Experimental Investigation of Bridge with Footing Uplift under Near-fault Earthquake

Yuanzhi Chen, Chern Kun, Nawawi Chouw and Tam Larkin

Department of Civil and Environmental Engineering, Faculty of Engineering, The University of Auckland, Auckland, New Zealand

E-mail: yche521@aucklanduni.ac.nz

Abstract

Many investigations have confirmed the beneficial effects of footing uplift on structural performance, i.e. reduction of the ductility demand of structural members. Bridge piers have been designed to rock in some seismic retrofit projects, e.g. the South Rangitikei railway bridge in New Zealand. However, research on bridge with footing uplift is still limited and performed mainly numerically. Only a few experimental works on simplified single degree-of-freedom bridge models have been conducted. Another aspect that is seldom addressed is the effect of near-fault earthquake on bridge with uplift, even though destructive damage to bridges has been observed in the near-source regions.

In this study the response of a single-span model bridge with uplift due to simultaneous vertical and horizontal excitations is investigated using a shake table. Artificial plastic hinges are constructed to replicate the nonlinear behaviour of the bridge piers. The excitations are selected from ground motions recorded in the 2010 and 2011 earthquakes in Canterbury. The transversal displacements at deck and footing responses under near-source and far-field ground motions have been discussed.

Keywords: footing uplift, shake table test, plastic hinge, bridge, near-fault earthquake

1. Introduction

The beneficial effect of structural uplift was probably first recognised by Housner (1963) in the 1960 Chile earthquake. Several unstable elevated water tanks performed well in this destructive event. Investigations on the seismic behavior of structure with uplift were then carried out numerically (e.g. Yim et al., 1980) and experimentally (e.g. Huckelbridge and Clough, 1978). Kodama and Chouw (2002) considered structural uplift in near-source earthquakes including soil-structure interaction. It was confirmed that a structure with planned uplift capability is more likely to survive a strong earthquake. Recently, Qin et al. (2013) conducted shake table tests on a single-degree-of-freedom (SDOF) structure and found that uplift reduces the plastic hinge development in structures. The beneficial effect of uplift is also confirmed by the investigation of different structure types, e.g. a timber wall (Loo et al., 2012), a liquid storage tank (Ormeno et al., 2012) and structures with multiple uplift abilities (Ali et al., 2013).

The implementation of the uplift mechanism is contained in the design of the South Rangitikei Railway Bridge in New Zealand (Beck and Skinner, 1974). This low-damage earthquake resistance technique is also adopted in the design of several bridges in America and Canada (Palmeri and Markis, 2008; Dowdell, 2000). Although planned footing uplift of bridges has been adopted, the number of studies on its effect on bridge performance is still limited. Most of the previous investigations are numerical in nature, e.g. Mergos and Kawashima (2005). The experimental studies usually focus on the performance of bridge piers. Hung et al. (2011) conducted a series of pseudo-dynamic and cyclic tests on bridge piers with rocking spread footing, and Deng et al. (2012) performed a set of centrifuge tests on bridge piers on soil with uplift.

Although it is known that the characteristics of ground motion in the vicinity of a fault are different from those of far-fault motions, the effect of near-fault ground motions are seldom considered in shake table tests. The near-fault ground motion in the fault-normal direction usually has a strong pulse, and the acceleration in the vertical direction is also stronger than that in the horizontal direction. In the study by Hung et al. (2011) the response of piers subjected to near-fault ground motions and simulated ground motions were compared, and higher displacement demand at the deck level was found in the case of near-fault ground motion. However, the effect of vertical ground motion was not taken into account in the experiment. In the numerical study of Hao and Zhou (2012) the responses of rigid rocking blocks subjected to simultaneous horizontal and strong vertical excitations were investigated.

In order to have a better understanding of bridge performance under near-fault earthquakes and further examine the effect of uplift, shake table tests on a single-span bridge were carried out. Excitations in the transversal and vertical directions were applied. The excitations were selected from ground motions recorded in the 2011 earthquakes in Canterbury. A pair of simulated ground motion was also considered to represent the far-field ground motion. Artificial plastic hinges were constructed to replicate the nonlinear behaviour of the bridge piers. The response of the bridge with and without uplift is discussed.

2. Experimental investigation

The small scale model is designed based on a 15 m long, 5 m height single span bridge. The prototype has a 6 m wide concrete-steel composite deck. The fundamental periods are 0.63, 0.18 and 0.1 s in the longitudinal, transversal and vertical direction, respectively.

To correctly replicate the effect of excitation on the bridge, the scale factors were determined based on the dimensionless analysis in the study of Qin et al. (2013). Similar scaling methodology was also adopted by Li et al. (2012) to investigate the pounding effects on the Newmarket Viaduct in Auckland, New Zealand.

To simulate the bi-axial excitations, a shaker, which is able to move vertically, was fixed on the top of a shake table moving in the transverse horizontal direction (Figure 1(a)). Two shake tables were controlled simultaneously using a National Instrument controller (Li et al., 2012). To check the synchronization and interaction between two shake tables, concurrent harmonic signals were sent to both shake tables. Vibrations in horizontal and vertical directions were recorded and compared with the control signals. Tests on the structure fixed at the base without and with plastic hinge development, as well as, elastic structure with uplift available were performed.

To achieve fixity of bridge, the piers were bolted on a rigid board, which was fixed on the platform of vertical shaker. To simulate the possible damage of bridge piers under strong earthquake motion, artificial plastic hinges (Qin et al., 2013) were constructed at the pier-footing connection. The capacity of plastic hinge is controlled by addressing the torque applied. A 1.5 Nm capacity of hinge was adopted to allow plastic hinge development, and a 6 Nm capacity was found large enough to replicate the elastic behavior of pier. To allow for uplift, the piers were connected to two 82 mm wide footings.

Strain gauges were glued beneath two edges of the footings to detect possible uplift and also on the side of column to measure the bending moment. An LVDT was used to record the transversal displacement at deck-level. The artificial plastic hinges, footing and instrumentations are shown in Figure 1(b).

3. Near-fault ground motions

The pair of near-fault excitations discussed here was recorded at the Christchurch Rest Haven (REHS) in the 2011 Christchurch earthquake (GeoNet, 2011). The station is 8 km away from the epicenter. According to the NZS 1170.5 (2004), the horizontal ground motion was scaled based on a structure with 2500 years return period and located on class D soil in Wellington (hazard factor Z = 0.40). The scale factor for horizontal component was then applied on the vertical component. The scaled acceleration history of the S88E and vertical components are displayed in Figure 2. As shown in Figure 2(a), a strong long duration single cycle pulse is recorded from 16 s to 18 s in the S88E excitation, which is due to the forward-directivity effect in the fault-normal direction. Figure 2 clearly shows that the peak acceleration of the vertical component, which corresponds to compressive waves, as expected arrives earlier than that of the horizontal component. In addition, the vertical component also has a pronounced high frequency content. It can be seen in Figure 2(c) that the spectral values of the vertical component at both the transverse and vertical fundamental periods are greater than those of the horizontal component. Although the peak ground acceleration of the vertical component is about 70% of the horizontal component, the peak spectral acceleration is slightly greater than that of the horizontal component. The near-fault ground motion is denoted as "REHS" in the coming discussion.

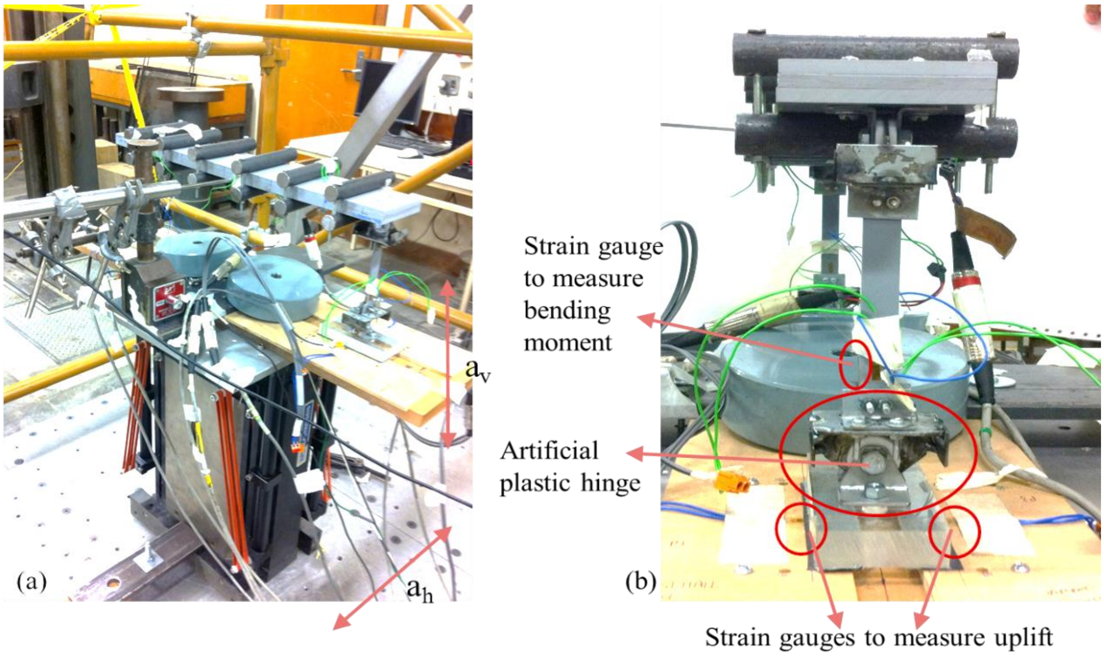

Figure 1. (a) Experimental setup and (b) instrumentations on bridge model

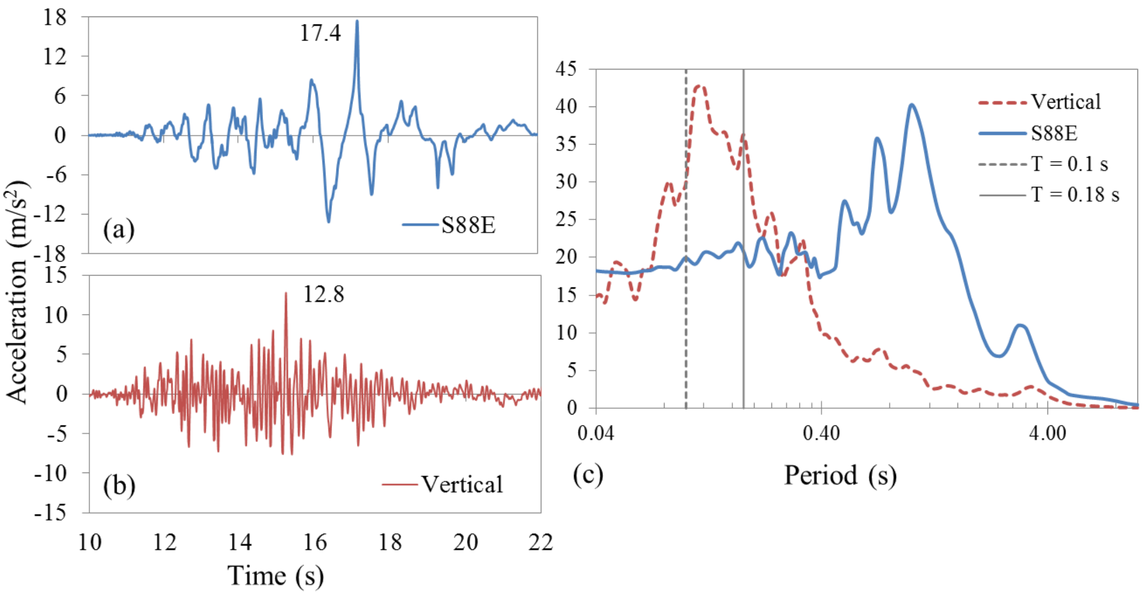

Figure 2. Accelerations in (a) S88E and (b) vertical direction recorded at REHS station and (c) acceleration spectra with 5% damping

4. Simulated ground motion

In conventional seismic design, the effect of vertical ground motion is seldom taken into account. The spectral value of the vertical ground motion is normally assumed to be 70% of that of the horizontal component at the same period (NZS 1170.5, 2004). This assumption ignores the difference of frequency content of horizontal and vertical components. To examine the efficiency of NZS design spectra in the design of a bridge in the near-fault region, an excitation, as shown in Figure 2(a), was stochastically generated to fit the shape of the specified spectrum for soil class D. The full scale and 0.7 scale of the simulated excitations was applied in the horizontal and vertical directions, respectively (Figure 2(b)). The simulated ground motion does not have a near-source related strong pulse. The simulated ground motion is denoted as "NZS" in the following discussion.

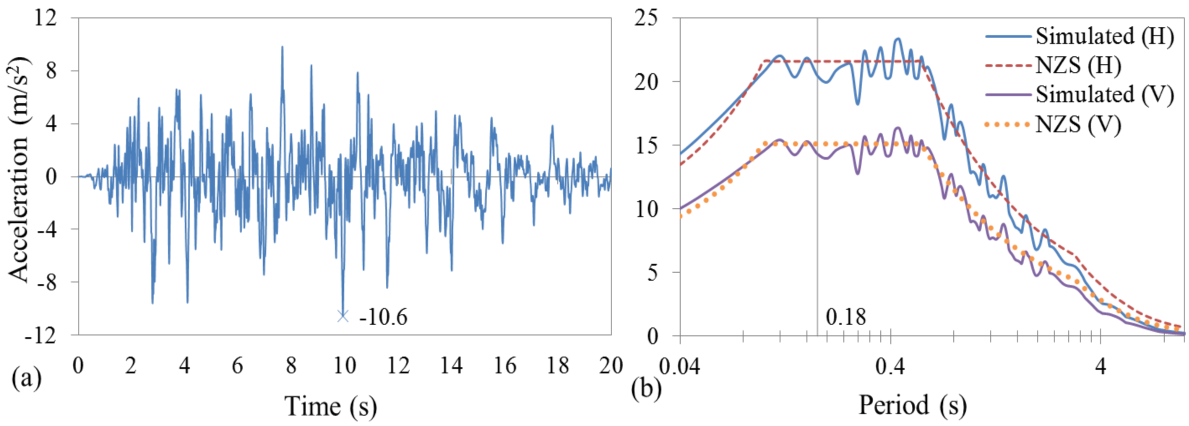

Figure 3. (a) Simulated ground acceleration in horizontal direction and (b) acceleration spectra of simulated excitations in both directions with 5% damping

5. Results and discussion

5.1 Transversal displacement

The maximum displacements at deck-level of the model are summarized in Figure 4. The maximum displacement of the bridge with footing uplift is greater than that of the bridge with plastic hinge development, while the bridge with neither plastic hinge development nor uplift has the least lateral displacement. The results also indicate that the maximum responses predicted using the NZS motion are always lower than that from the REHS motion. Considering the horizontal component only (Figure 4(a)), the differences of the maximum lateral displacement induced by these two motions are similar to the fixed base bridge with and without plastic deformation. This difference is the smallest in the case of uplift. Once uplift occurs, the rigid body motion of the structure is activated. Thus, the increase in structural response due to the near-fault ground motion is reduced.

In the case when the concurrent vertical excitation is considered, the effect of uplift or plastic hinge development on the maximum transverse lateral displacement is similar to the case of horizontal excitation only. Except for the fixed base elastic bridge response, the difference in lateral displacements induced between the two sets of excitations is smaller than the case without vertical motion. It is found that the REHS vertical ground motion can reduce the maximum lateral displacement of bridge, while the NZS vertical ground motion will increase it.

The effect of vertical excitation of the plastic deformation of the structure is not significant. This may be seen by comparing the residual out-of-plane displacements in Figures 4(a) and (b). Larger plastic deformation is measured in the case of near-fault ground motion. This deformation may be the result of the strong pulse in the horizontal excitation.

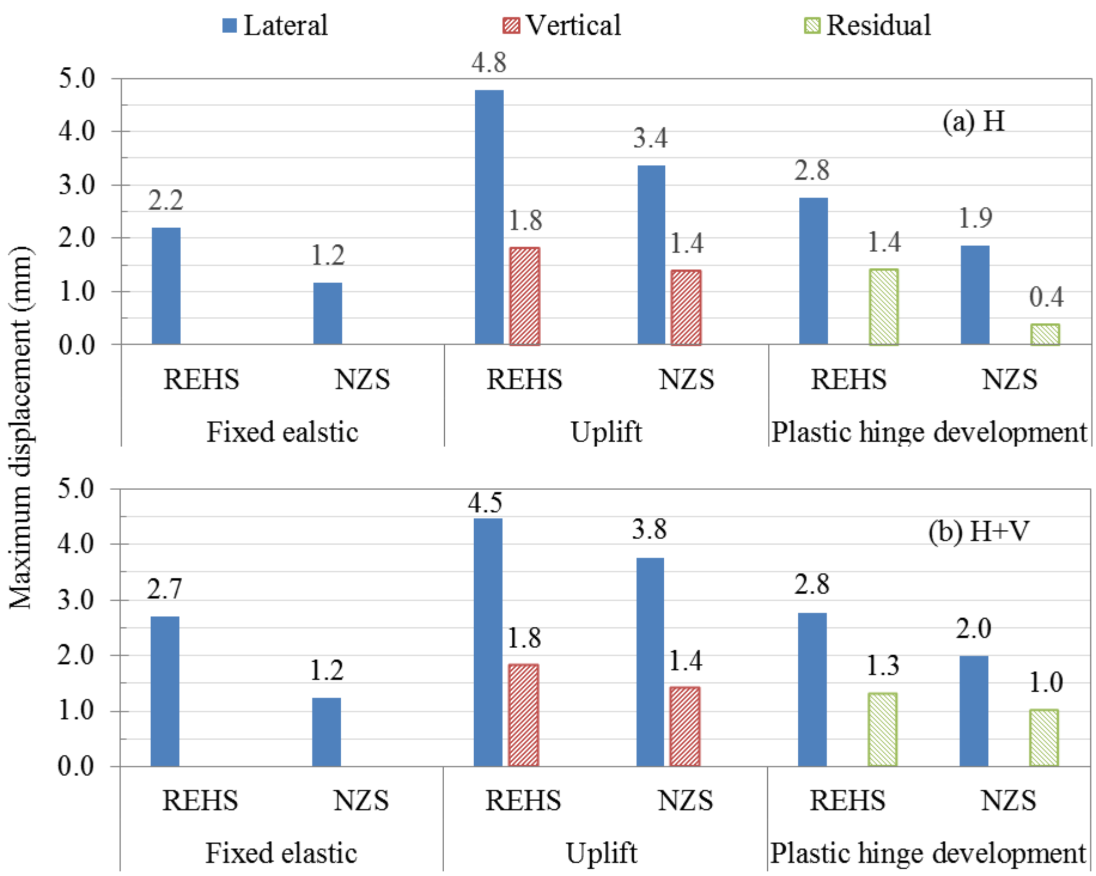

Figure 4. Maximum lateral, vertical and residual out-of-plane displacements of the bridge (a) without and (b) with vertical excitation

5.2 Vertical footing displacement

Figure 5 illustrates the footing response of the bridge under different excitations. Both Figures 4 and 5 indicate that the effect of vertical ground motion on the vertical footing displacement of the bridge is not significant. In both load cases considered, the footing response of the structure with uplift is more determined by the characteristics of the horizontal excitation. When the structure is subjected to near-fault ground motion, larger uplift can be observed. The duration of the footing rotation is also larger than those induced by the simulated motion. As shown in the Figure 5(b), a high frequency motion is superimposed on the long duration uplift due to the vertical ground motion, e.g. the large displacement around 14 s and 18 s. This effect cannot be seen in the case of the NZS motion which induces a short duration of uplift.

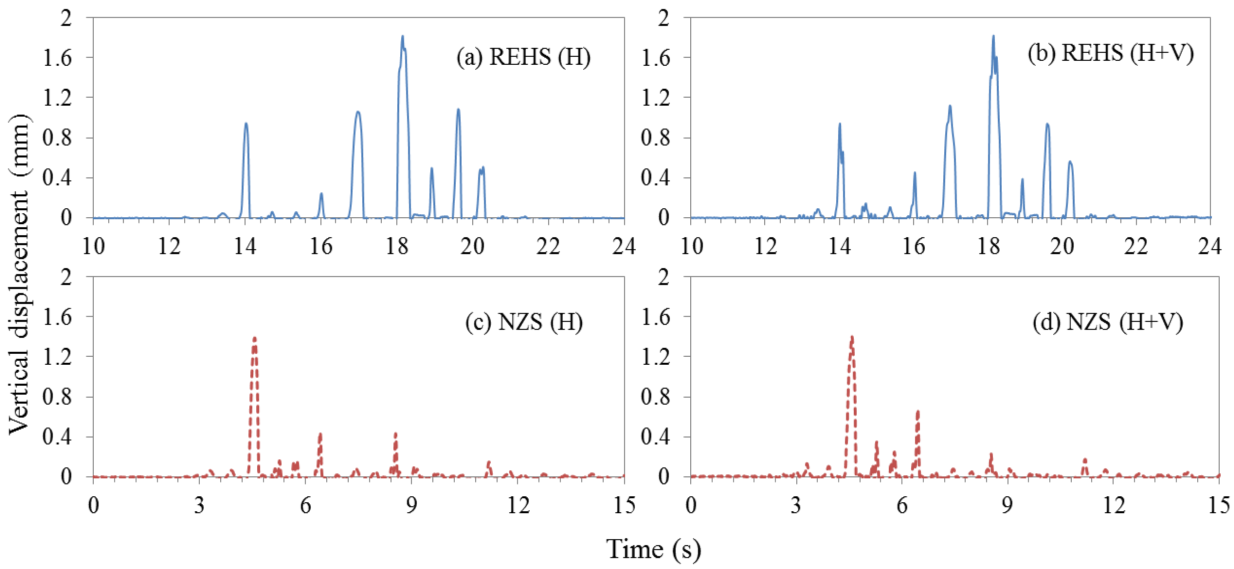

Figure 5. Vertical displacement of footing under the REHS and NZS motions (a)(c) without and (b)(d) with vertical component

6. Conclusions

Shake table tests on a small scale single-span bridge were performed to investigate the effect of near-fault ground motions on bridge with uplift abilities. Excitations were applied in the transversal and vertical directions. Two sets of excitations were considered, i.e. one recorded in 2011 Christchurch earthquake and another stochastically generated to fit the shape of NZS 1170.5 design spectra. Artificial plastic hinges were constructed to replicate the nonlinear behaviour of the bridge piers. The responses of bridges fixed at base with and without plastic hinge development, and with footing uplift were studied. The results show that:

- Stronger transversal displacement at deck-level is induced by the near-fault ground motion with forward directivity.
- The difference of the maximum displacement due to near-fault and simulated ground motions can be reduced by uplift.
- Both footing response and plastic deformation are more associated with the horizontal component than the vertical component.
- A large number of episodes of long duration strong uplift occur from near-source ground motion with strong directivity pulses.

ACKNOWLEDGEMENTS

The research is funded by the Ministry of Business, Innovation and Employment through the Natural Hazards Research Platform under the Award UoA 3701868. The authors would like to thank the University of Auckland for the doctoral scholarship for the first author, and the anonymous reviewer for the constructive comments.

REFERENCES

Ali, M., Briet R., and Chouw, N. (2013) Dynamic response of mortar-free interlocking structures, *Construction and Building Materials*, Vol 42, pp168-189.

Beck, J.L. and Skinner, R.I. (1974) Seismic response of a reinforced concrete bridge pier designed to step, *Earthquake Engineering and Structural Dynamic*, Vol 2, No 4, pp 343-358.

Deng, L., Kutter, B.L. and Kunnath, S.K. (2012) Centrifuge modelling of bridge system designed for rocking foundations. *Geotechnical and Geoenvironmental Engineering*, Vol 138, pp 335-344.

Dowdell, D. J. (2000) Lion's Gate Bridge North Approach - Seismic retrofit. *Behaviour of Steel Structures in Seismic Areas*, pp 319-326.

GeoNet (2011) Strong motion FTP site, from ftp://ftp.geonet.org.nz/strong/processed/Proc/2011/02_Christchurch_mainshock_extended_pass_band

Hao, H. and Zhou, Y. (2012) Dynamic response of rigid blocks to simultaneous vertical and horizontal ground shock. *Advances in Structural Engineering*, Vol 15, No 7, pp 1069-1082.

Huckelbridge, A.A. and Clough, R.W. (1978) Seismic response of uplifting building frame. *Journal of Structural Division*, Vol 104, No 8, pp 1211-1229.

Housner, G.W. (1963) Behavior of inverted pendulum structures during earthquakes. *Bulletin of the Seismological Society of America*, Vol 53, No 2, pp 403-417.

Hung, H-H, Liu, X-Y, Ho, T-H and Chang, K-C. (2011) An experimental study on the rocking response of bridge piers with spread footing foundation. *Earthquake Engineering and Structural Dynamics*, Vol 40. No 7, pp 749-769.

Kodama, T. and Chouw, N. (2002) Soil-structure interaction with uplift due to near-source earthquakes. *Proc. of European Conf. on Structural Dynamics*, Germany, pp 1375-1380.

Li, B., Bi, K., B., Chouw, N., Butterworth, J. W. and Hao, H. (2012) Experimental investigation of spatially varying effect of ground motions on bridge pounding, *Earthquake Engineering and Structural Dynamics*, Vol 41, pp 1959-1976.

Loo, W.Y. Quenneville, P. and Chouw, N. (2012) A numerical study of the seismic behaviour of timber shear walls with slip-friction connectors. *Engineering Structures*; Vol 34, pp 233-243.

Mergos, P.E. and Kawawshima, K. (2005) Rocking isolation of a typical bridge pier on spread foundation, *Earthquake Engineering*, Vol 9, No 2, pp 395-414.

Ormeño, M, Larkin, T and Chouw, N. (2012) Influence of uplift on liquid storage tanks during earthquakes. *Coupled Systems Mechanics*, Vol 1, No 4, pp 311-324.

Palmeri, A. and Markis, N. (2008) Response analysis of rigid structures rocking on viscoelastic foundation, *Earthquake Engineering and Structural Dynamic*, Vol 37, pp 1039-1063.

Qin, X, Chen, Y, and Chouw, N (2013) Effect of uplift and soil nonlinearity on plastic hinge development and induced vibrations in structures. *Advances in Structural Engineering*, Vol 16, No 1, pp 135-148.

Standards New Zealand (2004) *Structural Design Actions, 1170 Part 5: Earthquake actions in New Zealand*.

Yim, C.S., Chopra, A.K., and Penzien, J. (1980) Rocking response of rigid blocks to earthquakes. *Earthquake Engineering and Structural Dynamics*, Vol 8, pp 565-587.