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Retaining wall performance during the February 2011 Christchurch Earthquake

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ABSTRACT

Retaining wall performance during the February 2011 Christchurch earthquake was evaluated during a post-earthquake reconnaissance mission in March 2011 and follow up assessments in 2011. More than 500 walls in Port Hills suburbs of Christchurch were observed. Most retaining walls exhibited structural damage; many retaining walls experienced structural collapse; but collapse due to ground failure was rarely observed. In addition, ground deformation behind retaining walls manifested as tension cracks and settlement. Retaining walls that supported fill performed poorly compared to retaining walls that supported native soil. Flexible walls were observed to have more ground damage than brittle walls, but brittle walls exhibited more structural damage than flexible walls. Engineered retaining walls performed well overall.

Keywords: 22 February 2011 Christchurch Earthquake, retaining wall

1 INTRODUCTION

The author participated in a post-earthquake reconnaissance mission of the 22 February 2011 Christchurch Earthquake a. The reconnaissance mission was sponsored by the Earthquake Engineering Research Institute (EERI), of Oakland, California, USA, and comprised a multidisciplinary team of engineers, medical researchers, architects, and sociologists. The reconnaissance was conducted between 10 March and 18 March 2011. Results of the reconnaissance were published in the May 2011 issue of the EERI newsletter (EERI, 2011). The effects of the earthquake on Christchurch and its surrounding suburbs are summarized in the EERI newsletter, as well as in many other publications; therefore, the purpose of this paper is to present the author's personal observations of retaining walls made during the reconnaissance mission and subsequent assessments made during 2011.

2 BACKGROUND

The 22 February 2011 Christchurch Earthquake was a magnitude 6.2 (M_W) earthquake with epicenter about 10km south of the Christchurch Central Business District (CBD). This was the second of three large magnitude events to occur near Christchurch, the first being the M_W 7.1 Darfield Earthquake on 4 September 2010, and the last being the M_W 6.0 aftershock that occurred on 13 June 2011. The 22 February 2011 Christchurch

Earthquake was the most damaging of the three and was responsible for 181 deaths (NZ, 2011), the majority of which occurred when the Canterbury Television and Pyne Gould buildings collapsed.

Outside of the CBD, more than 7,000 homes in the Port Hills suburbs reported earthquake damage. In many cases this damage was due to severe shaking of the structure, whereas the homes on the flat lands suffered from liquefaction-induced land damage. Port Hills properties also included many retaining walls and fills that comprised the majority of land-related damage on the hill side slopes. In several cases, more than a dozen earthquake-damaged retaining walls were observed on a single site.

Ground Motions

The great amount of damage to the CBD was due in part to the large ground motions, which exceeded the New Zealand Standard 1170.5, 2,500 year return period spectral acceleration for many structural periods. Ground motions experienced in the Port Hills, where the majority of earthquake-damaged retaining walls exist, were also larger than New Zealand Standard 1170.5. Figure 1 compares the New Zealand Standard design response spectra with the response spectra from the ground motions recorded at the Lyttelton Port Company in the Port Hills.

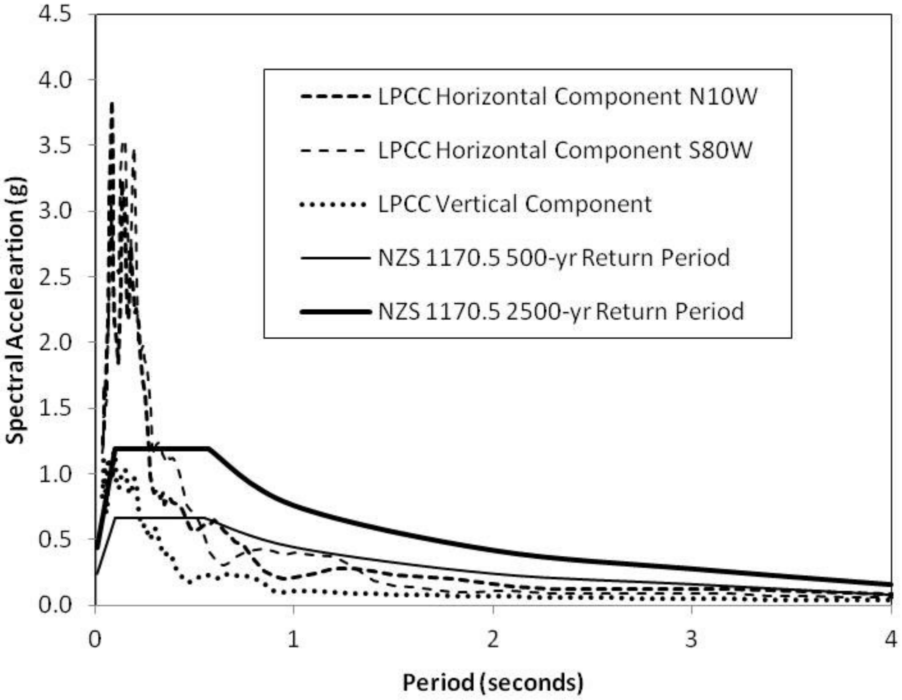

Figure 1: 5% Damped Acceleration Response Spectra for LPCC Station (GNS, 2011)

Site Conditions

The Port Hills are underlain by bedrock known as the Lyttelton Volcanic Group, which comprises layered lava and ash. The bedrock is mantled by loess (windblown glacial silt) and deeper in the valleys the loess is covered by loess-derived colluvium. The thickness of loess and colluvium ranges from a few metres to more than 50 metres.

Loess slopes are self supporting, and near vertical loess slopes several metres high exist throughout the Port Hills. For reference, typical design shear strength parameters for loess used in Christchurch are on the order c' of 5 kPa and ϕ' of 30°, but in many cases loess has demonstrated apparent cohesion on the order of 100 to 200 kPa and ϕ' above 30°.

3 RETAINING WALL SURVEY AND OBSERVATIONS

Interest in retaining walls was prompted by the observation of an anchored rock wall in Lyttelton. The wall was observed to be completely destroyed by the earthquake, but the supported native loess slope remained standing at a nearly vertical inclination (Figure 2). Additionally, an adjacent concrete crib wall was observed to be generally unharmed by the earthquake, which provided an interesting juxtaposition with the rock wall and loess slope. In response to the observation in Lyttelton, a performance survey of retaining walls was conducted, the results of which are discussed in this paper.

Figure 2: Collapsed Rock Wall and Free Standing Loess Slope in Lyttelton

A majority of the retaining walls in the Port Hills were built more than 20 years ago, well before the current New Zealand Standard. Although council consent requires structures to be designed for earthquake loading, many retaining walls were neither designed for earthquake loads, nor engineered.

Initial Survey, March 2011

More than 100 walls, ranging in height from 1 to 6m were observed in the Port Hills suburbs during the EERI reconnaissance mission in March 2011. The location of the Port Hills is shown on Figure 3. The survey was limited to walls that could be observed from public right-of-ways. Statistics of the survey are summarized in Table 1.

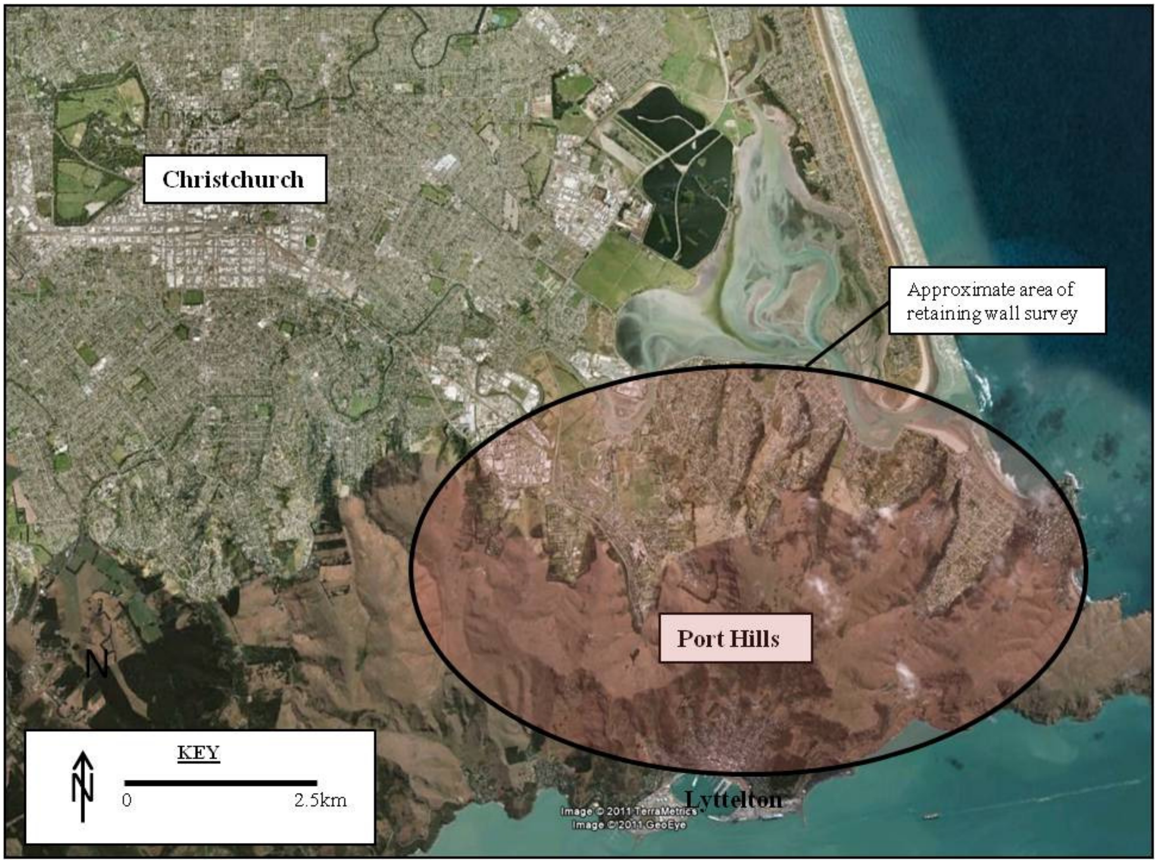

Figure 3: Site Location Map

Table 1: Summary of retaining wall survey

Number of Walls Observed	**Height (m)**	**Description of structural damage**	**Description of ground deformation**	**Description of walls with structural and ground failure**
Rock Walls (grouted and ungrouted)				
51	0.9 to 6	47% rock walls with structural damage: 13 cracked walls 6 structural collapse 5 with displaced rocks	11% rock walls with ground deformation: 6 walls with tension cracks behind wall (25 – 50 mm)	1 failed grouted rock wall, 2.2 m high
Timber Pole Walls (anchored and unanchored)				
27	1.0 to 6	22% timber pole walls with structural damage: 3 walls rotated (50 – 150 mm) 3 cracked walls	19% timber pole walls with ground deformation: 5 walls with tension cracks and settlement behind wall (50 – 1000 mm)	0 failed timber pole walls

Table 1: Summary of retaining wall survey (continued)

Number of Walls Observed	Height (m)	Description of structural damage	Description of ground deformation	Description of walls with structural and ground failure
Crib Walls (timber and concrete)				
27	1.8 to 4.6	33% crib walls with structural damage: 7 walls with broken cribs 2 walls with broken cribs and noticeable bulging	15% crib walls with ground deformation: 4 walls with tension cracks and settlement behind wall (50 – 600 mm)	3 failed crib walls: both concrete and timber, 2.1 to 2.7m high
Masonry Block Walls				
5	1.0 to 2.4	100% of masonry block walls with hairline cracks along grout line.	100% of masonry walls with settlement behind wall (25-50 mm)	0 failed masonry block walls
Gabion Walls				
3	1.1 to 1.9	0% gabion walls with structural damage	100% gabion walls with ground deformation: 3 walls with tension cracks behind wall (25 – 50 mm)	0 failed gabion walls
Cast-in-situ Concrete Walls				
2	1.0 to 1.5	0% cast-in-situ concrete walls with earthquake damage (both exhibited old cracks)	100% of cast-in-situ concrete walls with settlement behind wall (25-50 mm)	0 failed cast-in-situ concrete walls

Other Retaining Wall Observations in 2011

Approximately 500 additional retaining walls were observed by the author throughout 2011. These observations were conducted in the same areas as the initial survey, but included many observations of walls in backyards and other previously inaccessible areas. A discussion of wall composition, design, use, and performance is provided below.

Rock Walls

Rock walls were the most common type of wall observed. They were either dry or grouted and were used generally for gardens or as decoration. Dry stone walls were commonly 1m or less in height and nearly all were toppled by the earthquake. Grouted rock walls were observed to be greater height than dry rock walls, with the maximum height observed estimated to be about 6m; however, the majority of grouted rock walls were between 1 and 2m in height. Grouted rock walls were nearly all damaged; they were either cracked through the grout, experienced loss of stones, or completely collapsed. Figure 4 shows examples of rock wall performance.

Figure 4: Rock Walls (a) cracks along grout; (b) structural collapse; and (c) toppled dry rock wall

Timber Pole Walls

Timber pole walls were also commonly observed, though less frequently than rock walls. Timber pole walls provided a variety of uses, but were regularly observed protecting road reserve. Timber pole walls were frequently on the order of 2m or more in height comprising poles between 175 and 225 mm small end diameter with pole spacing of 0.9 to 1.2m. Taller walls were also anchored. Structurally, timber pole walls performed well. Most timber pole walls experienced rotation and settlement of drainage material, but were rarely observed to collapse. Figure 5 shows an example of timber pole wall performance.

Figure 5: Timber pole walls (a) good performing timber pole wall with unsupported loess slope; (b) rotated timber poles; and (c) settlement of fill behind timber pole wall

Masonry Block Walls

Masonry block walls were about equally common as timber pole walls. Masonry block walls frequently supported driveways, divided boundary lines between sites, and were used in gardens for landscaping. Masonry block walls were generally between 1 and 2m in height, but the tallest observed was about 4m. Masonry blocks were typically 140, 190, or 240mm wide. Newer masonry block walls were reinforced and performed well, but many older walls were unreinforced and performed poorly. Nearly all masonry walls exhibited at least hairline cracking through the grout, but many, presumably old and unreinforced masonry block walls, experienced more severe consequences, such as rotation, bulging, or collapse. Settlement of drainage material and fill behind masonry walls was common.

Cast-in-Situ Concrete Walls

Cast-in-situ concrete walls were uncommon. These walls were generally older walls with a variety of uses. Cast-in-situ concrete walls were observed to be on the order of 1m in height. The performance of these walls was poor, as most were rotated or severely cracked. It was often difficult to ascertain whether the damage was pre-existing or earthquake-related. All cast-in-situ concrete walls were reinforced.

Crib Walls

Crib walls were initially thought to be a common wall type in Christchurch because the March 2011 survey was conducted from the roadway, where most crib walls are located. After further observations, crib walls, both timber and concrete, were found to be uncommon compared to other wall types because they were not typically used within the properties. The crib walls observed were generally tall, on the order of 2 to 4m. Nearly all crib walls were broken and contained displaced cribs. Many had collapsed. Settlement of fill behind crib walls was also a common feature. Figure 6 shows some examples of crib wall damage.

Figure 6: Crib walls with (a) displaced and settled concrete cribs; (b) settlement of fill behind timber crib wall; and (c) collapse of concrete crib wall

Gabion Walls

Gabion walls were the least commonly observed type of wall. Gabion walls were on the order of 1 to 2m in height and were typically used for roadway support. Settlement was observed behind all gabion walls. Structural collapse of gabion walls was not observed, but bulging and deformation of the gabion baskets was ubiquitous.

4 OBSERVATIONS AND CONCLUSIONS

Retaining walls experienced a range of performance during the 22 February 2011 Christchurch Earthquake. A survey of retaining wall performance was conducted during a post-earthquake reconnaissance mission about three weeks after the earthquake, and was supplemented with additional observations over the course of 2011. The retaining wall survey highlighted three key conclusions:

Walls that retained fill performed poorly

Walls that retained predominantly native soil (loess) performed well, whereas walls that retained predominantly fill performed poorly. In general, retaining wall damage went hand in hand with areas of fill.

Fill is expected to settle, and this was evident in the Port Hills. Settlement of fill was observed behind a majority of walls to varying degrees. The most extreme settlements were behind timber pole and crib walls, but these were also among the tallest walls observed (supporting the greatest thicknesses of fill and drainage material). Many fills settled on the order of 100mm or more.

Flexible versus brittle

Flexible and brittle walls exhibited different performance. Flexible walls, such as timber pole and crib walls, were the least structurally damaged, but the retained fill behind flexible walls exhibited large magnitudes of settlement. Conversely, brittle walls (grouted rock and masonry block) were frequently cracked or structurally collapsed, but exhibited less extreme settlement than flexible walls. These observations are consistent with expectations in that settlement behind flexible walls is partially due to relaxation of the wall, and structural damage to brittle walls is due to the walls inability to accommodate the large ground motions.

Engineered retaining walls performed well

Retaining walls that were engineered, that is walls that were reinforced and included a reasonable footing size, were among the best performing walls. It was not apparent to what degree each wall was engineered or to what design strength and loading was used; but, walls that were new looking or were indicated by the owner as having been engineered exhibited the following characteristics: the wall showed minimal cosmetic cracks or no cracks at all; the wall was vertical or laid back with no indication of sliding or rotation; and the supported ground was minimally distressed.

Engineered walls were not designed for the ground motions experienced during the earthquake based on the fact that the actual ground motions were significantly larger than the New Zealand Standard 1170.5 design ground motions. Council building codes require that seismic loading be considered pseudostatically, and walls must achieve various factors of safety for serviceability and ultimate limit states. The fact that engineered walls performed well is due to the conservative design assumptions (eg. loess shear strength parameters) and may be an indication that typical pseudostatic design procedures for seismic loading on low-importance level retaining walls is overstated.

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