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Bridge performance during the 2010/2011 Canterbury Earthquakes

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Abstract

The 4 September 2010 Darfield earthquake and the 22 February 2011 Christchurch earthquake caused extensive damage to the city of Christchurch and adjacent areas due to soil liquefaction and related phenomena, such as settlement and lateral spreading. Following the earthquakes, the authors performed reconnaissance work and investigated the performance of road bridges in Christchurch, especially those crossing Avon River where liquefaction and lateral spreading were extensive. In general, the performance of bridge foundations, abutments, and approach fills during the September 2010 earthquake was satisfactory, although several road bridges were out of service in the days following the earthquake mainly due to damage on the approaches to the bridge induced by liquefaction, lateral spreading, and settlement of approach fills. However, none of the road bridges were damaged to the extent that they needed immediate replacement. Following the February 2011 earthquake, more bridges suffered damage due to liquefaction-induced lateral spreading at the abutments, although no bridge collapsed. Several bridges already damaged by the previous earthquake were again damaged. Detailed descriptions of the liquefaction observed following the earthquakes and the overall performance of bridges are presented in the paper.

Keywords: Bridge, Christchurch earthquake, liquefaction, lateral spreading, soil settlement

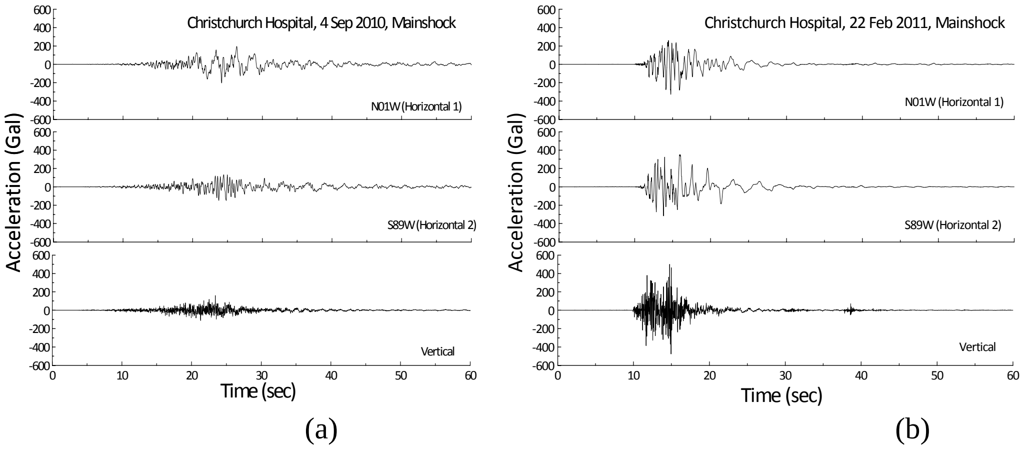
1. INTRODUCTION

On 4 September 2010, a magnitude 7.1 earthquake struck the Canterbury region on the South Island of New Zealand. The epicentre of the earthquake was located near the Darfield area, about 40 km west of the central business district (CBD) of the city of Christchurch and at a depth of about 10 km. Almost six months later, on 22 February 2011, the region was hit again by a magnitude 6.3 earthquake with epicentre located near Lyttelton, only 6 km to the southeast of the Christchurch CBD and at a depth of 5 km. In spite of its smaller magnitude, the second earthquake resulted in more damage to pipeline networks, transport facilities, residential houses/properties and multi-story buildings in the CBD than the 2010 event mainly because of the short distance to the city and the shallower focal depth. It is extremely rare to have the opportunity to learn how the same ground and infrastructure responded to two significant near-source earthquakes having different intensities of shaking.

In this paper, an overview of the occurrence and impact of liquefaction and lateral spreading on the affected areas is presented, with emphasis on the performance of road bridges. Lessons learned from these earthquakes are then discussed.

2. STRONG MOTION RECORDS

The 2010 Darfield earthquake was caused by a rupture of a previously unrecognized strike-slip fault, now well-known as the Greendale fault. During the earthquake, a series of strong motion accelerographs was triggered and motions recorded at several stations. Based on the GeoNet strong motion FTP site, the maximum recorded acceleration was in the order of 0.95g near the earthquake epicentre (GeoNet, 2010). However, no serious damage was reported in the area. In the city of Christchurch, the recorded peak ground accelerations (PGA) were in the order of 0.15g - 0.30g, as shown in Table 1. Figure 1a shows a typical acceleration record obtained during the 2010 earthquake. It is observed that the duration of significant shaking at Christchurch Hospital (CHHC), located at the southwest edge of the CBD, is in the order of about 25 sec.



(a) (b)

Figure 1. Acceleration time histories recorded at Christchurch Hospital during the (a) 2010 Darfield Earthquake; and (b) the 2011 Christchurch Earthquake (data from GeoNet strong motion FTP website). Note: 1g = 980 Gal.

The 2011 Christchurch Earthquake has an epicentre located on an unmapped fault which is different from the Greendale Fault. Yet, it is considered as an aftershock because it was caused by a fault rupture within the zone of aftershocks that followed the September 2010 main shock (NHRP, 2011). The ground accelerations experienced in the CBD as a result of the 2011 earthquake were 3-4 times greater than during 2010 event (see Table 1); in the eastern suburbs, they were about 5 times greater. A feature of this earthquake was the very strong vertical component of PGA, which in general was greater than the horizontal components. Figure 1b illustrates the time histories of ground acceleration recorded at Christchurch Hospital on 22 February 2011. Because of the shorter distance to the epicentre, the acceleration records in this earthquake have higher frequency and shorter duration time as well as larger amplitude in comparison with the ones recorded in 4 September 2010.

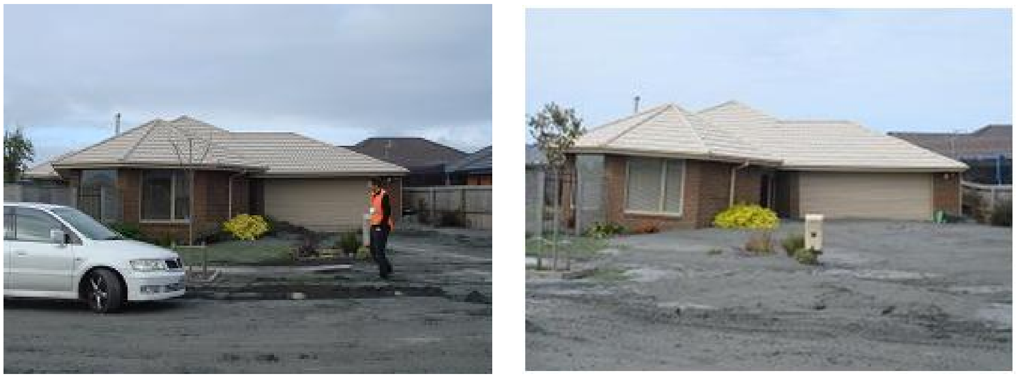
Table 1: Comparison of peak ground accelerations recorded at strong motions sites near the city during the 2010 Darfield Earthquake and 2011 Christchurch Earthquake. Data were from GeoNet Strong Motion FTP site. The unit of acceleration is g (1 g = 9.80 m/s^2)

Seismic stations	Site Name	2010 Darfield Earthquake					2011 Christchurch Earthquake				
		Ep. Dist. (km)	Vert	Hor-1	Hor-2	Max Hor	Ep. Dist. (km)	Vert	Hor-1	Hor-2	Max Hor
HVSC	Heathcote Valley	43	0.28	0.56	0.62	0.66	1	1.47	1.46	1.19	1.50
LPCC	Lyttelton Port Company	45	0.16	0.33	0.23	0.37	4	0.41	0.78	0.88	1.00
CCCC	Chch Cathedral	38	0.16	0.23	0.20	0.24	6	0.69	0.48	0.37	0.49
CMHS	ChCh Cashmere	36	0.25	0.25	0.24	0.26	6	0.80	0.35	0.38	0.42
PRPC	Pages Road Pumping	41	0.31	0.20	0.23	0.23	6	1.63	0.66	0.59	0.73
CHHC	Christchurch Hospital	36	0.16	0.20	0.15	0.20	8	0.51	0.34	0.36	0.46
REHS	Christchurch Resthaven	37	0.21	0.24	0.25	0.33	8	0.53	0.71	0.37	0.73
CBGS	Christchurch Botanic	36	0.11	0.15	0.17	0.18	9	0.27	0.53	0.43	0.64
HPSC	Hulverstone Dr Pumping	43	0.13	0.16	0.11	0.16	9	0.86	0.15	0.24	0.25
SHLC	Shirley Library	39	0.12	0.18	0.18	0.19	9	0.50	0.31	0.34	0.34

Note: Ep. Dist – Epicentral distance; Vert – vertical acceleration; Hor-1 and Hor-2 – horizontal components of acceleration; Max. Hor – calculated maximum resultant acceleration of horizontal components. Unit of acceleration is g (1 g = 980 cm/s^2). Source: GeoNet 2011.

3. LIQUEFACTION-INDUCED DAMAGE

Although structural failure of commercial buildings led to the greatest casualties in the M6.3 Christchurch earthquake, by far the most significant damage to residential buildings, bridges and other lifelines in both Canterbury earthquakes was the result of liquefaction and associated ground deformations. Liquefaction occurred in areas which are known to have a high potential to liquefy – former river channels, abandoned meanders, wetlands, and ponds. Immediately following some of the largest aftershocks



(a) (b)

Figure 2: Damage to a residential house due to liquefaction in Seabreeze Close, Bexley: (a) 2010 earthquake; and (b) 2011 earthquake.

from the M7.1 earthquake, liquefaction re-occurred in some of these areas. During the M6.3 earthquake, liquefaction was more widespread and vents continued to surge during the aftershocks immediately after the event. The impact of sand boils and cracks caused by lateral spreading was that parts of the suburbs were inundated with sand and silt – in places there were layers of ejected soil that was many tens of centimetres thick.

Following both earthquakes, liquefaction and lateral spreading were extensive in areas adjacent to Avon River, which follows a meandering course through Christchurch from its source in the west through the CBD, then towards the east, and finally flowing through to the Pacific Ocean via the Avon-Heathcote Eastuary. It is worthy to note that while major liquefied sites in the September 2010 earthquake were concentrated along Avon River, liquefaction was observed in the 2011 earthquake across a wider area, i.e., not only in the eastern suburbs but in the north and in the CBD as well. The southern portion of the Bexley suburb, which was reclaimed in the late 1990s, suffered extensive damage due to the liquefaction of the loose uncompacted fill which resulted in ground settlement and lateral spreading. Ejected sands filled up the whole neighbourhood in the 2010 earthquake, as thick as 30 cm in some areas (Figure 2a). Following the 2011 earthquake, Bexley was again one of the worst hit areas in terms of liquefaction-induced damage. Massive amounts of sand were again ejected and deposited around houses (Figure 2b). The massive sand boils ejected from underground caused differential ground settlements, resulting in tilting of many houses. More detailed comparison of soil liquefaction observed in both events is presented by Orense et al. (2011).

Following the September 2010 earthquake, the NZ-GEER-JGS Reconnaissance team conducted Swedish Weight Sounding (SWS) tests at numerous locations affected by liquefaction. SWS is a simple manually operated penetration test under a dead-load of 100 kg in which the number of half-rotations required for a 25 cm penetration of a rod (screw point) is recorded. One of the advantages of the SWS test is the ability to perform the test within a confined space in backyards of residential properties. Typical results of SWS tests conducted at two locations in Dallington and Avonside, expressed in terms of the number of half-rotations per metre, N_{SW}, are shown in Figure 3. The depth to the water table in these areas varied between 0.5m and 2.5m. It can be seen from the strength-depth profiles that in these areas, layers of about 5 m or thicker exist

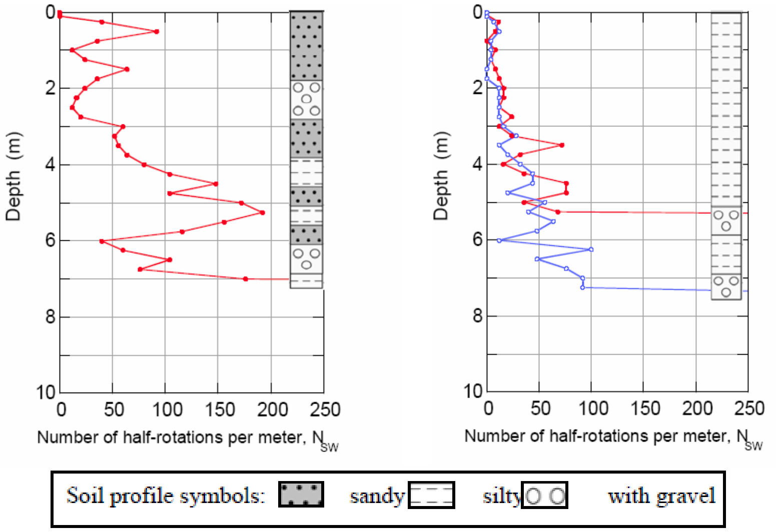


Figure 3: Post-event penetration resistance in Dallington and Avonside measured in SWS tests (after Cubrinovski and Orense, 2010).

with a high potential to liquefy (very loose silt/sand layer with N_{SW} value < 100).

4. PERFORMANCE OF BRIDGES

The Christchurch region contains more than 800 road, rail, and pedestrian bridges. Most of these bridges are reinforced concrete, symmetric, and have small to moderate spans (15 - 25 m). Following the 2010 Darfield earthquake, reconnaissance inspections showed that in general, the performance of bridge foundations, abutments, and approach fills in the earthquake was satisfactory, as almost all bridges were serviceable after the event. Information from various authorities revealed that eight road bridges were out of service in the days following the earthquake, and five remained closed for at least 5 days. Except for one bridge with structural damage, these bridge closures were due to damage on the approaches to the bridge, e.g. liquefaction, lateral spreading, and settlement of approach fills. However, none of the road bridges were seriously damaged. The most significant road bridge damage observed was the 70 m - span Bridge Street bridge in South Brighton. The bridge was reportedly closed for about 10 days following the earthquake due to differential settlement at the east abutment. However, it became apparent that repair work was already underway (Figure 4a).

(a) (b)

Figure 4: Typical damage to road bridges during the 2010 Darfield Earthquake:
(a) Bridge Street bridge; and (b) Gayhurst Road bridge

(a) (b)

Figure 5: Typical damage to road bridges within or near the CBD during the 2011 Christchurch Earthquake: (a) Colombo Street bridge; and (b) Fitzgerald Avenue bridge

Another bridge that suffered some damage was the bridge along Gayhurst Road. This bridge is relatively short, about 30 m in length with simple spans. Following the earthquake, road cracks were observed on the approaches to the bridge. These cracks had been backfilled with aggregate (Figure 4b). Cracks had been formed in the retaining walls on both approaches, however, the bridge remained serviceable.

Although liquefaction was widespread in central and eastern Christchurch following the February 2011 Christchurch earthquake, only five bridges suffered major damage and about ten other bridges developed moderate damage. Most of the damage was caused by lateral spreading of river banks. Eleven of the 14 bridges inspected along Avon River within the CBD suffered only minor damage, such as minor lateral spreading, compression or slight slumping of approach material, and minor cracking in abutments. All bridges were single span and all were passable by recovery/emergency vehicles soon after the event. Figure 5a shows buckling of roadway pavement in Colombo Street bridge as a result of liquefaction-induced lateral spreading of the river banks. Sand boils were observed on the river bed of the Avon.

The bridge along Fitzgerald Avenue just outside the CBD suffered minor damage, with its northern pier tilting slightly due to lateral spreading (Fig. 5b). Several tens of meters away from the north approach, a 50 m section of the roadway collapsed into Avon River due to liquefaction.

The Bridge Street bridge, which was damaged during the 2010 earthquake, was damaged again in 2011 due to liquefaction. Cracks were observed on the bridge approach while the western pier tilted, again due to liquefaction-induced lateral spreading (Fig 6a). A similar phenomenon was noted in the vicinity of the Avondale Road bridge, with large ground cracks observed along the banks of the river, (Fig 6b).

Figure 7 shows the consequence of soil liquefaction on the ANZAC bridge and its surroundings due to the 2011 Christchurch earthquake. The extensive sand boil in the surroundings (Figure 7a), the fissures along the walkway beneath the bridge (Figure 7b)

(a) (b)

Figure 6: Typical damage to road bridges outside the CBD during the 2010 Darfield Earthquake: (a) Bridge Street bridge; and (b) Avondale Road bridge

and the large relative permanent ground settlement, e.g. more than 20 cm (Figure 7c), clearly indicate the soil effect on the bridge site. The damage to the abutment is displayed in Figure 7(d). The rotation of the abutment due to the lateral movement of the ground surface caused pounding-induced damage between the abutment and the bridge superstructure.

(a) (b)

(c) (d)

Figure 7: Damage to the ANZAC bridge and surroundings due to the 2011 Christchurch Earthquake: (a) sand boils on local site; (b) damage to walkway beneath the bridge; (c) relative ground movement around a manhole next to the bridge; and (d) damage to bridge abutment.

Compared to the Avon River bridges, those crossing the Heathcote River on the southern side of the region suffered much less damage. Typical damage observed was minor approach settlement, with little impact on the bridge abutments and superstructure.

5. CONCLUDING REMARKS

The road bridges in Christchurch generally performed well following the two major earthquakes that shook the region. No road bridge collapsed and almost all the bridges were serviceable within a week after the earthquakes. Liquefaction and associated ground deformations were the major causes of damage to the bridges.

The Christchurch CBD bridges crossing Avon River performed well, while some of those outside the CBD underwent moderate damage. The types of damage observed for bridges along the Avon were fairly consistent, such as settlement and lateral spreading of approaches, back rotation and cracking of the abutments, and minor pier damage. The approach fill of several bridges subsided, sometimes as much as several centimeters, resulting in temporary closure of the bridges.

It is worth mentioning that most of the damaged bridges are founded on piles, and the lateral forces induced by the laterally spreading ground placed large demands on the abutment piles and this could have resulted in plastic hinging below grade. Further investigations are now underway to investigate the behavior of the pile foundations.

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