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Foundation uplift of a single-span bridge subjected to simultaneous strong horizontal and vertical ground motion

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ABSTRACT

From the assessment of past earthquakes, severe damage of structures induced by strong vertical ground motion has been observed. Although compared to horizontal ground motion vertical ground motion usually has a higher predominant frequency, current design standards do not account for the higher frequency of the vertical response. Instead, most standards consider the spectral value of vertical ground motion to be 70% of the horizontal ground motion. However, records of previous earthquakes, especially near-fault earthquakes, have shown that this value is not sufficient. Analyses of structures subjected to strong vertical ground motion confirm that including vertical ground motion is essential in capturing the contribution of vertical modes to structural response. However, these studies have been carried out using numerical models with very limited experimental work to validate the theoretical modeling.

In this experimental study a single-span bridge with foundation uplift is investigated. The small scale model has been subjected to transverse and vertical seismic ground motions simultaneously. Two support conditions, fixed at the base and free to uplift on a rigid base, are considered. Ground motions were selected from the Christchurch New Zealand earthquake of February 2011. To measure the vertical displacement of the footing, sensors were attached underneath the foundation. The uplift behavior, including the effect on the bridge deck, and the pier response under horizontal excitation along with simultaneous horizontal and vertical excitations are discussed.

1. INTRODUCTION

Damage of structures due to strong vertical excitation in the Kalamata, Greece earthquake in 1986 was noted by Elnashai et al. (1988) to occur early in the motion. The researchers suggested that the compression failure of concrete columns and shear-compression failure of the concrete wall was the result of strong axial compression induced by vertical motion in combination with poor detailing. Similar failures of structures were also observed in the 1994 Northridge earthquake (Elnashai

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1995), the 1995 Kobe earthquake (AIJ 1995) and the recent Christchurch earthquake in 2011 (Chouw and Hao, 2012). Several numerical simulations of structures under earthquake loading also suggested presence of strong impact loading from vertical ground motion which cannot be observed when only horizontal ground motions are considered (Chouw and Hirose, 1999, Chouw, 2002, Kodama and Chouw, 2002, Hashimoto and Chouw, 2002). However, in most investigations of seismic performance of structures the effect of vertical ground motion is seldom taken into account and the number of studies that consider both footing uplift and vertical ground motion are even more limited.

After studying footing uplift, engineers have attempted to implement this featurein bridgedesigns in the last few decades (Beck and Skinner 1974, Palmeri and Markis 2008). It has been reported in a number of investigations that uplift is beneficial to the seismic performance of a number of different structural types, e.g. a timber wall (Loo et al. 2012), a tank (Ormeno et al. 2012) and a simplified building model (Qin et al. 2013). The previous studies on bridges with foundation uplift are generally numerical in nature (Folic and Folic 2009), and only a few experiments have been conducted. Hung et al. (2011) carried out a series of pseudo-dynamic and cyclic tests on bridge piers with rocking spread footings on a rigid base, and Deng et al. (2012) performed a set of centrifuge tests on piers with footing uplift on sand. However, the effect of strong vertical ground motion is not considered in these works. Mergos and Kawashima (2005) studied the response of a bridge with uplift subjected to uniaxial, biaxial and triaxial excitations using a numerical model. They found that the isolating effect of rocking of the footing was amplified under biaxial loading and the additional effect of concurrent vertical ground motion was not significant. There is no similar experimental work known to the authors to date.

In this paper, shake table tests on a single span bridge subjected to simultaneously vertical and horizontal ground motions were performed. This experiment focused on the effect of footing uplift on bridge response. Thus, two support conditions: fixed at the base and free to uplift on a rigid base were implemented. Ground motions recorded during the February 2011 Christchurch earthquake were applied. The response of the deck, pier and footing in cases with and without participation of vertical ground motion is compared and discussed.

2. VERTICAL GROUND MOTION

In most of the current design codes the frequency content of all components of motion are assumed to be the same (Newmark 1973). This assumption has been adopted in the New Zealand Design Standard for earthquake action 1170.5 (2004), in which the spectral value of the vertical component is equal to 70% of that of the horizontal component at the same period. However, a number of records from previous earthquakes, especially near-fault earthquakes, have shown that the vertical component has pronounced high frequencies due to compressive waves as well as a peak vertical-to-horizontal spectral ratio in excessof 70% (GeoNet 2011).

The ground motions recorded at the station PRPC (Pages Road Pumping Station) in the February 2011 Christchurch earthquake is a typical example. Fig. 1(a) shows the time history of both vertical and horizontal (south component) accelerations. It can be seen that the peak acceleration in the vertical direction (15.98 m/s^2) is 2.78 times larger than that in the horizontal direction (5.75 m/s^2). Fig. 1(b) displays the spectra of the two components with a 5% damping ratio. Different frequency content can be observed. The predominant period of the vertical component is approximately 0.12 s while that of the horizontal component is approximately 0.18 s. The vertical spectral acceleration for periods less than 0.4 sis significantly larger than the corresponding value of the horizontal component. The maximum vertical-to-horizontal spectral ratio of 6.37 occurs at 0.12 s.

In this study the vertical and south components of the PRPC records are scaled and simulated using a shake table.

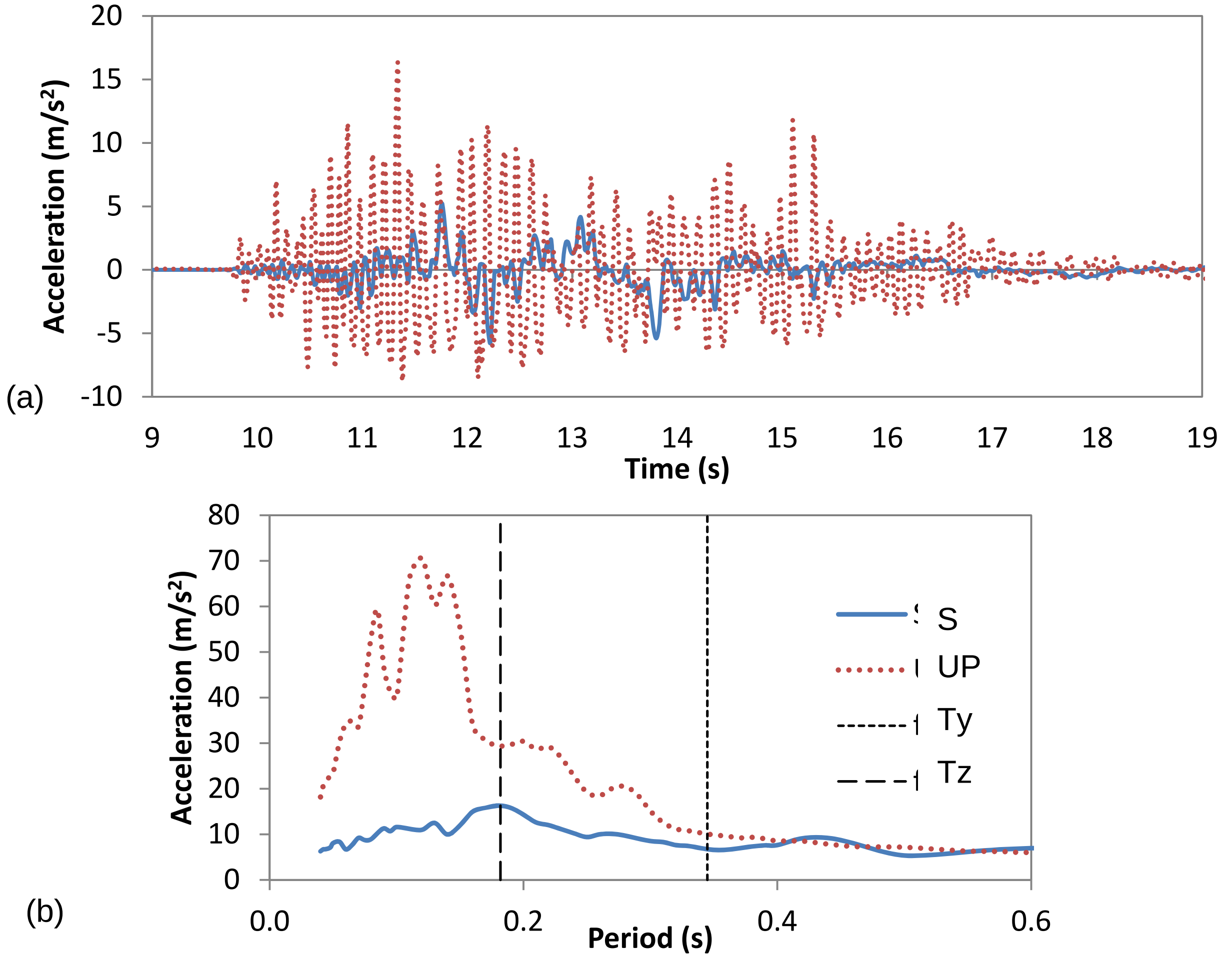

Fig. 1 (a) Acceleration time history and (b) spectra of vertical (UP) and horizontal (S) components of ground motion recorded at PRPC station in the 2011 Christchurch Earthquake

3. EXPERIMENTAL INVESTIGATION

3.1 Model design

The dimensions of the model used in this study resulted from scaling the dimensions of a prototype down by a factor of 100, as shown in Fig. 2. The prototype was a single-span bridge with a steel and concrete composite deck. The properties of the prototype are given in Table 1. To correctly replicate the effect of the earthquake on the prototype,the scalefactors are determined according to the dimensionless analysisproposed by Dove and Bennett(1986). This scalling methodology was adopted by Li et al. (2012) to examinethe pounding effects of the Newmarket Viaduct in Auckland, New Zealand. The scale factor of threebasic dimensions, i.e. mass M, length L and time T are predefined. The other parameters are then determined based on these basic dimensions. The scale factors of different physical parameters of the structure and ground motion are shown in Table2. It should be noted that instead of directly scaling down the cross section dimensions of the prototype, the size of model pier and deckisadjusted to achieve scaled lateral stiffness in the *y* and *z* directions equivalent to the prototype. The fundamental periods of the model in the *y* and *z* directions are 0.17 and 0.09 s, respectively. These natural periods before time scaling are highlighted in Fig. 1(b).

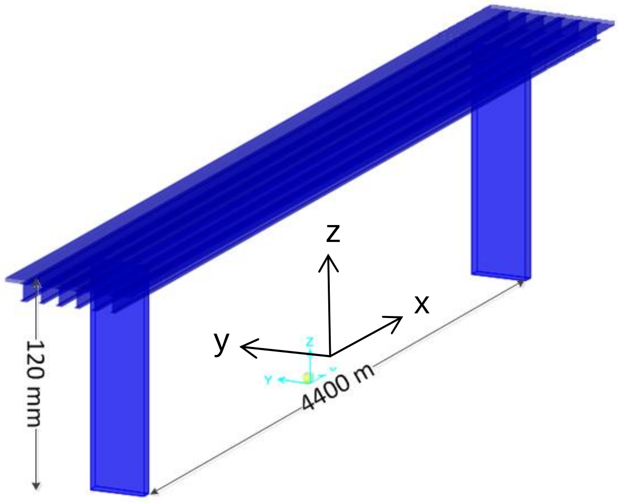

Fig. 2 Prototype

Table. 1 Properties of prototype

Seismic mass	392029 kg
$\mathbf{I_{y\text{-}deck}}$	1.02m^4
$\mathbf{I_{y\text{-}column}}$	0.054m^4
Column depth	600 mm
Column width	3000 mm

Table. 2 Dimensions and scale factors for selected parameters

Parameters	Dimensions	Scale factors
Mass	M	100000
Length	L	100
Time	T	2
Acceleration	LT^{-2}	25
Stiffness	MT^{-2}	25000
Frequency	T^{-1}	0.5

3.2 Test setup

To simulate the excitations in two different directions (vertical and transverse horizontal), a shaker, which can move vertically, was fixed on top of a hydraulic shake table moving in the transverse horizontal direction. The two shake tables are driven simultaneously by the Data Acquisition Toolbox developed by the University of Auckland. As shown in Fig. 3(a), the model was subjected to the horizontal excitation in transversal direction (y) to replicate possible footing uplift.The response of the model under horizontal excitation only and concurrent horizontal and vertical excitations were measured to investigate the effect of a strong vertical component.

On the other hand, tests on the model both fixed at the base and with footing uplift were conducted so the effect of uplift can be highlighted. In the fixed base case the model was anchored to an aluminum box section which was fixed to the platform of the vertical shaker (Fig. 3(a)), whilein the case of uplift this box section was replaced by 100 mm × 30 mm PVC footings (Fig. 3(b)).

Strain gauges were placed at the center of the footing under the edge of the plane of contact to measure the contact force on the footing-base interface (Fig. 3(b) and Fig. 4(a)).The vertical displacement on one edge of the footing could also be evaluated by the calibrating the force changed on the opposite edge as explained byFig. 4(b). Other instrumentation includedan accelerometer on each mass and strain gauges on the middle of the deck, deck-column joints and the bases of the piers, see Fig. 4(c).

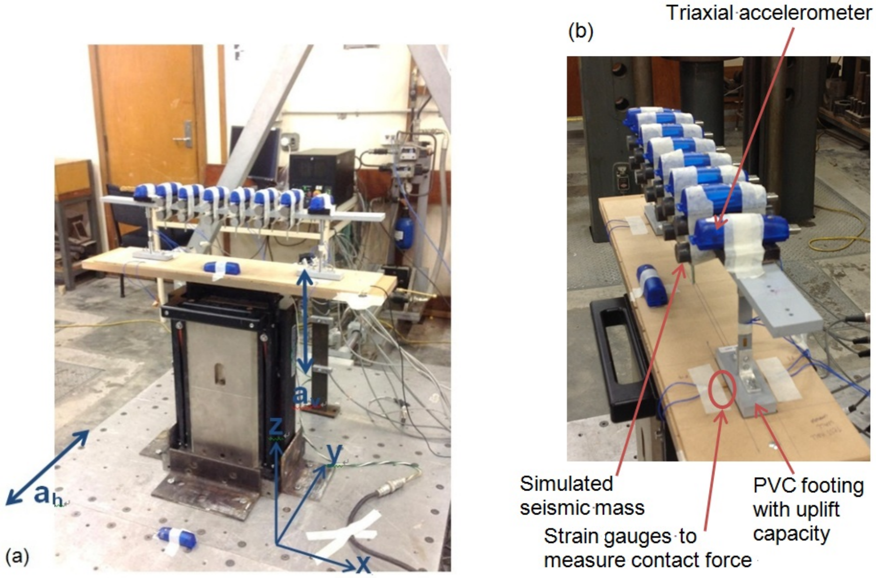

Fig. 3 Test setup of (a) fixed base model and (b) model with possible uplift

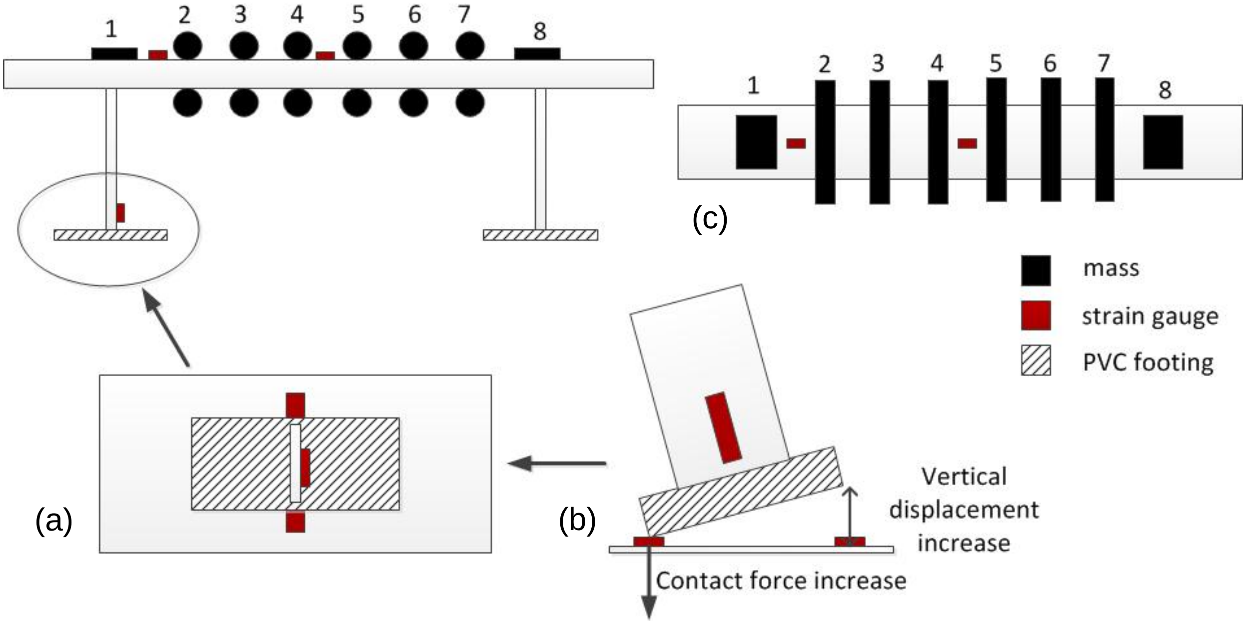

Fig. 4 (a) Plan showing the strain gauges on the footing, (b) side view of footing showing the evaluation of vertical displacement (c) plan showing the location of strain gauges on deck

4. RESULTS AND DISCUSSION

4.1 The effect of concurrent vertical and horizontal excitation on structural accelerations

The seismic mass of the deck is equally divided into eight discrete masses with uniform spacing (Fig. 4). In addition, the mass of the top half of the prototype column is assumed to be concentrated at the corresponding deck-column joint. The maximum acceleration of each mass induced by excitation has been evaluated and the effect of concurrent vertical and horizontal excitations(R) is quantified by Equation (1).

$$R = \frac{a_{H+V} - a_H}{a_H} \quad (1)$$

where a_{H+V} is the maximum acceleration recorded in the case when simultaneous horizontal and vertical excitationswere applied and a_H is the maximum acceleration in the case of horizontal excitation only.

In Fig. 5 the effect of vertical excitation on the acceleration of the mass at each location is summarized. The positions of the masses are shown in Fig 4(c). It can be observed from the result without considering uplift effect (solid lines) that the concurrent excitation increases the response in all directions, and the increase in the vertical directions is significant. The average increases of vertical and transverse accelerations due to concurrent excitation are 12.9and 0.4 times those due tothe horizontal excitation case in the respective directions.

In the case of uplifta consideration of vertical motion results in weaker vertical structural response compared to that recorded for the fixed base. However, in the transverse direction the structural response in the case of uplift is stronger, i.e. the situation is reversed.The structure acts more as a rigid body (i.e. less relative deformation between structural elements). However, the rotation of the footing under uplift conditions produces large transverse displacements.

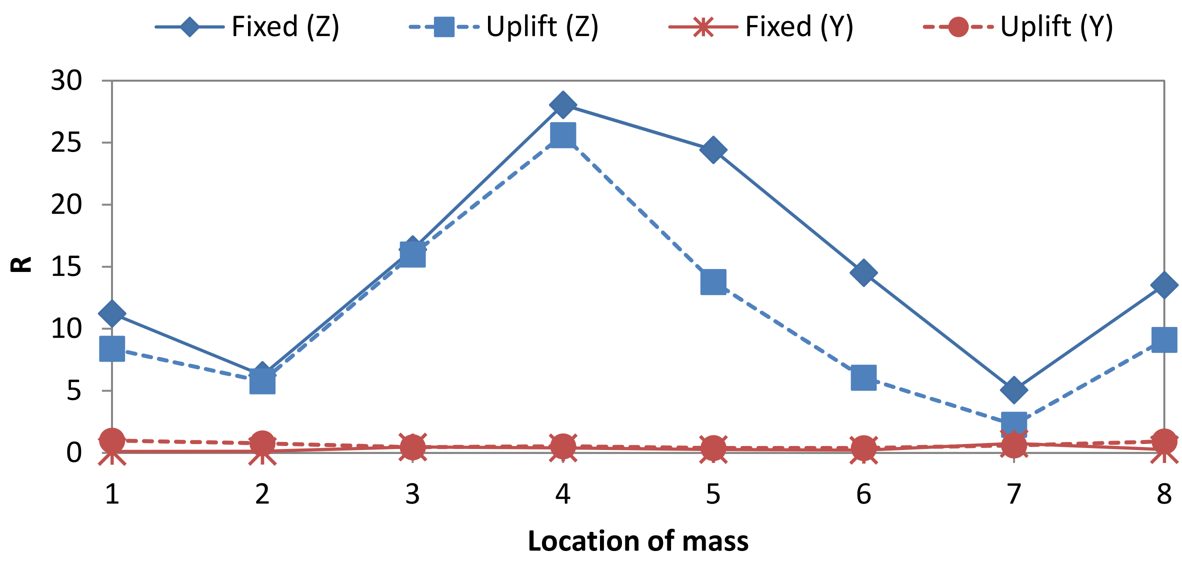

Fig. 5 Amplification of acceleration of each mass due to concurrent vertical and horizontal excitations

The vertical response at the center of the deck (location 4) is substantially stronger by a factor of 5 than that at the ends (location 2 and 7). This response is clearly associated with the fundamental vertical mode (see Fig. 6).Positions 1 and 8 are located at the ends of the columns and the vertical response at these locations largely reflect the incident vertical motion.At all other locations the motion is governed by the fundamental vertical mode of the deck.Considering the characteristics of the whole structure it is clear that with respect to the transverse direction the system can be modeled as a single degree-of-freedom system.Thus, the transverse response of all masses is almost the same. The results show that the effect of vertical motion should be included in the seismic design.Otherwise,the strength demand of structural members will be significantly underestimated, especially in the vertical vibrationof the bridge deck.

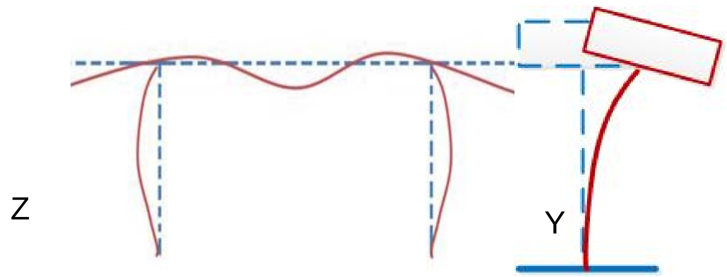

Fig. 6 The shape of the vertical and transverse fundamental modes of the model

4.2 Effect of concurrent vertical and horizontal excitations on footing response

The footing behaviour has been studied using the vertical displacement of the edge and the frequency content of the reaction force. Fig. 7(a) shows the vertical displacements on one side of the foundation for both loading cases during the time window of peak response from 7.8 to 12.8 s. It can be seen that uplift occurs considerably more frequently when vertical excitation is taken into account. The uplift is also stronger than that due to the horizontal excitation. The maximum vertical displacement due to vertical excitation is approximately twice that measured when only horizontal excitation is considered.

A Fourier analysis of the reaction force at the edge of the footingis displayed in Fig. 7(b). Compared to the response due to the horizontal excitation only the vertical excitation amplifies the response in most of the consideredperiod range, i.e. in the period ranges from 0.07 to 0.14, 0.18 to 0.28, 0.30 to 0.45 and 0.54 to 1.17 s. All these periods are shorter than the fundamental periods(Ty = 0.172s, Tz = 0.09s). The dominant response at high frequenciesmay be a result of stronger impact of the footing after a strong uplift.

The strong vertical displacement of the footingmay increase the load on the foundation soil in a real scenario. Hence, a possibility of a bearing failure needs to be considered. However, a number of previous investigations have shown that plastic deformation of the foundation soil can be an energy dissipation mechanism and provide beneficial effectson structural response (Qin et al. 2013). Further studies on structures with footing uplift when subjected to concurrent vertical and horizontal excitations should include the flexibility of the subsoil.

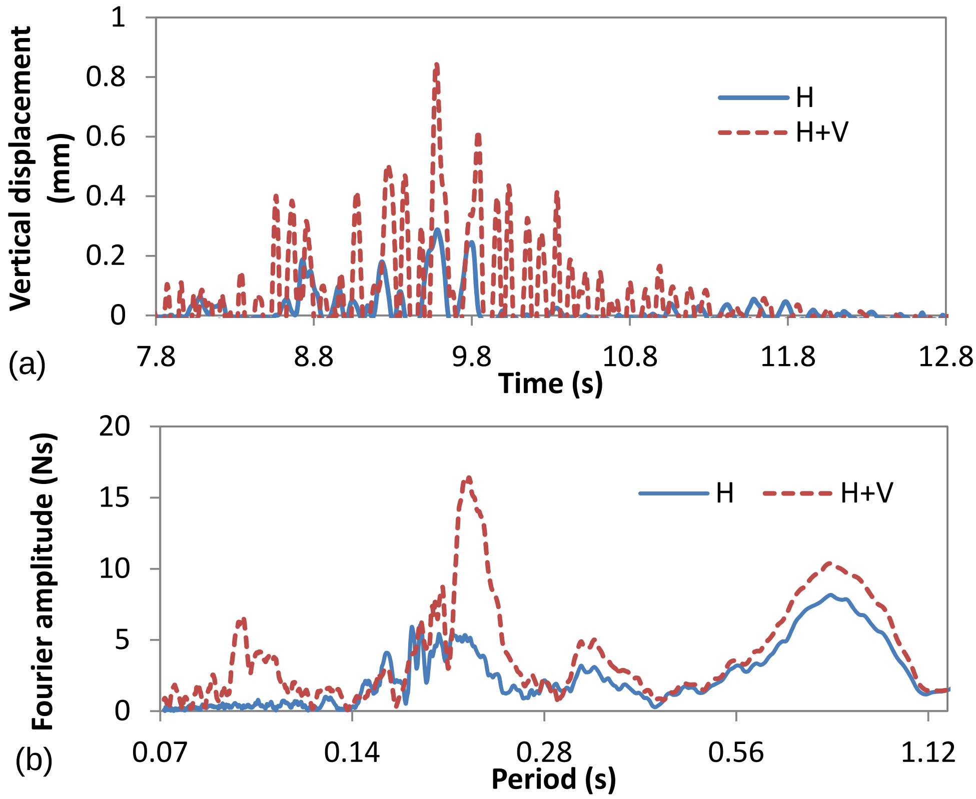

Fig. 7 (a) The time history of vertical displacement of a footing and (b) Fourier spectra of the reaction force on a footing base for the two load cases

Strain gauges were glued to detect the bending moment induced by the earthquake. Fig. 8illustrates the bending moment at the center of deck with and without uplift effectwhen subjected to horizontal excitation only. Since uplift results in a rigid motion of the structure,less relative deformation comparing to the fixed base case is anticipated. Consequently, the bending moment with uplift is less.

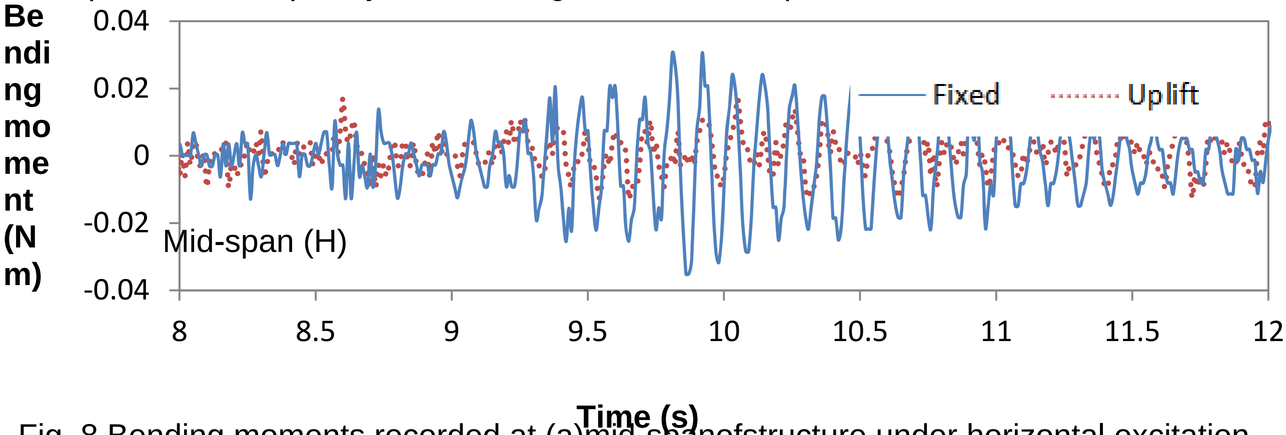

Fig. 8 Bending moments recorded at (a)mid-spanofstructure under horizontal excitation only, at (b) mid-span, (c) beam-column joint and (d) pier closed to the base of structure under simultaneous horizontal and vertical excitation

5. CONCLUSIONS

The effect of strong vertical ground motion on a structure with uplift has been studied using shake table tests of a single span bridge. An APS dynamic shaker was utilized to simulate the vertical earthquake motion and a supporting hydraulic shake table underwent simultaneous horizontalmotion. The prototype was scaled according to dimensionless analysis principles proposed by authors of past studies on small scale bridge models. In order to reveal the influence of footing uplift, two rigid base conditions were utilized, that of fixed and free to uplift. The experimentally determined responses of the model structure when subjected to scaled motion recorded at the PRPC station in the February 2011 Christchurch earthquake were presented and discussed. This investigation revealed that:

- Strong vertical motion concurrent with horizontal motion will amplify the response in all directions, especially the vertical component. The amplification is associated with the mode shape of the fundamental response in the corresponding direction.
- The seismic action of the bridge deck is very likely to be underestimated if vertical motion is not considered.
- Simultaneous horizontal and strong vertical motionwill increase the probability of uplift occurring, increase the vertical displacement ofthe footing and amplify the significance of higher frequency components.

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