Pounding behaviour of adjacent structures in the 2011 Christchurch Earthquake

Nawawi Chouw[1] and Hong Hao[2]

1. Corresponding author, Associate Professor, Department of Civil and Environmental Engineering, the University of Auckland, Auckland 1142, New Zealand
E-mail: n.chouw@auckland.ac.nz

2. Professor, Department of Civil and Resource Engineering, the University of Western Australia, Crawley WA6009, Australia
E-mail: hao@civil.uwa.edu.au

Abstract

The paper describes the damage to buildings and bridges due to relative movements between adjacent structures observed by the authors in the field investigation performed two weeks after the Christchurch earthquake of 22 February 2011. Relative responses of neighbouring structures occur in general as a result of the different dynamic properties of the structures. An inadequate seismic gap between buildings, especially in the central business district (CBD) of Christchurch City became a major cause of damage because it cannot cope with the large closing relative movements during the earthquake. A large number of buildings already weakened by the previous main shock on 4 September 2010 and by the several thousand aftershocks suffered severe pounding damage during the February earthquake. Damage to bridges due to the relative movement between their components occurred in conjunction with the strong liquefaction induced differential surface ground movements.

Keywords: Pounding, Christchurch earthquake, liquefaction, adjacent building, bridge

1. INTRODUCTION

After the M7.1 earthquake on 4 September 2010 struck the Canterbury region on the South Island of New Zealand several thousand aftershocks took place. The largest aftershock occurred on 22 February 2011 with a magnitude of 6.3. The epicenter was located near the town Lyttelton about 6 km southeast from the Christchurch CBD. Despite its smaller magnitude, this aftershock caused a severe destruction to Christchurch City, especially to structures in the CBD because of the shallow focal depth of 5 km and the close distance to the city. The intensity of the shaking was immediately visible from wide spread liquefied soil and flooding resulting from the bursting underground pipes. On 9 March 2011 the authors arrived in Christchurch for several days, performed several level 1 and 2 building inspections and field investigations in the red zone of the CBD, surroundings of Christchurch and in Lyttelton.

As expected the severe consequence of soil liquefaction for upper ground structures, e.g. residential houses and bridge structures can be seen in most places. Other severe damage was observed especially to unreinforced masonry buildings, i.e. old URM buildings and historical buildings like Christchurch cathedral. In the CBD the pounding damage to buildings due to their relative movements was very obvious. In total more than one hundred buildings with relative movement induced damage have been identified. Previous studies on damage due to relative movements of adjacent structures have identified the different dynamic properties of the participating structures as one of the main causes. The other significant factors are the spatial variation of ground excitation especially in the case of long extended structures, e.g. pipe systems and bridges (Bi et al. 2010, 2011, Chouw and Hao 2010) and the unequal soil-structure interaction due to non-uniform soil profile and local site conditions (Chouw 2008). It should be noted that severe pounding might induce building collapse. In the 1985 Mexico earthquake many collapses were attributed to pounding between adjacent structures. In Christchurch, no building collapse was caused solely by pounding although more than 100 pounding damage cases were observed. In this paper only a few selected pounding damage cases to buildings in the CBD and bridges in Christchurch City are presented.

2. CHRISTCHURCH GROUND MOTIONS

The strong shaking in Christchurch was caused by the event in close proximity. The other reason was that the direction of the oblique-reverse rupture towards Christchurch led to a strong directivity effect in the city. At this stage it is not clear how the activated liquefaction at the surface layer affects the surface ground motions although the liquefaction induced differential ground movement is expected. The February aftershock was characterized by much stronger magnitudes than those of the main shock motions in September 2010 (Orense et al. 2011). The February quake is also characterized by several vertical components which were stronger than the horizontal ones. Figure 1(a) shows the ground motions at the Heathcote Valley Primary School (GeoNet Strong Motion site, 2011). The epicentral distance is 2 km. The peak ground accelerations (PGAs) of the vertical and horizontal components are 14.34 m/s^2 and 14.30 m/s^2, respectively. The strong motions last for about 10 seconds. The higher frequencies of the vertical component (dash line) can also be seen in the corresponding response spectra in Figure 1(b). In the case considered the dominant frequencies of the horizontal and vertical components are below and above 5 Hz, respectively.

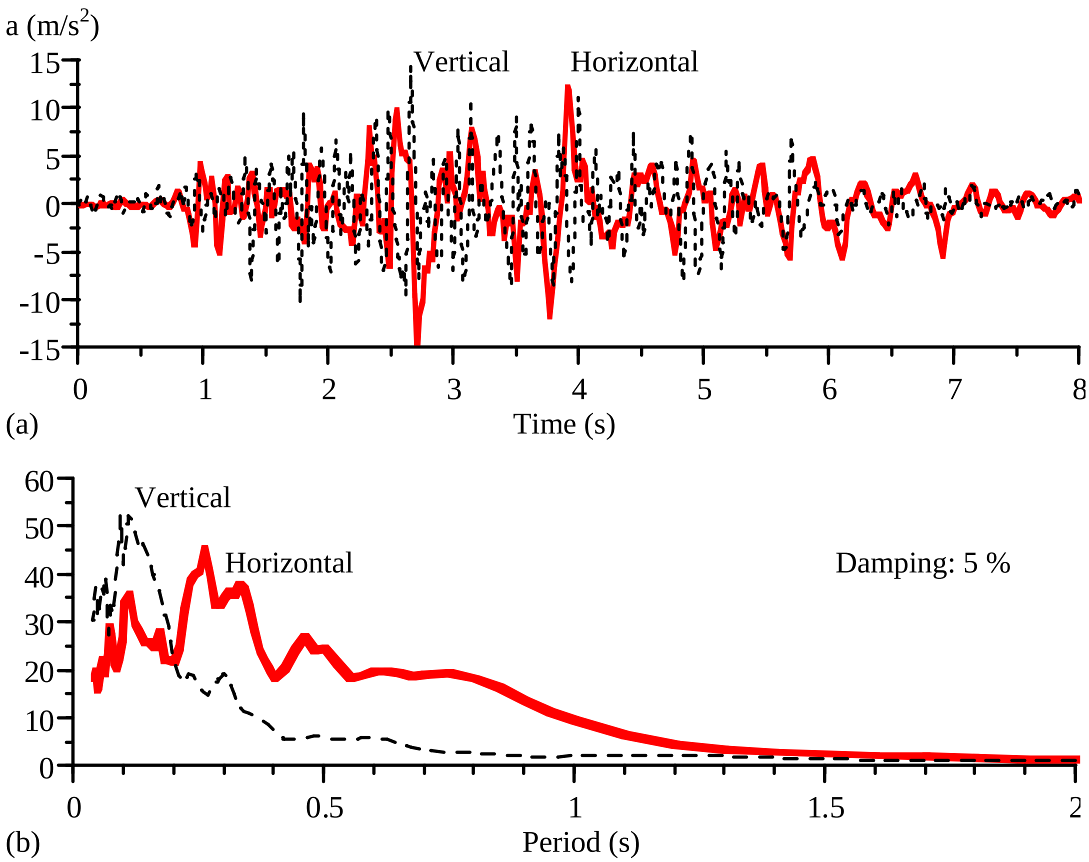

Figure 1. Acceleration recorded at the Heathcote Valley Primary School during the 2011 Christchurch Earthquake; (a) Time histories and (b) their response spectra.

3. POUNDING-INDUCED BUILDING DAMAGE

Damage due to relative movements between the structural components can be clearly seen from Figure 2. The building along Lichfield Street was under construction when the earthquake struck. All the columns pound with the floor and separate again. The pounding damage to the column indicated by a circle in Figure 2(a) can be seen in Figure 2(b).

Figure 3 shows the pounding induced damage mainly to the left building. Because of the larger openings damage occurred to all lower sections between the openings, where not all windows are displayed in the figure. However, those close to the pounding walls can be seen in Figure 3(a). Apparently, the right and stiffer building experienced less damage. The visible damage above the top window of the right building is indicated by the top right circle. Figures 3(b) and 3(c) show the damage at the locations indicated by the left and middle circles. At the location indicated by the arrow in Figure 3(a) damage is also observed even though it is not so easy to see. These observations show that a number of large openings can cause a cut-off of the entire upper structure indicated by the dash line.

(a) (b)

Figure 2: Damage due to relative movement between columns and floor in the CBD. (a) Overview and (b) pounding location.

(a) (b) (c)

Figure 3: Pounding induced damage to locations between large openings in the CBD. (a) Adjacent buildings, (b) detailed view of the left and (c) right damage locations.

Figures 4(a) and 4(b) show pounding between three adjacent buildings in the CBD. The middle building is slightly shorter than both adjacent buildings. From the external inspection no damage to the middle building was observed. In contrast, the left building has a visible damage to the parapet and the top edge column (Figure 4(c)). The right adjacent building also suffered damage at the floor level (Figure 4(d)) as indicated by the circle in Figure 4(b).

Similar observation has been made on the pounding behaviour between the adjacent buildings in Figure 5. There was practically no gap between them. Severe damage to the taller right building can be seen along the stress path about 45 degree from the pounding location toward the lower corner of the opening indicated respectively by the large circle and the lower small circle in Figure 5(a). Pounding caused a residual opening at the interface between the buildings. Damage to both buildings at the pounding location and the vicinity of the top corner of the right window can be seen in Figure 5(b). Figures 5(c) and 5(d) display the pounding induced damage to the top and lower right corners of the window of the right building. This observation shows that a consideration of wave propagation in the analysis of pounding-induced damage to the whole participating buildings might be significant.

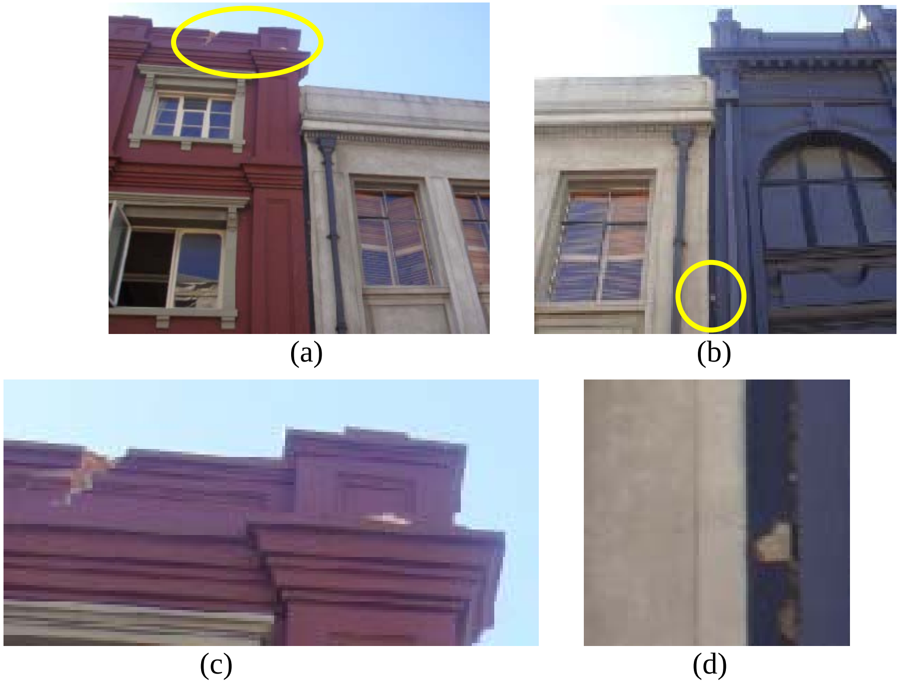

Figure 4: Pounding induced damage to adjacent buildings in the CBD.
(a) and (b) Adjacent buildings, damage (c) to parapet and (d) at the adjacent walls.

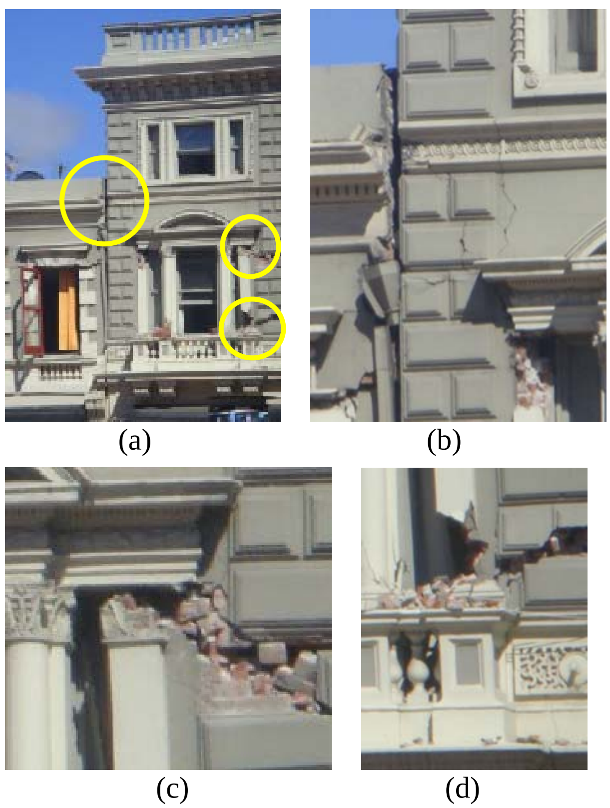

Figure 5: Pounding induced damage to adjacent buildings in the CBD.
(a) Adjacent buildings, (b) damage at the pounding location, (c) induced damage at the top and (d) at the right corner of the right window.

(a)

(b) (c)

Figure 6: Pounding induced damage to end building.
(a) Adjacent buildings, (b) damage to parapet and (c) damage to end wall.

Figure 6 shows the damage to one of the many end buildings in the CBD. The severe impact caused the loss of the entire parapet of the right building. Figure 6(b) displays the damage at the pounding location as indicated by the small circle in Figure 6(a). The induced propagating waves must be so strong that the end wall was almost pushed away (see large circle in Figure 6(a) and the developed large crack at the interface between the perpendicular walls and in the end wall in Figure 6(c)).

4. RELATIVE MOVEMENT INDUCED BRIDGE DAMAGE

The February earthquake caused damage to many bridges in the Canterbury region. Most of the damage was related to the lateral spreading and settlements of the ground surface due to strong soil liquefaction. The unequal movements of the ground at abutments, bridge approach and intermediate supports induced significant relative movements between the adjacent bridge structures. Figures 7(a) and 7(b) show the damage due to lateral and longitudinal relative movements between the segments of the Fitzgerald Avenue Bridge over Avon River just outside of the Christchurch City centre. At both locations more than 5 cm residual relative movements were observed. Pounding damage due to the closing relative movement can be seen in Figure 7(b).

(a) (b)

Figure 7: Relative movement induced damage to the Fitzgerald Avenue Bridge.
(a) Lateral relative movement and (b) opening longitudinal relative movement.

(a) (b) (c)

Figure 8: Pounding-induced damage to the Fitzgerald Avenue Bridge.
Damage (a) at the abutment, (b) to the girder and (c) to the other abutment.

Damage due to pounding can also be observed at the abutments (Figures 8(a) and 8(c)) and at the bridge girder (Figure 8(b)). Especially, at the right abutment damage occurred along the entire height of the abutment wall. A few other pounding damage cases to bridges were also observed, which are not shown here owing to page limit. As one can notice in this event, pounding only caused minor to moderate damage to bridge structures, unlike in some other earthquakes such as the 1999 ChiChi earthquake in Taiwan and the 2010 Maule earthquake in Chile that pounding pushed the bridge deck off the pier and resulted in the bridge collapse.

5. CONCLUDING REMARKS

The paper presents some observations performed by the authors two weeks after the Christchurch earthquake of 22 February 2011. The event has shown that even though the duration of the strong motions is very short the strong pulses have initiated a large number of pounding-induced damage to buildings and bridges.

The following structural relative movement induced damage has been observed:

1) One and two storey buildings with inadequate or without gap can experience severe damage due to pounding.
2) Large wall openings can significantly attract wide spread damage
3) Damage to adjacent buildings with openings will likely occur in the propagation path of the pounding-induced waves, i.e. about 45 degree from the pounding location.
4) Previous observations of more severe damage to end building are confirmed.
5) It is likely that the relative movement between adjacent structures is amplified by the unequal ground movement due to liquefaction at local site.
6) In this event pounding only cause minor to moderate damage to bridges.

The observations suggest that the overall interaction between the characteristic of the ground motions, adjacent structures and the spatial soil conditions should be considered in the future analysis of damage induced by relative movements between structures.

ACKNOWLEDGMENTS

The authors would like to thank the three anonymous reviewers for their constructive suggestions.

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