13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1206

HYBRID VIBRATION EXPERIMENT ON INTERACTIVE RESPONSE OF SUPERSTRUCTURE AND FOUNDATION OF HIGHWAY BRIDGE

Keiichi TAMURA[1], Hiroshi KOBAYASHI[2], Shunsuke TANIMOTO[3] and Mitsu OKAMURA[4]

SUMMARY

In order to improve seismic design technology of highway bridges, it is most essential to investigate seismic behavior of a whole bridge system. For this purpose, we have developed a hybrid experiment technique, which integrates numerical response analysis with vibration experiment, and applied it for studying seismic behavior of highway bridge system including surrounding soils. In our hybrid vibration experiment, we made a pile foundation and surrounding soils as the actual model, which were constructed in a laminar box placed on a shake table, and we made a footing, pier and girder as the numerical model. We assumed in the present study two kinds of highway bridges that have different horizontal capacities of pier, conducted hybrid vibration experiments with those models, and systematically examined the interactive seismic response of bridge pier and pile foundation.

INTRODUCTION

In the seismic design of highway bridges, we generally divide a bridge into two parts, i.e., superstructure-pier and foundation. This is mostly for simplicity, however, there exists interaction between them, and studying this interaction is most essential to solve the seismic behavior of whole bridge system, which would contribute to the further development of seismic design technology. Vigorous efforts have been devoted to study this interaction analytically. On the other hand, experimental studies have been rather limited, because they generally require large-scale experiments.

We examined in this study the seismic behavior of highway bridge system that consists of superstructure, pier, foundation and surrounding soils by using hybrid vibration experiment technique, which integrates numerical response analysis with vibration experiment. Based on the experimental results, we investigated the interaction between seismic response of bridge pier and foundation.

[1] Team Leader, Ground Vibration Research Team, Public Works Research Institute, Japan
E-mail: tamura@pwri.go.jp
[2] Senior Research Engineer, Intelligent Transport Systems Division, National Institute for Land and Infrastructure Management, Japan
[3] Ground Vibration Research Team, Public Works Research Institute, Japan
[4] Senior Research Engineer, Ground Vibration Research Team, Public Works Research Institute, Japan

OVERVIEW OF HYBRID VIBRATION EXPERIMENT

As illustrated in Figure 1, an original structure is divided into two parts in the hybrid vibration experiment. One is an actual model specimen of original structure. This specimen is usually taken as a part of structure whose seismic behavior is unknown or complicated. The other is a numerical model for vibration response analysis. This model represents a part of structure whose seismic behavior can be evaluated by numerical analysis.

In our hybrid vibration experiment [1], we made a pile foundation and surrounding soils as the actual model, and footing, pier and girder as the numerical model. An outline of experimental process is as follows:

(1) Place a spacer and balance weight on the pile foundation model, and connect an actuator with the balance weight. For the vertical direction, adjust the weight of balance weight so that the total weight of spacer and balance weight corresponds to the dead weight of superstructure, pier and footing that acts on the pile foundation.
(2) Shake the table horizontally with an input motion, and measure the reaction force of model specimen at the boundary of specimen and numerical model. Compute response displacement of numerical model to this reaction force and external force such as inertia force.
(3) Apply the calculated displacement of numerical model to the specimen by the actuator and thus reproduce seismic response of highway bridge system. Note that we ignore the rotational motion in this experiment.

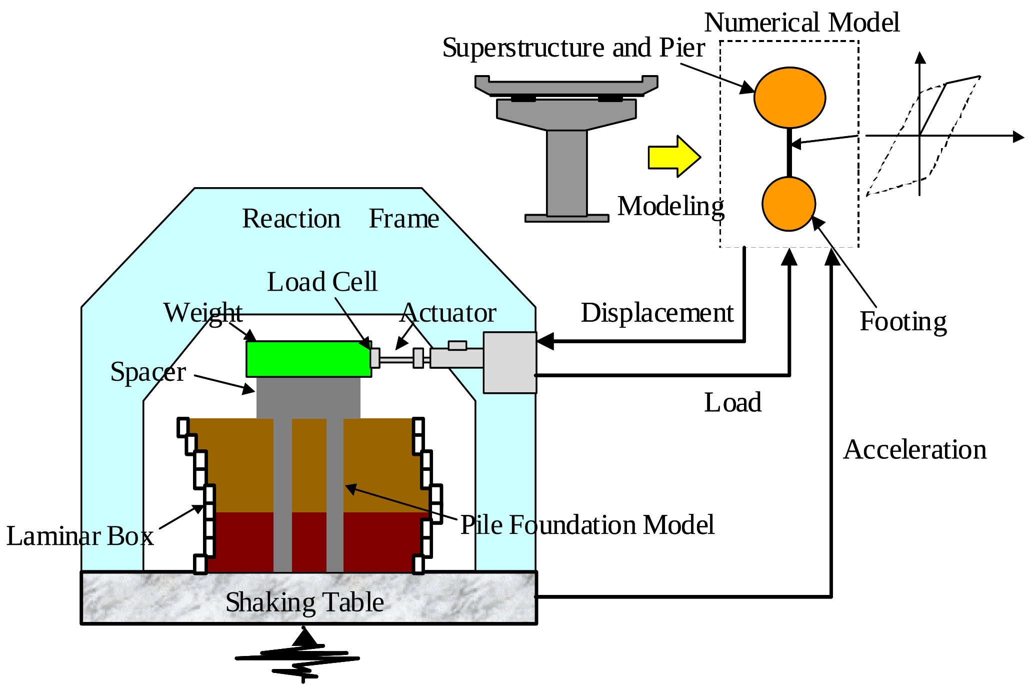


Figure 1 Conceptual view of hybrid vibration experiment

PROTOTYPE AND EXPERIMENTAL MODEL

We assumed two kinds of bridge models in this study; Model-1 was designed after the 1971 Seismic Design Guidelines for Highway Bridges in Japan [2] (hereinafter mentioned as "1971 Guidelines"), and Model-2 was designed after the 1996 Design Specifications for Highway Bridges [3] ("1996 Specifications"). The prototype of experimental models is a 30m-span simple girder bridge on the medium soil ground, which is schematically illustrated in Figure 2. The difference between those two experimental models is the horizontal capacity of bridge pier. To realize this, we changed the number and diameter of reinforcing bars of pier between the two models, and the rests were set as the same.

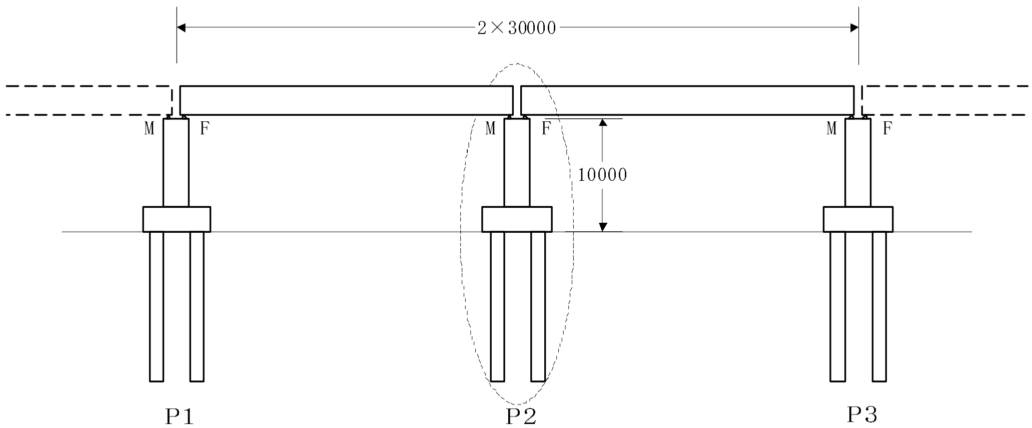


Figure 2 Schematic view of prototype bridge

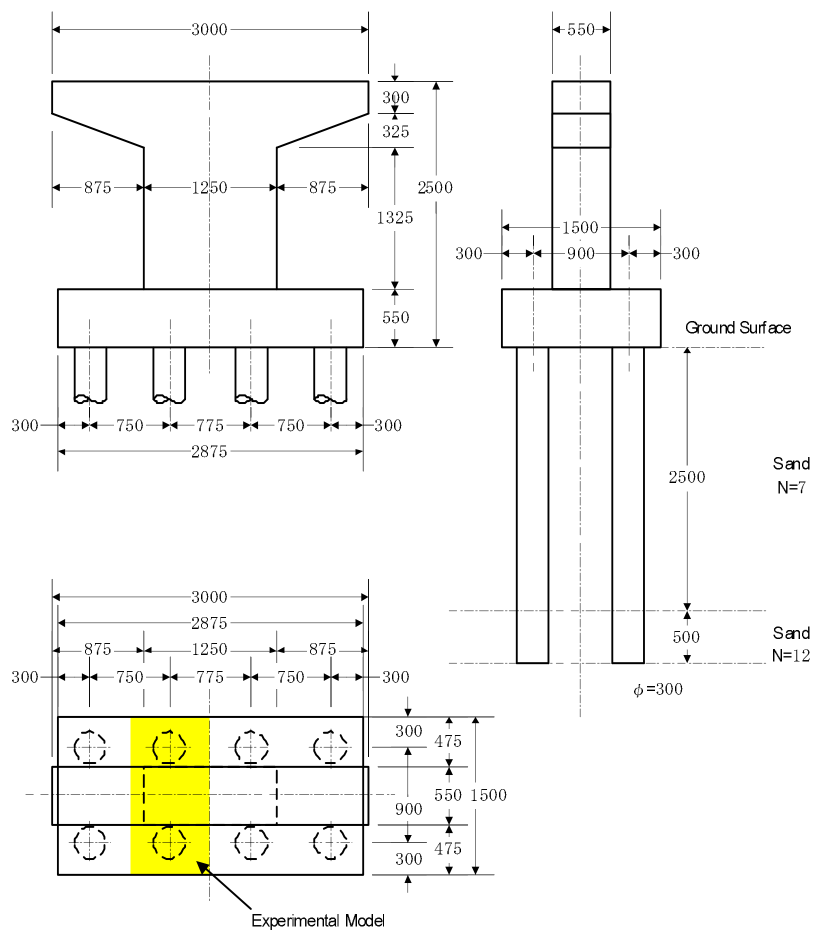


Figure 3 Overview of experimental model

The prototype bridge was reduced to 25% in size to produce an experimental model. Two piles in the longitudinal direction were extracted for the test specimen as shown in Figure 3. According to the number of piles of experimental model, we reduced the external force generated at the boundary of real specimen and numerical model to 25% of the prototype. Since the preliminary objective of this study is to examine nonlinear seismic response of both bridge pier and foundation, we used RC piles for experiments.

The number and diameter of reinforcing bars of a model pile were determined to be consistent with the reinforcement ratio of the prototype pile. The diameter and length of model pile are 300mm and 3.0m, respectively. The pile heads were rigidly connected to the footing, while their tips were connected to the bottom of laminar shear box by hinges to allow rotation.

We made model ground in a laminar shear box, which was mounted on the shake table. The inner size of laminar box is 3.5m high, 4m wide and 4m long. The ground model used consists of two layers, i.e., 2.5m-thick surface layer and 0.5m-thick lower layer. Both layers were of dry silica sand, and the major physical properties of the sand are as follows: maximum void ratio e_{max}=1.044, minimum void ratio e_{min}=0.616, mean grain size D_{50}=0.172mm and fines content FC=2%. The target N-values, i.e., blow count per foot by standard penetration test, were 7 and 12 for the surface and lower layers, respectively. We adopted compaction control by density when we constructed the ground model. N-value and shear-wave velocity were measured at each stage of experiments by Swedish-sounding test and bender element test, respectively, and the test results are plotted in Figure 4. Although N-value has changed before and after a series of experiments, change of shear-wave velocity is insignificant.

In order to examine the vibration characteristics of experimental model, eigenvalue analysis was carried out, in which the ground and pile foundation were modeled by plane elements, and the footing and pier were modeled by beam elements. Figure 5 shows the first and second natural vibration modes, and the first and second natural frequencies were computed as 8.02Hz and 27.82Hz, respectively. We see from this figure that the footing and superstructure vibrate in phase for the first mode and they vibrate out of phase for the second mode.

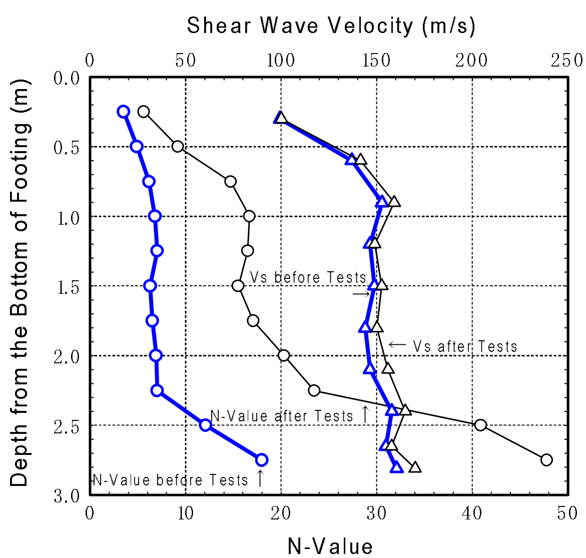
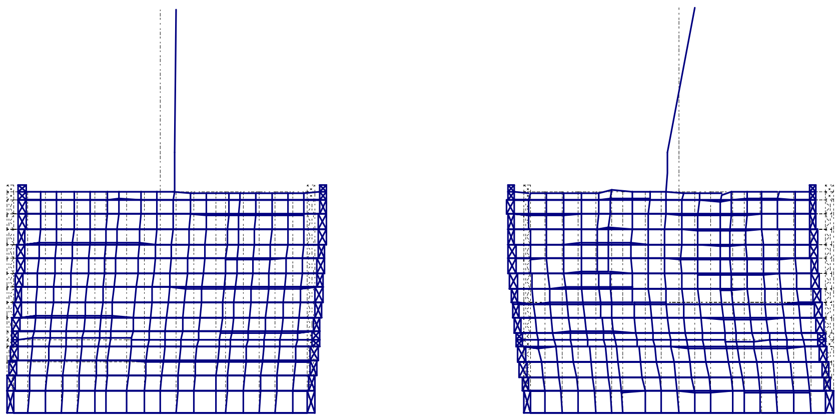


Figure 4 N-value and shear-wave velocity of ground model



(a) First vibration mode (b) Second vibration mode

Figure 5 Natural vibration mode

VIBRATION RESPONSE ANALYSIS

The numerical model consists of structural elements (mass, damping and stiffness matrices), external force that is calculated from the acceleration of shake table, and reaction force generated at the boundary of the actual and numerical models. In the numerical analysis, the external and reaction forces are inputted, and the displacement of actual model for the next time step is calculated. This displacement is realized by an actuator. Then, the external and reaction forces are measured and taken into numerical analysis. Iterating these procedures, the seismic behavior of original structure can be accurately simulated. The equation of motion for numerical analysis may be described as

$$M\ddot{x} + C\dot{x} + Kx = p + q \tag{1}$$

where

- M: Mass matrix
- C: Damping matrix
- K: Stiffness matrix
- x: Relative displacement vector
- p: External force (seismic response) vector
- q: Reaction force vector.

Using Eq. (1), the vibration response (displacement vector x) after a short interval Δt can be calculated from the measured reaction force vector q and the external force vector p. The central difference method is employed in vibration response analysis, because it requires short time to generate actuator signal for the next time step after measuring reaction force. The equation of motion can be rewritten as Eq. (2) at time t_i, where a subscript i represents the i-th time step.

$$M\ddot{x}_i + C\dot{x}_i + Kx_i = p_i + q_i \tag{2}$$

Since the change of motion during calculation time interval Δt is small, we assume constant acceleration over the period between $t_{i-1}=t_i-\Delta t$ and $t_{i+1}=t_i+\Delta t$, as shown in Figure 6. Displacement at t_{i+1} can be obtained from the known data at t_i, using Eq. (3). Time required for one cycle process is 2.08ms [4].

$$x_{i+1} = \left(M + \frac{\Delta t}{2} C \right)^{-1} \left\{ M(2x_i - x_{i-1}) + \frac{\Delta t}{2} C x_{i-1} + \Delta t^2 (p_i + q_i - K x_i \right\} \tag{3}$$

As the numerical model, we assume a 2-degree-of-freedom system consisting of mass of footing, and that of pier and girder. Table 1 gives the parameters of numerical model. Figure 7 shows the force and displacement relationship of pier, which is idealized as a bi-linear system.

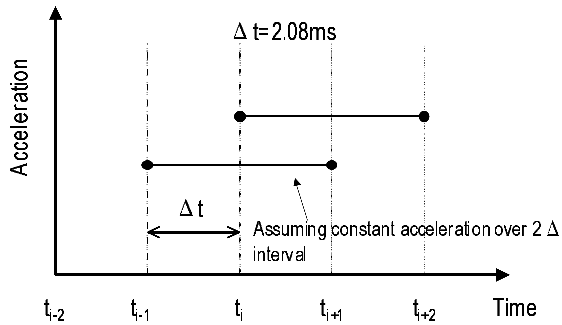


Figure 6 Concept of central difference method

Table1 Parameters of vibration response analysis

Mass	Footing	1482 kg
	Pier and superstructure	2225 kg
Stiffness of pier	–	4.1195×10^7 N/m

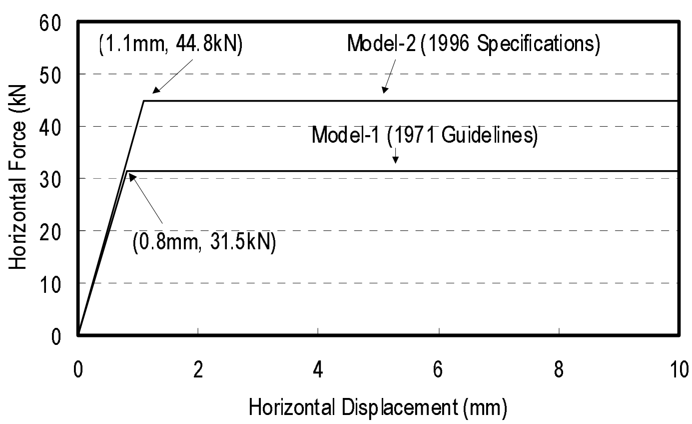


Figure 7 Horizontal force-displacement relationship of pier

EXPERIMENTAL METHOD

Although actuator response delay has unfavorable influence on the hybrid vibration experiment, it is inevitable with a hydraulic actuator. Consequently, a compensation technique is adopted. This technique predicts the displacement of an actuator at the time after actuator delay time [5].

In our previous study [6], we directly inputted the measured acceleration of the shake table to the vibration response analysis of hybrid experiment for interlocking numerical calculation and shake table test. This caused divergent phenomenon in some cases, because vibration of the hybrid experiment apparatus interfered with the control of shake table. In the present study, we used the control signal of shake table for numerical analysis instead of the measured acceleration of shake table.

To connect a specimen with the hybrid vibration experiment apparatus, we placed the spacer between the specimen and the load cell, resulting in a fact that the inertia force due to weight of spacer is included in the measured reaction force. To remove this inertia force, we introduced the following equation:

$$q = q' - M \cdot A_x \tag{4}$$

where, q is modified load, q' is load measured by the load cell, A_x is the acceleration measured by the accelerometer on spacer, and M is the weight of spacer and balance weight shown in Figure 1.

As the input motions for experiments, we used sinusoidal waves with frequencies corresponding to the first natural frequency of experimental model and the mean of first and second natural frequencies. Also employed was the strong motion record obtained at the Kobe Maritime Observatory, Japan Meteorological Agency during the 1995 Hyogo-ken Nanbu (Kobe) earthquake. This record was converted to the surface of base layer of the site, which will be referred as "JMA record" in this paper. The time axis of JMA record was compressed to 23.5% of the original record based on the ratio of first natural frequencies of prototype bridge (1.89Hz) and experimental model (8.02Hz), and the peak accelerations were adjusted to 0.49G and 0.07G, which correspond to 70% and 10% of the peak accelerations on the surface of base layer. To secure stability of the hybrid vibration experiment, we expanded the time axis of input motions three times as long as the original time axis. Table 2 summarizes the experimental cases.

Table 2 Experimental cases

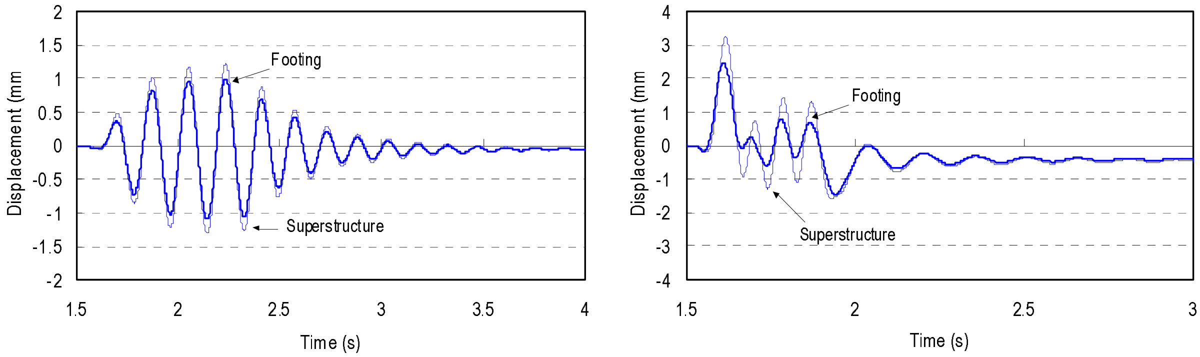
Input motion	Frequency	Bridge model*	Peak acceleration	Case No.
Sinusoidal wave	8.1 Hz	Model 1	0.05G	1
	18 Hz	Model 1	0.4G	2-1
		Model 2	0.4G	2-2
Seismic wave	JMA record	Model 1	0.07G	3-1
			0.49G	3-2

*Model 1 and Model 2 were designed after 1971 Guidelines and 1995 Specifications, respectively.

EXPERIMENTAL RESULTS

Figure 8 shows displacement time histories of footing and superstructure for experimental Cases 1 and 2-1. The footing and superstructure vibrate in phase in Case 1. In Case 2-1, there exists phase difference between footing and superstructure for the early stage of excitation, however, they gradually vibrate in phase, which suggests that the first natural vibration mode is predominant. These facts imply that the experiment results are consistent with numerical analysis.

Relationships between horizontal force and displacement of pier are plotted in Figure 9 for Cases 2-1 and 2-2. As seen from this figure, the pier of Model-1, which was designed after the 1971 Guidelines, shows plastic behavior, while the pier of Model-2, which was designed after the 1996 Specifications, remains elastic. Figures 10 and 11 compare the maximum acceleration and pile curvature for Cases 2-1 and 2-2, respectively. Acceleration response of Model-1 is a little smaller than that of Model-2, whereas the distributions of pile curvature are almost similar between these two models except the intermediate part of pile. It seems within the scope of present study that the acceleration response is affected by the horizontal capacity of pier, while bending moment is rather insensitive to it.



(a) Case 1 (f=8.1Hz)   (b) Case 2-1 (f=18Hz)

Figure 8 Response displacement of numerical model

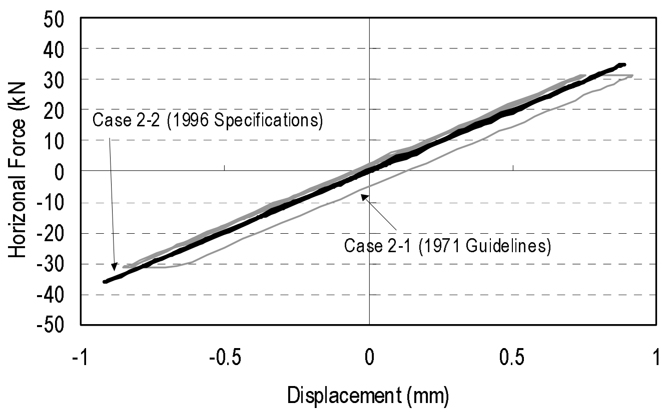


Figure 9 Horizontal force-displacement relationship of pier (Cases 2-1 and 2-2)

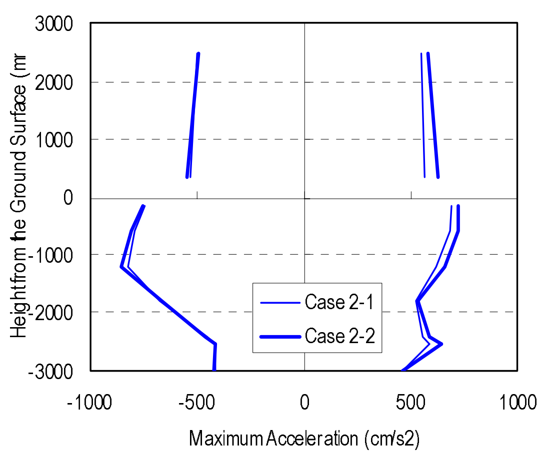


Figure 10 Maximum acceleration distribution (Cases 2-1 and 2-2)

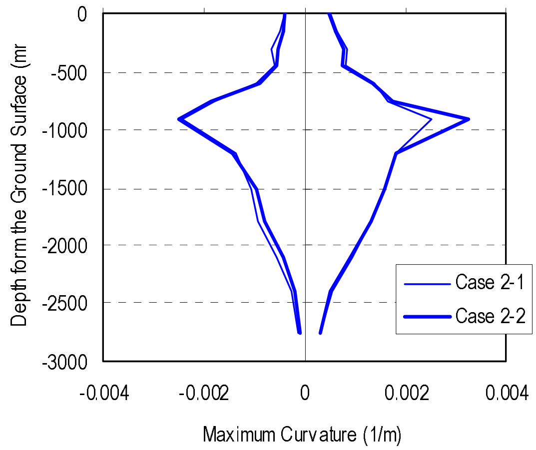


Figure 11 Maximum curvature distribution (Cases 2-1 and 2-2)

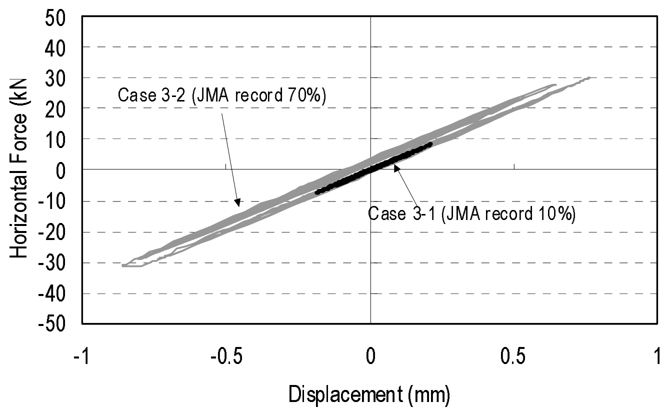


Figure 12 Horizontal force-displacement relationship of pier (Cases 3-1 and 3-2)

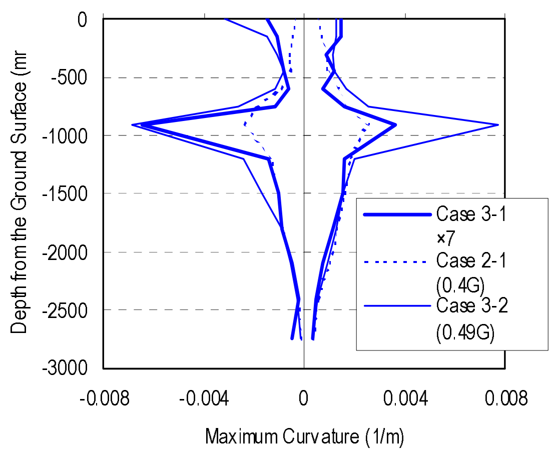


Figure 13 Maximum curvature distribution (Cases 3-1, 2-1 and 3-2)

Relationships between horizontal force and displacement of pier are shown in Figure 12 for Cases 3-1 and 3-2. The bridge pier behaviors plastically in Case 3-2, where 70 % amplitude of JMA record was inputted.

Figure 13 compares the distributions of pile curvature. Also plotted is the seven times of the curvature obtained in Case 3-1. The maximum curvature for Case 3-2 at the intermediate part of pile is larger than the seven times of Case 3-1, which suggests that the pile plasticizes around this depth. Figure 14 presents the distributions of maximum acceleration for Cases 3-1, 2-1 and 3-2. These three cases correspond to the followings; both pier and pile remain elastic (Case 3-1), pier becomes plastic, while pile remains elastic (Case 2-1), and both pier and pile become plastic (Case 3-2). Regarding pile response, Case 2-1 in which the pier has become plastic yields the largest value. Case 3-2, in which the pile behaviors plastically, develops small pile response. As for pier response, Case 3-1 produces the largest, and Case 2-1 yields the smallest acceleration. Note that Case 2-1 yields the largest pile acceleration. Case 3-2 locates somewhere between Cases 2-1 and 3-1. Comparison of Cases 2-1 and 3-2 indicates that nonlinearity of pile may affect the seismic response of pier.

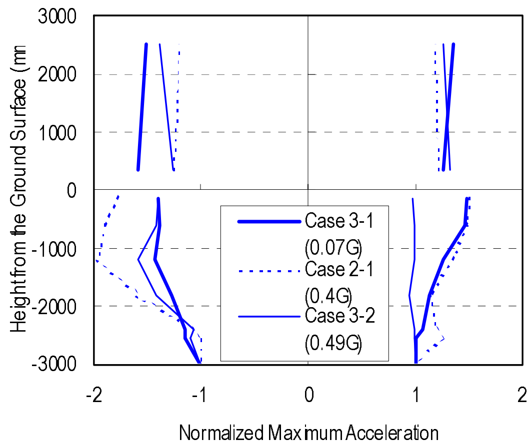


Figure 14 Maximum acceleration distribution (Cases 3-1, 2-1 and 3-2)

CONCLUSIONS

We have developed a hybrid vibration experiment technique, and applied it for studying seismic behavior of highway bridge system. We assumed two kinds of highway bridges in this experiment; one was design after the 1971 Design Guidelines and the other was design after the 1996 Design Specifications. Main conclusions of the present study may be summarized as follows:

(1) Seismic response of the bridge by hybrid vibration experiment technique to the moderate input motions is consistent with the result of eigenvalue analysis, which supports the validity of the hybrid experiment technique.
(2) According to the experimental results with two different highway bridge models, it seems that the acceleration response is affected by the horizontal capacity of pier, while bending moment of pile is rather insensitive to it.
(3) The generation of plasticity in bridge pier or pile foundation may affect the mutual seismic response. For example, large pile acceleration was observed when the pier had become plastic. Pier acceleration decreases when the pier plasticizes, in which the decrease rate is small when the pile also becomes plastic.

REFERENCES

1. Kobayashi, H., Tamura, K. and Tanimoto, S.: Hybrid Vibration Experiments with a Bridge Foundation System Model, *Soil Dynamics and Earthquake Engineering*, Vol.22, No.9-12, 2002.
2. Japan Road Association: *Seismic Design Guidelines for Highway Bridges*, 1971 (in Japanese).
3. Japan Road Association: *Specifications for Highway Bridges*, *Part V*, *Seismic Design*, 1996 (in Japanese).
4. Umekita, K. *et al*.: Development of C Language Library for Super Real-Time Controller (SRC) for Real-Time Hybrid Seismic Testing System with Three-dimensional-in-plane Excitation, *Proc. 40th Japan Joint Automatic Control Conference*, 1997 (in Japanese).
5. Horiuchi, T., Nakagawa, M., Sugano, M. and Konno, T.: Development of a Real-Time Hybrid Experimental System with Actuator Delay Compensation, *Proc. 11th World Conference on Earthquake Engineering*, 1996.
6. Tamura, K. and Kobayashi, H.: Real-time Hybrid Vibration Experiment with a 2-Degrees-of-Freedom Model, *Proc. 30th Joint Meeting*, Panel on Wind and Seismic Effects, UJNR, 1998.