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Seismic performance of retaining walls on the Christchurch Port Hills during the 2010/2011 Canterbury Earthquakes

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ABSTRACT

The retaining walls in the Christchurch Port Hills were exposed to strong ground motions associated with numerous seismic events during the Christchurch Earthquake Sequence. Measured horizontal peak ground accelerations during the larger earthquakes ranged from 0.2g to 2g, with large vertical accelerations in excess of 1g. The strong ground motion resulted in damage to many retaining walls.

Retaining walls on the Port Hills provide either structural support to fill materials or act as non-structural facings to limit erosion of loess or pyroclastic cut faces. Many of the walls are over 40 years old, having limited site specific engineering design consideration of earthquake loading. The observed performance of the walls was generally very good compared to the theoretical assessment of the earthquake loadings experienced. Many of the walls that were considered to have limited seismic resilience appear to have experienced negligible to minor damage.

This paper discusses wall performance observations considering; proportion of the wall assets damaged, relative performance for the range of wall types and materials, typical failure mechanisms, influence of backfill material type, wall height, and spatial location. Proposed factors contributing to the observed wall performance include; cohesion of the loess, pyroclastic and backfill materials; wall displacement without structural damage; shaking directivity; and consideration of surcharge in static wall design. Assessment is based on Christchurch City Council retaining walls in the Port Hills, which were reviewed as part of the Stronger Christchurch Infrastructure Rebuild Team (SCIRT) earthquake rebuild.

Keywords: SCIRT, retaining wall, earthquake, performance, Christchurch

1 INTRODUCTION

Christchurch's retaining walls on the Port Hills were subjected to very strong ground motions during the Canterbury Earthquake Sequence (CES) throughout 2010 and 2011. Some of the Christchurch City Council (CCC) owned retaining walls suffered extensive damage and collapse. The most significant retaining wall damage resulted from the 22 February 2011 (M_w6.2) and the 13 June 2011 (M_w6.0) events, which had epicentres located directly beneath or adjacent to the Port Hills.

The SCIRT alliance was established in response to the extensive damage sustained during the 22 February 2011 earthquake. This alliance comprises the New Zealand Government (CERA and NZTA), Christchurch City Council (CCC), and 5 civil contractors. SCIRT is supported by an integrated design office of engineers from 14 local engineering consultancies. SCIRT was tasked with the assessment and repair of earthquake damaged infrastructure, creating a legacy of earthquake resilient infrastructure, whilst also providing value for the client organisations.

SCIRT's scope included the assessment of around 1000 retaining wall assets on the Port Hills to identify the extent and severity of earthquake damage. Following this assessment, a prioritisation score was developed for each wall considering the significance of the wall, damage severity, and the consequence of significant damage or collapse. This assessment and prioritisation score was then used to select and prioritise the repair of 440 walls which were included in the SCIRT rebuild programme.

This paper discusses the observed extent, severity and nature of earthquake damage to retaining walls on the Port Hills. It focuses on compiling lessons learnt that can be considered in future design. The approximate 1000 retaining walls within the Port Hills, owned by CCC, have been included in this study. The authors are familiar with a large proportion of the walls within the dataset, having undertaken condition assessments and/or design of earthquake remedial works for many of the walls.

2 PORT HILLS GEOLOGY

The Port Hills form the northern spur of the extinct Lyttelton Volcano that erupted between 9.7 and 11 million years ago (Sewell et al., 1988). The geology comprises Lyttelton and Mt Pleasant Formation volcanics made up of extremely variable volcanic derived rock. This includes an alternating stratigraphy of basalt lava flows and pyroclastic material, both of varied degrees of weathering. Strength parameters for the volcanic deposits allow cut slopes to be self-supporting.

Wind deposited erodible loess mantles the volcanic rock on some of the less steep slopes and valleys where it has washed down and been mixed with volcanic rock debris to form loess Colluvium. Undisturbed dry to moist loess exhibits high apparent cohesion, allowing it to be self-supporting on large cut slopes. However, once disturbed or wet, loess and loess Colluvium loses much of its apparent cohesion.

Fill makes up the remainder of the geological setting on the Port Hills. Historically fill has been placed in a non-engineered manner in the older areas of development. Zones of unsuitable materials or poor compaction can be encountered. Inspections have shown that the quality of filling generally improves with the more recent the development. Typical fill materials consist of reworked loess and loess Colluvium, cut volcanic material and granular backfill materials.

3 CANTERBURY EARTHQUAKE SEQUENCE STRONG GROUND MOTION

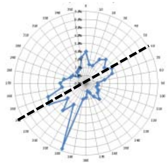
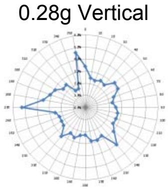
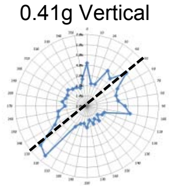
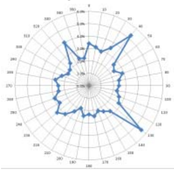
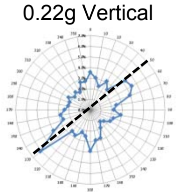
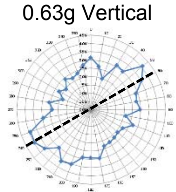
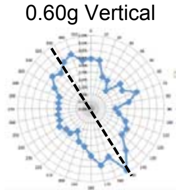
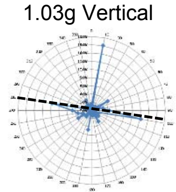
The Christchurch Earthquake Sequence (CES) commenced on the 4 September 2010 with the Darfield Earthquake (M_w7.1). An extensive aftershock sequence followed with over 4000 earthquakes (>M_w3.0). The most significant earthquakes were the 22 February 2011 Christchurch Earthquake (M_w6.2) and 13 June 2011 earthquake (M_w6.0), both triggered by faults passing beneath the Port Hills. Strong ground motion associated with these earthquakes was significant, with horizontal and vertical peak ground accelerations (PGAs) recorded on the Port Hills exceeding 1g (refer Table 1).

Observations in the Port Hills show that structural damage manifested more prominently at ridge top and cliff edge. The authors believe this is associated with topographic amplification effects. As shear waves travel from their source they reflect off the sloping ground surface and focus towards the crest (Kramer, 1996).

Velocity and displacement strong ground motion records from seismographs located on the Port Hills identified shaking directivity. The Lyttelton Port Company (LPCC, rock) seismograph exhibited consistent directivity on an orientation of 50^o / 230^o for each of the Darfield, Christchurch and 13 June earthquakes (refer Table 1). This directivity correlates with the orientation of the ridgeline located upslope of the seismograph. Analysis of seismographs on alluvial soils, such as Riccarton High School (RHSC) founded on deep alluvial gravels, contrasts the consistency of shaking directivity observed on the Port Hills. Insufficient records are available for seismographs on Clifton Hill (PARS) and at Scarborough (GODS) to establish directivity trends.

Following the Christchurch Earthquake, GNS Science installed small-scale temporary accelerometer arrays on the Port Hills. Kaiser et al (2013) identified in this study that local topographic shape and/or lithology strongly influences ground motion in areas of highly variable topography. Amplification and polarization of strong ground motion occurs over short distances. Refraction of shear waves around topographic features leading to polarization could explain the observed directivity in shaking at LPCC. Similar observations of polarization and topography focusing shaking directivity, and therefore focusing structural damage, have been observed following the 2014 Cephalonia earthquake sequence, Greece (GEER/EERI/ATC 2014).

Table 1: Port Hills Strong Ground Motion

Earthquake	Peak Ground Accelerations and Directivity Orientation[1]			
	Lyttelton (Rock) [LPCC]	**Heathcote Valley [HVSC]**	**Clifton Hill [PARS]**	**Scarborough [GODS]**
4 September 2010, M_w7.1 [Epicentre ~40km west]	**0.38g Horizontal** 0.13g Vertical  Directivity: **60° / 240°**	**0.66g Horizontal** 0.28g Vertical  Varying Directivity	Not Commissioned	Not Commissioned
22 February 2011, M_w6.2 [Epicentre 0-5km]	**1.00g Horizontal** 0.41g Vertical  Directivity: **50° / 230°**	**1.51g Horizontal** 1.46g Vertical  Varying Directivity	Not Commissioned	Not Commissioned
13 June 2011, M_w6.0 [Epicentre 0-5km]	**0.63g Horizontal** 0.22g Vertical  Directivity: **50° / 230°**	**1.00g Horizontal** 0.63g Vertical  Directivity: **60°/240°**	**0.83g Horizontal** 0.60g Vertical  Directivity: **150°/330°**	**1.87g Horizontal** 1.03g Vertical  Directivity: **100°/280°**

[1] Dominant directivity orientation from seismograph velocity records. Raw data modified for this assessment sourced from www.geonet.org.nz, web address ftp://ftp.geonet.org.nz/strong/processed/Proc.

4 PORT HILLS RETAINING WALLS

4.1 Retaining Wall Type on the Port Hills

Residential development on the Port Hills has been ongoing for approximately 150 years. Throughout this period, trends in development and changes in engineering methods have resulted in a range of retaining wall types being present on the Port Hills. Observations indicate many of the retaining walls in the Port Hills were not engineered, with very few engineered for seismic loading. Apart from walls associated with state highways, retaining walls are not generally designed for earthquake loading (Wood 2014). CCC retaining walls are typically associated with the roading network on the Port Hills; of which approximately half are constructed downslope of local and arterial roads to support the carriageway. The remainder of the CCC retaining walls are located above roads supporting cut slopes or fill platforms. CCC owned retaining walls can be split into six main wall types:

- "Non-Structural" Stone Facing
- Post and Panel
- Gabion Basket
- Concrete Crib
- Reinforced Concrete
- Timber Crib

4.2 Retaining Wall Earthquake Damage

4.2.1 Assessment

At the commencement of SCIRT, the structures asset assessment team collated and rationalised data from various sources including; CCC asset database, structural assessments, and topographical surveys. The data was managed through RAMM (Road Assessment and Maintenance Management), providing a single source of information, which could be viewed through the SCIRT GIS system. There were a significant number of additional walls located previously unknown to the council. Through the council ownership review process, these were incorporated into the rebuild programme where appropriate.

Extensive further fieldwork was undertaken by SCIRT to confirm key attributes of the retaining walls including location, wall type and condition. Refinement of the data set was undertaken during the concept and detailed design stages.

The condition rating of the walls was performed in a subjective manner based on observed visual condition and comparative observations. A simplified condition rating system was developed to describe the nature of earthquake damage, details are provided in Table 2. This condition rating was considered along with factors affecting the potential hazard and consequence of wall failure, to develop a remedial works prioritisation.

Table 2: Retaining Wall Condition Assessment Categorisation and Descriptions

Damage	Category Description
None	No/very minor earthquake damage to wall structure or road asset. No repairs or minor works required.
Minor	Minor earthquake damage to wall. Minor repairs required to maintain integrity of wall and/or long term durability/longevity.
Moderate	Moderate to major earthquake damage to wall; e.g. displacement, partial collapse, bulging. Minor to major damage to road asset, e.g. cracks, minor depressions or damage requiring resurfacing. Low to moderate likelihood and consequence of failure.
Major	Collapse of wall and/or severely damaged. Majority of this damage affects the road and poses a risk to the public. High likelihood and/or consequence of failure/collapse.

4.2.2 Severity of Wall Damage

Inspection and recording of earthquake damage to retaining walls following the Darfield Earthquake was limited. Generally the nature of this damage was Minor, or damage could not be observed.

Following the Christchurch earthquake and 13 June earthquakes, CCC retaining walls sustained a wide range of damage and a higher severity was recorded. Table 3 provides a summary of the proportion of wall damage for the severity categories and wall type. Analysis considers a 967 wall data subset of CCC owned walls on the Port Hills. Visual examples of the nature of Major wall damage are provided in Figure 1.

Table 3: Summary of CCC owned retaining wall damage categorisation for wall type

Wall Type	Proportion of Data Set	Damage Categorisation			
		None	***Minor***	***Moderate***	***Major***
“Non-Structural” Stone Facing	43%	47%	19%	16%	19%
Post and Panel	16%	64%	27%	6%	3%
Gabion Basket	14%	33%	36%	27%	3%
Concrete Crib	13%	42%	29%	21%	9%
Reinforced Concrete	11%	42%	36%	16%	6%
Timber Crib	3%	48%	24%	24%	4%
Summary	*100%*	*47%*	*26%*	*17%*	*11%*

The most common retaining wall type is “non-structural” stone facings. This type of wall has been adopted since the time of the early settlers, as considered an appropriate protection for the highly erodible loess slopes. These walls have historically been of relatively low cost and are aesthetically pleasing. Where constructed in front of self-supporting loess cuts, damage and failure of the facings were largely observed to be associated with dynamic inertia forces from the wall mass. The data subset considers “Non-structural” stone facings and “stacked stone gravity walls” as the same wall type. It was difficult to distinguish the difference where collapse was not observed or geotechnical investigation not performed. Where stacked stone gravity walls retained fill materials (volcanic gravel through to boulders, silt and demolition waste), the walls exhibited very low levels of seismic performance. This is consistent with independent observations. Dismuke (2011) suggested that walls that retain fill performed predominantly poorly.

Figure 1. Examples of Major retaining wall earthquake damage

Post and panel, gabion baskets, concrete crib, reinforced concrete, and timber crib have been utilised in more recent residential developments on the Port Hills. They have exhibited improved levels of seismic performance compared to walls constructed in earlier phases of development. Timber has been predominately used for post and panel walls, however other materials used include steel railway iron posts or precast concrete panels. The construction standard of reinforced concrete walls also varies, in some cases only minimal reinforcement is present (typically those which performed poorly in the earthquakes).

4.2.3 Effects of Retaining Wall Damage

Major damage to retaining walls resulted in significant adverse effects on the public especially local residents, functionality of the road networks was decreased, and adjacent infrastructure assets were damaged. Key effects included:

- Restricted or limited road use due to loss of retaining wall support and or debris, temporary buttressing required to maintain stability, and later reconstruction.
- Extensive damage to road pavements, kerb and channel, footpath and pedestrian safety fences
- Damage to buried horizontal infrastructure adjacent to retaining wall damage areas.
- Saturation and erosion of slopes due to uncontrolled stormwater discharge, leading to development of tunnel gully erosion (piping failure), wall failures and slope instability
- Safety hazards associated with unstable structures or unsupported soil, in some cases preventing occupancy, and or repair and rebuild of private property

Walls with only Minor and Moderate wall damage displaced and deformed, but continued to provide post disaster functionality even if it was of limited resilience.

4.3 Causes of Retaining Wall Failure

4.3.1 Failure Mechanisms

The retaining walls in the Port Hills failed in a number of ways. These failure mechanisms were dependent on ground accelerations experienced, wall type, rockfall impact, global slope stability and workmanship. Observed typical failure mechanisms for the various wall types are summarised below:

- <u>Non-Structural Stone Facing</u>: Loosening, movement or unravelling; loss of stone/blocks; bulging or outward displacement of the wall crest; partial or complete collapse. Many facings collapsed though the competent loess behind remained self-supporting.
- <u>Gabion</u>: Wall translation, bulging and overturning of wall; deformation and settlement of the rounded stone infill (typical) within baskets; partial or complete collapse; settlement of backfill materials.
- <u>Post and Panel</u>: Outward rotation of the wall; structural damage to individual members (panels, posts, wailers and anchors).

- Reinforced Concrete: Cracking, bulging, outward rotation, separation from end connection(s) (where applicable); exposure of reinforcing (through major cracking or cover falling off); partial or complete collapse.
- Concrete Crib and Timber Crib: Loss of infill aggregate; wall translation and bulging of wall; member movement and damage, loss of member interlock and unravelling; partial or complete collapse; settlement of backfill materials.

4.3.2 Influence of Strong Ground Motion Bias on Wall Damage

A subset of 162 CCC retaining walls having a minimum retained height of 3m was reviewed for influence of strong ground motion topographic amplification and directivity on wall damage. Wall face orientation, and wall spatial location relative to ridges, cliffs and slopes on the Port Hills was recorded for each wall. A simple damage index was developed to numerically quantify the proportioning of wall damage categorisation. Review identified a weak, though not conclusive, trend suggesting a minor increase in wall damage severity when the front face was orientated 50-90^{o} / 210-250^{o}. This trend links in with strong ground motion directivity recorded at LPCC, and the general orientation of the northern spurs of the Port Hills. Reliable conclusions cannot be drawn from this assessment due to the; size of the data set, local topographic variation in strong ground motion, and the severity of ground accelerations in all directions masking trends.

Review of damage severity related to spatial location on the Port Hills identified a clear trend with majority of wall damage occurring within the lower half of the slopes and ridges. This observation can be explained by the progression of urbanisation, commencing on the lower slopes progressively extending upward with development. The non-structural stone facing walls that exhibited lowest seismic performance dominate the lower slopes, with the walls associated with modern development in the upper slopes (post and panel, timber crib and gabion) performing relatively well during the CES. Increased severity of wall damage with proximity to ridge crest or cliff top was not identified in the dataset reviewed, unlike that clearly observable with residential dwellings. This highlights potential bias, and the technical complexity and variability of strong ground motion and seismic response and performance of retaining structures. Conclusions could not be drawn with respect to effects of topographic amplification on retaining walls on the Port Hills during the CES. However, consideration of topographic amplification in retaining wall design and assessment is recommended.

5 LESSONS LEARNT

5.1 Design Considerations

Back analysis of walls within the SCIRT programme of works identified that many retaining walls performed better when exposed to the high ground accelerations during the CES than theory and typical retaining wall design methods would predict. This is due to conservatism in assumptions and simplifications that are made during the design process. Key factors contributing to better than expected wall performance include:

- Flexible retaining walls have the ability to displace outward without collapse. Displacement significantly lowers seismic earth pressures and therefore a significant reduction in collapse potential. Rigid walls which had inadequate capacity for the earthquake loading typically exhibited poor performance.
- The high apparent cohesion of competent undisturbed loess limits static and seismic earth pressures applied to the retaining wall.
- Conservatism when assessing soil parameters and material strengths.
- Strength reduction factors adopted in limit state design provide factors of safety against triggering of wall damage and failure.
- Consideration of surcharge design loads for walls designed for static loading only – provides additional capacity during seismic events.
- Wall shape has also been observed to affect the amount of damage sustained to retaining walls, such as concave shaped retaining walls which exhibited benefit from arching.

Bray and Travasarou (2010) conclude that field performance observations and experimental evidence indicates that well-built retaining wall structures with competent ground conditions and quality backfill perform satisfactorily at moderate levels of ground shaking (<0.3g). The observations of the limited extent and severity of earthquake damage to retaining walls on the Port Hills following the Darfield Earthquake (~0.2g) further supports Bray's conclusions. The authors suggest that damage from the Darfield Earthquake was likely under reported. Displacement magnitudes anticipated for the strong ground motion experienced would not have been observable in many cases, without close inspection and understanding of baseline conditions.

5.1.1 Wall Type

The level of seismic performance of different wall types was not consistent. It was observed that often the selection of the specific wall type at the design stage had more influence in dictating performance than the project design criteria (comparing relative performance). Though many retaining walls provided continued minimum functionality post-earthquake, the displacement or deformation of the wall decreased stability and residual durability to levels significantly lower than pre-earthquake. Many cases required seismic retrofit or rebuild was required for these reasons. Wall types that exhibited overall good seismic performance, comprise the following groups:

- Flexible timber post and panel walls. Walls that were tied back exhibited the highest level of performance.
- Semi-rigid and flexible reinforced concrete walls. Few examples of these walls are present on the Port Hills, and where poor performance was observed this could be attributed to no or poor design. The authors believe that if designed appropriately, reinforced concrete walls can exhibit good seismic performance and can provide a 100-year design life. Many of the SCIRT designed replacement walls have utilised reinforced concrete.
- Flexible timber crib walls, exhibited reasonable seismic performance. These generally provided continued albeit reduced functionality post-earthquake. However, these walls often required retrofit or replacement to repair excess deformation or displacement.
- Gabion walls can provide adequate performance if constructed with well compacted infill material with good interlock, placed in a stepped back manner, and with adequate separation to critical infrastructure to mitigate influence of deformation.

The observed trends of directivity in strong ground motion and retaining wall damage were useful for assessment of performance of retaining wall types during the CES, as discussed in this paper. The authors do not recommend any adjustment from current retaining wall design assumptions of applying the design acceleration perpendicular the wall face. However, consideration of topographical amplification of design accelerations is recommended. The recently released MBIE (2014) guideline for seismic design of retaining wall structures in the greater Christchurch provides a topographic amplification factor for wall design.

5.2 Influence of Loess on Wall Performance

Retaining walls with loess cut slopes behind performed well (Dismuke 2011). These were predominantly non-structural stone facings, which performed much better than expected. Undisturbed loess was largely self-supporting during the earthquake, due to the relatively high apparent cohesion associated with negative pore water pressures (suction forces). Where these facings failed, it was generally due to the horizontal seismic inertia of the facing material itself, resulting in bulging and toppling failure. Un-pointed (no mortar between stones) stone walls failed due to internal sliding of blocks and unravelling of the wall.

Observations following the CES have discovered that many loess slopes sustained minor Newmark Sliding Block type slope failures of small magnitude (<100mm displacement). This resulted in distributed ground cracking. These typically thin cracks (<10mm) have provided pathways for water to manifest within the loess. Water is able to flow down below the frangipane layers that previously limited further ingress. When competent loess becomes saturated the material loses its apparent cohesion. Cohesion reduces to that of firm to stiff silt, resulting in the wall experiencing a larger magnitude earth loading. If exposed to multiple large earthquakes (like that observed in the CES), and high or prolonged rainfall events, loess slopes may progressively exhibit increasing poor retaining wall performance and increased frequency of associated slope failures.

5.3 Wall Materials

It is important to consider properties of backfill and infill (crib and gabion) material when designing retaining walls. The quality of backfill and infill both material type and placement has been an important factor in the failure of many of the retaining walls on the Port Hills. Backfill type can influence seismic loading on the wall and mobility of the seismic soil wedge during strong ground motions.

Rounded aggregates, which were historically used extensively on the Port Hills, were observed to exhibit settlement during the CES where not adequately compacted. Rounded aggregates can also promote permanent outward wall displacements during dynamic shaking of the structure through 'ratcheting'. Ratcheting occurs when backfill materials fall or roll to fill the void created by outward displacement of the wall during shaking. This prevents a return of the wall to its original position. To counter these effects, the authors recommend aggregates used in retaining wall construction be a well-compacted, permeable, well-graded and angular granular material. If river sourced aggregates are utilised, they should be crushed to introduce broken faces to allow for interlocking.

6 CONCLUSIONS

Observation of seismic performance of retaining walls on the Port Hills during the 2010/2011 CES provide valuable information to inform seismic design and detailing of future retaining walls. The following key conclusions have been reached:

- The seismic performance of retaining walls on the Port Hills was very good considering the significant ground accelerations and multiple earthquakes. Engineered flexible walls exhibited the best performance, displacing and deforming reducing seismic loading.
- Moderate ground motions during the Darfield Earthquake (~0.2g) typically resulted in very minor damage to retaining walls.
- Spatial location and topography can influence experienced strong ground motion. However, in the Port Hills during the CES the ground accelerations were sufficiently high in all directions and locations that only weak trends were observed with the assessed wall data subset.
- When selecting retaining wall options, designers should consider potential failure mechanisms as part of the design process, and consider how these failure mechanisms might affect adjacent infrastructure and private property. Where allowance for displacements is designed into retaining walls, care must be taken to ensure the wall structure can accommodate this whilst still maintaining functionality.
- Competent loess was observed to be typically self-supporting, therefore imparting only limited earth loads onto walls. However, the loess is adversely affected by ingress of water, which decreases or removes the apparent cohesion. Design should consider wall location and water ingress potential. Sensitivity checks are recommended for post-earthquake and long term effects of water ingress.
- Use of permeable well-graded angular backfill and infill materials with controlled field compaction is recommended.
- It may be more economically viable to design a low threshold for failure into retaining walls. If this approach is taken the designer should consider the criticality of the retaining wall, effects of failure, risks to the general public and private infrastructure. Safety in design for the dismantling and or repair should also be considered.

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