The influence of vertical seismic ground motion on structures with uplift

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ABSTRACT: In the current design standard NZS1170.5 and other design specifications the vertical seismic load is assumed to be 70 per cent of horizontal load. However, in many near-source earthquakes vertical peak ground acceleration (PGA) larger than horizontal PGA have been observed. Previous investigation has shown that the strong vertical force could cause significant damage to the structure. Recent investigations indicated that structural uplift can be beneficial under strong earthquake. However, it is not clear whether the magnitude of uplift can be strongly related to the vertical load, because the effect of vertical ground motion is usually neglected. Experimental study including uplift and vertical ground motion has not been conducted so far. In order to understand the coupling effect of strong vertical ground motion and horizontal ground motion, biaxial shake table testing on a small scale single span bridge is carried out. Ground motions recorded in the recent Christchurch earthquake are applied. Two support conditions, i.e. fixed at the base and with allowable uplift, are considered. The bending moments of deck and piers will be discussed.

1 INTRODUCTION

Recent observations of earthquakes have revealed that vertical excitations have far exceeded the estimated values that the current New Zealand design standards predict. Currently the design standard NZS1170.5 (2004) estimates vertical load to be 70 percent of the horizontal load. During the 22 February 2011 Christchurch earthquake it was recorded at station HCVS (Heathcote Valley School) PGA_H was 1.41g and PGA_V was 2.21g. Also at HPSC (Hulverstone Pumping Station) PGA_H and PGA_V were 0.22g and 1.03g respectively (GeoNet, 2011).

Significant damage to structures due to vertical excitation has been observed in previous earthquakes. The 17 January 1994 Northridge, California earthquake was one of the first earthquakes to record large vertical PGA on modern buildings. Many of the building failures were attributed to brittle failure in the reinforced concrete due to direct compressive failure resulting from the large vertical actions. It was suggested that the vertical motion may lead to both shear and flexure failures (Papazoglou & Elnashai, 1996). Other investigations also suggested the possible strong impact of vertical ground motions which cannot be observed when only horizontal ground motions were considered (Chouw & Hirose, 1999, Chouw, 2002, Kodama & Chouw, 2002).

It has been noticed that foundation uplift can be beneficial to structural seismic performance (Loo et al., 2012, Ormeno et al., 2012, Qin et al., 2013). In an early research analysing the effect of uplift on base shear it was found that for a structure with short period, uplift has the effect of reducing base shear (Yim & Chopra, 1984). A numerical experiment was conducted considering the effect of uplift on a single-degree-of-freedom structure by Oliveto et al. (2003). They developed nonlinear equations of motions for the structure and concluded that the maximum horizontal displacement was greater for flexible structures than for rigid. Uplift has reduced structural responses to vertical ground motions. They also found that rigid systems were more prone to uplift. Structures that are tall and thin will uplift more easily than short and squat structures.

Because of the very limited number of physical experiments to investigate the effect of strong vertical ground motion, shake table tests were performed in this project. This experiment focused on the effect of footing uplift on a bridge subjected to both vertical and horizontal ground motions simultaneously. Two support conditions: 1) fixed at the base and 2) free to uplift, were considered. The ground motions recorded during the February 2011 Christchurch earthquake at station REHS (Christchurch Resthaven) were applied. The bending moments of the deck and pier of the bridge are discussed.

2 METHODOLOGY

2.1 *Prototype and scaled model*

To investigate the effect of uplift on the structure a 100 times scaled model was built (Fig. 1). The prototype was a single span fixed supported (proposed composite steel and concrete) bridge with the properties given in Table 1. The scaled parameters of the model were derived by the use of principles outlaid by a detailed report into scale modelling (Dove & Bennett, 1986). To replicate the effect of the earthquake on the prototype the earthquake loads had to be scaled accordingly along with the physical parameters of the structure (Tables 2). It should be noted that instead of directly scaling down the prototype, the width and depth of the cross sections were adjusted to achieve equivalent scaled lateral stiffness in the *y* direction. The fundamental frequencies of the scaled model in the *x*, *y* and *z* directions are 6.0, 5.8 and 11 Hz, respectively.

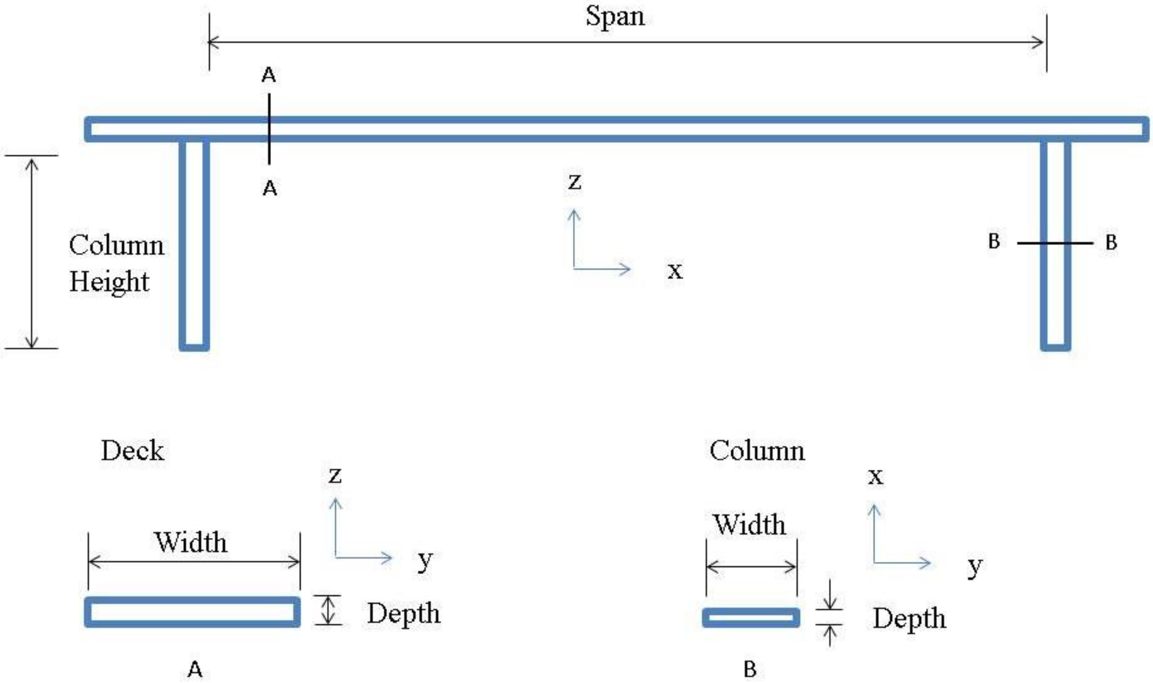


Figure 1: Bridge structure and its cross sections of bridge structure

Table 1. Prototype parameters

Span	44 m	$I_{y\text{-deck}}$	1.02 m^4
Column height	120 m	$I_{y\text{-column}}$	0.054 m^4
Column depth	0.6 m	E_{steel}	200 GPa
Column width	3 m	$E_{concrete}$	25 GPa
Seismic mass	392029 kg		

Table 2. Scale model parameters

Span	440 mm	$I_{y\text{-deck}}$	3250 mm^4
Deck depth	10 mm	$I_{y\text{-column}}$	109.4 mm^4
Deck width	39 mm	E_{PVC}	2.5 GPa
Column height	120 mm	Seismic mass	3.92 kg
Column depth	5 mm		
Column width	10.5 mm		

2.2 *Setup*

The experiment involved the use of a vertical shaker placed on top of a horizontal shake table to provide coupled vertical and horizontal accelerations (Fig. 2). The vertical shaker was fixed to the deck of the horizontal shake table. An acrylic board was fixed on top of the vertical shaker to provide a rigid platform to support the structure. The *y* axis of structure was aligned with the shaking axis of horizontal shake table.

Figure 2: Experimental setup

The following two set ups were used during the experiment. The base of the model was fixed onto an aluminium box section to simulate a fixed base condition. For the uplift tests 100 mm × 30 mm PVC footings were constructed and uplift was allowed as it was just placed on the acrylic board. To follow the development of uplift more accurately, strain gauges were placed beneath both edges of footings. Accelerometers and strain gauges were also placed on the deck and columns.

2.3 *Ground motion*

The ground motions used in this experiment were from the February 2011 Christchurch earthquake in New Zealand. The specific ground motion used was recorded at station REHS (Christchurch Resthaven). This station was one of many that recorded significant peak vertical accelerations larger than 70% of the horizontal PGA. The ratio of vertical-horizontal PGA ratio is 1.43. The time histories of the scaled horizontal and vertical ground acceleration are displayed in Figure 3.

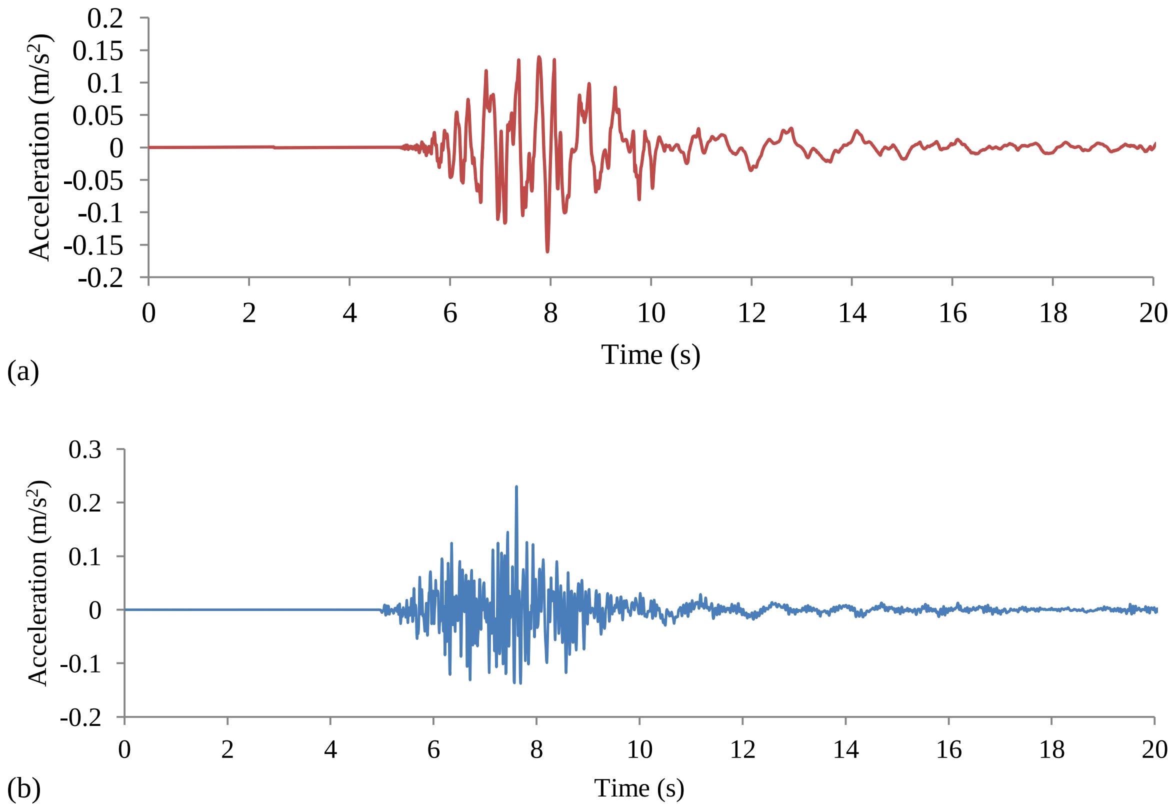


Figure 3: Scaled ground accelerations. (a) Horizontal and (b) vertical component

3 RESULTS AND DISCUSSION

3.1 *Effect of coupled vertical and horizontal ground motions*

The scaled model with fixed base supports was exposed to both pure horizontal and combined horizontal and vertical ground excitations to investigate the effect of biaxial excitations. The model was horizontally excited in the *y* direction. The acceleration responses in three orthogonal direction of the structure were investigated.

A comparison of *y* component accelerations in the deck near pier is shown in Figure 4a. A noticeable difference can be seen with the maximum accelerations for pure horizontal to biaxial excitation, which were 1.13 m/s^2 and 1.26 m/s^2, respectively. This 11% increment indicates that strong vertical excitation may increase the transversal response.

A more noticeable effect of multi-directional ground motions can be seen when examining the responses in the *x* direction (Fig. 4b). There is a significant increase to the response when the structure was subjected to combined horizontal and vertical ground motions. The peak recorded acceleration was 0.59 m/s^2 compared to 0.15m/s^2 when just horizontal ground motions were applied. With strong vertical ground motions it is clear that peak longitudinal horizontal accelerations would be underestimated if the effect of vertical motion is not considered.

As anticipated, without considering the vertical ground motions the deck response in the vertical direction is negligible. In contrast, the vertical ground motions cause a maximum vertical acceleration of 4.97 m/s^2. The result confirms the significance of considering strong vertical ground excitation. In most current design only horizontal ground motions will be considered. While this will not produce bending moment in the middle of the bridge deck, the vertical ground excitation will just cause the largest bending moment.

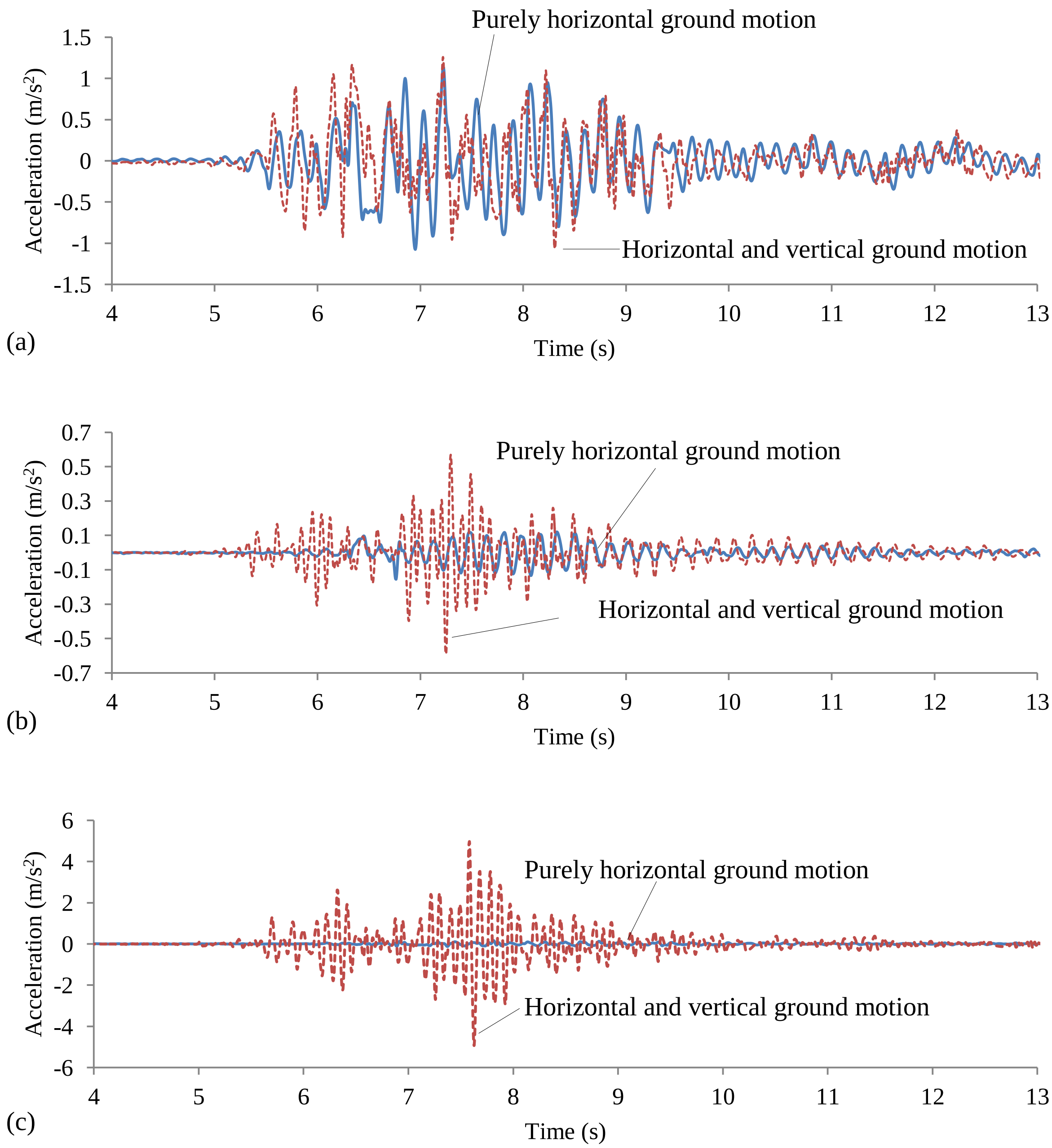


Figure 4: Effect of combined vertical and horizontal ground motions on the structure. Deck response in the (a) y-direction, (b) x-direction, and (c) vertical direction

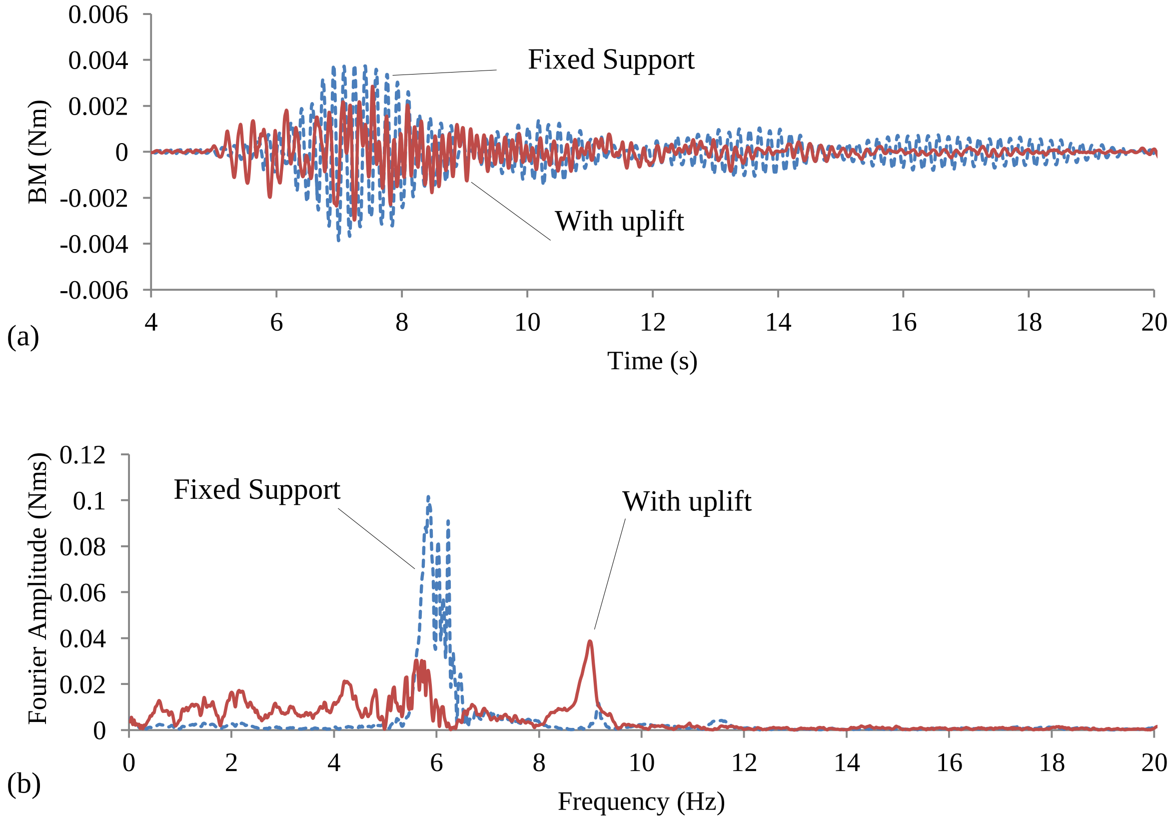
3.2 *Effect of uplift on bending moments*

The effect of uplift on the column bending moment subjected to horizontal ground excitation only can be seen in Figure 5a. With a fixed support the column bending moment reached a peak value of 0.00386 Nm. However, the peak bending moment decreased to 0.00297 Nm when uplift takes place.

The Fast Fourier transform spectrum (FFT) is plotted in Figure 5b. With a fixed support it can be seen that the amplitudes are largest around 5.8, 6 and 6.2 Hz. The maximum amplitude of 0.10 Nms occurred at 5.8 Hz. Once uplift is facilitated the response at 5.8, 6 and 6.2 Hz are significantly decreased. The maximum amplitude of 0.04 Nms occurs at 9.0 Hz. The structures natural frequency in the z component is 11Hz, uplift may have facilitated z component movement more than fixed support conditions and allowed this fundamental vertical mode to be excited.

Figure 5 shows the combined effect of the two component ground excitation and uplift on the bending moment at the bridge pier support. Figures 5a and 5c clearly show that uplift reduces the bending moment. The maximum bending moment due to the combined loading reduces from 0.028 Nm to 0.022 Nm. Figure 5d shows that uplift reduces the amplitude significantly, especially at 6 Hz. From the comparison of fixed-base case in Figures 5b and 5d it can be seen that the frequency content between 8 to 12 Hz exists which cannot be observed when pure horizontal excitation is considered. The vertical fundamental frequency was 11 Hz which explains why this content exists, as vertical motion was facilitated. With uplift, the frequency content in this range has similar amplitudes and was not reduced as significantly as at the 5 to 7 Hz range. It was also noticed that with the presence of strong vertical ground motion the frequency content is far broader than pure horizontal ground motion. This indicates that it is likely more modes are excited due to the vertical ground motions.

The bending moments at the bridge deck near the support are displayed in Figures 6a and 6b to investigate whether a similar effect due to uplift can be observed. For purely horizontal ground motions the peak bending moment was similarly reduced, from 0.0038 Nm to 0.0024 Nm. However, the bending moment due to combined vertical and horizontal ground motions does not decrease the response. In contrast, uplift increased the maximum bending moment from 0.018 Nm to 0.026 Nm (Fig. 6b). With the combined effect of uplift and strong horizontal and vertical ground motions the deck would experience a greater bending moment.



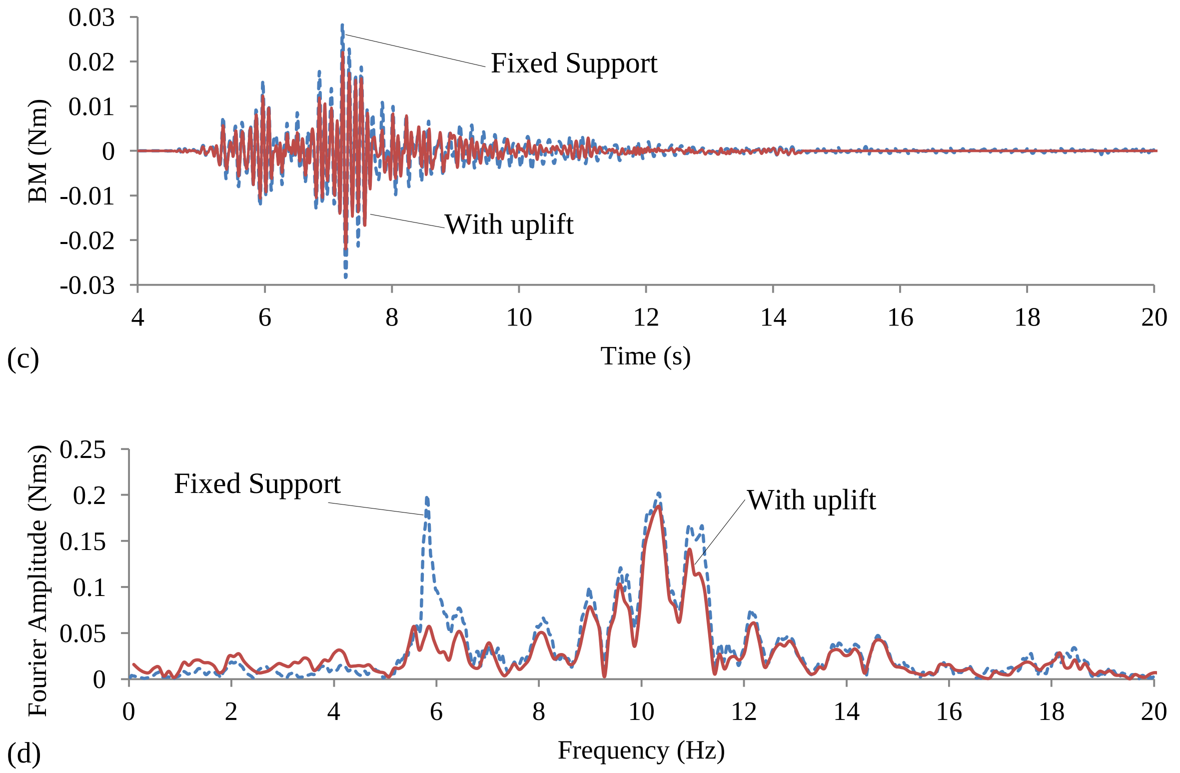


Figure 5: Effect of uplift on (a) bending moment at the column support, (b) fast Fourier transform spectrum in pure horizontal ground motion and (c) bending moment, (d) fast Fourier transform spectrum for the case of combined horizontal and vertical ground motion

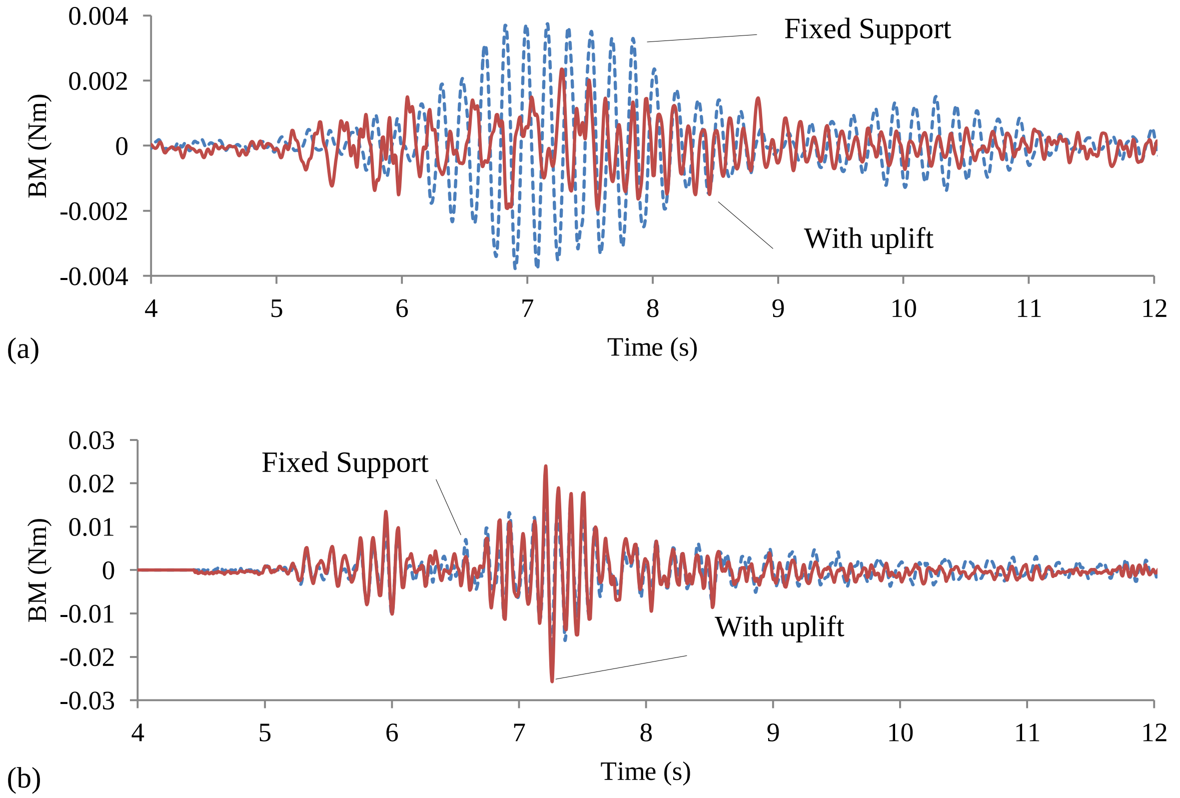


Figure 6: Effect of uplift on bending moment at deck-pier location due to (a) pure horizontal ground motion and (b) combined horizontal and vertical ground motion

4 CONCLUSIONS

The work addressed the consequence of uplift due to horizontal and vertical ground excitation for a bridge structure. The 2011 Christchurch earthquake at the Christchurch Resthaven was considered.

This experiment reveals that:

- There is a significant increase in out-of-plane and vertical acceleration of the structure when subjected to combined vertical and horizontal ground motions compared to pure horizontal motion.
- There is a slight increase of in-plane acceleration of the structure when subjected to combined vertical and horizontal ground motions.
- Under pure horizontal and combined horizontal and vertical ground excitations, the bending moments in the column was reduced when uplift was facilitated.
- Under pure horizontal ground excitations the bending moments in the deck was reduced when uplift was permitted, whilst under combined horizontal and vertical ground excitations, uplift increases the bending moment response in the deck.

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