wave transmitted to the surface showed an amplification trend, and the surface acceleration amplification factor decreased with the increase of the incident seismic wave intensity. Compared with the free field, the surface magnification factor will be smaller when the tunnel exists, but the amplification factor at the location of the tunnel (buried depth 7.5 m) will be larger than that of the corresponding position in the free field. The reason for this phenomenon may be due to seismic waves are difficult to pass through the hollow tunnel structure compared with the free field, and part of the energy accumulates around the tunnel and dissipates, and the seismic intensity decreases correspondingly when it reaches the surface.

Fig.6 shows the seismic wave spectrum comparison between the bottom (A1) and the surface (A5) in Test2. It is clearly that the high-frequency components of the seismic wave are filtered by the soil during the propagation of the seismic wave, and the low-frequency characteristics are more evident at the ground surface.

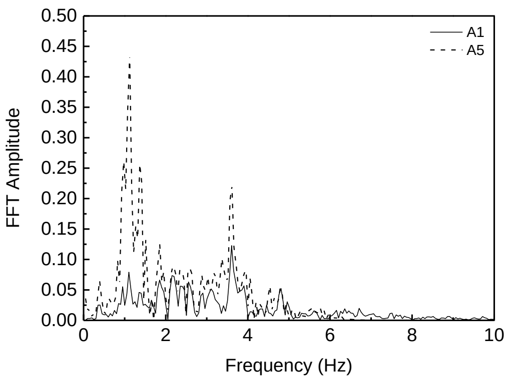

Fig. 6 Seismic wave spectrum at surface and basement for Test 2

3.2 Tunnel deformation

The tunnel's dynamic strains during the earthquake were recorded. The maximum strain value of each measuring point was selected and drawn into a tunnel deformation sketch. The maximum strain points would happen at an angle of 45º relative to tunnel vertical or horizontal axis under earthquake loading (Fig.7). The strain distribution of the tunnel will be similar under different seismic intensities, but the specific strain values are different. Under the static condition, the strains of the four measuring points (point1, 3, 5, 7 in Fig.1) in the horizontal and vertical directions of the tunnel are more significant, and the tunnel model turned to be ovally deformed (Fig.8).

3.3 Lateral displacements

Generally, for the free field condition, lateral displacement increases as the peak acceleration increases, and the displacement increases as the depth decreases. When the tunnel structure exists, the lateral displacement value of L2 (the same level as tunnel center) is the smallest one (Fig.9). This may be due to the interaction of tunnel and soil.

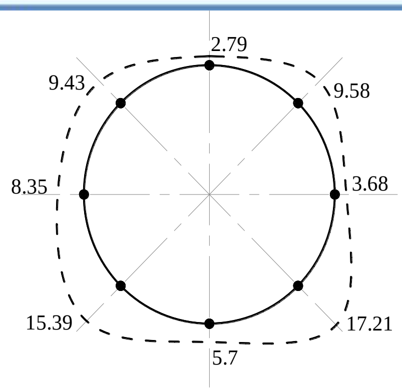

Fig. 7 Tunnel's peak strain distribution under seismic loading (Test2 SSE unit : E-06)

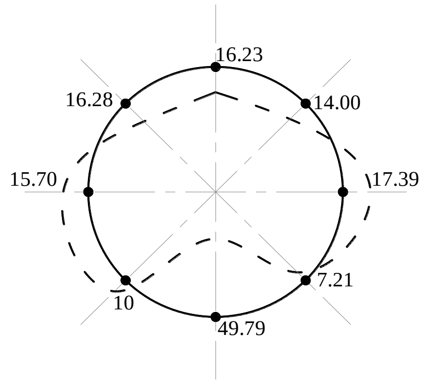

Fig. 8 Tunnel's strain distribution under static loading(unit : E-06)

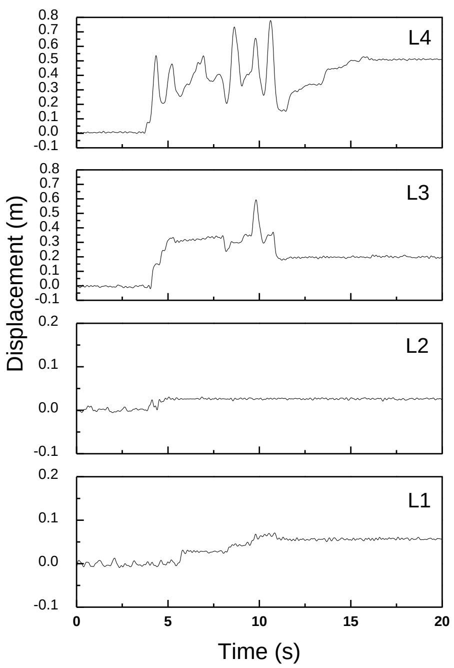

Fig.9 Lateral displacements of ground in Test 2 (SSE, 0.15g, Non-free field)

3.4 Ground surface settlement

Fig.11 presents a comparison of the ground settlements recorded in Tests 1~3. It is clearly that, the higher the earthquake intensity, the larger the settlement value of the ground surface, and the more severe the fluctuation of the settlement curve.

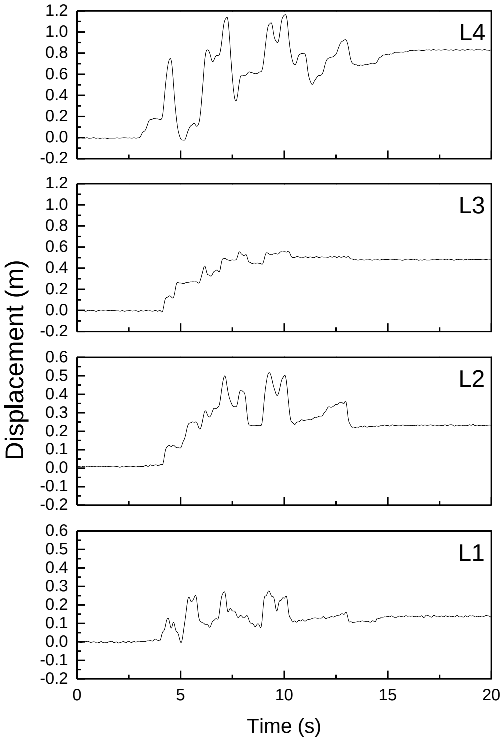

Fig. 10 Recorded lateral displacement in Test8 (SSE, 0.15g, Free field)

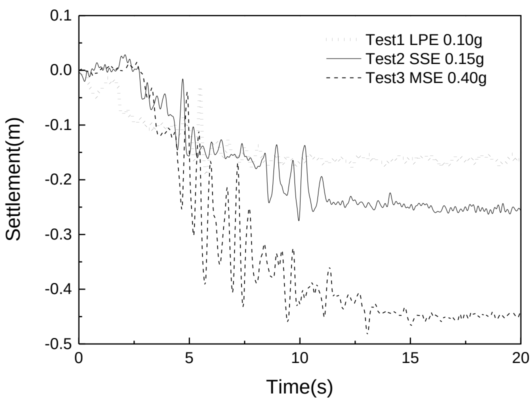

Fig. 11 Surface settlements with different earthquake intensities

4. CONCLUSIONS

Major conclusions are summarized as follows:

(1) When the seismic wave in dry dense soils propagates to the surface, the peak acceleration response of the ground is generally enlarged. The seismic acceleration amplification factor at the surface decreases with the increase of the input peak acceleration.

(2)The tunnel turned to be ovally deformed under static condition. Under the seismic load, the largest deformation occurred at the points of 45^o relative to the horizontal direction of the tunnel cross section during the earthquake process.

(3) Higher seismic intensity led to more apparent lateral displacement and surface settlement. The lateral displacement increases from the base to the surface. However, the soil layer located at the same horizontal position with tunnel will be in the slim lateral movement because of the interaction between the tunnel and its surrounding medium.

5. DISCUSSION

In terms of the study, improvements may be made in future trials:

(1)The conclusions are based on the centrifuge tests in dense sandy silt, which may not be applicable to other soils, e.g. soft clay. The tunnel model occupied one-third of the laminar box in the cross direction, boundary effects may create certain test errors.

(2) Displacements of soil were measured relative to reference supports which were not completely rigid. The desired signal of soil displacement and mechanical noise of transducer support superimposed with electrical noise.

(3) It is important for researchers to become familiar with the principle of digital signal processing.

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