Seismic Response at Soft Ground Sites, Bay of Plenty

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Summary: This work reports on an investigation into the seismic response of soft sites. An effective stress site response analysis is presented for three sites in the Whakatane area. Significant pore pressure develops at two of the sites and greatly modifies the surface response. Time histories of dynamic pore pressure are presented along with surface spectra that are compared to the draft earthquake loading code. The importance of recognising the effect of thin layers of soft cohesionless soil is identified, and suggestions made as to provision for this feature in a code. An interpretation of LIDAR data over the Whakatane area shows variation in surficial deposits that would be expected to give rise to different response during strong ground shaking. The LIDAR data also show evidence of permanent ground deformation due to past liquefaction.

INTRODUCTION

New Zealand is about to implement a new code for assessing earthquake loading on structures (Standards Association of New Zealand 2003). The draft code sets out procedures and criteria for establishing the earthquake actions to be used in the limit state design of structures and parts of structures that are within the scope of AS/NZS 1170.0. Using the code, an elastic site hazard spectrum for horizontal loading is calculated for a given earthquake return period.

One of the key determinants of the site hazard spectrum is the spectral shape factor, which depends on the site subsoil class. At this part of the analysis, some geotechnical understanding of the site is required to determine which of 5 subsoil classes applies, from Strong Rock (Class A) through Very Soft Soil (Class E). The behaviour of non-rock class ground during strong earthquake shaking is of interest, particularly given the potential effects of soil softening and liquefaction. These nonlinear effects are not easily taken into account in a codified approach to site response, and we have undertaken a study to compare the spectra derived from the draft loading code with spectra computed using an effective stress site response program.

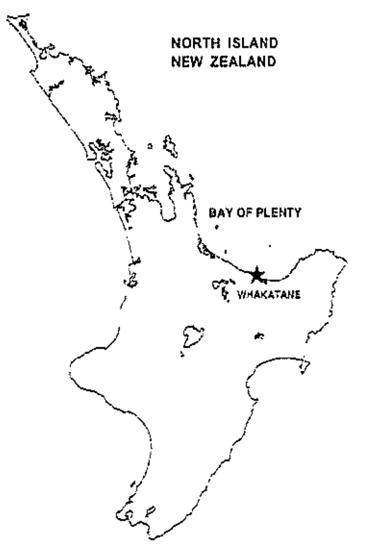


Figure 1. Location map

For our study we have modelled the ground response at three sites at Whakatane, Bay of Plenty (Figure 1), that were investigated following the 1987 Edgecumbe earthquake (Christensen 1995). Two of these sites experienced liquefaction during the 1987 Edgecumbe earthquake, and one did not. Our analyses have provided time histories of excess pore pressures at depth, and ground accelerations and displacements.

SEISMIC HAZARD AT WHAKATANE

On March 2, 1987 a shallow M_L 6.3 earthquake located north of Edgecumbe in the Bay of Plenty, New Zealand, caused strong ground shaking in the area, and new fault traces were observed near the epicentre. The highest intensities of shaking were assessed as *MM* X. About 20km from the epicentre, in the town of Whakatane, intensities were in the range of MM V and MM VIII (Lowry *et al.* 1989). Some of the damage at Whakatane was caused by liquefaction, and workers at University of Canterbury have studied this aspect of ground behaviour.

The wide variation in felt intensities over a small area is of interest. An explanation for the nature of ground motions experienced at Whakatane could depend on whether or not any of the underlying soils liquefied, with liquefied layers providing isolation to further strong shaking until the excess pore pressures dissipated.

The work of Stirling *et al.* (2002) has been incorporated into the draft loading code, and is reflected in the distribution of hazard factors (Z). The value of Z that has been recommended for Whakatane is 0.3. The draft code also allows for near-fault effects, and increased seismic loadings are indicated for 11 of New Zealand's major active faults. However the Whakatane Fault is not taken into account when assessing potential earthquake loads on structures because of the relatively long recurrence interval.

SITE CONDITIONS IN THE WHAKATANE AREA

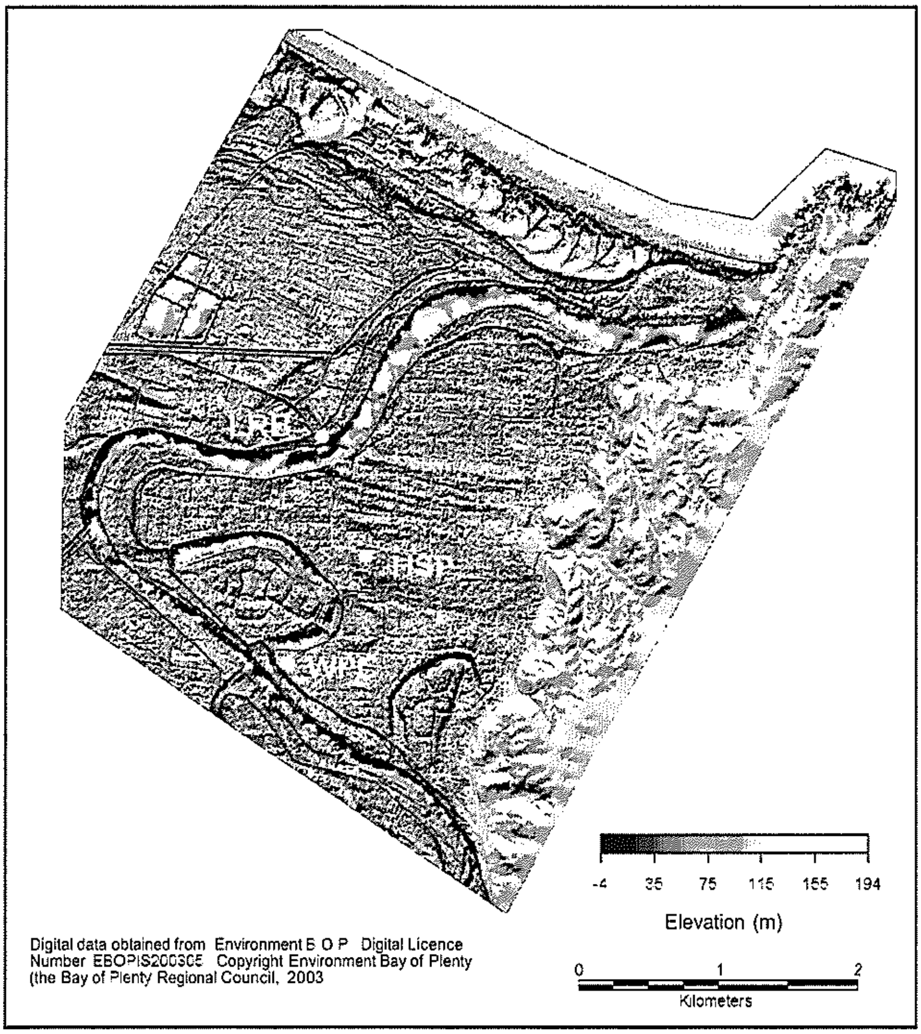


Figure 2. Image of topography around Whakatane, derived from LIDAR data

The Whakatane graben is filled with hard compacted alluvium, overlain by extensive ignimbrite sheets and recent near surface deposits of volcanically derived alluvium and flood plain material. Figure 2 is an image of topographic data captured around Whakatane using LIDAR (light detection and ranging). Environment Bay of Plenty has provided these closely spaced precise elevation data, and image processing software has been used to display the them. Interpretation of these elevation data shows surface textures that reflect different soil depositional environments, and indicates variation in ground conditions on the low lying alluvial areas of Whakatane which would be expected to give rise to differences in ground response.

To investigate the liquefaction potential and surface seismic response of the Whakatane area three sites were chosen; their location is shown on Figure 2. Landing Road Bridge (LRB) is located seaward of an old beach ridge, while Whakatane Hospital (HSP) is located on a slightly elevated surface of older age. Whakatane Pony Club (WPC) is near an old meander of the Whakatane River. Ground surface effects of liquefaction were observed at Landing Road Bridge and Whakatane Pony Club following the 1987 earthquake (Christensen 1995).

SOFT GROUND RESPONSE AT THREE SITES

The detail of the site conditions at the three Whakatane sites is contained in Christensen (1995). A variety of data in the form of bore logs, CPT and SPT test data were available. Computer models of the sites were prepared that are a compromise between simplicity and the need to represent the features of the site that are important in determining the ground response.

We have used the program NESSA (Larkin 1978) which uses an effective stress method of one dimensional site response. The excess pore pressure from the propagation of shear waves is computed using the model described in Larkin and Marks (1994). The shear stiffness is calculated at each time step and is then used to determine the soil response. Simultaneous dissipation of excess pore pressure is provided by coupling a solution of the diffusion equation. The program calculates a time history of excess pore pressure and effective stress down through the profile. The surface response is determined and response spectra computed.

The N83E component of the 1987 Edgecumbe earthquake recorded at the base of the Matahina dam was used as the forcing motion. This record has a peak acceleration of 0.28g and was obtained at the surface of a deposit of alluvium that is of the order of 40m thick. The Matahina dam is located about 20 km south of the Edgecumbe earthquake epicentre while Whakatane is a similar distance to the east. For our analyses, the event was applied at the base of the soft soil as the incident wave emerging from the competent material, as was the case at Matahina dam. NESSA has a transmitting boundary to account for the shear stiffness of the underlying material. While this procedure is not ideal, in that it is not a basement rock record, it was the same for the three sites. The spectrum of the Matahina dam input motion suggests that no significant ground softening occurred at the recording site. The magnitude of the peak ground acceleration in Whakatane for a 500 year return period may be calculated from the code to be approximately 0.3g. Thus this input motion is appropriate for an event with a return period of approximately 500 years.

Landing Road Bridge Site

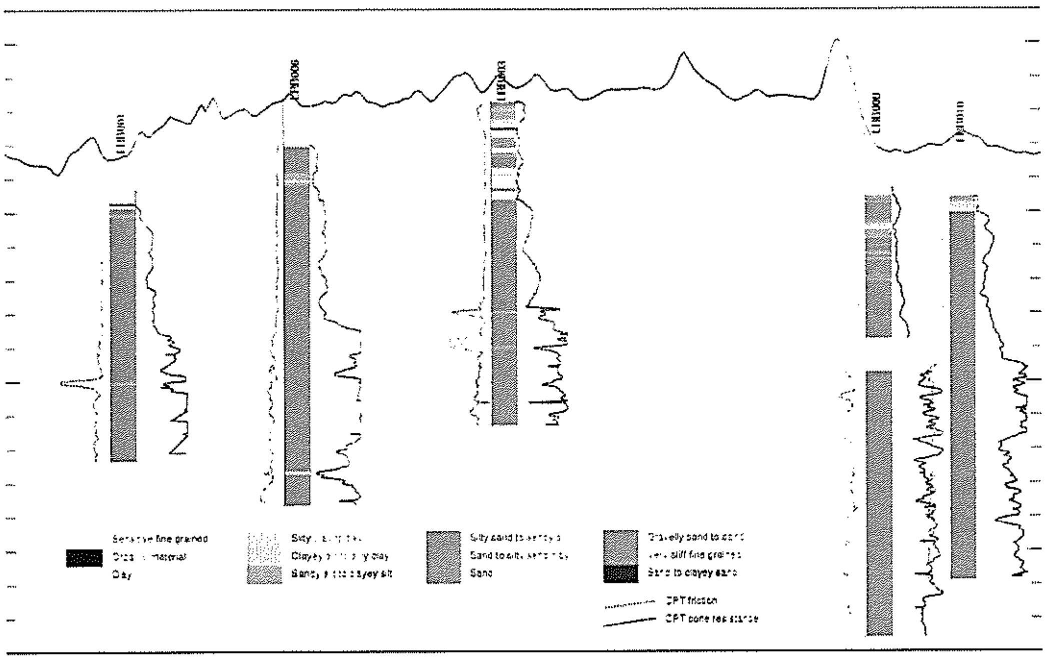
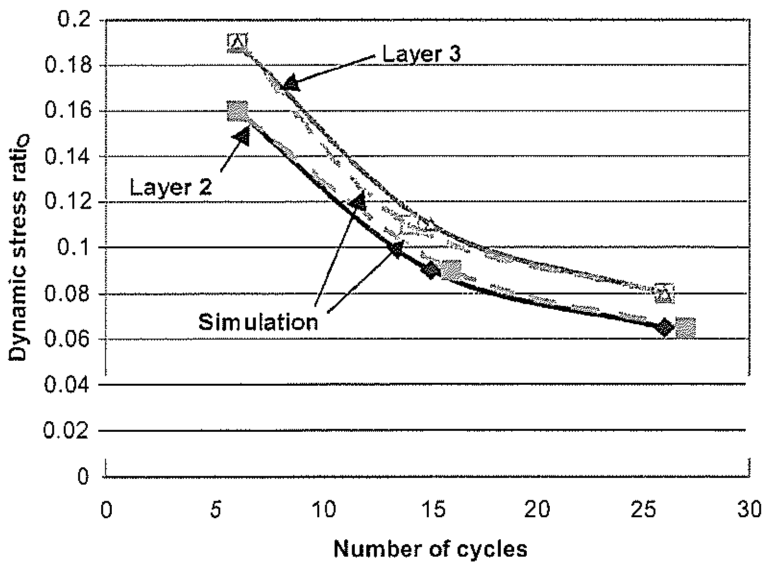


Figure 3. Cross section at Landing Road Bridge

This site is in the vicinity of the Whakatane River estuary and contains medium to coarse pumiceous sands overlain by approximately 1.7m of silty clay. In general the sands are loosely compacted to a depth of about six metres after which they become denser. The water table varies with tidal level in this area, and for this analysis the water table was taken at 1.7m depth. The cone penetration data and inferred soil profile are shown in Figure 3.

The site liquefaction resistance was evaluated from the measured cone values using the methods of Seed and Idriss (1982) and Robertson and Wride (1998). The parameters used in NESSA to compute the excess pore pressure are based on this liquefaction resistance. The agreement between the computer model and the calculated liquefaction resistance from CPT data is shown in Figure 4. The agreement is seen to be very close.



The dynamic pore pressure ratios calculated at Landing Road Bridge and the Whakatane Pony Club are shown on Figure 5. The ratio is defined as the excess pore pressure divided by the initial vertical effective stress. The dynamic pore pressure ratio reaches a value of 1 at both sites, implying liquefaction occurs. Extensive liquefaction was observed at these sites following the Edgecumbe event. The calculation of negative gradients in places suggests that there was concurrent partial diffusion of excess pore pressure during the period of strong shaking.

Figure 4. Landing Road Bridge, liquefaction resistance ratios: field and simulation

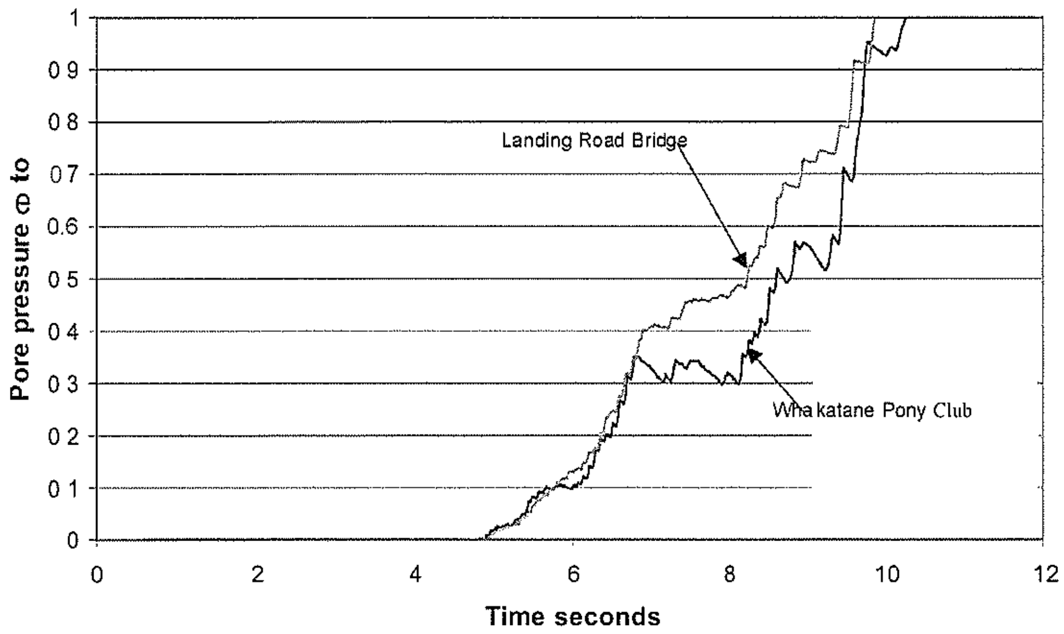


Figure 5. Dynamic pore pressure ratios

Whakatane Pony Club

This site lies on the outskirts of Whakatane on the right bank of the Whakatane River. The near surface soils at the site are predominantly alluvial sands derived from greywacke and rhyolitic ash. Below these soils are pumice sands and gravels overlying greywacke gravels. The soil profile adopted in the analyses is based on the profile shown on Figure 6.

Parameters for the analytical model were generated from the site liquefaction resistance curves as described above. The agreement between field and simulation was of a very similar nature to that shown in Figure 4.

Extensive liquefaction was experienced at this site in the Edgecumbe earthquake. Lateral spreading occurred with extensive ground cracking and ejection of sand to the ground surface. Christensen (1995) estimated that soils above about 5.5 m depth liquefied if the deposit was below the water table.

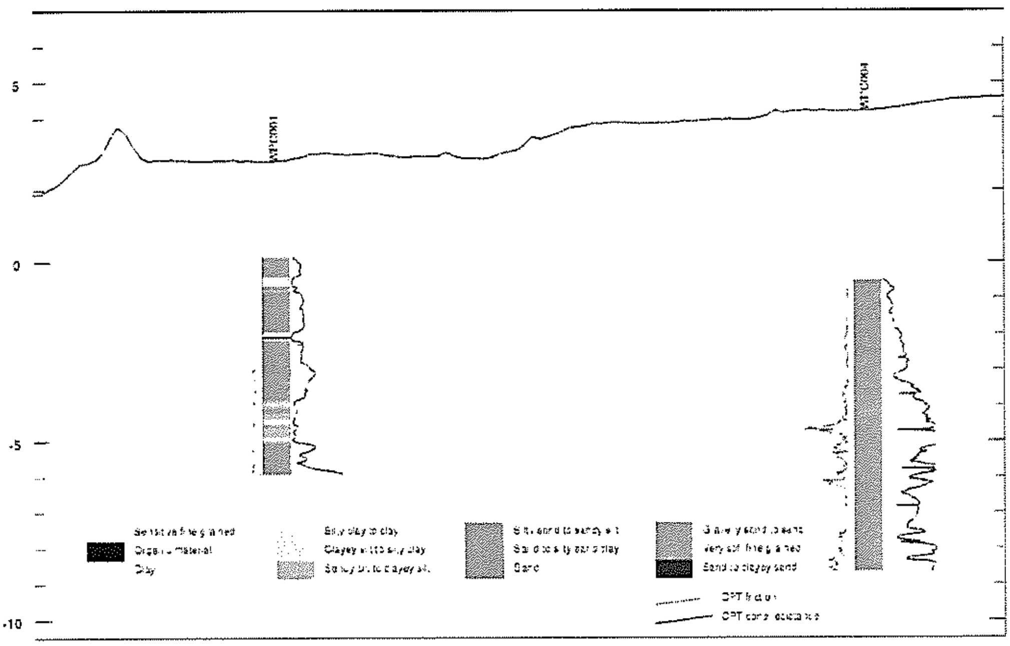


Figure 6. Cross section at Whakatane Pony Club

The permanent ground displacements that occurred in this area have given rise to subtle bumps and hollows that have been recorded by the LIDAR survey; the LIDAR data were used to plot the ground surface on Figure 6.

Whakatane Hospital Site

At this site the depth of the water table precluded liquefaction of the near surface soils, and at depth the soils are of high strength. The water table position has been estimated at approximately 4.5m below the surface at the time of the Edgecumbe earthquake.

SITE HAZARD SPECTRA

All of the three sites have relatively thin layers (approximately 1m) of low strength soil. We judge that the soil profiles place the sites in Class D of the proposed code, as the profile comprises soils with an N value less than 6 that are less than 10m in thickness. This N value is approximately equivalent to a cone resistance of 3 MPa. While all three sites are in this category there is substantial difference between the spectra of the two that liquefied and the one that did not. The use of this method of classifying sites is coarse and liable to miss the importance of strength loss through excess pore pressure generation. Thin layers of low strength soil may contribute little to the low strain site period but have a very substantial effect on the seismic response. Such layers pose problems for both nonlinear numerical analyses and site classification in codes.

The draft code gives a hierarchy for site classification methods involving different methods for estimating the site period. One recommended method that is not referenced or explained, is "Nakamura ratios". We understand this technique is based on very low amplitude ambient vibrations, and hence will not disclose the potential for period lengthening due to excess pore pressure development.

It is perhaps unfortunate that small strain site periods are used in the draft code without acknowledging the need for extra study in the case of sites with thin low strength layers of cohesionless soil. The low strain period is not the predominant site periodicity that will be operative at higher levels of shaking. Where soils are particularly prone to reductions in stiffness at strong levels of shaking, then there will be a significant increase in the site periodicity.

The response spectra for each of the three sites are compared with the draft code Class D (return period of 500 years) in Figure 7. The spectra for all three sites, and the Matahina record (not shown) are significantly below the code for periods in excess of 0.75 seconds. These analyses were conducted using a single input motion so too much should not be read into this disparity.

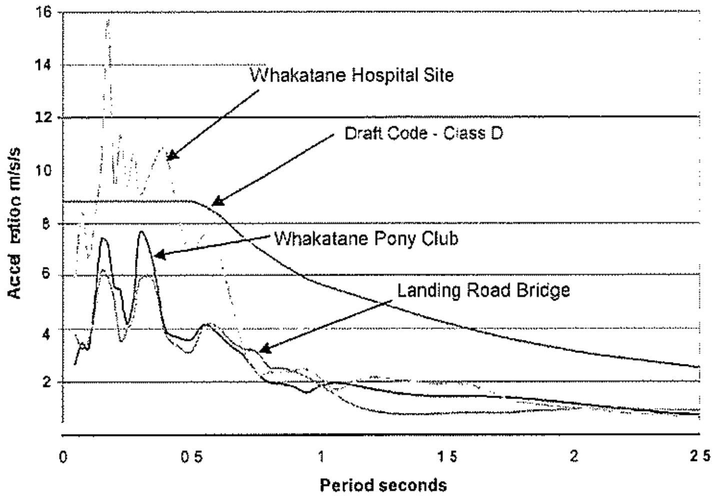


Figure 7. Ground surface response spectra

The site that did not liquefy (Whakatane Hospital) has significantly more high frequency motion. Some of the very high frequency motion shown in the spectra may be due to numerical noise. However these spectra highlight the difference between surface motion on liquefied ground compared to that on more competent terrain. This was reflected in the range of intensities recorded for the Edgecumbe earthquake in the Whakatane area.

IMPLICATIONS FOR DESIGN OF STRUCTURES

The nature of seismic response of soft ground has been described. The presence of liquefiable soil at a site will change the nature of the response if significant excess pore pressure develops, even if liquefaction does not occur. The soil will soften with reduced stiffness that leads to larger strains and lower frequencies in the ground response. This produces spectra with higher response in the high period range that has significant implications for flexible/tall structures sitting on shallow foundations. In a physical sense the soils can be considered to act as a low pass filter.

Structures on pile foundations that derive their vertical load carrying capacity from end resistance at depth are also vulnerable to these effects. The nature of the lateral soillstructure interaction may change with increased lateral displacements due to lowered shear stiffness of the near surface soils that provide most of the restraining effect during inertial soil/structure interaction. The potential effects on shallow foundations are more obvious.

CONCLUSIONS

We have found difficulty applying the draft code for assessing earthquake loading on structures at the three Whakatane sites. There is a lack of site data at depth, which is a common feature of site investigations. The use of elastic low strain wave velocities to categorise sites that have the potential for developing excess pore pressure has been shown to be problematic.

There does not appear to be a generic clause in the draft code indicating that low strength cohesionless soils need special consideration. Such a statement should be independent of any thickness criterion since even thin layers may have a pronounced effect. A concern with the draft code at present is that it may impart a false sense of security by not identifying a potential serious issue.

Nonlinear effective stress site response programs such as NESSA are a useful engineering tool to establish the likelihood of significant excess pore pressure during seismic motion. In the case of cohesionless soils a total stress analysis will not capture the pronounced effects of change in soil stiffness with stress history. Such analyses at best are only a guide to effective stress dependent seismic soil response.

The response spectra calculated at the two sites that liquefied (Landing Road Bridge, Whakatane Pony Club) are similar. However the Whakatane Hospital site shows significantly higher accelerations. This variation in ground response over a short distance is consistent with the variation in felt intensities during the 1987 Edgecumbe earthquake.

LIDAR data have been useful for interpreting the geomorphology of the Whakatane area. The detailed topography shows permanent deformation features that occurred during the 1987 Edgecumbe earthquake. LIDAR is a useful tool for post-earthquake analysis of ground damage.

ACKNOWLEDGMENTS

Dr John Berrill of Canterbury University provided digital records of CPT data from Whakatane, and encouraged our study of this area. Mr Stuart Halliday of Environment Bay of Plenty made the LIDAR data available for our use. June Cahill of Ian R Brown Associates Ltd processed and imaged the LIDAR data and assisted with preparation of the paper.

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