Wave Propagation Effect on Seismic Response of Cable-stayed Bridge: A Multiple Shake Tables Test

Cheng-Yu Yang
State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University

Moe M.S. Cheung
Dept. of Civil and Environmental Engineering, The Hong Kong University of Science and Technology

Xin Xu
College of Civil Engineering, Tongji University

SUMMARY:
For long span bridges such as cable-stayed bridges, which are long with respect to the wavelengths of the input earthquake ground motions, different supports might be subjected to significantly different seismic excitations. The wave propagation effect is considered one of the main contributors to the spatial variation of earthquake excitations. The effect of wave propagation on seismic response of cable-stayed bridge is studied in this paper by applying a multiple shake tables test. The prototype is a long span cable-stayed bridge and a 1:120 reduced scale model is designed for the multiple shake tables test. The earthquake records from the SMART-1 and the PEER Strong Motion Database are used in this study. The test results are presented, for the purpose of a) evaluating the design of the reduced scale model and b) improving the understanding of the effect of wave propagation on seismic response of cable-stayed bridge.

Keywords: Wave propagation effect, Cable-stayed bridge, Multiple shake tables

1. INTRODUCTION

The traditional approach for seismic analysis of structures is based on a uniform excitation assumption, which postulates that earthquake excitations at all the points along the base are identical. The identical input mode is easy to execute and can provide reliable analysis results for regular structure which covers a limited space or span. However, for long span or wide spread structures, such as cable-stayed bridges, which are long with respect to the wavelengths of the input earthquake ground motions, different supports might be subjected to significantly different seismic excitations. In general, four main factors may contribute to the spatial variation of earthquake excitations, i.e., incoherence effect, attenuation effect, site effect as well as wave propagation effect (Kiureghian et al. 1992 and Mylonakis et al. 2001).

The wave propagation effect is considered one of the main contributors to the spatial variation of earthquake excitations. The velocity of seismic wave isn’t infinite, therefore, an earthquake excitation needs some time to be transmitted from one support to another, which will result in different arrival times of the ground motion among different supports. The uniform excitation assumption only works when the seismic wave velocity is rather large compared to the distance between two supports. As to long span cable-stayed bridges, with distances between towers easily exceeding hundreds or thousands of meters, the arrival-time difference, i.e., the wave propagation effect should be taken into consideration. Although other factors such as local site effect are also worthy of consideration in studying spatially varying earthquake ground motion, to avoid interference and simplify analysis process, only the wave propagation effect, is considered in this research.

Numbers of achievements have been reported in the numerical analysis of seismic behavior of long span bridges subjected to spatially varying earthquake ground motion; however, few experimental studies have been published in this area. Several shake table tests of full bridge model of long span bridges has been reported in the past few decades (Godden et al. 1978, Garevski et al. 1991 and Wang et al. 2006), while none of them include the effect of spatially varying earthquake ground motion. Shake table tests of two girder bridge model, including the non-uniform cases, were accomplished at the University of Nevada, Reno, by using a multiple shake table system (Carden et al. 2006 and Saiidi et al. 2007).

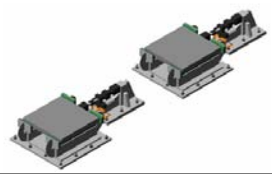
The effect of wave propagation on seismic response of cable-stayed bridge is studied in this paper by applying a multiple shake tables test. The prototype is a typical cable-stayed bridge with a main span of 430 m and side spans of 160 m on either side. A unique multiple shake tables testing system, including two 1.5m*1.5m 1-DOF shake tables, is developed and a 1:120 reduced scale model of the prototype cable-stayed bridge is designed and constructed for the purpose of this study. During the multiple shake tables test, the earthquake records from the SMART-1, as well as the PEER Strong Motion Database, are used in the study. The testing results are finally presented and discussed, for the purpose of a) evaluating the design of the reduced scale model and b) improving the understanding of the effect of wave propagation on seismic response of cable-stayed bridge.

2. MODEL DESIGN

2.1. Testing facility

A multiple shake tables testing system is developed for the purpose of this study. The testing system is composed of 2 shake tables. Each table has a table size of 1.5m by 1.5m, with a maximum design payload of 2 ton. Each table is driven by an MTS 244.22 hydraulic actuator (force rating of 10ton), providing a maximum acceleration of 1g and maximum stroke of +75mm in terms of the table motion. The specification of the multiple shake tables testing system is listed in Table 2.1.

Table 2.1. Specifications of the multiple shake tables testing system

Item	Spec.	
Table size	1.5m by 1.5 m	
Maximum payload	2 ton	
Actuator	MTS 244.22 (force rating 10 ton)	
Shaking direction	1-D.O.F.	
Maximum travel	+/- 75mm	
Maximum acceleration	1.0 g	
Operating frequency	0-50Hz	
Distance between two tables	4.8 m (center to center)	
Working mode	In-line excitation 	Parallel excitation 

2.2. Prototype bridge

The prototype bridge adopted in this study is a double-deck cable-stayed bridge with a main span of 430 m and side spans of 160 m on either side, as shown in Fig. 2.1. The upper deck has been designed for highway traffic and the lower deck for railway traffic plus emergency lanes for vehicles. Most of the main span, 387 m, is made of steel/concrete composite construction, consisting of steel frames, steel webs and concrete slabs. The rest of the main span and both side spans are constructed by using prestressed concrete box girders. The cross sections of the main span and side span are shown in Fig. 2.2. The two H-shape concrete towers are founded on bedrock, with a height of 150 m above the water level. Each tower consists of 2 shafts and 3 cross beams. The bridge consists of 176 stay cables, arranged in two vertical planes. The bridge girder is vertically supported by 4 piers and 2 towers (Pier

1-4 and Tower 1-2), as shown in Fig. 2.1. Along the longitudinal direction, the deck is only fixed at the cross beam of the Tower 2, and is movable at the other supports. Along the transverse direction, the deck is fixed at all six supports.

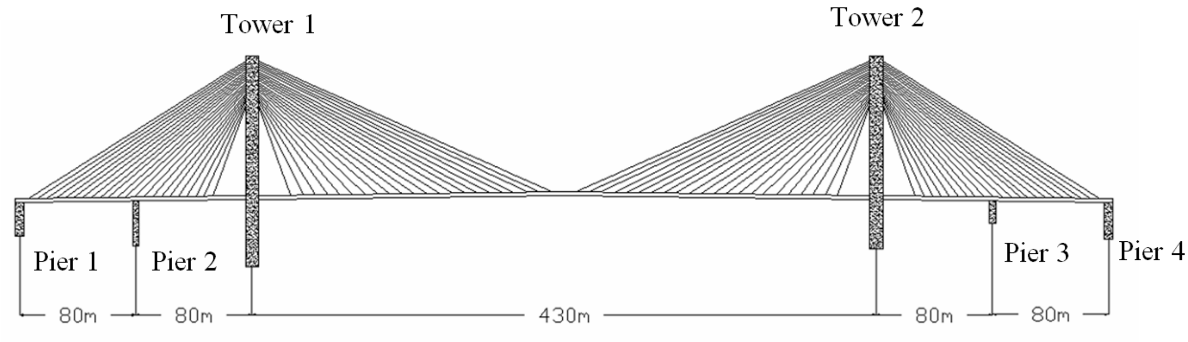


Figure 2.1. Elevation of the prototype cable-stayed bridge

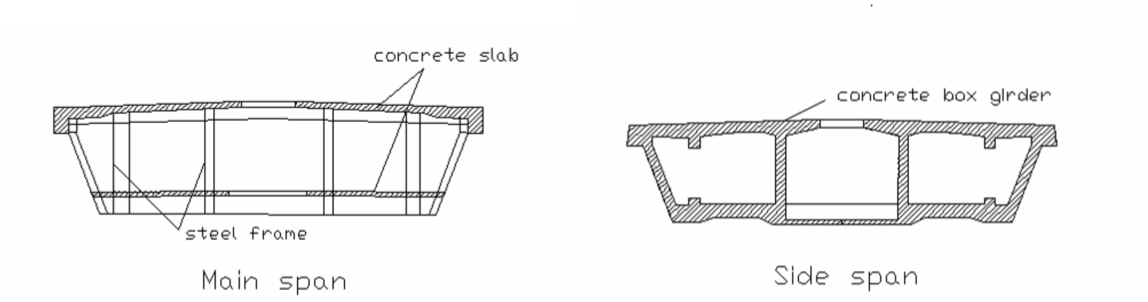


Figure 2.2. Cross section of the bridge girder

2.3. Testing model

In model testing, it is the "similitude requirements" that relates the reduced scale model to the prototype structure. The similitude requirements are based on the theory of modeling, and can be derived from dimensional analysis. The Artificial-Mass-Simulation (AMS) model, which can adequately simulate the dynamic behavior of the prototype, is considered a practical modeling method for shake table testing. Either prototype material or a new material may be used in the AMS model. Additional structurally uncoupled masses (artificial-mass) are attached to the reduced scale model in order to augment the density of the model structure and satisfy the uniform vertical compressive strain. The amount of artificial mass added is set equal to the shortage of "required model weight" to the self-weight of the model. Detailed derivations and descriptions of dimensional analysis, modeling theory as well as AMS model can be found in Harris et al. 1999.

A reduced scale model of the prototype cable-stayed bridge is designed based on the scaling law of AMS model. In order to derive the scale factors for all the design quantities, first of all, two crucial parameters should be determined, i.e., the geometric scale S_L and the scale factor for Young's Modulus S_E. The geometric scale S_L is set to 1:120 in this study, which is determined by the length of the prototype and the dimensions of the multiple shake tables system. Although the prototype tower is made of concrete, acrylic is selected to fabricate the model tower in this study, which results in a scale factor for Young's Modulus S_E of 1:11.182. Not only acrylic can provide a good fabricating performance in machining and bonding, but the selection of acrylic helps to reduce the total weight of the model, which limits the total weight of reduced scale model within the maximum payload capacity of the multiple shake tables testing system.

After these two key parameters are determined, scale factors for all other quantities can be derived accordingly. A summary of scale factors adopted in the proposed testing model can be found in Table 2.2.

Table 2.2. Summary of main scale factors used in the model

Quantity	Unit	Scale factor
Length	m	1:120
Acceleration	m/sec^2	1:1
Time	sec	1:10.954
Frequency	hz	1:0.0913
Modulus	kN/m^2	1:11.182
Strain	N/A	1:1
Model weight	kN	1:161022

Acrylic is selected to fabricate the model tower. Aluminum plate with rectangular cross-section is selected to model the girder with satisfaction of ratio of similitude on vertical and transversal bending stiffness. High-strength stainless steel wire is used for modeling cables and machined iron blocks are attached to the model as artificial mass.

2.4. Instrumentation

An instrumentation scheme including 33 channels of accelerometers, displacement transducers and strain gauges is designed for the shake table testing. Photograph of finished model with instrumentation scheme can be seen in Fig. 2.3.

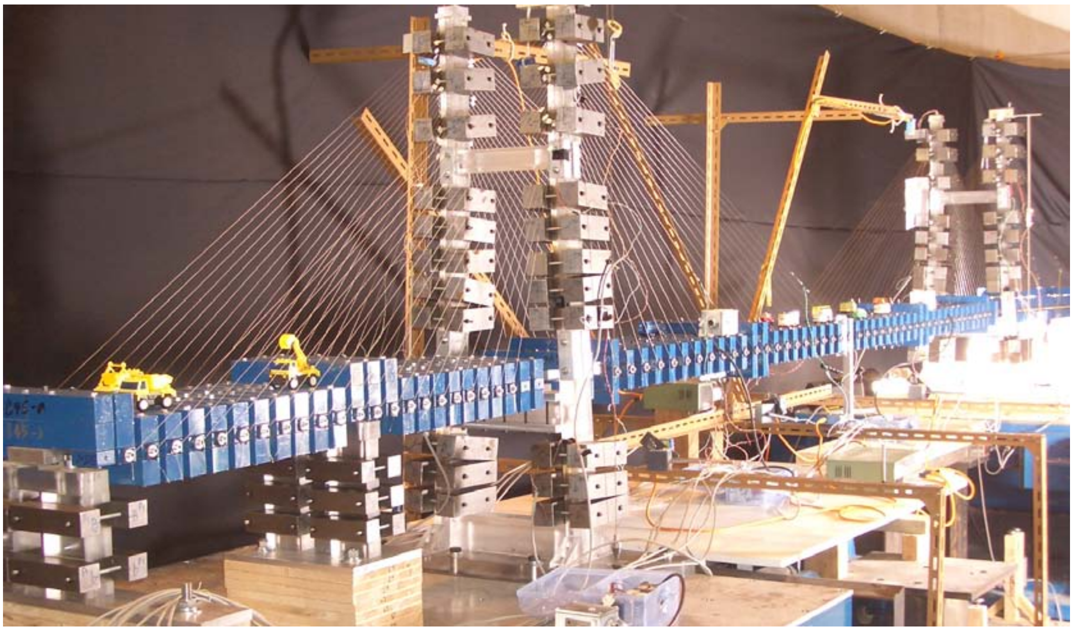


Figure 2.3. Finished model with instrumentation scheme

There are 10 channels of accelerometers installed on the model. Two accelerometers are fixed on the dual shake table in order to measure the actually achieved response of the shake tables. Four accelerometers are used to measure the longitudinal response of the Tower 1 and Tower 2, one at the top of the tower and one at the middle of the tower, respectively. Four accelerometers are fixed on the aluminum girder, three of them are used to measure the vertical accelerations at the 1/4, 1/2 and 3/4 locations of the girder, and one installed at the 1/2 locations of girder for measuring the longitudinal responses.

The displacement transducers adopted in this test include 8 channels. Two displacement transducers are used to measure the actual response of the dual shake table. Two displacement transducers are used for measuring the longitudinal displacements at the tower tops. Three channels measure the vertical response of the aluminum girder at the 1/4, 1/2 and 3/4 locations of the girder, and one channel measures the longitudinal displacement of the aluminum girder at the 1/2 locations.

There are 15 channels of strain gauges are used in this test. Six channels are used for measuring the response of Tower 1 at the top, middle and bottom sections, and 6 channels are measuring Tower 2 correspondingly. Three channels are used for measuring the response of the girder.

3. INPUT GROUND MOTIONS

There are 6 ground acceleration records from the SMART-1 as well as the PEER Strong Motion Database are used in this test. Since the displacement time-histories are required for shake table commanding, the numerical processing scheme suggested by the USGS (United States Geological Survey) is adopted in this study to transform the collected acceleration records to the displacement records. The acceleration time-histories and the corresponding displacement time-histories of all the inputs in this study are shown in Fig. 3.1-3.6.

SMART-1 (Strong Motion Array in Taiwan, phase I) is a dense digital array of strong-motion seismographs, which was built up by the Institute of Earth Sciences (Taiwan) and the University of California at Berkeley, in 1980. The array consists of 41 stations in total, and 60 earthquakes were observed and recorded during its operation period (1980-1991). Four records generated from 2 different events are used in this study, named as Wave No.1-4 in Fig. 3.1-3.4.

PEER Strong Motion Database, supported by the PEER (Pacific Earthquake Engineering Research Center, UC Berkeley, CA), collects the earthquake records from different parts of the world. Two records from the PEER Strong Motion Database are used in this study, named as Wave No.5-6 in Fig. 3.5-3.6.

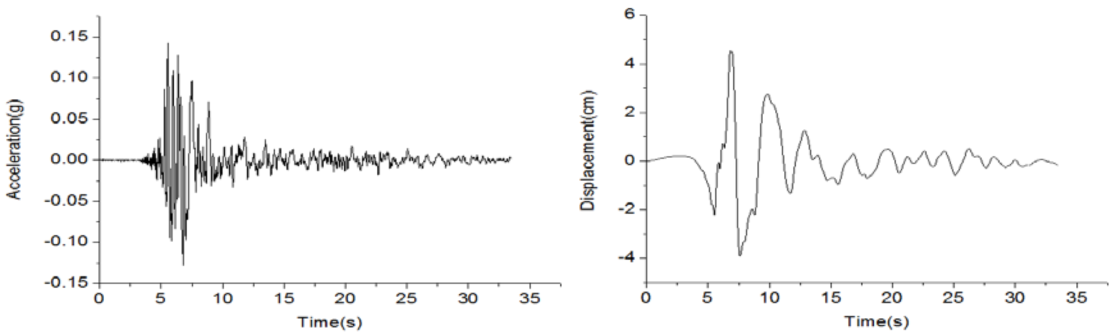


Figure 3.1. Acceleration and displacement time-history of Wave No.1

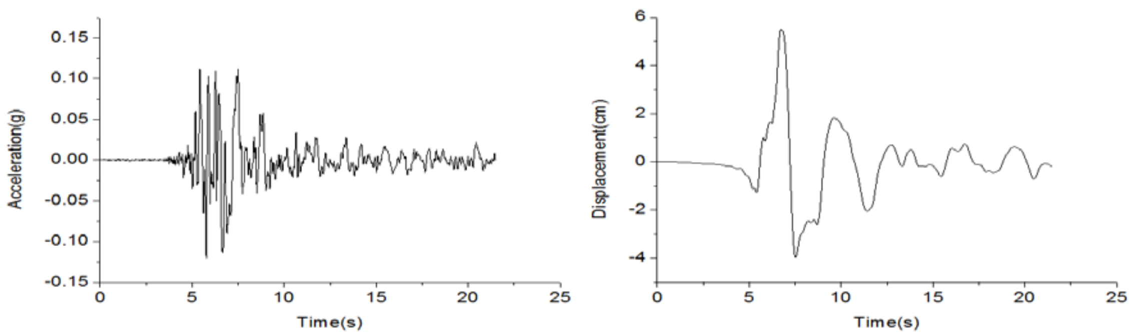


Figure 3.2. Acceleration and displacement time-history of Wave No.2

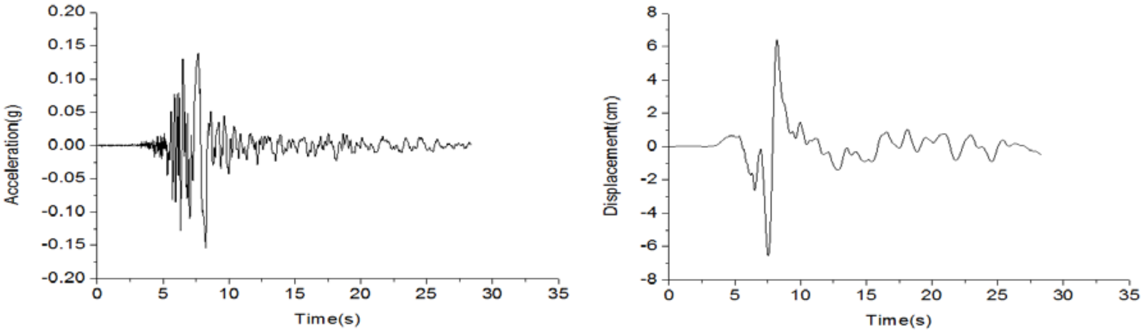


Figure 3.3. Acceleration and displacement time-history of Wave No.3

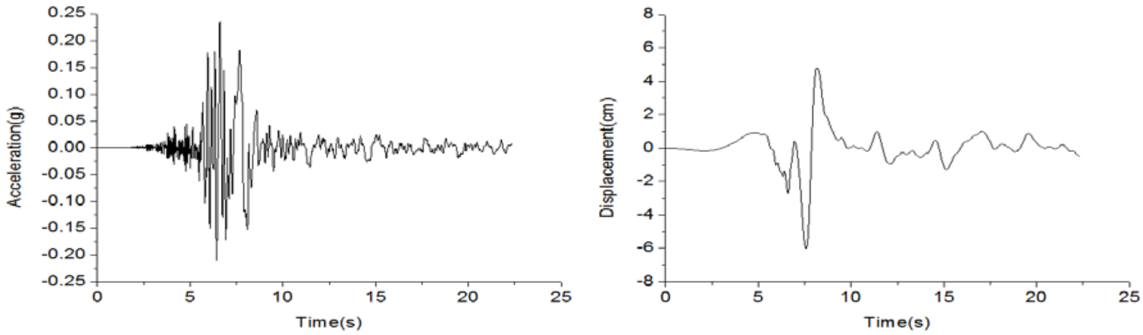


Figure 3.4. Acceleration and displacement time-history of Wave No.4

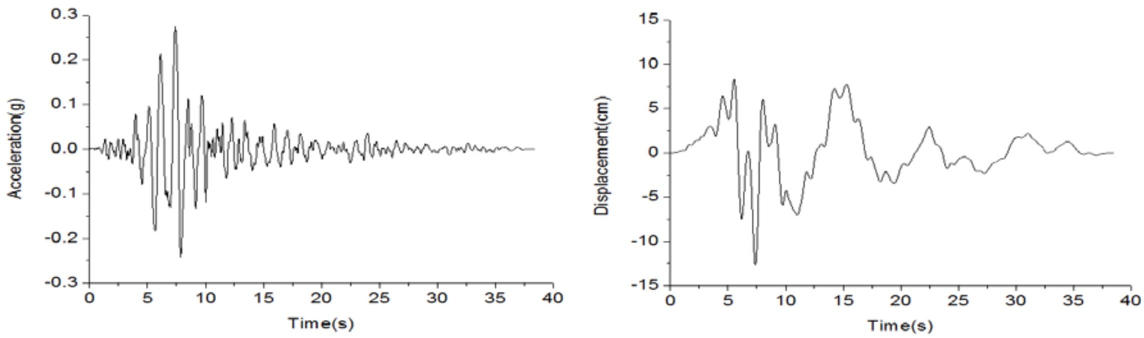


Figure 3.5. Acceleration and displacement time-history of Wave No.5

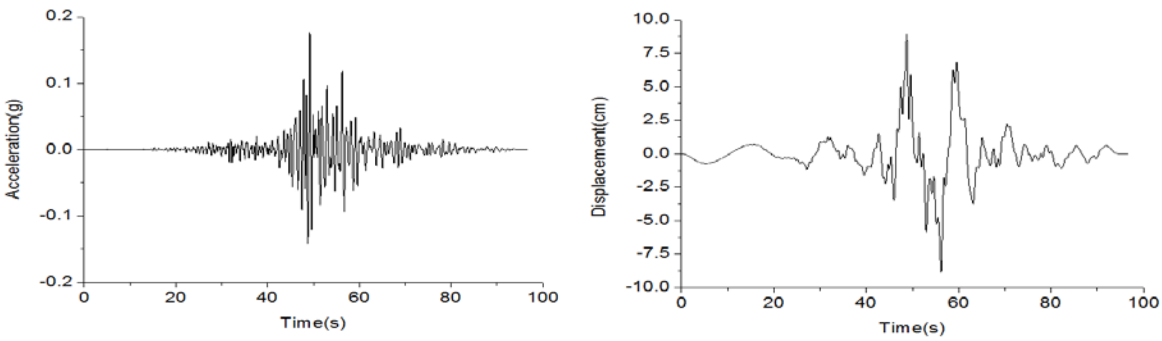


Figure 3.6. Acceleration and displacement time-history of Wave No.6

4. TESTING RESULTS

4.1. White noise input (modal test)

By inputting white noise excitation with a constant acceleration of 0.1g, the modal test is carried out before the earthquake ground motion excitation tests. A finite element model of the prototype bridge is developed in SAP2000. The modal test result is compared with the result from the FEM analysis for evaluating the design of the reduced scale model.

From the spectral response of the signals recorded by the strain gauge near the bottom of Tower 2, the frequencies of the first three longitudinal vibration modes of the reduced scale model can be easily identified, and are 4.4 Hz, 7.5 Hz and 10 Hz. Since the scale factor for the frequency is 0.0913 (see Table 2.2), the natural frequencies of the corresponding prototype bridge can be calculated accordingly, namely 0.40 Hz, 0.68 Hz and 0.91 Hz. Compared with the results from the finite element analysis, which are 0.41 Hz, 0.60 Hz and 0.94 Hz, the reduced scale model represents the dynamic nature of the prototype quite well.

4.2. Earthquake record input

The wave propagation effect is studied by changing the wave passage velocity, including five cases: 400 m/s, 600 m/s, 1000 m/s, 2000 m/s and infinite (uniform excitation). The distance between the two main towers (430 m) is used to calculate the difference of the arrival time for the two tables. Only the longitudinal input is considered in this study. Due to space limitation, typical results of earthquake record input considering the effect of wave propagation are listed as follows.

4.2.1. Longitudinal acceleration at tower tops

Typical results of peak longitudinal acceleration recorded at the tops of Tower 1 and Tower 2 are shown in Fig. 4.1.

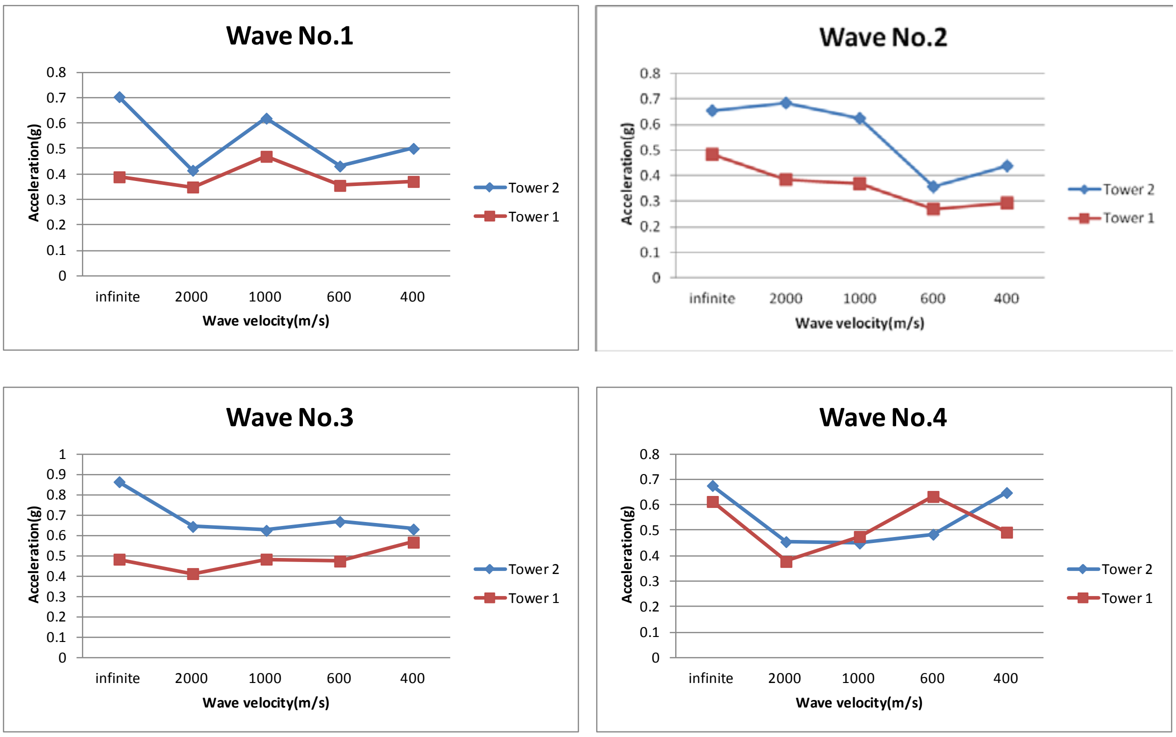


Figure 4.1. Peak longitudinal acceleration at tower tops

From Fig.4.1, one finds that wave propagation effect strongly influences the dynamic response of the cable-stayed bridge model. Take the results of identical input (wave velocity: infinite) as benchmark, a maximum variation of +5% to -40% can be observed. The above results imply that, except for several cases, in general the wave propagation effect has a beneficial influence on the structure, which reduces the longitudinal vibration of the tower, especially for the fixed-connection tower (Tower 2 in this bridge).

4.2.2. Strain along the Tower 2

Typical results of peak strain along the Tower 2 are shown in Fig. 4.2.

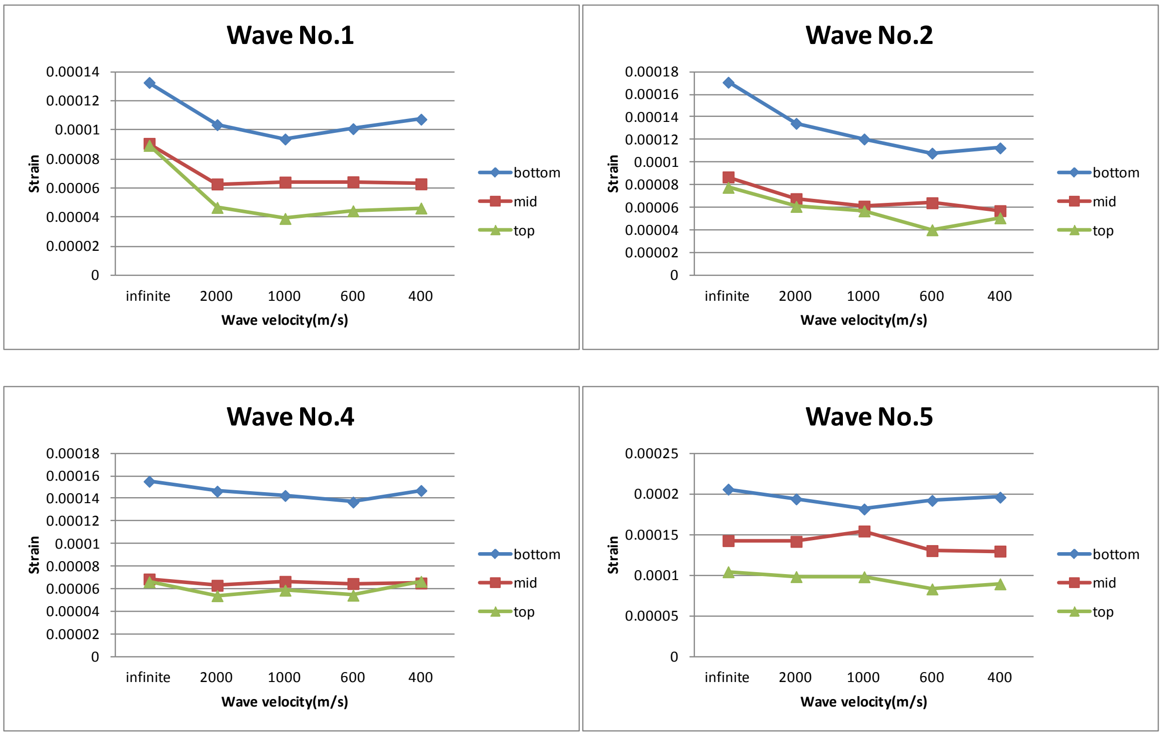


Figure 4.2. Peak strain along the Tower 2

From Fig.4.2, still taking the results of identical input (wave velocity: infinite) as benchmark, one finds when considering the wave propagation effect, a maximum variation of +5% to -25% can be observed. The results of strain along Tower 1 also have similar findings (results of Tower 1 haven't been included in this paper due to space limitation). The above results imply that, except for several cases, in general the wave propagation effect has a beneficial influence on the structure, which reduces the longitudinal response of the tower, especially at the most critical section (bottom section). This finding agrees with the previous one in 4.2.1.

4.2.3. Vertical acceleration along the girder

Typical results of peak vertical acceleration along the girder (recorded as 1/4, 1/2 and 3/4 locations) are shown in Fig. 4.3.

From Fig.4.3, still taking the results of identical input (wave velocity: infinite) as benchmark, one finds when considering the wave propagation effect, a maximum variation of +50% to -25% can be observed. The findings from Fig.4.3 are different from Fig.4.1 and Fig.4.2. The above results imply that, the wave propagation effect may have a beneficial or adverse on the structure. In some cases, the wave propagation effect may largely increase the vertical response of the girder, which should be noticed during the design.

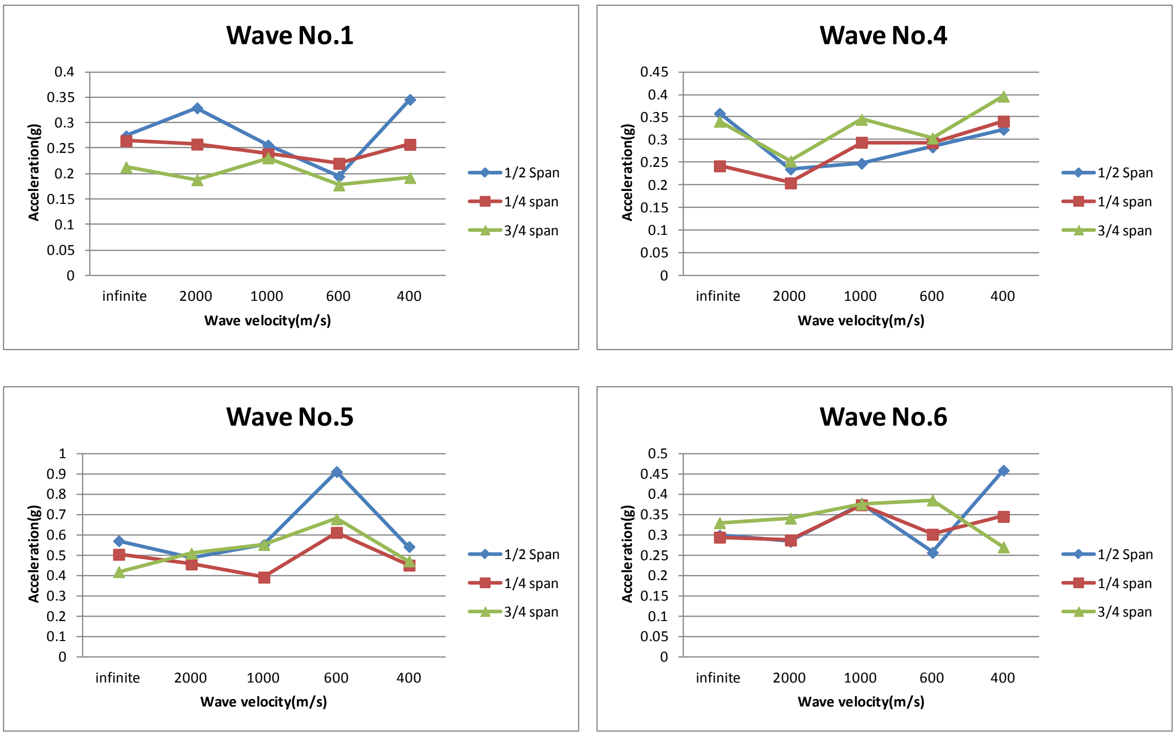


Figure 4.3. Peak vertical acceleration along the girder

5. CONCLUDING REMARKS

The effect of wave propagation on seismic response of cable-stayed bridge is studied in this paper by applying a multiple shake tables test. The following concluding remarks can be drawn:

1) A dual shake table testing system and a 1:120 scaled cable-stayed bridge model is designed and constructed for this study. The favorable match of the modal test results with the numerical analysis results in terms of dynamic characteristics of the prototype implies that the AMS (Artificial Mass Simulation) model, which can adequately simulate the dynamic behavior of the prototype, provides a practical modeling method for shake table testing.
2) The results of multiple shake tables testing show that the wave propagation effect strongly influences the dynamic response of the cable-stayed bridge model. Take the results of identical input (wave velocity: infinite) as benchmark, an overall variation of +50% to -40% can be observed.
3) Based on this preliminary study, the conducted test provides some credible results, which help to improve the understanding of dynamic response of long span bridges subjected to spatially varying earthquake ground motion. To further study the topic, more test data should be analyzed and numerical simulation for comparison should be included.

ACKNOWLEDGEMENT
This research is supported by the National Natural Science Foundation of China (Grant No. 51108339) and Kwang-Hua Fund for College of Civil Engineering, Tongji University.
The authors are also grateful to the Institute of Earth Sciences (Taiwan) for providing the seismic records of SMART-1 and the Pacific Earthquake Engineering Research Center for providing the seismic records from PEER Strong Motion Database.

REFERENCES

Mylonakis, G., Papastamatiou, D., Psycharis, J. and Mahmoud, K. (2001). Simplified modeling of bridge response on soft soil to nonuniform seismic excitation. *ASCE Journal of Bridge Engineering* **6:6**,587-597.

Kiureghian, A.D. and Neuenhofer, A. (1992). Response spectrum method for multi-support seismic excitations. *Earthquake Engineering and Structural Dynamics*, **21:8**,713-740.

Godden, W.G. and Aslam, M. (1978). Dynamic model studies of Ruck-A-Chucky Bridge. *Journal of the Structural Division, ASCE,* **104:ST12**, 1827-1844.

Garevski M.A., Brownjohn J.M.W., Blackborough A. and Severn R.T. (1991). Resonance-search tests on a small-scale model of a cable-stayed bridge. *Engineering Structures*, **13:1**,59-66.

Wang J.J., Zhang X.T., Fan L.C., Wang Z.Q., Chen H., Zhou M., Li S.Y., Mo H.L. and Ni Z.J. (2006). A brief introduction to the shaking-table test of Liede Bridge. *4th PRC-US Workshop on Seismic Analysis and Design of Special Bridges: Advancing Bridge Technologies in Research, Design, Construction and Preservation,***Vol I**.

Carden L.P., Itani A.M. and Buckle I.G. (2006). Seismic performance of steel girder bridges with ductile cross frames using single angle X braces. *ASCE Journal of Structural Engineering*, **132:3**,329-337.

Saiidi M.S., Nelson R., Sadrossadat-Zadeh M. and Buckle, I.G. (2007). Shake table studies of a 4-span reinforced concrete bridge model. *2007 ANCER Meeting, Earthquake Engineering Research: From Strong Seismic Regions to Regions of Moderate Seismicity,* **Vol I.**

Harris H.G. and Sabnis G.M. (1999). Structural Modeling and Experimental Techniques, 2nd edition, CRC Press.