Cyclic softening case study: Wendover Retirement Village, Christchurch

R J Heritage
Aurecon, Wellington, NZ
richard.heritage@aurecongroup.com

Keywords: cyclic softening, earthquake, Christchurch, peat, seismic

ABSTRACT

Wendover Retirement Village is located in Papanui, Christchurch, adjacent to a minor tributary of Dudley Creek on the edge of a drained peat swamp. The site suffered damage as a result of the recent major seismic activity in Canterbury, including ground settlement and lateral spreading.

To assess the subsurface profile, cone penetration tests (CPT) and hand auger boreholes were carried out and the results used to back-analyse the failures that occurred during the recent seismic activity. The site is typically underlain by 5–6m of peat and organic clay with a high water table. The organic material overlies 1–2m of sand, then gravel.

The initial assumptions of liquefaction causing the ground damage were dismissed when analysis predicted that liquefaction would be restricted to the sand that underlies the organic deposits at 5–6m depth. To determine the cause of the ground damage, a cyclic softening assessment was undertaken based on the method of Idriss and Boulanger (Idriss & Boulanger, 2008). By comparing the results with the earthquake records from seismographs located nearby, it was demonstrated that cyclic softening was expected in the 22 February 2011 earthquake event and unlikely in the 4 September 2010 event. This correlated well with the observations of ground damage. In addition, by using probabilistic predictions of the magnitude of ground accelerations (Gertsenberger, 2011), the likelihood of cyclic-softening-induced ground damage reoccurring was able to be estimated.

1 INTRODUCTION

The Darfield Earthquake of 4 September 2010 caused significant damage to the land, infrastructure and buildings of Christchurch City and the wider Canterbury region. However, it was the subsequent Christchurch Earthquake of 22 February 2011 that caused the greatest damage to Christchurch City with liquefaction and associated lateral spreading causing severe ground damage on the flat land where the majority of Christchurch City is located. At Wendover Retirement Village, located in the suburb of Papanui on the flat land of Christchurch City, what appeared to be typical liquefaction induced lateral spreading had caused ground cracks and lateral movement towards the adjacent Dudley Creek. However, investigations into the nature of the soil below the site revealed that liquefaction was now the cause of the observed damage. This paper describes the assessment of the land at Wendover Retirement Village and presents the results of an analysis of what may have caused the observed land damage.

2 BACKGROUND

Wendover Retirement Village is located on the floodplain of the Waimakariri River in the suburb of Papanui in Christchurch. The site is predominantly flat, surrounded by residential properties. The land to the northeast of the site is parkland that slopes gently down away from Wendover Retirement Village. Within 10–15m of the northeast boundary of the site is a small watercourse that is a tributary of Dudley Creek (see Figure 1).

The geological maps of Christchurch City (Brown & Weeber, 1992) describe the site as being on the edge of an area of "peat swamps, now drained" and historic maps of the area dating back to 1850 (Sibley, 1989) describe the land as "swamp, raupo and tussocks".

There is a seismograph in Papanui High School located approximately 1.0km northwest of Wendover Retirement Village which recorded the accelerations of all the recent earthquake events in the Canterbury Region. There are also seismographs located at Christchurch Resthaven (approximately 3km to the southeast) and Shirley Library (approximately 3.7km to the east). The assessed levels of shaking at Wendover Retirement Village during the most significant recent earthquakes are shown in Table 1.

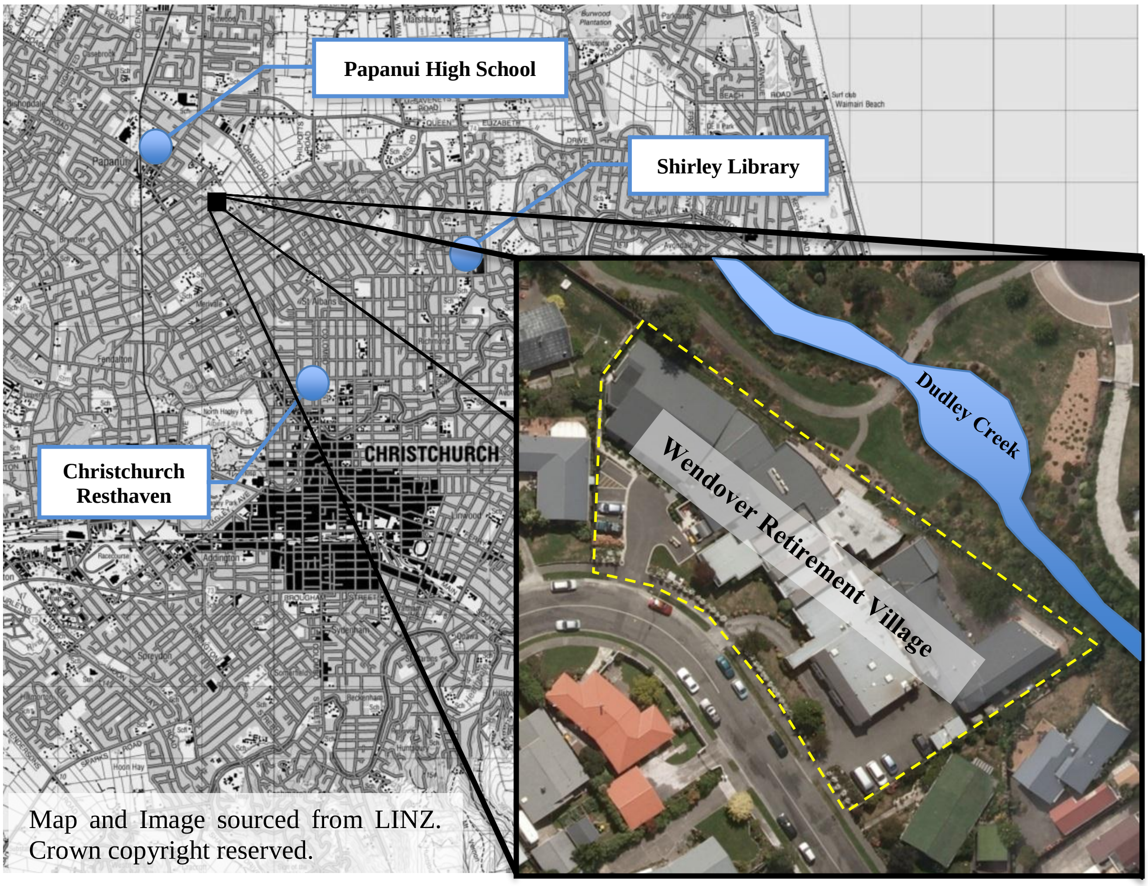

Figure 1: Wendover Retirement Village location plan

3 OBSERVED LAND DAMAGE

The Darfield Earthquake caused only minimal ground damage, whereas significant ground settlement and movement relative to the retirement village buildings was observed across the site following the 22 February 2011 Christchurch Earthquake. In places the ground settlement was upwards of 100mm, with the greatest relative settlement in the northern corner of the site along the grassed terrace area on the north-eastern boundary. What appeared to be lateral spreading was observed in the same grassed terrace area as well as in the banks adjacent the watercourse located within 10–15m of the buildings. In places lateral movements of up to 100mm were noted.

Some minor traces of liquefaction-induced surface expression (light grey fine silt sand material) were noted along the road frontage adjacent to Wendover Retirement Village. However, no notable damage to road pavements or other liquefaction-induced damage was observed.

Table 1: Levels of shaking at Wendover Retirement Village

Name	Date	Moment Magnitude, M_w	Averaged Peak Ground Acceleration (PGA)[(1)]
Darfield Earthquake	4 September 2010	7.1	0.26g
Christchurch Earthquake	22 February 2011	6.2	0.34g

(1) The peak ground accelerations are based on averaging the values recorded at the nearby seismographs inversely proportional to the distance of the seismograph from Wendover Retirement Village.

4 SOIL PROFILE

To assess the local ground conditions, six Cone Penetration Tests (CPT) were undertaken, along with three hand-auger boreholes with Scala penetrometer (Dynamic Cone Penetrometer or DCP) testing in locations where the CPT rig access was not available. The tests were conducted between October and December 2011 because of access issues. The inferred ground conditions are shown in Table 2.

Table 2: Typical soil profile

Layer	Depth below ground to top of layer	Layer thickness	Description	Consistency
1	0m	5m to 6m	Peat and Organic Clay	Very Soft to Soft
2	5m to 6m	1m to 2m	Sand and Gravelly Sand	Dense to Very Dense
3	6m to 8m	-	Sandy Gravel (inferred)	-

The water table was measured in the hand-auger boreholes at 0.2m to 0.7m below ground level, which corresponds to approximately the water level of the nearby watercourse. For the purposes of all analyses the groundwater level was assumed to be at the elevation of the average level of the nearby watercourse (typically 0.5m below ground level depending on the location measured).

5 TECHNICAL ANALYSIS

The ground damage on site appeared to be typical of liquefaction-induced lateral spreading. However, once ground investigations were undertaken, this became increasingly unlikely, as analysis predicted that the only soils susceptible to liquefaction were located below the organic deposits at 5–6m depth. The organic deposits of peat and organic clay were too cohesive to have undergone liquefaction. The failure mechanism being something other than liquefaction was further supported by the lack of liquefaction surface expression anywhere near the lateral spreading. It was postulated that the ground damage may have been caused by cyclic softening of the cohesive soils, and so an analysis of the investigation data was undertaken to verify this theory.

5.1 Cyclic softening methodology

In order to assess the soil's susceptibility to cyclic softening the method of Idriss and Boulanger (Idriss & Boulanger, 2008) was utilised. This method is based on the ratio of the cyclic stress ratio (CSR) to the cyclic resistance ratio in a similar approach to liquefaction susceptibility analysis of the NCEER method (Youd et. al., 2001). The main difference being that the CRR is calculated based on the undrained shear strength of the cohesive soil. The formulae that Idriss and Boulanger have recommended for calculating the CRR are:

$$CRR = 0.80 \frac{S_u}{\sigma'_{vc}} MSF \cdot K_\alpha \quad (1)$$

$$MSF = 1.12 \cdot e^{\left(\frac{-M}{4}\right)} + 0.828 \quad (2)$$

$$K_\propto = 1.344 - \frac{0.344}{\left(1 - \frac{\propto}{0.22 \cdot OCR^{0.8}}\right)^{0.638}} \quad (3)$$

$$\propto = \frac{\tau_s}{\sigma'_{vc}} \quad (4)$$

Where:
S_u = undrained shear strength of cohesive soil
σ'_{vc} = vertical effective stress at consolidation
MSF = magnitude scaling factor
M = earthquake magnitude
$K_\propto$ = static shear stress correction factor
OCR = over consolidation ratio
τ_s = static shear stress

Note that the MSF formula is different from that used for a liquefaction analysis as clays are less susceptible to cyclic loading.

The CSR is calculated in the same manner as used in a liquefaction method based on the method proposed by NCEER (Youd et. al., 2001):

$$CSR = 0.65 \frac{a_{max}}{g} \frac{\sigma_{vo}}{\sigma'_{vo}} r_d \quad (5)$$

Where:
a_{max} = peak ground acceleration
g = acceleration due to gravity
σ_{vo} = in-situ vertical total stress
σ'_{vo} = in-situ vertical effective stress
r_d = stress reduction factor

As with the NCEER method, if CSR > CRR then cyclic softening will occur.

5.2 Assessment of parameters

The various parameters needed for these equations were assessed as follows:

- The undrained shear strength (S_u) was assessed based on an average value interpreted from the CPT logs.
- Using assumptions of typical soil densities for the soil types encountered and the depth of the water table as measured on site the vertical total and effective stresses were estimated (σ_{vo} and σ'_{vo}).
- The ground is essentially flat so it was assumed that the static shear stress (τ_s) is zero and hence the static shear stress correction factor ($K_\propto$) is also zero.

- The soil was assumed to be normally consolidated and so the overconsolidation ratio (OCR) is unity and hence $\sigma'_{vo} = \sigma'_{vc}$
- The stress reduction factor r_d was assessed based on the graph of r_d vs. depth produced by Seed and Idriss (Seed & Idriss, 1971)

5.3 Yield acceleration calculations

By substituting in the values assessed above the formula for the CRR can be simplified as follows:

$$CRR = 0.80 \frac{S_u}{\sigma'_{vo}} MSF \quad (6)$$

And hence for cyclic softening to occur:

$$0.65 \frac{a_{max}}{g} \frac{\sigma_{vo}}{\sigma'_{vo}} r_d > 0.80 \frac{S_u}{\sigma'_{vo}} MSF \quad (7)$$

The assessed calculations found that the yield accelerations for the Darfield and Christchurch earthquakes were as follows:

Table 3: Calculated yield accelerations

Earthquake	Moment Magnitude, M_w	Averaged Peak Ground Acceleration (PGA)	Calculated Yield Acceleration (a_y)
Darfield Earthquake (4 September 2010)	7.1	0.26g	0.28g
Christchurch Earthquake (22 February 2011)	6.2	0.34g	0.29g

Note that the vertical stresses were calculated at the base of the layer of the peat and organic clay; and difference between the two yield accelerations is caused by the variation in the magnitude scaling factor. All other parameters are the same.

5.4 Time history analysis

The initial results suggest that the yield acceleration would have been reached during the Christchurch Earthquake but not during the Darfield Earthquake. This matches the observed ground behaviour as minimal ground damage occurred after the Darfield Earthquake whereas significant ground damage occurred following the Christchurch Earthquake. To have a closer look at what occurred during each earthquake, a time history analysis was undertaken based on the shaking records from three nearest seismographs. Illustrative results of this analysis are shown below in Figure 2 and the full results are tabulated in Table 4.

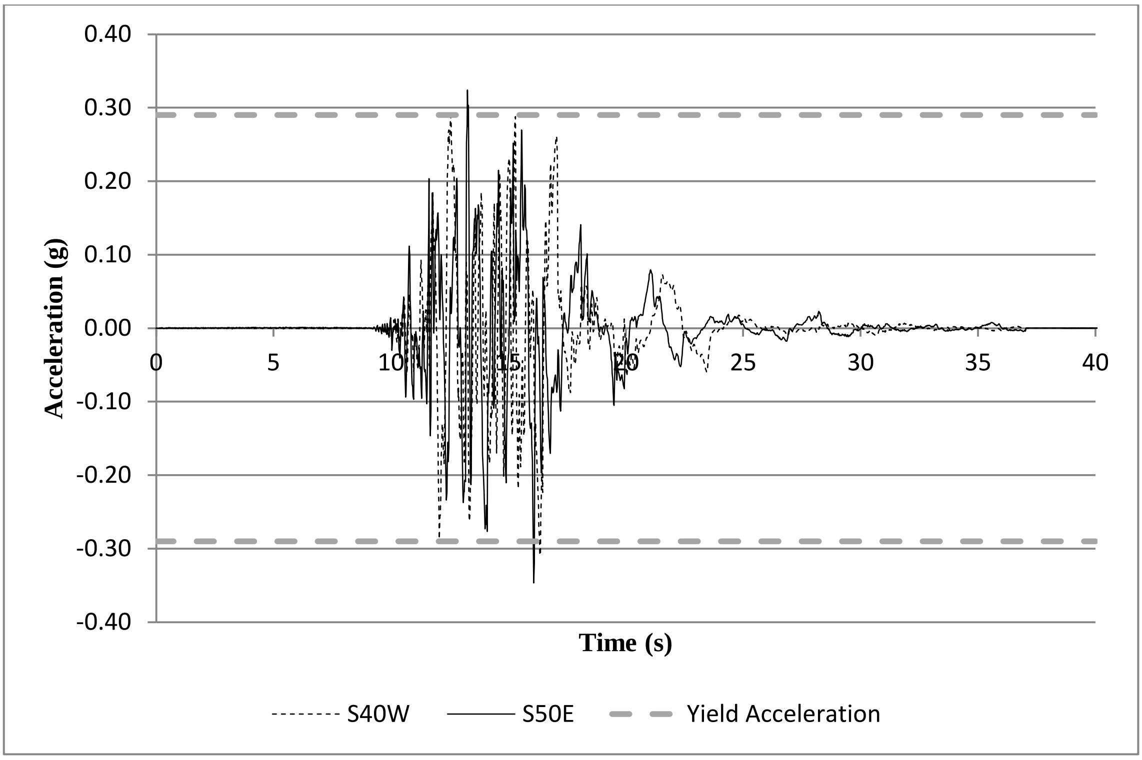

Figure 2: Christchurch Earthquake – Shirley Library Accelerogram (combined directions)

Table 4: Frequency of yield accelerations

Earthquake	Location	Yield cycles in each direction(1)		
		X	Y	Average
Darfield Earthquake (4 September 2010)	PPHS	0	0	0
	REHS	0	0	
	SHLC	0	0	
Christchurch Earthquake (22 February 2011)	PPHS	0	0	2
	REHS	4	5	
	SHLC	1	2	

(1) The number of times that a cycle of acceleration exceeded the yield acceleration for each earthquake.

The results show that the yield acceleration was never reached for the Darfield Earthquake and is likely to have been reached up to nine times during the Christchurch Earthquake. This indicates that the probability that cyclic softening occurred to a sufficient extent to cause ground damage is much more likely to have occurred following the Christchurch Earthquake. This matches the observed ground damage and gives confidence as to the accuracy of our assessment.

5.5 Probability of reoccurrence

To predict the effect that future earthquake events would have on the Wendover Retirement Village land the analysis was re-run using predicted earthquake magnitudes and accelerations as recommended by the Ministry of Buisness, Innovation and Employment (MBIE, 2012, p. C2.2) for geotechnical design in Canterbury. The results are tabulated below:

Table 5: Design earthquake accelerations compared with yield accelerations

Design Earthquake Event	Magnitude	Peak Ground Acceleration (PGA)	Calculated Yield Acceleration (a_y)
Serviceability Limit State (SLS)	7.5	0.13g	0.27g
Ultimate Limit State (ULS)	7.5	0.35g	0.27g

The next step was to more accurately determine the probability that an earthquake would cause the levels of shaking that are predicted to trigger cyclic softening. To do this, the results of the GNS Science probabilistic assessment of liquefaction for Christchurch in the next 50 years (Gerstenberger et al., 2011) was referred to. This study gave estimates that various acceleration levels in Christchurch would be exceeded in seismic events in the next year, ten years and fifty years. By interpolating between the values given by GNS we were able to state that probabilities of cyclic softening reoccurring in the future. The GNS values along with the results that have been interpolated are tabulated below:

Table 6: Exceedance probabilities for liquefaction thresholds in Christchurch

	GNS Results				Calculated Results
Timeframe	Shallow Threshold (>0.10g)	Lower Deep Threshold (>0.13g)	Lower Deep Threshold-1 (>0.2g)	Lower Deep Threshold-2 (>0.3g)	Yield Acceleration (>0.27g)
In the next 1 year	46%	92%	60%	24%	34%
In the next 10 years	86%	70%	35%	12%	18%
In the next 50 years	98%	32%	14%	5%	7%

Note that these probabilities are based on magnitude weighted PGA and are based on earthquake likelihoods assessed in May 2011 and may need to be revised.

6 DISCUSSION

This analysis was conducted in December 2011 and so some of the information used to assess the cyclic softening hazard at Wendover Retirement Village may be out of date. Notwithstanding this, the results of this analysis can be considered reasonably accurate – in a geotechnical sense – thanks to the density of seismographs in Christchurch City and the ongoing research being conducted in to the effects of the recent earthquake sequence.

The results predict whether or not cyclic softening will occur and lend support to the accuracy of the method of Idriss and Boulanger (Idriss & Boulanger, 2008). However, the analysis does not cover the magnitude of failure, which may be significantly more important when designing structures in soils where cyclic softening is considered a hazard.

7 CONCLUSION

The effects of the recent earthquake events on Christchurch have provided valuable insight into the behaviour of soils during earthquakes. The analysis of the cyclic softening that occurred at Wendover Retirement Village is an example of this. The high density of seismographs in Christchurch City, the huge amounts of data collected, and the ongoing research that is being conducted has allowed this analysis to be completed to a reasonably high degree of accuracy. The results lend support to the accuracy of the cyclic softening analysis methods proposed by

Idriss and Boulanger (Idriss & Boulanger, 2008) and serve as a reminder to be aware of the potential for cyclic softening to cause ground damage in earthquake events.

8 ACKNOWLEDGEMENTS

I want to thank the following people for their help and assistance during this analysis and the publishing of this paper:

- Dominic Mahoney, Dr Jan Kupec, Ian McPherson and Alan Wightman – colleagues whose advice greatly assisted me in conducting the analysis.
- Wendover Retirement Village – in particular Mr Charlie Hand – for permitting me to publish this paper.
- All the geotechnical engineers, geologists and support staff across New Zealand and overseas who have helped put together the huge amounts of research and information regarding the Canterbury Earthquakes.

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