Vertical component of earthquake motion and inelastic response of RC piers

Vertical Component of Earthquake Motion and Inelastic Response of RC Piers

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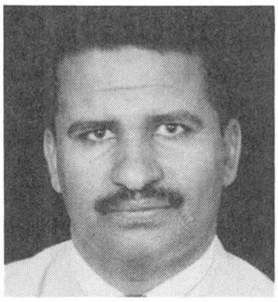

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Summary

In this study, inelastic response analysis was carried out to analyze the effect of vertical component of motion on inelastic response of RC bridge piers. RC piers with different properties and dimensions were studied under two cases of earthquake waves. In the first case, piers were subject to horizontal motion only whereas in the second case piers were subject to horizontal and vertical components. Comparing the results of the two cases indicated that effect of vertical component should be included in the analysis and design of piers to resist strong motions such as the Great Hanshin earthquake. Vertical component had influence on both of axial and lateral load capacities and caused change of failure mode of many cases. In general, vertical motion increases the level of damage, generates fluctuating axial forces and leads to non-ductile behavior of piers consequently bigger quantity of shear reinforcement is needed to maintain ductility level.

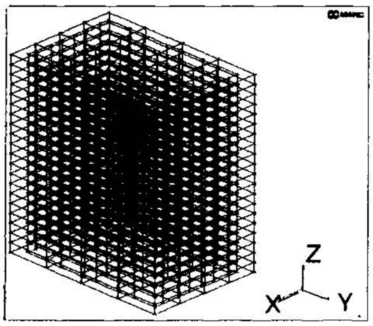
1. Introduction

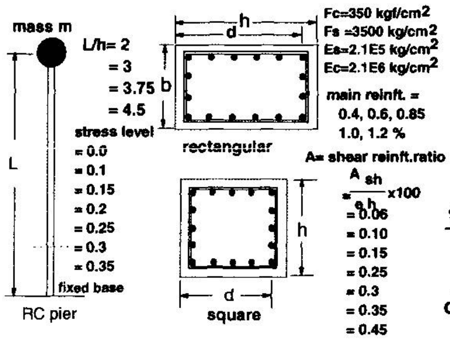
In seismic design of RC structures, designers usually do not consider that the effect of vertical motion is important because horizontal motion usually has the most significant role on the behavior of bridge piers. However, in many earthquakes of the last twenty years, the vertical component was high relative to the horizontal one. The Great Hanshin earthquake on January 17, 1995, was characterized by its high horizontal peak acceleration (**0.8 g** in some sites) and its high vertical or up-down motion which reached about **0.6 g** in some sites. More details about Hanshin Earthquake were given in reference (1). The question is: what is the influence of the vertical component on the severe collapse of RC bridge piers that occurred during such earthquake? To answer this question, we utilized nonlinear 3D FEM to carry out inelastic response for RC piers under two cases of loading; in the first case- denoted by **HZ** motion only- the piers were subject to horizontal wave of **0.8g** peak acceleration which was recorded at Nishinomya City during the Great Hanshin earthquake whereas in the second case- denoted by **HZ & VL** motion- piers were subject to horizontal motion of case 1 in addition to vertical motion of **0.6g** peak acceleration. For each studied case, the pier was subject to constant compressive stress during the motion.

2. Modeling

In 3D model, concrete was modeled as 8-node isoparametric 3D element and 2 node 3D truss element for modeling both of longitudinal and transverse reinforcement. The super structure was represented by concentrated mass at top of the pier and mass of pier was lumped at the joints. Nonlinear Newmark approach (2,3) was used to solve the nonlinear equation of motion. A finite element software named MARC was utilized in the analysis. Fig. 1(a, b) shows the simplified 3D finite element model and parameters of the study respectively. Von Mises criterion with normality flow rule was adopted to consider nonlinearity of steel reinforcement. Nonlinearity of concrete was adopted through constitutive equations which were considered in two stages. For uncracked concrete, we used a model based on theory of plasticity (4) to model concrete in compression as in Fig. 2. We modified the model to consider the effect of transverse reinforcement on increasing both of ultimate strength and corresponding strain due to confinement. The modification was based on a model proposed by Mander et al (5,6) as in Fig. 3.

For cracked concrete, we used constitutive equations based on smeared crack model as in Fig. 4 (a, b). More details were illustrated in previous works by the authors, e.g. (7,8). In this study, shear reinforcement ratio was defined as $A_{sh}/(e.h)$ in which A_{sh} is the area of stirrup branches in the direction considered, e and h are spacing of stirrup and depth of the pier respectively. Stress level was defined as $P/(A_c.f'_c)$ in which P is the axial load, f'_c is the concrete strength and A_c is the area of concrete section. Percentage of main reinforcement was defined as $A_s/(d.b)$ where A_s is the area of main steel in tension side, d and b are effective depth and width of pier respectively.





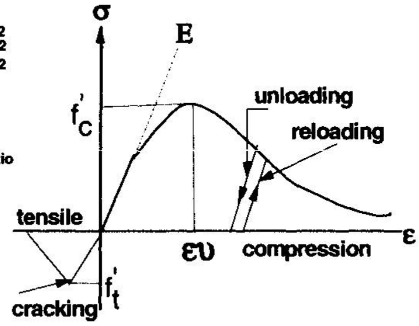
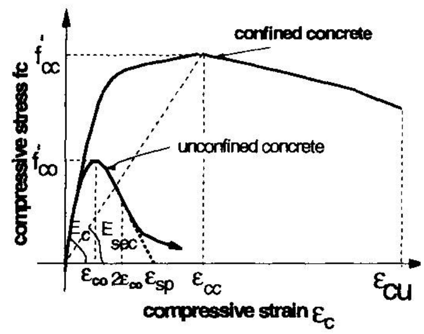
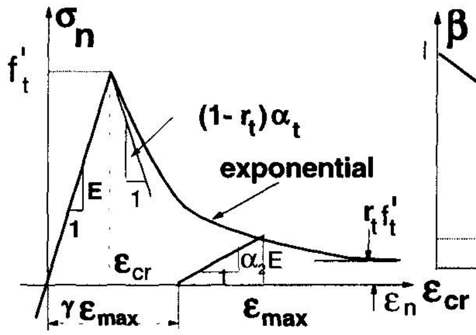


Fig. 1 A) 3D model *b) Parameters of the study* *Fig. 2 Modeling of concrete in compression*





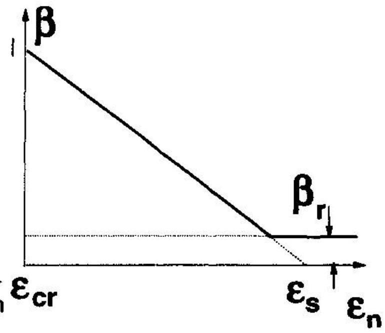


Fig. 3 Park model *Fig. 4 a) Tension stiffening* *b) Retention factor*

3. Results and Discussion

3. 1 Effect of Vertical Motion on Inelastic Response

Fig. 5 (a & b) illustrates the effect of vertical motion on acceleration response of RC pier of 0.3 % shear reinforcement. Including vertical component caused significant increase in the level of response. The rate of increase of peak acceleration was 80 % for the given case. Fig. 6 illustrates effect of shear reinforcement and vertical motion on the peak acceleration of the same pier. By increasing the ratio of shear reinforcement, the effect of vertical motion on changing the level of the response decreased. This implied that effect of shear reinforcement on behavior of piers was more significant in case of VL & HZ motions than that in case of HZ motion only. For example, by increasing the ratio of shear reinforcement from 0.06 % to 0.3 %, peak acceleration was reduced by 3.8 and 7.0 % respectively for the cases of HZ motion only and HZ & VL motions .

Fig. 7 illustrates the effect of vertical motion on axial load response of RC pier. Vertical motion induced fluctuating axial forces in the piers which lead to unstability of the structure and increase in ductility demand (9). Also, due to changing of the sign of axial force, ultimate strength of concrete was reduced. Generally, compressive axial load causes increase whereas tensile load causes decrease of lateral load capacity. If the induced axial force is tensile, the stiffness of the pier decreases and hence its ultimate shear capacity decreases. The tensile forces cause yielding of main reinforcement and diagonal shear failure. On the other hand, if the induced axial force is compressive, then ultimate load carrying capacity of the pier increases, however ductility of piers decreases significantly due to crushing of concrete at the ends of the diagonal cracks.

In previous studies (7,8,9,10), we determined the optimum shear reinforcement ratios at which failure mode changes from diagonal shear to flexural mode and this was done by considering plastic strain as damage index for concrete. We showed that the optimum shear reinforcement ratio depends on axial stress level, ***L/h*** ratio and percentage of main reinforcement. Also, the required ratio of shear reinforcement increases significantly as the axial compressive stress level increases. In the current study, we analyzed the rate of increase of the axial compressive load due to vertical motion with different peak acceleration. Fig. 8 illustrates the relation of g_v/g_h and $P_{hz\&vl}/P_{hz}$ for different ***L/h*** where g_v and g_h are peak acceleration of vertical and horizontal motions respectively and $P_{hz\&VL}$ and P_{hz} are the maximum induced compression load in cases of HZ & VL motions and HZ motion only respectively. For example if the pier is supposed to be subjected to vertical motion having peak acceleration of 0.5 times the horizontal peak acceleration, then the pier should be designed to carry 1.2 times the actual axial load.

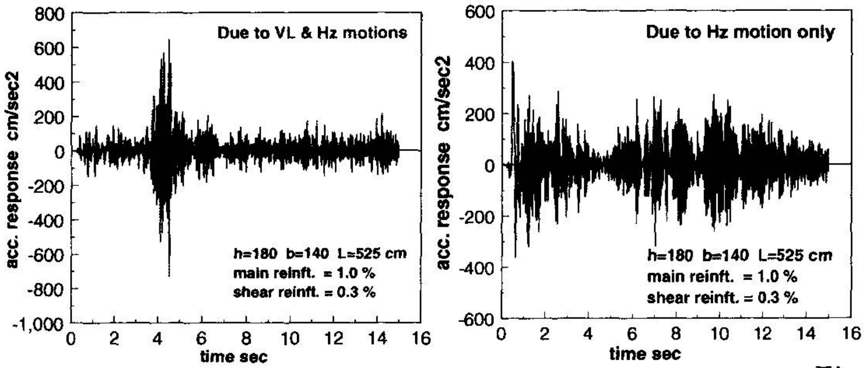


Fig. 5 (a, b) Effect of V. motion on HZ acceleration response

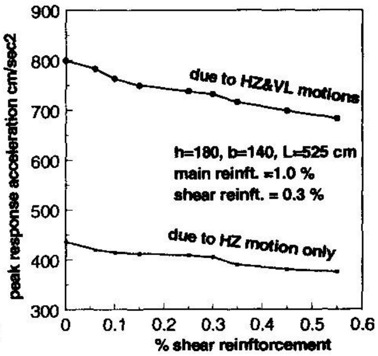


Fig. 6 Effect of shear reinft. and V. motion on peak acceleration

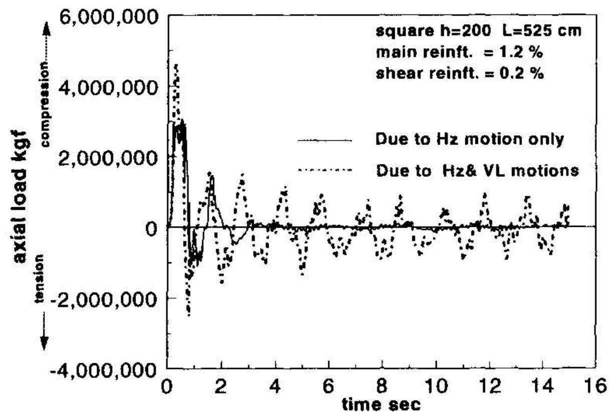


Fig. 7 Effect of vertical motion on axial load response of RC pier

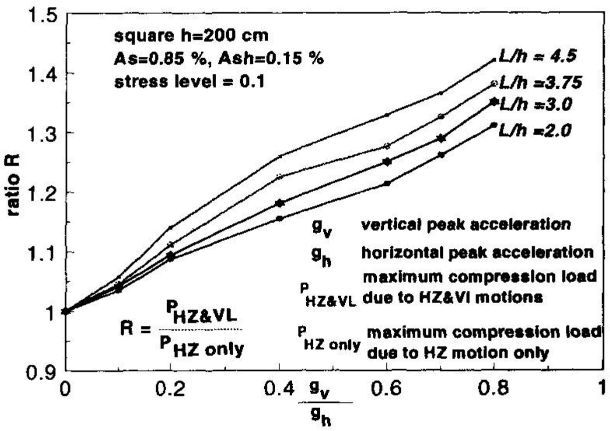


Fig. 8 Effect of vertical motion on maximum axial compression load on the pier

3.2 Vertical Motion and Ductility Level of RC Piers

Displacement ductility of piers factor was calculated from inelastic responses from the relation:

$$D.F = \frac{\Delta_u}{\Delta_y} \tag{1}$$

Δ_u is the horizontal displacement at the top when lateral load capacity of the pier drops to 80 % of the maximum carrying load (6,8,10,12,13,14). At this level the pier was assumed to collapse due to plastic deformations. Δ_y is the lateral displacement at the top corresponding to first yielding of main reinforcement. Fig. 9 (a, b) illustrates the relation between shear reinforcement and ductility factor of piers having different axial stress level for the two cases of HZ motion only and HZ & VL motions. Ductility level decreased significantly due to vertical motion and maximum percentages of reduction were 20, 18, 18, 16, 15 % for stress levels 0.1, 0.15, 0.2, 0.25 and 0.3 respectively. So, bigger quantity of shear reinforcement is needed to maintain ductility level if the piers are expected to subject to HZ & VL motions than that in case of HZ motion only. Also, it is clear that the role of shear reinforcement in increasing ductility level was more significant in case of HZ & VL motions especially for higher axial stress levels.

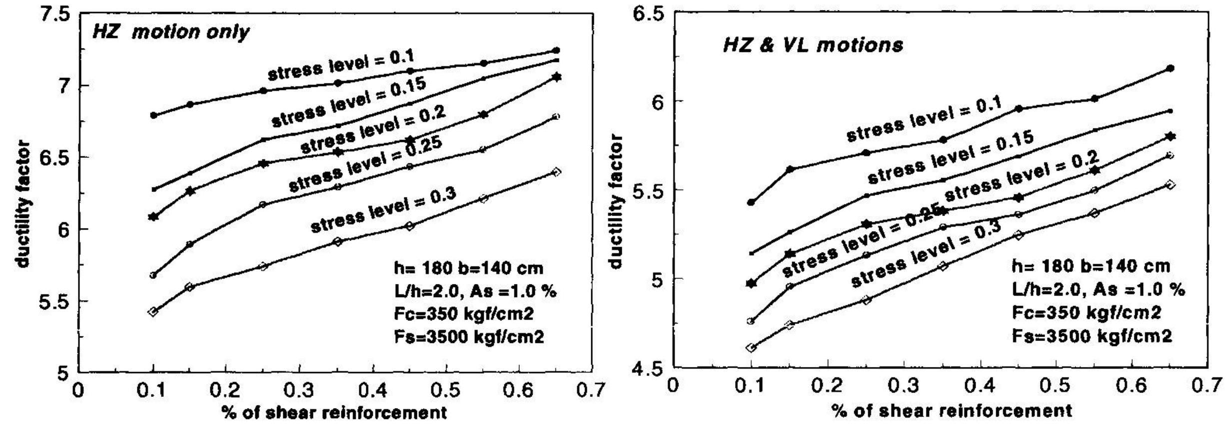


Fig. 9 (a, b) Ductility of piers with different ratios of shear reinforcement and stress level
Case A: *Due to HZ motion only* ***Case B:*** *due to HZ & VL motions*

3.3 Vertical Motion and Failure Mode

We determined final failure mode of piers (8) based on comprehensive analysis of base shear response, stresses and strains. Fig. 10 (a, b) illustrates the effect of vertical motion on the base shear response of piers with two ratios of shear reinforcement, 0.06 and 0.3 %. Vertical motion caused increase in the base shear and the rate of increase was high for higher shear reinforcement. For the given examples, the ratio of maximum shear in case of HZ & VL motion to that of HZ motion only was **1.5** and **1.65** indicating 50 % and 65 % increase in shear response. However, this maximum value dropped to zero after short time of applying the motion in case of HZ & Vl motions whereas in case of HZ motion only, the loss in the load was not so big.

Fig. 11 illustrates the effect of vertical motion on lateral strain response at base of RC pier. Including vertical motion resulted in significant increase in the lateral strain and the rates of increase of both of the maximum tensile and compressive values were 421 and 335 % respectively. The higher tensile lateral strains accelerated the occurrence of diagonal failure. In previous study (8), we showed that for diagonal shear failure, lateral plastic strain is tensile and it is compression if final failure mode is flexural. Also, we noticed that diagonal failure occurred when lateral tensile plastic strain was higher than or equal to 0.004. Applying these considerations on the given example, we see that diagonal failure occurred in case of HZ & VL motions however flexural failure occurred in case of HZ motion only.

Fig. 12 illustrates the effect of vertical motion on axial strain response for RC pier. Both of the tensile and compressive strains increased significantly due to vertical motion. Maximum values increased by 86.6% and 216 % for tensile and compressive strain respectively.

Fig. 13 (a, b) illustrates lateral stress strain relations at base of RC pier for HZ motion only and HZ & VL motions respectively. In the second case, stresses were several times larger than that of the first case. Tensile stresses and strains were high in the second case resulting in diagonal shear failure however flexural failure occurred in case of HZ motion only Also, number of cycles which can be resisted safely was very small in the case of applying the vertical motion. However in other cases, diagonal collapse occurs for the two cases of loading however the severity of diagonal collapse is higher in case of HZ & Vl motions than that of HZ motions.

From these points, the authors concluded that due to vertical motion, piers lost their shear base responses at early stages associated with higher lateral and axial strains. Also the ductility level of the piers decreased significantly. These reasons resulted in severe diagonal shear collapse. This was one of the reasons of such severe collapse of the bridge piers during the Great Hanshin earthquake. The other reasons included the insufficient shear reinforcement ratio and the characteristics of the Great Hanshin motion. These points were studied in other works by the authors, and those who are interested can refer to references (8,15).

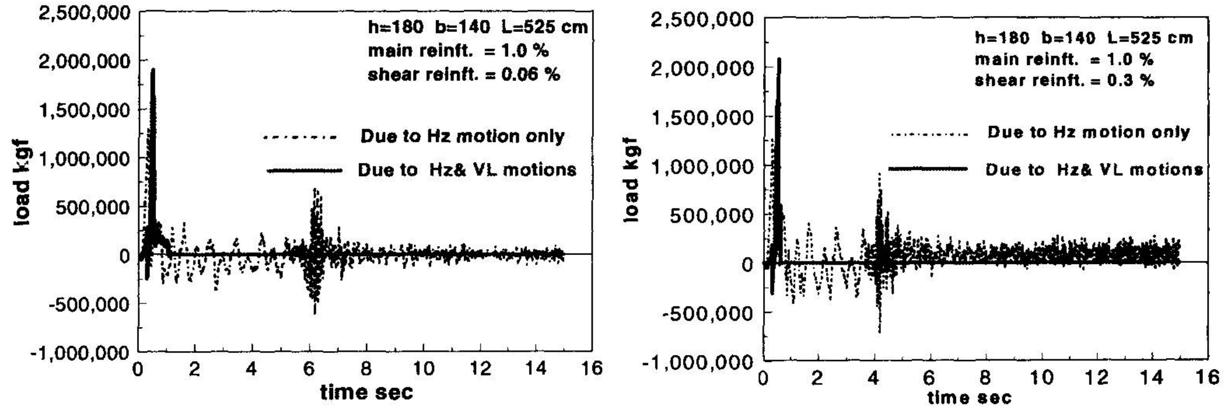


Fig. 10 (a, b) Effect of vertical motion on load capacity for ratios of shear reinft. 0.06 and 0.3 %

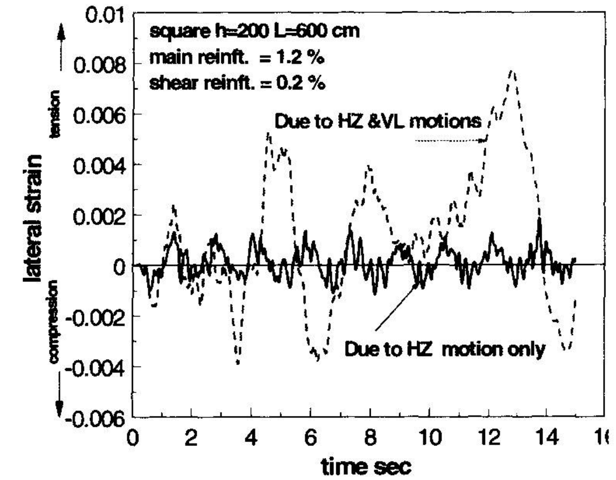


Fig. 11 Effect of vertical motion on lateral strain response of RC pier

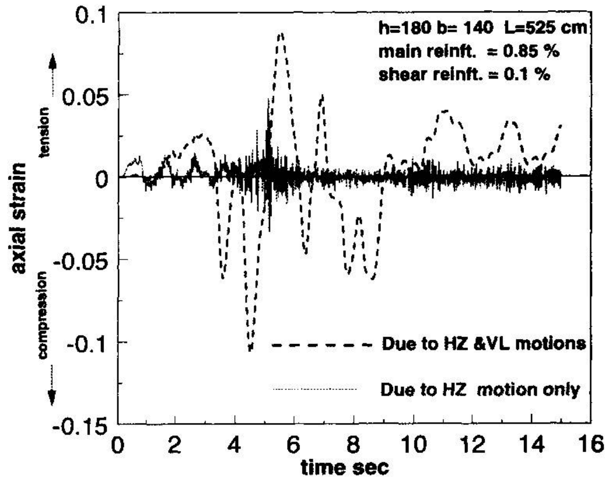


Fig. 12 Effect of vertical motion on axial strain response of RC pier

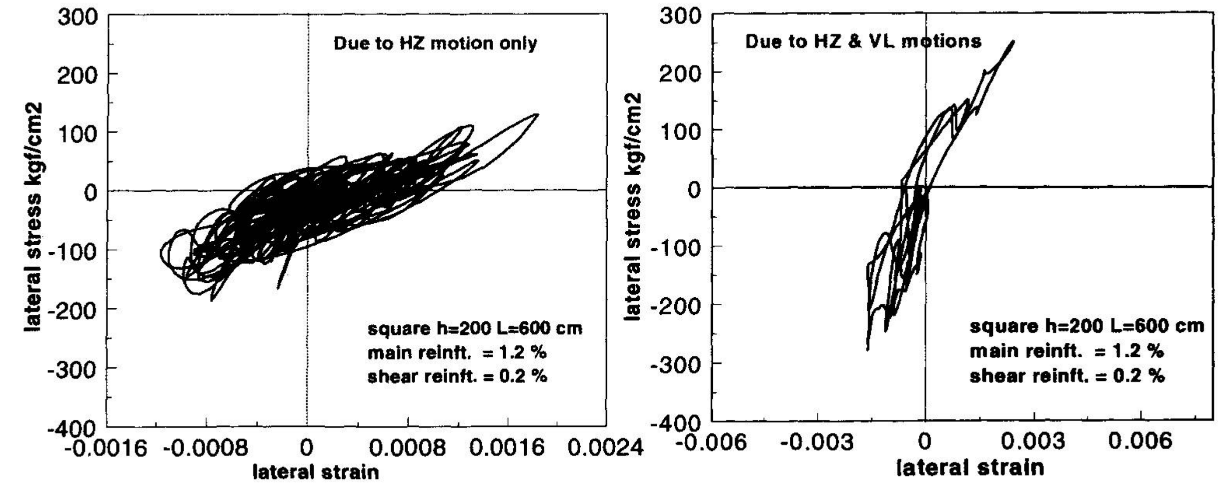


Fig. 13 (a, b) Effect of vertical motion on lateral stress strain for RC pier
Case A *HZ motion only* ***Case B*** *HZ & VL* motions.

4. Conclusions

- Vertical component has remarkable influence on the inelastic response of RC piers and should be included in the seismic design of such structural elements.

- Due to vertical motion, ductility level of piers decreases and the induced plastic strain increases. The induced fluctuating axial forces and plastic strains result in collapse of piers at early stages of applying the motion. The base shear response of piers increases associated with severe drop leading to shear failure. Vertical motion causes change of final failure collapse of some of the studied piers from flexural to severe diagonal shear failure. However in other cases, diagonal collapse occurs for the two cases of loading however the severity of diagonal collapse is higher in case of HZ & VI motions than that of HZ motions.

- Vertical motion was relatively high during the Great Hanshin Earthquake in Japan, 1995 and this was one of the reasons of the severe collapse of bridge piers occurred during the motion.

Acknowledgment

Financial support by grant-in-aid by the Ministry of Education, ***Monbusho***, for the first author is gratefully appreciated.

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