16th World Conference on Earthquake, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 4628
Registration Code: S-J1463159584

EXPERIMENTAL INVESTIGATION ON SEISMIC RESONANCE BEHAVIOR OF PILE FOUNDATION STRUCTURES UNDER SCOURING CONDITION

Y. Shang(1), X. Wang(2), A. Ye(3), A. Alipour(4)

(1) *Ph.D Candidate, State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China.*
Email: 0725shangyu@tongji.edu.cn
(2) *Ph.D Candidate, State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China.*
Email: 10_xiaoweiwang@tongji.edu.cn
(3) *Professor, State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China.*
Email: yeaijun@tongji.edu.cn (Corresponding author)
(4) *Assistant Professor, Department of Civil, Construction and Environment Engineering, Iowa State University.*
Email: alipour@iastate.edu

Abstract

Dynamic response mechanism of soil-pile-structure system (SPSS) is a complicated problem in the field of earthquake engineering. To this end, a series of shake table tests were carried out to investigate the seismic resonance behavior of SPSS. A reinforced concrete (RC) specimen comprised of a lumped mass representing the superstructure, a single pier, and a cap supported by a 2×2 pile group was constructed and embedded into unitary dry sand. First the dynamic properties of SPSS were investigated using white noise input. In order to excite resonance response of each fundamental vibration modes, three sinusoidal waves with the same peak acceleration of 0.1g with frequencies of 2Hz, 7Hz and 15Hz were utilized. To represent the scouring phenomena, which is common for the foundation of bridges over waterways, soil layers were removed. The acceleration response of the structure and sand, as well as curvature of pier and foundation, were detected. The results showed that the SPSS has three fundamental vibration modes, which are dominated by the motion of superstructure, pile-cap and soil layers, respectively. Due to the resonance effect between earthquake input and certain vibration modes, seismic response of SPSS varied significantly when the frequency of the dynamic loading changed. This underlines the importance of studying the careful selection of ground motion inputs for seismic design of bridges that have the possibility of a scoured foundation.

Keywords: soil-pile-structure system, shaking table test, resonance response, foundation scour, input motion types

1. Introduction

Response of structures to dynamic loads (such as an earthquake), could be significantly amplified if the period of external loading approaches the fundamental vibration periods of the structure [1] resonance happens. For bridges with pile foundation embedded in soil, the dynamic behavior is very complicated, and could be influenced by several fundamental vibration modes that associated with the motion of superstructure, foundation or soil. Therefore, when considering resonance, earthquake loads with different frequencies, would result in different seismic response of soil-pile-structure system (SPSS).

Despite many research efforts that have been made in past decades to study the seismic behavior of pile-supported structures in soil, there are still issues with understanding the complex seismic resonance behavior of SPSS. Previous studies mainly focused on the soil-pile-structure interaction mechanism. Many attempts have been made through centrifuge test or shake table test. Wilson [2] and Boulanger [3] investigated seismic soil-pile-structure interaction using a centrifuge test and found that accelerations in deeper soil layers show a progressive amplification of motion up through the soil profile. Brandenberg [4] performed the centrifuge test on the dynamic response of piles in saturated sand, and found that directions of lateral loading from the different soil layers are shown to depend on the mode of pile deflection relative to the soil. Tokimatsu [5] studied the effects of inertial and kinematic forces on pile stresses based on large shaking table tests on pile-structure models. This is in addition to the extra complication introduced by scouring at the foundation of bridges passing waterways [6]

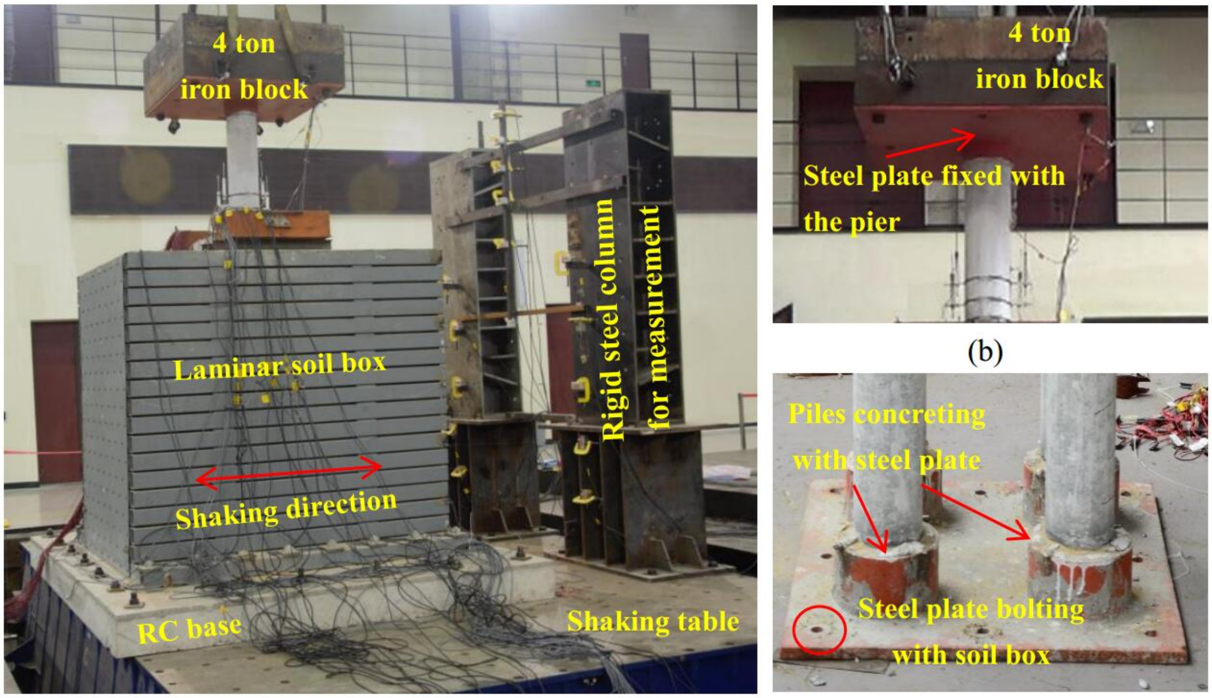
The decline of surrounding soil level would decrease the lateral stiffness of foundation, and change the periods of vibration modes for SPSS. These changing soil levels, in addition to the resonance effect between SPSS and earthquake input loading, will make it more difficult to perform seismic analysis of bridges with pile foundation. Some previous studies have investigated the combined effect of scouring and earthquake on bridges. Liang and Lee [7, 8] have presented a reliability-based approach to combine the effect of scour with other load effects in bridge design. With the specific scour failure model, the limit state equations of bridge failure was established, in which the scour effects are treated as equivalent loads. Alipour et al. [9] developed a multi-hazard reliability framework to assess the load modification factor for bridge design considering the scour and earthquake effects. Research efforts have also been made in using the sophisticated finite element method to assess the seismic response of bridges affected by foundation exposure. Wang et al. [10] quantified the effect of scour on the dynamic behavior and seismic performance of reinforced concrete bridges, and investigated potential structural design alternatives to mitigate damage from earthquake exposure in given scour conditions. Klinga and Alipour [11] provided a comprehensive analysis procedure to estimate the performance of scour-critical bridges considering the soil-pile-structure interaction. The study by Wang and Liu [12] on seismic performance of a scoured bridge model with single pile on a shake table showed an increase in the moment demand on the pile and a decrease in the moment demand of the pier after scouring. However, the effect of ground motion frequency content and possibility of resonance due to changes in the soil conditions have not been studied previously. Therefore, more experimental tests and numerical analyses are needed to provide a comprehensive and confident assessment on the seismic behavior of the SPSS.

In this study, a series of shake table tests were conducted to investigate the resonance behavior of soil-pile-structure system (SPSS) in presence of scouring effects. A reinforced concrete (RC) comprised of a single pier, and a cap supported by a 2×2 pile group was embedded in dry sand. The dynamic properties of SPSS were investigated firstly, using white noise input. Then, in order to study the seismic characteristics of each vibration mode of SPSS, three sinusoidal waves are utilized to excite resonance response. The acceleration response of soil and structure are presented to show the amplification behavior of SPSS on bedrock input earthquake waves. Recorded structural curvature distributions are presented to reveal the seismic resonance of the system in presence of scouring.

2. Experimental Program

The tests in this study were conducted in the Multi-Functional Shake Tables (MFST) Lab of Tongji University, Shanghai (Fig. 1). A laminar soil box with a reinforced concrete (RC) base was mounted on the 4×6 m shaking table with maximum bearing capacity of 70 tons. A RC specimen composed of a 0.1 m-diameter

(D)/1.9 m-length (19D) 2×2 pile group and a 0.6 m×0.6 m×0.3 m cap and a 0.214 m-diameter /1.0 m-height single pier was constructed and partially embedded into unitary dry sand layers with similar D_r around 50%. A 4 ton iron block was fixed on top of the pier to represent the superstructure.



(a) (b) (c)

Fig. 1 – Test specimen embedded in laminar soil box on the shake table at the Multi-functional Shaking Table Lab of Tongji University: (a) global view, (b) pier-superstructure connection and (c) pile-tip connection.

2.1 Soil property and placement

The sand box in the tests is a one dimensional laminar shear box designed by Wu [13]. It has a rectangular cross section with interior dimensions of 2000×1500mm^2 and 2000mm in depth. The laminar box allows for free movement of soil along the transverse cross section. Previous investigation [13] has shown that the laminar box boundary effects are negligible at distances 400mm from the boundary. Thus to minimize the boundary effects, the specimen was positioned in the center of the soil box with the distance to the box wall of 800mm in the shaking direction and 550mm in the orthogonal direction.

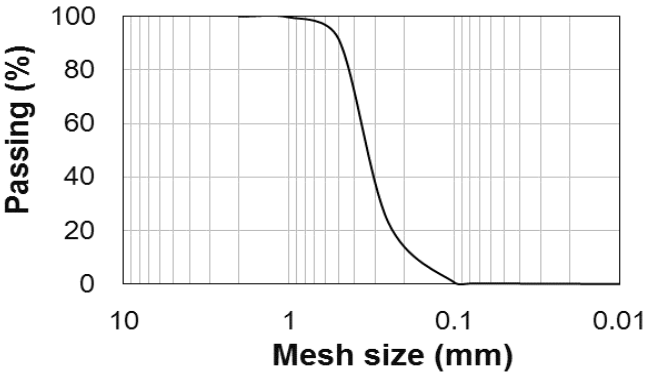


Fig. 2 – Grain size distribution of test sand

The Shanghai sand was used for the soil layers. The sand is poorly graded, with a mean grain size D_{50} of 0.33 mm, a coefficient of uniformity C_u of 2.06, maximum and minimum dry densities of 1.654 and 1.429 g/cm^3, respectively. The grain size distribution was depicted in Fig. 2, which indicated poorly graded sand used for the test. The air pluviation approach [14] was adopted to place the sand into the box, to achieve unitary sand layers with D_r of 50%, which targets a medium dense sand specimen [15], a large steel bucket full of weighted dry sand was suspended over a long hopper. Then, the dry sand was dropped into the box slowly and evenly through the hopper. After the sand was compacted to a scheduled height, another sand layer was placed into the container.

2.2 Pile foundation bridge specimen

The pile foundation bridge model inside the sand box is shown schematically in Fig. 3. A single pier was taken to represent the bridge, and superstructure was simplified as lumped mass on top of the pier. According to the American Association of State Highway and Transportation Official (AASHTO) [16], the primary period for bridges is considered to be between 0.2 and 1.0 s. Thus, in the specimen design procedure, a value of lumped mass (M_{ss} = 4 ton) was chosen, which can meet the target and result in a predominant period of 0.4 ~ 0.5 s. The axial compressive ratio under such design also agrees with that of bridge columns in current practices (i.e., between 5% and 35%) [17]. As seen in Fig. 1(b), the pier head is fixed with the lumped mass through a steel plate with a collar, which was casted together with the pier by welding the top of the reinforcing rebar to the steel plate.

The single pier was supported by a RC cap with a 2×2 pile group. The center-to-center spacing of piles was 3D (D is the diameter of the pile) which is consistent with the commonly adopted spacing of 3D to 4D [18]. Fig. 1(c) shows the pile-tip and base connection. A 4-collar steel plate was casted together with the 2×2 pile group and bolted with the bottom of soil box to simulate the condition of the pile embedded in a firm stratum.

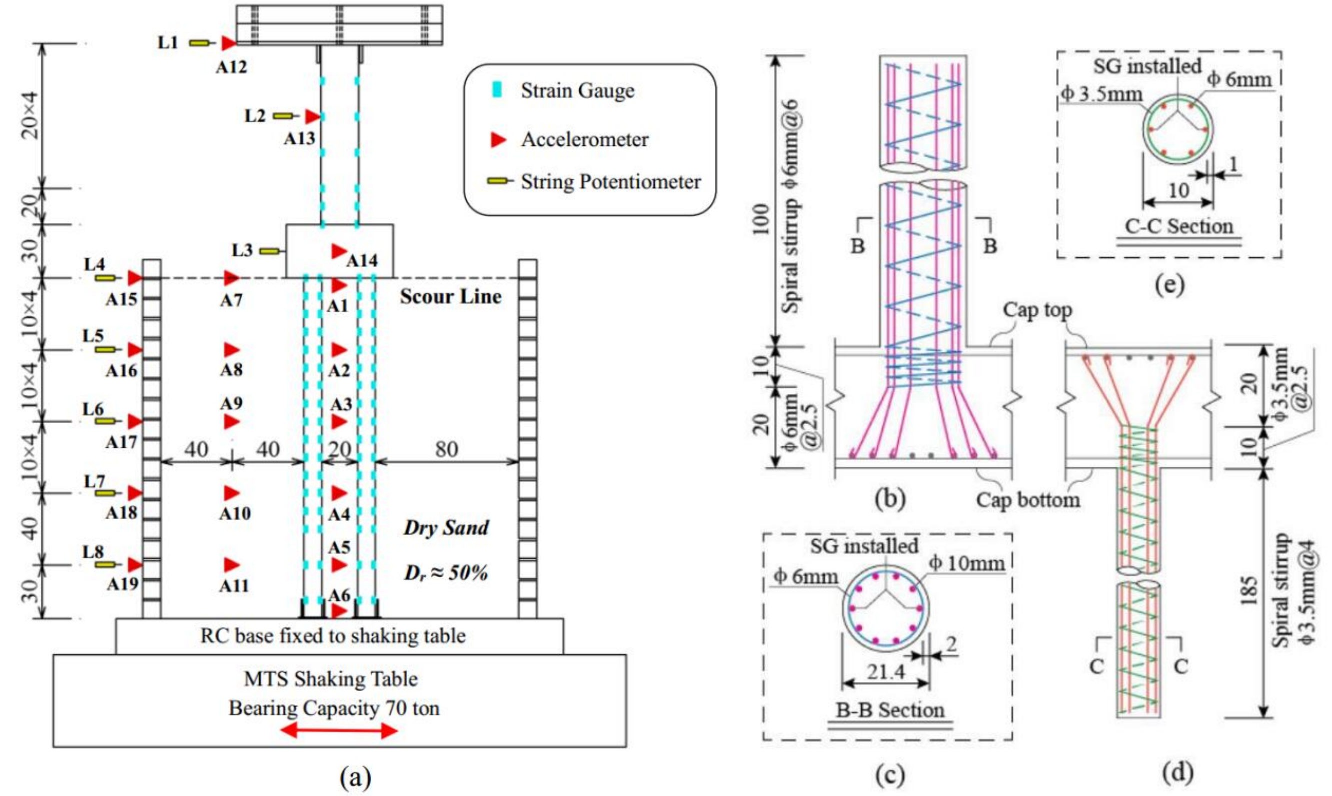


Fig. 3 – Bridge specimen in saturated or dry medium dense sand for shaking table tests: (a) global schematic diagram, (b) pier reinforcement, (c) pier section, (d) pile reinforcement and (e) pile section
(Note: unit is centimeter except for specific annotations)

A longitudinal and transverse reinforcement ratio of 2% and 0.8% was assigned for the pier and piles of the specimen, respectively. Specifically, as shown in Fig. 3, for the pier component, the longitudinal reinforcements were provided by 10 ϕ10-mm rebar with a concrete cover of 2 cm. In regard to the pier confinement, spiral ϕ6-mm stirrups were arranged with an interval of 6 cm. In addition, longitudinal rebars and dense spiral stirrups were extended into the cap to ensure the fixed connection between the pier and cap top. In terms of the pile components, 6 ϕ6-mm rebar were assembled as longitudinal reinforcements with a cover of 1 cm. ϕ3.5-mm spiral stirrups with 4 cm spacing provide the transverse reinforcement in the piles.

2.3 Installation and test setup

The laminar soil box and the bridge specimen were instrumented with 112 sensors, including accelerometers, string potentiometers, and strain gauges. As shown in Fig. 3, accelerations of soil were recorded at 0, 300, 700, 1100, 1500 and 1900mm along the height of soil level during the tests. Displacements and accelerations of the superstructure and pile-cap were also recorded. 40 pairs of strain gauges were glued on representative longitudinal rebars (shown in Fig. 3) of the pier and two of the four-pile group to monitor the variation of sectional curvature during the test. The strain gauges on the pile were arranged every 100mm (1D). For the pier, strains were measured at 0, 100, 200, 400, 600 and 800mm from the pier bottom. In addition, the frame movements at different depths of the laminar shear box were recorded using magnetostriction type linear displacement transducers and accelerometers.

2.4 Test protocol

Table 1 summarizes the adopted ground motions and scouring scenarios during the test. The white noise was input firstly to investigate dynamic properties of SPSS. Frequencies of sinusoidal waves were decided according to the fundamental periods of specimen. As failure mechanism is not the concern of this study, peak input accelerations are all 0.1g, which would be convenient to compare the results and insuring that the specimen will remain in elastic state. The scour conditions were simulated by removing surface soil layers. Three scour depths (SD) were performed, that is 0D, 2D and 4D.

Table 1 - Relative density of soil layer

Scour depth	**Input earthquake motions**	**Peak input acceleration (g)**
0D	White Noise (0.25 ~ 50*Hz*), Sine 2*Hz*, Sine 7*Hz*, Sine 15*Hz*	0.1
2D	White Noise (0.25 ~ 50*Hz*), Sine 2*Hz*, Sine 7*Hz*, Sine 15*Hz*	0.1
4D	White Noise (0.25 ~ 50*Hz*), Sine 2*Hz*, Sine 7*Hz*, Sine 15*Hz*	0.1

3. Test results and discussion

3.1 Dynamic properties of soil-pile-structure system

To study the seismic behavior of the SPSS under scouring effects, the dynamic characteristics of the system need to be measured. To this end, the response spectrum of acceleration (RSA) has been generated for superstructure, pile cap, and sand surface without scouring (SD: 0D) as shown in Fig. 4. The dynamic behavior of SPSS in this test showed three obvious vibration modes. The first mode has a period of 0.40s, with the highest participation from superstructure representing the transitional vibration of superstructure. The second mode has a period of 0.14s representing the vibration of soil layers by comparing it to the fundamental mode of soil in free field test. The third mode has the smallest period (0.03s), and only motion of cap and soil are included representing the transitional vibration of pile cap. Reviewing the mode shapes of the SPSS system reveals that the acceleration of the pile cap and soil surface are very close before scouring. In addition, the motion of structures could influence the motion of soil layers around.

Because scour has washed away the sand layers, the dynamic properties of the structure could be changed. Fig. 5 (a) ~ (c), shows the variation of RSA of superstructure, pile cap and soil surface with an increase in scour depth (SD). Because of the decrease of support by surrounding soil, the fundamental periods of superstructure increases slightly when SD changes from 0D to 4D (Fig. 5 a). However, the periods of soil layers decrease after scouring (Fig. 5 b), due to the proportional relation between fundamental periods and height of soil layers. The response of pile cap is more complicated because of the combined effects of superstructure and soil. In Fig. 5 (c), it can be found that all the three modes are reflected in the motion of cap. With the increase of scour depth, the periods of first and third increase, while the period of second mode decreases.

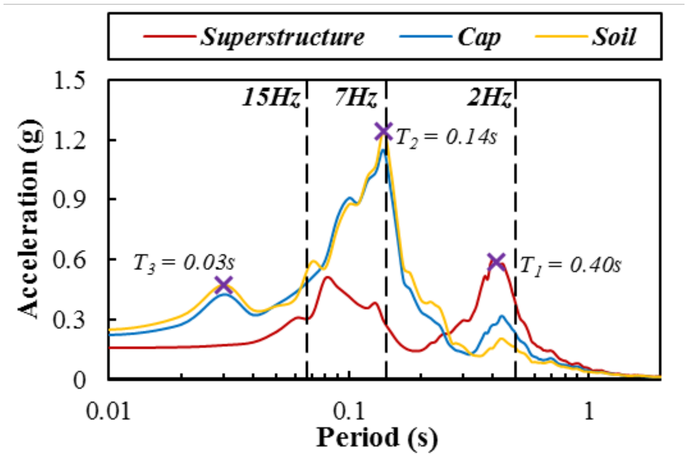
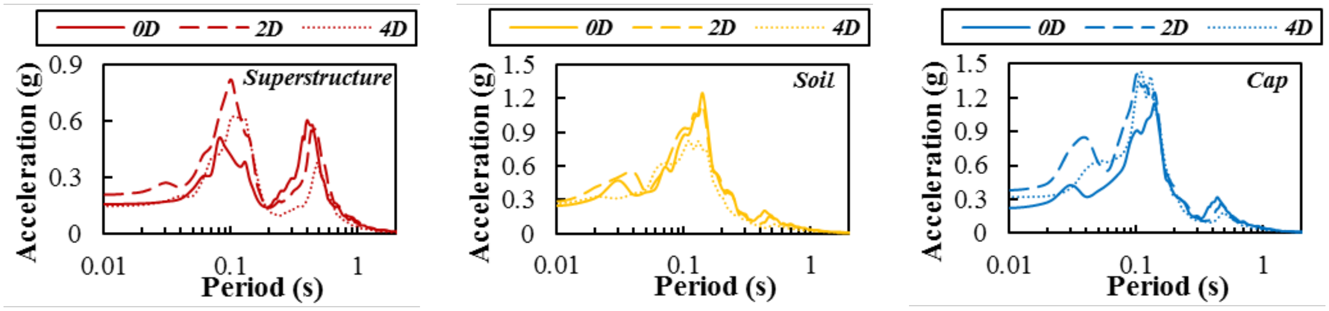


Fig. 4 – Response specturm of acceleration (RSA) respose of SPSS for pier with no scour (SD: 0D)



(a) RSA of superstructure

(b) RSA of soil

(c) RSA of pile-cap

Fig. 5 – Response specturm of acceleration (RSA) respose on supersturcture, pile-cap and sand surface considering the scour depth of 0D, 2D and 4D

3.2 Dynamic amplification behavior of SPSS

During an earthquake, the waves are transferred from the bedrock to the overlying soil layers, and then input to the structures through the interaction between the soil and pile. Depending on the type of the soil layers, usually the acceleration amplifies when transmitted from bedrock to soil layers and structure. This is mostly caused by the resonance effect between input earthquake waves and SPSS when their periods approach. To investigate this resonance behavior, several shake table tests were performed on the SPSS specimen under three different sinusoidal waves. The dominant frequencies of the sinusoidal waves were 2Hz, 7Hz and 15Hz, which are close to the periods of the three modes respectively as shown in Fig. 4.

Fig. 6 shows the maximum acceleration amplification factors (AAF) for the structure and soil layers at different depths. It can be found that the amplification behavior of SPSS could be very different when dominate frequency of input changes. For sinusoidal input of 2Hz, the accelerations of superstructure, pile-cap and soil were all obviously amplified. Due to the resonance response of input and the first mode, the amplification factor of superstructure was the largest and had a value of about 2. The acceleration of the cap and soil surface were also amplified over 1.5 times. Under the sinusoidal input of 7Hz, the resonance effect happened between input and the second mode. The AAF of soil and pile cap reached to 2, while the acceleration of superstructure was reduced. When the frequency of sinusoidal input was 15Hz, which was close to that of the third mode, the acceleration response of the structure was the smallest among the three inputs. Because of the participation of higher modes of soil layers, the acceleration did not increase along soil depth for the sinusoidal inputs of 2 and 7Hz. Instead, acceleration of soil layers decreased at first, and then amplified near the surface of soil.

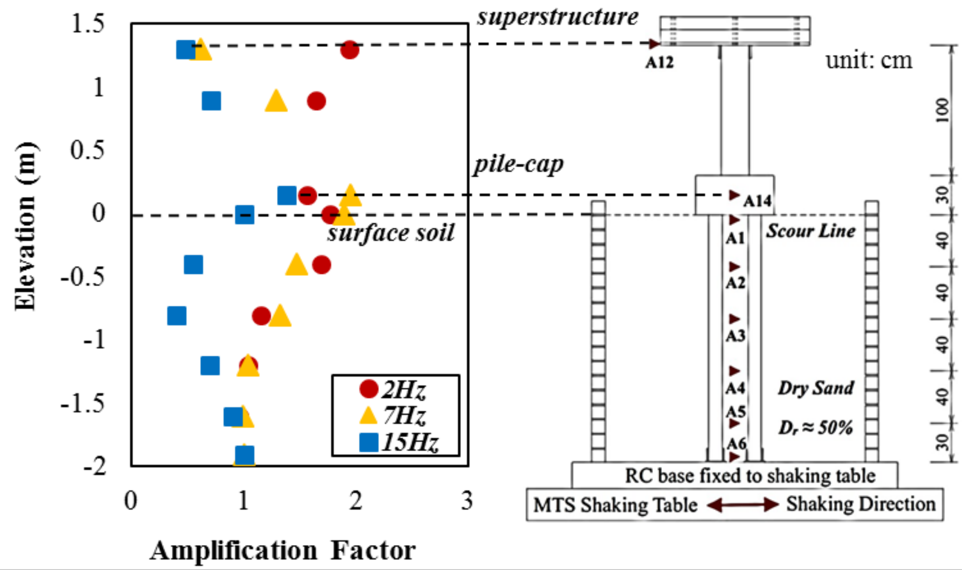
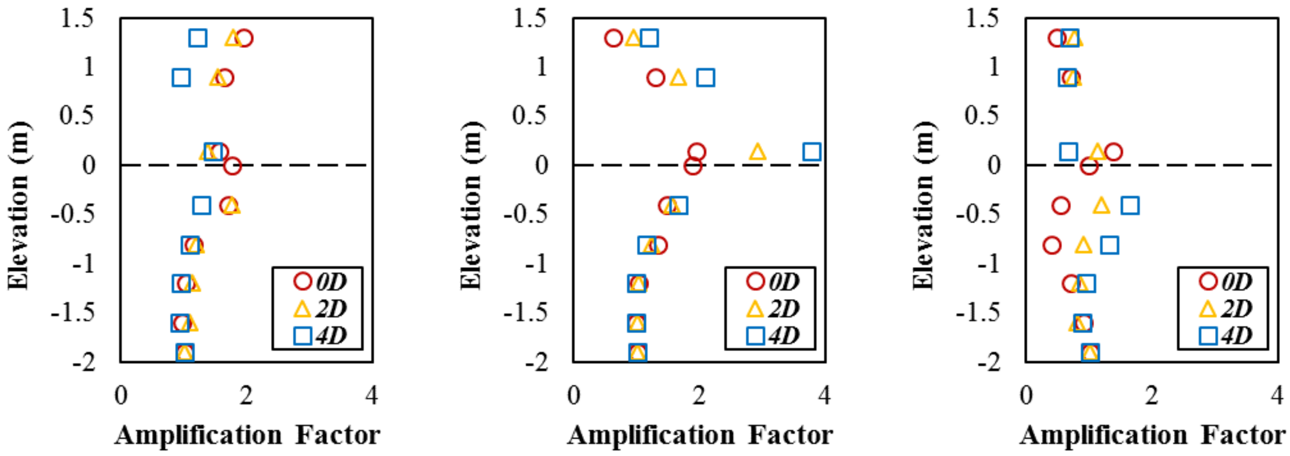


Fig. 6 – Acceleration amplification factor of SPSS under different sinusoidal waves (SD: 0D)



(a) sinusoidal input (2*Hz*)

(b) sinusoidal input (7*Hz*)

(c) sinusoidal input (15*Hz*)

Fig. 7 – Acceleration amplification factor of SPSS under different scour depths for each sinusoidal input

The resonance effects could also influence the variation of structural acceleration distribution with the change of scour depths. Fig. 7 presents the change of structural AAF when scour depth increased from 0D to 4D for each sinusoidal input. In Fig. 7 (a) and (b), the acceleration response of soil hardly changed after scouring, while the AAF of structure varied obviously in both cases. For the sinusoidal input of 2Hz, the AAF of cap showed no change while the one for superstructure decreased after scouring. This is because the decrease on the participation of first mode in superstructure acceleration response for larger scour depth (Fig. 5a). On the contrary, when using 7Hz sinusoidal wave as input motion, the AAF of superstructure hardly changed, but that of pile cap increased largely after scouring. This phenomenon can be explained by the decrease in lateral support of surrounding soil near pile cap when SD change from 0D to 4D. In Fig. 7 (c), for the input of 15Hz, the AAF of structure changed slightly, while the AAF of soil obviously changed.

3.3 Bending curvature response of pile foundation structure

Bending curvature of structure is another important factor in bridge seismic design. Thus the curvature distribution, calculated from data of several pairs of strain gauges along pier and pile columns, is presented in this section.

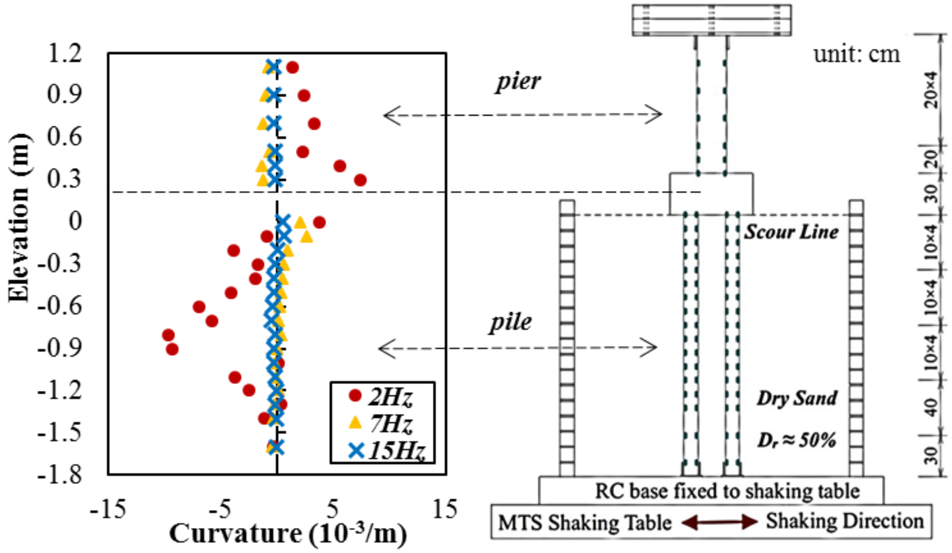
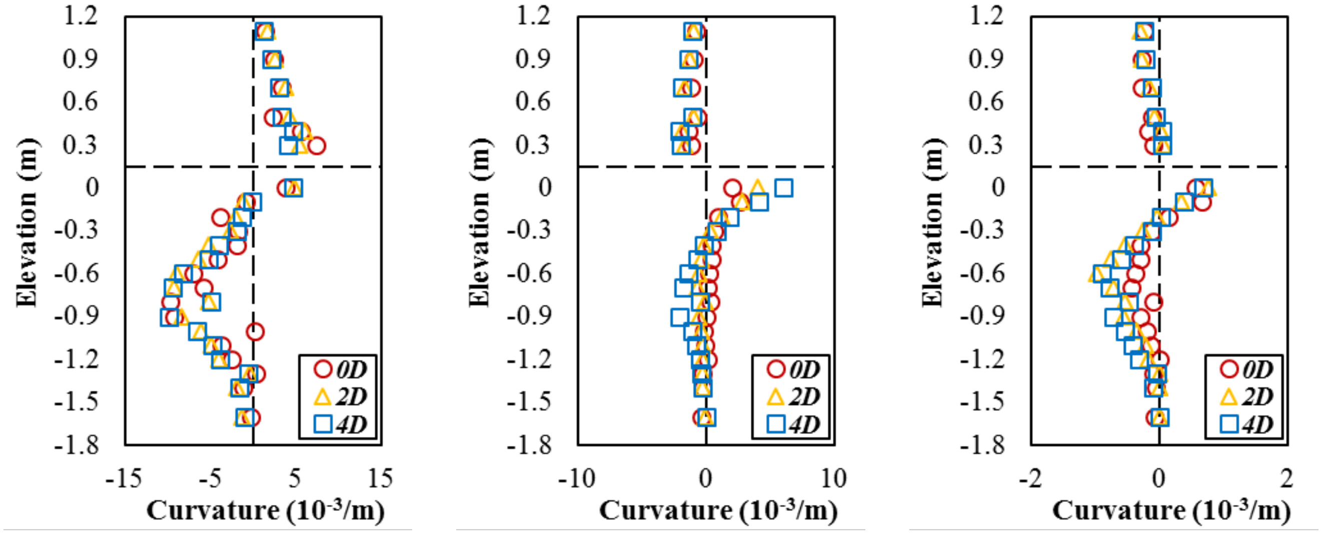


Fig. 8 – Curvature distribution of SPSS under different sinusoidal waves (SD: 0D)



(a) sinusoidal input (2*Hz*)

(b) sinusoidal input (7*Hz*)

(c) sinusoidal input (15*Hz*)

Fig. 9 – Acceleration amplification factor of SPSS under different scour depths for each sinusoidal input

Fig. 8 shows the structural curvature distribution at the moment that the maximum curvature value of pile appeared for each input motion (SD: 0D). The curvature under input of 2Hz is much larger than the others, and that of the 15Hz input is the smallest. Because most of the mass of the structure is concentrated in the superstructure, the first mode, which caused larger inertial force on the superstructure, will contribute the most to the structural bending behavior.

In order to show the curvature distribution form of SPSS under each type of input clearly, Fig. 9 presents the structural curvature of each input separately considering the scour effect. Scouring has not caused much change on structural bending behavior under the same sinusoidal inputs. However, for different sinusoidal inputs, the curvature varied significantly on both the magnitude and the distribution type along pile height. For input of 7Hz and 15Hz, nearly no bending behavior happened in pier due to the small inertial forces on the superstructure. For the pile, both the sections on the middle and top of pile experienced obvious bending response when the input frequency was 2Hz, and the maximum curvature appeared at section about 6D below ground level. On the contrary, for the input of 7Hz, the maximum curvature appeared on top of the pile, which was above the sand surface, and the curvature below ground was negligible. This is in accordance with the shape of fundamental mode of soil layers. For input of 15Hz, the distribution of curvature was similar with input of 2Hz, but the magnitude was much smaller. This is because the effect on the pile by active soil pressure (for input of 15Hz) is much smaller than the passive soil pressure (for input of 2Hz).

4. Conclusions

A series of shake table tests are carried out on the soil-pile-structure system (SPSS) to study the seismic resonance behavior of SPSS with and without scour effects. By detecting the acceleration response of both structure and sand, as well as curvature of pier and foundation, the dynamic characteristics of fundamental vibration modes of SPSS were presented.

(1) The soil-pile-structure system has three fundamental vibration modes, which are dominated by the motion of superstructure, pile-cap and soil layers. Scouring would increase the periods of modes dominated by superstructure and cap, but decrease the period of mode related to soil layers.

(2) Because of the resonance response between earthquake input and certain vibration modes, seismic response of SPSS significantly varies when the frequency component of dynamic loads changes. Thus, earthquake inputs should be carefully selected during seismic design of bridges which are expected to have scouring at the foundations.

(3) The acceleration response of SPSS is sensitive to both the frequency of input motions and scour depths. However, the curvature is more related to the input types. Inputs with longer periods would induce a larger bending response.

5. Acknowledgements

This work is supported by the National Natural Science Foundation of China (Grant No. 51278375) and the 973 National Basic Research Program of China (No.2013CB036302). The help from all of the staffs in the Multi-Functional Shaking Table Lab of Tongji University are greatly acknowledged, especially Drs. Yan Xu, Chengyu Yang and Jianzhong Li, who provided lots of insightful suggestions to our experiments. Partial funding from the Iowa State University Midwest Transportation Center is appreciated.

6. Copyrights

7. References

[1] Clough, R. W., & Penzien, J. (1995). Dynamics of Structures, Berkeley: Computers & Structures.

[2] Wilson, D. W. (1998). Soil-pile-superstructure interaction in soft clay and liquefiable sand. Report No. UCD/CGM-98/04, Center for Geotechnical Modeling, University of California, Davis, CA.

[3] Boulanger, R. W., Curras, C. J., Kutter, B. L., Wilson, D. W., & Abghari, A. (1999). Seismic soil-pile-structure interaction experiments and analyses. Journal of Geotechnical and Geoenvironmental Engineering, 125(9), 750-759.

[4] Brandenberg, S. J., Boulanger, R. W., Kutter, B. L., & Chang, D. (2005). Behavior of pile foundations in laterally spreading ground during centrifuge tests. Journal of Geotechnical and Geoenvironmental Engineering, 131(11), 1378-1391.

[5] Tokimatsu, K., Suzuki, H., & Sato, M. (2005). Effects of inertial and kinematic interaction on seismic behavior of pile with embedded foundation. Soil Dynamics and Earthquake Engineering, 25(7), 753-762.

[6] Melville, B.W. and Coleman, S.E. (2000) Bridge scour. Water Resources Publication, Highlands Ranch, CO.

[7] Liang, Z., & Lee, G. C. (2013). Bridge pier failure probabilities under combined hazard effects of scour, truck and earthquake. Part I: occurrence probabilities. Earthquake Engineering and Engineering Vibration, 12(2), 229-240.

[8] Liang, Z., & Lee, G. C. (2013). Bridge pier failure probabilities under combined hazard effects of scour, truck and earthquake. Part II: failure probabilities. Earthquake Engineering and Engineering Vibration, 12(2), 241-250.

[9] Alipour, A., Shafei, B., & Shinozuka, M. (2012). Reliability-based calibration of load and resistance factors for design of RC bridges under multiple extreme events: Scour and earthquake. Journal of Bridge Engineering, 18(5), 362-371.

[10] Wang, Z., Dueñas-Osorio, L., & Padgett, J. E. (2014). Influence of scour effects on the seismic response of reinforced concrete bridges. Engineering Structures, 76, 202-214.

[11] Klinga, J. V., & Alipour, A. (2015). Assessment of structural integrity of bridges under extreme scour conditions. Engineering Structures, 82, 55-71.

[12] Wang, S., Liu, K., Chen, C., & Chang, K. (2015). Experimental investigation on seismic behavior of scoured bridge pier with pile foundation. Earthquake Engineering & Structural Dynamics, 44(6), 849-864.

[13] Wu, X., Sun, L., Hu, S. and Fan, L. (2002) Development of laminar shear box used in shaking table test. Journal of Tongji University (Natural Science), 30, 781–5 (in Chinese).

[14] Carmelo, F., Diego, C. L. P., & Sergio, P. (1995). A pluvial deposition method to reconstitute well-graded sand specimens.

[15] Cubrinovski, M., Kokusho, T., & Ishihara, K. (2006). Interpretation from large-scale shake table tests on piles undergoing lateral spreading in liquefied soils. Soil Dynamics and Earthquake Engineering, 26(2), 275-286.

[16] American Association of State and Highway Transportation Officials (AASHTO) (2012). AASHTO LRFD Bridge Design Specifications (6th edn). American Association of State Highway and Transportation Officials: Washington, DC.

[17] Aviram, A., Aviram, A., Mackie, K., Mackie, K., Stojadinovic, B. and Stojadinovic, B. (2008) Guidelines of nonlinear analysis of bridge structures in California. PEER Rep. Pacific Earthquake Engineering Research Center, Berkeley, CA.

[18] Fleming, K., Weltman, A., Randolph, M. and Elson, K. (2008) Piling engineering. CRC press.