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NUMRICAL SIMULATION OF SEISMIC RESPONSE OF UNDERGROUND UTILITY TUNNEL ON SHAKTING TABLE TEST UNDER NON-UNIFORM EARTHQUAKE WAVE EXCITATION

Luzhen Jiang[1], Jun Chen[2], Jie Li[3]

ABSTRACT

Numerical simulation of underground utility tunnel with construction joint on shaking table test under non-uniform earthquake wave excitation was discussed in this paper. Firstly, details of experimental setup are presented with particular focuses on: design and fabrication of double-axis laminar shear box with a rectangular hole opened on its side walls; design of two devices for measuring the slippage between the interface of model ground and the structure, and the relative deformation and rotation between joints of the structure model; procedure for construction of input earthquake wave. Then, Finite Element Method is used to verify the test results using ABAQUS as a platform. The nonlinear property of soil is modeled by Drucker-Prager constitutive model and the master-slave surfaces are established to simulate the soil-structure dynamic interaction. The effect that the laminar shear box applied to soil is considered to simulate the boundary effect. Special nonlinear spring elements are used to consider the construction joint in the test. Meanwhile, the initial balance conditions of gravity field are also considered. Finally, the numerical results are compared with experiment measurements in terms of acceleration, displacement, and joint effect. The comparisons between experimental results and numerical ones show that they match quite well.

Introduction

Multi-support excitation is one of important study area in earthquake engineering, which is extremely significant in long-span structures, such as bridge, pipeline, utility tunnel, nuclear power plant etc. A lot of works have done on long-span Bridge under

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1 PH.D candidate, Dept. of Building Engineering, Tongji University, Shanghai, China, TN 200092

2 Associate professor, Dept. of Building Engineering & State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China, TN 200092

3 Professor, Dept. of Building Engineering & State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China, TN 200092

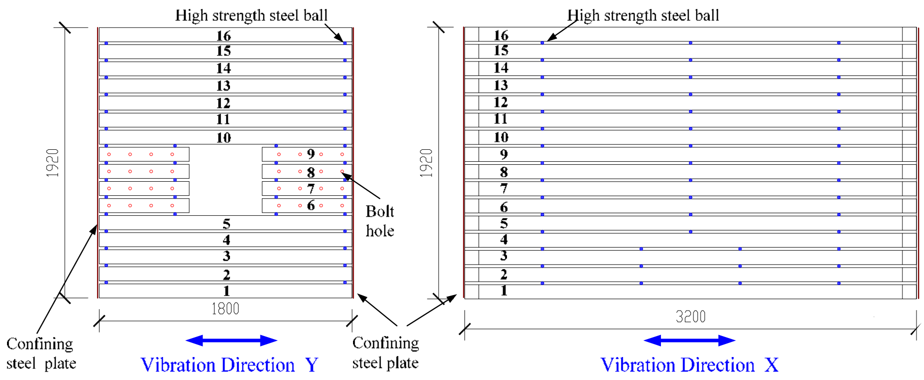
multi-support excitation. However, experimental investigation on the performance of utility tunnel under non-uniform earthquake wave excitation is fairly rare, so is numerical simulation based on experiment of utility tunnel. For this reason, a series shaking table tests were conducted on scaled utility tunnel model using non-uniform earthquake wave excitation (Shi, 2007, 2009). Shaking table test and numerical analysis of underground utility tunnel with construction joint under non-uniform earthquake wave excitation are discussed in this paper. Experimental setups are first presented. Numerical modeling is then employed in the second section. At last the comparisons between numerical results and test measurements are discussed.

Description of Shaking Table Test

The experiments was performed on a shaking table array consisting of two six-degree-of-freedom shake tables, named as dual multi-axis shake table system (DMSTS). The two shake tables are set on a common rail system with one table fixed and the other table movable, which is referred hereafter as Table A and Table B respectively.

Two identical lamina shear boxes (Shi, 2007, 2009) were fabricated and installed on each table of DMSTS in order to contain the soil in the test. Each laminar shear box has two openings on its side walls therefore scaled structural model can be put through the box. Figure 1 shows a photograph of the manufactured laminar shear box and conceptual schema of installation. The overall dimensions of each box are 3.00m long (x), 1.80m wide(y) and 1.91 m high (z). Each frame is made of steel pipe with rectangular cross section of 100mm×100mm×2mm (width×height×thickness). For adjacent frame, small piece of steel plates with guide grooves (denoted as guide hereafter) were welded on the bottom of the upper frame and on the top of the lower frame. Two rectangular holes of 520mm×520mm were opened on end walls of the shear box in x direction. In order to transfer lateral forces in these four frames for vibration in y direction, special rigid arms of shape were used to connect two ends of each frame crossing the hole.

(a) Photograph of lamina shear box on shaking table



(b) Side view

Figure 1 lamina shear box (all dimension in mm)

Taking an existing public utility tunnel in Shanghai City as prototype structure with geometrical scale of 1:8 was built and tested in the experiment. Dimensions and reinforcement details of model are demonstrated in Figure 2. It has two construction joints splitting the structure into three segments. Locations of the two joints are shown in Figure 4.

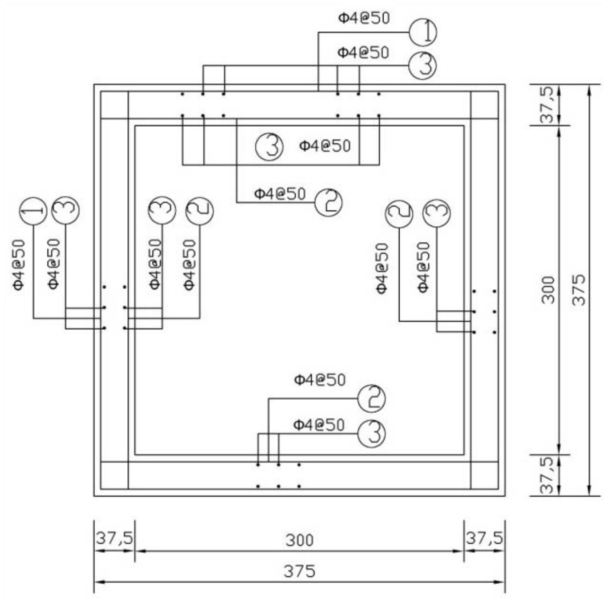
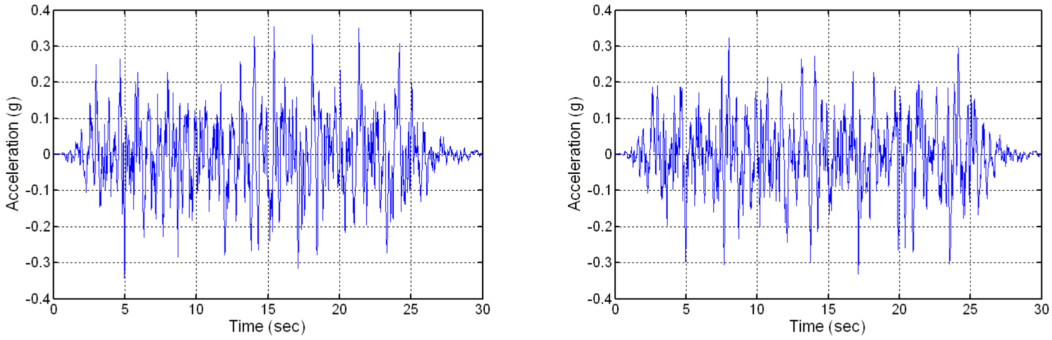


Figure 2 Dimensions and reinforcement details of structure model (all dimension in mm)

Unsaturated clay soil was used in the test. After the soil was placed in the box, its properties were tested on dynamic triaxial test system using samples taken directly from the shear box. Table 1 summarizes the test result of soil properties. Two earthquake waves with certain correlation (Shi, 2007) were constructed and adopted as the inputs for the test (see Figure 3).



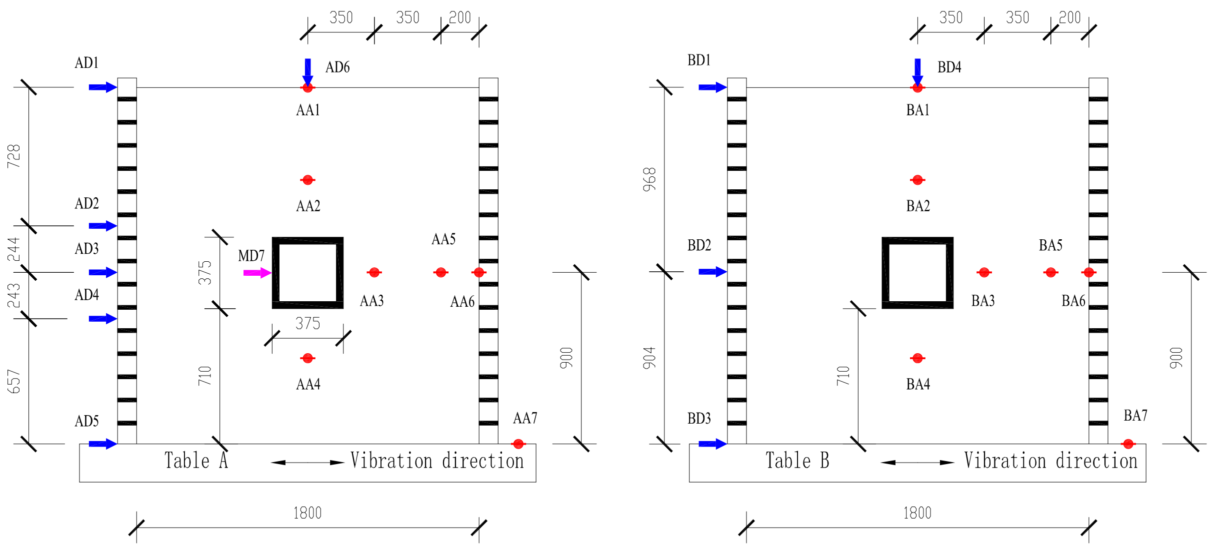
（a） W1　　　　（b） W2

Figure 3　Time history of W1 and W2

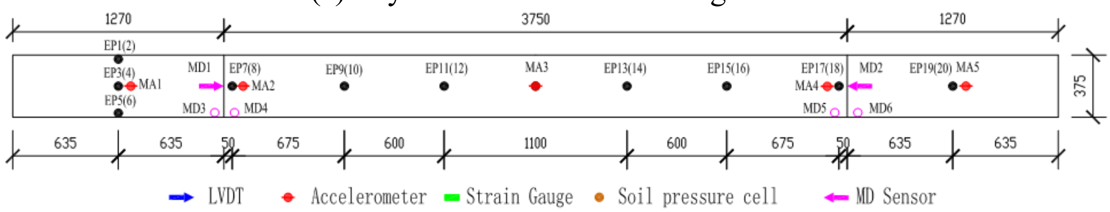
Test Program and Instrumentation

A large number of accelerometers, earth pressure cells, displacement transducers, and strain gauges are adopted to measure the seismic responses of the structure model and model ground. Besides, for analysis of underground structure subject to earthquake input, the relative slippage between soil and structure and the movement of structural joint are two important factors for seismic assessment of utility tunnel. Therefore, two special sensors were designed and manufactured, one (denoted as MD) is designed for measuring slippage displacement at the interface of structure model and model ground, and the other (denoted as RD) is designed for measuring displacement and rotation angle of joints during the test.

Figure 4 shows layout of instrumentation for joint model under lateral vibration. The type of sensor can be identified by the following nomenclature as: first letter + second letter + sensor number. The first letter denotes the location of sensor that letter A, B and M means shear box A (installed on fixed shaking table), box B(installed on moveable shaking table) and structural model respectively. The second letter denotes type of sensor that letter A, D, S and E means accelerometer, displacement transducer, strain gauge and earth pressure cell. For instance, AA1 means No.1 accelerometer in shear box A, BD1 means No.1 displacement transducer installed on the outer surface of shear box B. RD and MD sensors are special sensor as described above.



(a) Layout of sensors in model ground



(b) Layout of sensors on structural model

Figure 4 Instrumentation for joint model in lateral test

Finite Element Modeling

Finite element model of the tested utility tunnel is established in this section to simulate the shaking table test. Four factors are considered for the numerical modeling: the laminar shear box, soil-structure interaction, construction joint and initial stress field. Shell element is used to simulate laminar shear box and unit mass of 126.3kg is loaded on the outside of soil ground, and the rigidity of box is as small as the soil. Slippage and separation between soil and box are ignored. All nodes of the box element in the same height are considered as the same displacement along the vibration direction and no displacement on perpendicular of vibration direction. Another is soil-structure dynamic interaction, which is mainly caused by nonlinear property of soil and contact effect between soil and structure. Linear extended Drucker-Prager model is used to consider soil constitutive model, and linear and elasticity model to structure material (see Table 1). Master-slave surfaces are employed to simulate the soil-structure contact effect, with a coefficient of 0.22 between soil and structure. Besides, initial stress field cannot be ignored since it has great influence on coulomb friction force and normal stress on the soil-structure interface. Initial stress is applied by initial conditions in the geostatic step, and produces an initial vertical displacement of 0.005502m, which can be considered balance. The last is element selection. In the model, soil and structure are modeled as 8-node 3-D solid element and 4-node shell element respectively (see Figure 5).

First-order frequency of Experimental is 5.6Hz，while that of FEM is 5.2714Hz. Rayleigh damping ratio is used in the numerical modeling, Table 2 shows the damping ratio computed in numerical model in deferent PGA, which indicates an increasing tendency with the increase of peak input wave.

Table 1　Material parameter of soil and structure

	density/Kg/m3	Elastic modulus/Mpa	Poisson’s ratio	Inner friction angle/°	cohesion/KPa
soil	1800	16.5	0.4	27.9	24.4
structure	2400	33000	0.20	——	——

Table 2　Damping ratio

PGA/g	*0.1g*	*0.2g*	*0.4g*	*0.6g*	*0.8g*	*1.0g*
Damping ratio	0.06	0.11	0.15	0.20	0.25	0.30

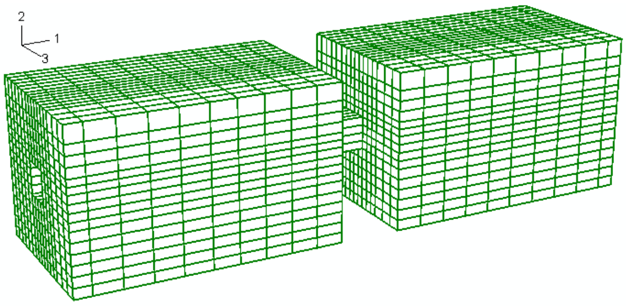


Figure 5　Meshing of soil-structure-box

Nonlinear spring elements are used to consider the joint effect between the two structure segments. The coefficient of spring element is based on the principle that the force in spring is very small when in tension, and quite large when in compression. That is, with the existence of the spring element the utility tunnel cannot be apart far away, nor come together. For the lateral vibration test with joint case, four nonlinear spring elements are defined to simulate the translation and rotation in direction 1 and direction 3. The value of the nonlinear spring element sees Table 3.

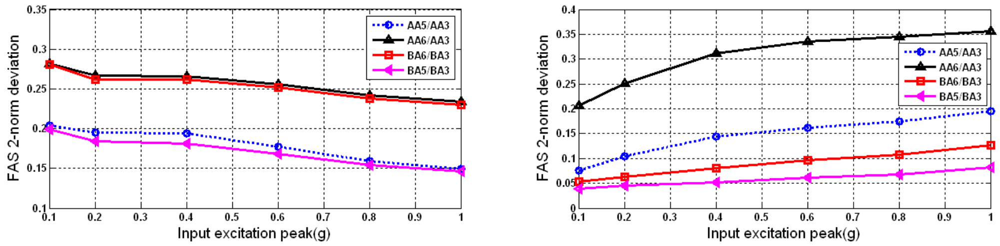
Table 3　value of nonlinear spring element

Displacement/m	*-1*	*-0.1*	*0*	*0.001*	*1000*
Force/N	-1e-9	-1e-9	-1e-10	500	500

Results Analysis

Boundary effect

An index based on 2-Norms deviation (Shi, 2009) is introduced to quantify the boundary effect of the shear box. Figure 6 shows 2-norm index calculated using acceleration response. It can be observed that the variation range of the index is 0.14 to 0.28 of FEM results and 0.04 to 0.36 of experimental results, which shows that boundary effect is small, and numerical results are reasonable.



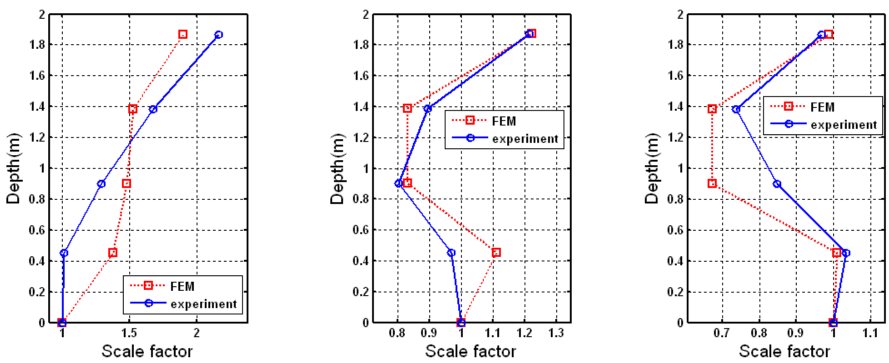
(a) FEM (b) Experiment

Figure 6 μ calculated using acceleration responses

Acceleration response

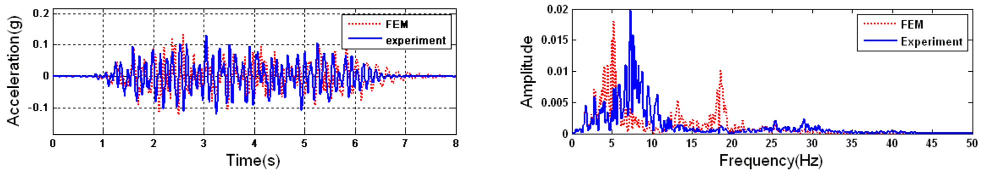
Figure 7 is the comparison of the amplification factor of acceleration response of model ground between numerical and experimental results, taking 0.1g, 0.4g and 1.0g cases as an example. It is seen that numerical results and experimental tests match quite well.

Figure 8 shows the comparison of time history of sensor AA2 and its Fourier spectrum between numerical results and the test. The comparison results indicate that numerical results are found to agree well with experimental measurements.

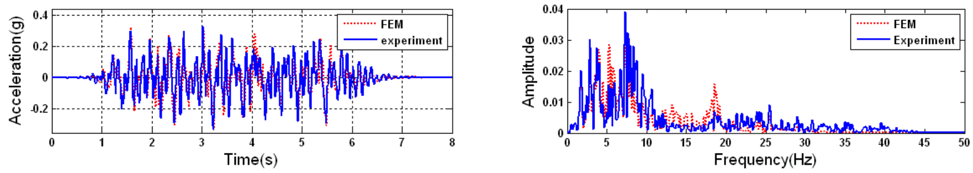


(a) 0.1g (c) 0.4g (f) 1.0g

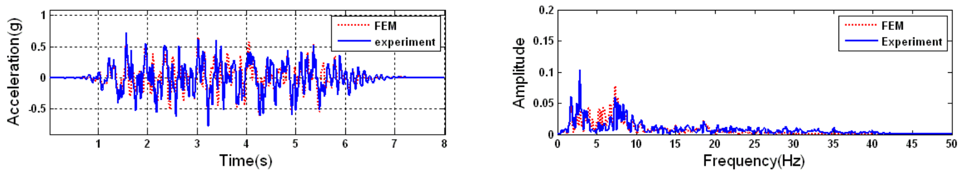
Figure 7 Amplification factor of acceleration response of box A



(a) 0.1g



(b) 0.4g

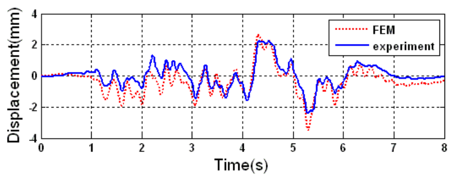


(c) 1.0g

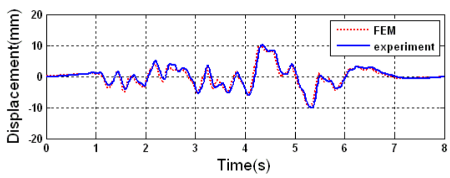
Figure 8 Time history of sensor AA2 and its Fourier spectrum

Displacement response

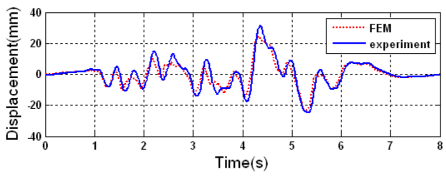
Figure 9 is the comparison of sensor AD2 between numerical and experimental result, which shows that numerical results and experiment measurements match quite well.



(a) 0.1g



(b) 0.4g

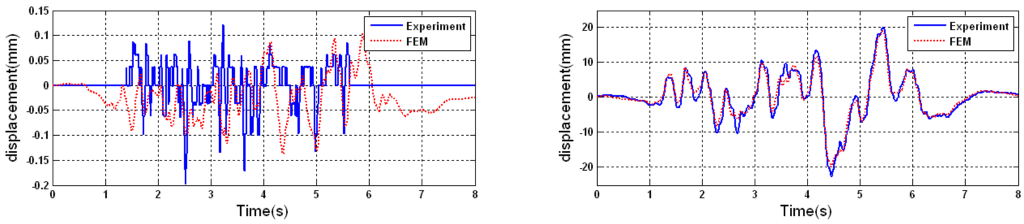


(c) 1.0g

Figure 9   Time history of sensor AD2

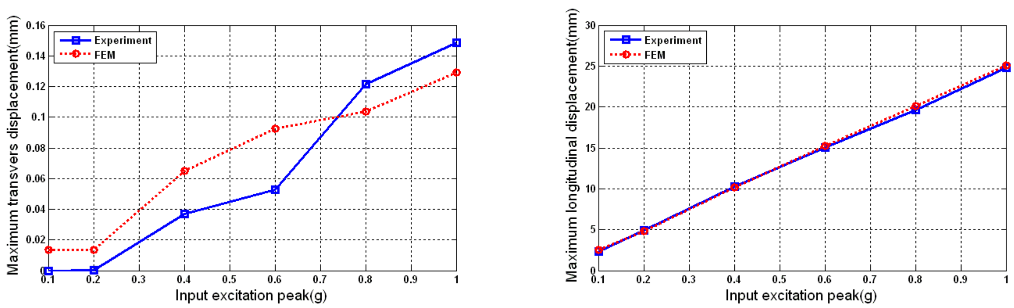
Joint effect

Figure 10 shows the time history of displacement at joint MD1 and MD7 in the 0.8g case. The reason that the comparison result at MD1 is not as good as that at MD7, is that there is no construction joint but only put the two segments together. It can be seen that the amplitude of displacement between numerical and experimental matches quite well. Figure 11 is the maximum displacement of MD sensors under different PGA. It can be observed that the displacement increases with the increase of PGA.



(a) MD1   (b) MD7

Figure 10 time history of displacement of joint (0.8g)



(a) MD1   (b) MD7

Figure 11   Maximum displacement of joint

Concluding Remarks

Numerical model based on shaking table test of underground utility tunnel is established. Numerical results and test measurements are compared in boundary effect, acceleration response, displacement response, and joint effect. The comparisons show the modeling of the laminar shear box does not impose significant boundary effect on the model ground. And the numerical results are in good agreement with the test; the nonlinear spring element can serve as the construction joint.

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