Institute of
GEOLOGICAL
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SCIENCES
Limited

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Mr John Buchan
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Dear John

Re: REPORT 2003/33, YOUR LETTER, FILE BC-002-1

As per your letter of 18th June 2003 and subsequent confirmation, we have reviewed a student report concerning the effects of liquefaction-induced differential settlement on residential dwellings in Christchurch.

We find that the student report is mostly complementary to a report by GNS (2003/33) that models the earthquake risks to property of the Christchurch City Council. Where there are areas of overlap, i.e. in estimation of the seismic hazard affecting Christchurch and in assessing the effects of liquefaction, the two reports are largely consistent.

The text of the student report includes discussion of the effects of liquefaction at high intensities of shaking, MM9 Zone and above. The probability of occurrence of such strong shaking in Christchurch is very low (return period > 70,000 years). The liquefaction and settlement computations in the report, however, are based on a PGA of 0.25g, which is broadly consistent with MM7 Zone shaking and has a return period of less than 1800 years.

Yours sincerely

Jim Cousins
Engineering Seismologist

cc Dick Beetham

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Review of:

Effects of Liquefaction-Induced Differential Settlements on Residential Dwellings in Christchurch (Author: Kirsti Maria Carr, Report Date: October 2001)

Reviewers:

Jim Cousins (Engineering Seismologist, Institute of Geological & Nuclear Sciences)
Dick Beetham (Engineering Geologist, Institute of Geological & Nuclear Sciences)

Purpose of Review:

To comment on the seismic hazard in Christchurch as per GNS report CR2003/33 (Section 2.4) and also on liquefaction (Section 2.6.3) [2].

Review Comments:

The purpose of the Carr report [1] was to evaluate "the effects of liquefaction induced differential settlement on concrete slab foundations of domestic dwellings in parts of the city of Christchurch". Although some discussion of the likely seismic hazard was needed and was provided, the aims of the work did not include providing an evaluation of the seismic hazard affecting Christchurch.

The strength of earthquake shaking can be quantified in two ways, either by using the Modified Mercalli (MM) Intensity scale (or equivalent European and Japanese scales) or by using instrumental parameters such as peak ground acceleration (PGA) and spectral acceleration. Loss modelling in New Zealand is usually based on the MM scale, whereas building and geotechnical design are usually based on the instrumental measures. The Carr report uses both measures, the MM scale for "scene-setting" and PGA for estimation of differential ground settlement. For reference the MM Intensity scale is provided here as Appendix 1.

Carr discusses several reports and case histories in setting the scene for Christchurch. Some were for more damaging levels of shaking than expected in Christchurch, and even though this was pointed out in the text there is a tendency for readers to focus on and remember the more dramatic details. Among the overly severe situations were the following:

- 1968 Inangahua earthquake, epicentral region, MM10 zone,
- 1987 Edgecumbe earthquake, epicentral region, MM8 Zone to MM9 Zone,
- 1994 Northridge earthquake, epicentral region, MM8 Zone to MM9 Zone,
- 1995 Kobe earthquake, epicentral region, c. MM9 to MM10 Zone, and
- 1999 Kocaeli earthquake, city of Adapazari, c. MM8 Zone to MM9 Zone.

In all five cases liquefaction contributed to the observed damage, sometimes severely so. However, in all cases the faults responsible for the earthquake were very close to the affected localities, closer than 10km.

For Christchurch the major known active faults are 25 to 45km away, and the likely strength of shaking as predicted by the New Zealand attenuation model for MM Intensity [3] is MM7

Zone (Table 1). Within Christchurch, however, the resulting damage is likely to be somewhat more severe than indicated by the MM7 Zone descriptors (see Appendix 1) as a result of amplification of the shaking by the soils underlying Christchurch, and sporadic liquefaction.

Thus, instead of

> *"a few instances of non-damaging liquefaction (small water and sand ejections) in alluvium",*

which is appropriate for an MM7 Zone, we would expect to see

> *"evidence of soil liquefaction common, with small sand boils and water ejections in alluvium, and localised lateral spreading (fissuring, sand and water ejections) and settlements along banks of rivers, lakes and canals etc."*

Nevertheless, we would not expect to see major damage to buildings as a result of the liquefaction, even though the total cost of damage to buildings in Christchurch could in some cases be in the vicinity of $1 billion (Table 1).

Table 1: Estimated impacts of known active faults affecting Christchurch. The estimated intensity at the CBD is that predicted by the Dowrick & Rhoades attenuation model for MMI [3] for average ground. We expect amplification to occur over much of Christchurch, though the amount of amplification is only poorly modelled at present. The estimated loss is derived from a first-order loss model for New Zealand earthquakes, and assumes a replacement value of $36 billion for all buildings in Christchurch.

Fault Name	Distance from CBD (km)	M_W	Recurrence Interval (years)	Estimated intensity at CBD	Amplified Intensity Range	Estimated Loss ($billions)
Pegasus 1	25	7.2	10,000	c. 7.8	7.9-8.8	1.5
Ashley	30	7.2	2000	7.5	7.5-8.6	1
Springbank	30	7.1	5000	7.4	7.3-8.5	1
Porters Pass to Mt. Grey	45	7.5	2800	7.4	7.4-8.4	1
Omihi	45	6.7	c. 470	6.7	6.8-7.8	0.3
Alpine	130	8.1	300	c. 6.7	6.7-7.6	0.3

Historical examples presented by Carr that are more analogous to the Christchurch situation than those listed above included the following

- 1968 Inangahua earthquake, Westport area, intensity MM8 Zone, and
- 1989 Loma Prieta earthquake, downtown San Francisco, intensity MM7 Zone, amplified to MM9 Zone in some localities with unusual soil types.

Although some houses in Westport were clearly badly damaged as a result of liquefaction in the 1968 Inangahua earthquake, inspection of insurance claims data held by GNS suggests that they constituted a small minority of all houses in Westport, even in the part of Westport affected by liquefaction. Nonetheless the average damage ratio (i.e. cost to repair divided by cost to replace) for the houses in and near the liquefaction zone appears to have been about 30% higher than that for houses in the remainder of Westport. The overall damage ratio for houses in Westport was about 0.03 [4].

In the above discussion we are not saying that intensities of MM9 and MM10 will never occur in Christchurch. There is a possibility, but the probability is very low (return period > 70,000 years [2, Table 2.1]). The probability is sufficiently low that, in our opinion, it would not be reasonable to require ordinary structures, like houses, be constructed to withstand all of the adverse effects of such strong shaking.

Carr uses a PGA ("$a_{max}(g)$") of 0.25g in her settlement calculations. The correlation between PGA and MM Intensity is not well defined and suffers from a very high degree of uncertainty, but an unpublished relation developed by David Dowrick of GNS indicates that a PGA of 0.25g is consistent with an intensity of MM7.7 (i.e. at the higher intensity end of an MM7 Zone). This is within the range of "amplified" intensities for most of the faults listed above in Table 1, and has a return period between 140 and 1800 years [2, Table 2.1].

It is important to note that PGA alone is a poor indicator of damage potential. A PGA of 0.25g caused by a magnitude 7.5 earthquake, with probable duration of strong shaking of 10's of seconds, will be accompanied by much more severe damage than the same PGA caused by a magnitude 5.5 earthquake, with probable duration of strong shaking of just a few seconds. The formula used by Carr to predict the occurrence of liquefaction [1, p14] makes allowance for this by inclusion of a magnitude term.

In our assessment of the cost of earthquake damage to the property of the Christchurch City Council [2] we made some assumptions about the effects of liquefaction. We believe that those assumptions are consistent with the work presented in the Carr report. Specifically:

"In allowing for potential liquefaction in Christchurch we assume the following:

- *Christchurch buildings of 3 or more storeys are generally supported on piles that pass through the liquefiable layers and as a result are resistant to liquefaction (even though in many cases pile systems may not have been specifically designed to resist liquefaction)."*

Data provided by the council indicated the 19 of the 20 highest-value buildings were on foundations classed as either "average" or "good" quality. Thus we assume that those 19 buildings will not be badly affected by liquefaction. The "top-20" buildings are important as they contribute more than 50% of the overall loss.

Forty-five of the remaining 1500 buildings were of 2 to 4 stories, and mostly of concrete construction. It is possible that at high intensities, MM9 Zone and above, some would suffer from tilting as observed at Adpazari in the 1999 Kocaeli earthquake, but the probability of MM9 intensity occurring in Christchurch is very low.

- *"The majority of houses in Christchurch will not be affected by liquefaction, even during the strongest shaking (MM8) likely to be experienced."*

This seems consistent with the findings of the Carr report. The case histories presented by Carr, which mostly are for more severe shaking than expected in Christchurch except at very low probabilities, indicate that damage to houses with well-constructed foundations, as a result of liquefaction and settlement, is a relatively rare occurrence. We would be comfortable with extending this assumption to cover all houses in Christchurch. The 30% increase in damage ratio at MM8.5 [2, Table 2.2], to allow for amplification/liquefaction, is in line with the experience at Westport in 1968.

- *"The proportion of low-rise buildings located in places likely to be affected by lateral spreading or substantial settlement is small, about 5% of all low-rise buildings at most."*

For lateral spreading to occur there needs to be a step in the topography or free surface, such as the bank of a lake or stream. The parts of Christchurch susceptible to liquefaction are generally very flat with only a few small streams passing through. Because of the small size of the streams, any lateral spreading is unlikely to extend more than a few metres from the original banks and will, therefore, affect only a small proportion of all houses. However, differential settlements caused by consolidation of peat horizons within the gravel and soil sediments underlying Christchurch may be more common.

Concluding Remarks:

The report by Carr [1] is mostly complementary to a recent report by GNS [2] that models the earthquake risks to property of the Christchurch City Council. Where there are areas of overlap, i.e. in estimation of the seismic hazard affecting Christchurch and in modelling the effects of liquefaction, the two reports are largely consistent, in our opinion.

The text of the Carr report includes discussion of the effects of liquefaction at high intensities of shaking, MM9 Zone and above. The probability of occurrence of such strong shaking in Christchurch is very low (return period > 70,000 years [2]). The liquefaction and settlement computations carried out by Carr, however, are for a PGA of 0.25g, which is broadly consistent with MM7 Zone shaking and has a return period of less than 1800 years.

References:

1. Carr, K.M. *Effects of liquefaction-induced differential settlement on residential Dwellings in Christchurch*. Department of Civil Engineering, University of Canterbury (October 2001).
2. Cousins, W.J., Smith, W.D., McSaveney, M. and Johnston D. *Earthquake, volcano and tsunami risks to property of Christchurch City Council*. Client Report 2003/33, Institute of Geological & Nuclear Sciences, Lower Hutt (April 2003).
3. Dowrick D.J. & Rhoades, D.A. "Attenuation of Modified Mercalli intensity in New Zealand earthquakes". *Bulletin of the New Zealand Society for Earthquake Engineering* 32(2): 55-89 (1999).
4. Dowrick, D.J., Rhoades, D.A. and Davenport, P.N. "Damage ratios for domestic property in the magnitude 7.2 1968 Inangahua, New Zealand, earthquake." *Bulletin of the New Zealand Society for Earthquake Engineering* 34(3): 191-213 (2001).

APPENDIX 1: MODIFIED MERCALLI SEISMIC INTENSITY SCALE FOR NEW ZEALAND

MM1 Zone

People

Not felt except by a very few people under exceptionally favourable circumstances

MM2 Zone

People

Felt by persons at rest, on upper floors or favourable placed.

MM3 Zone

People

Felt indoors; hanging objects may swing, vibration similar to passing of light trucks, duration may be estimated, may not be recognised as an earthquake.

MM4 Zone

People

Generally noticed indoors but not outside. Light sleepers may be awakened. Vibration may be likened to the passing of heavy traffic or to the jolt of a heavy object falling or striking the building.

Fittings

Doors and windows rattle. Glassware and crockery rattle. Liquids in open vessels may be slightly disturbed. Standing motorcars may rock.

Structures

Walls and frames of buildings, and partitions and suspended ceilings in commercial buildings, may be heard to creak.

MM5 Zone

People

Generally felt outside, and by almost everyone indoors.
Most sleepers awakened.
A few people alarmed

Fittings

Small unstable objects are displaced or upset. Some glassware and crockery may be broken.
Hanging pictures knock against the wall.
Open doors may swing.
Cupboard doors secured by magnetic catches may open.
Pendulum clocks start, stop, or change rate (H).

Structures

Some Windows Type I cracked.
A few earthenware toilet fixtures cracked (H).

MM6 Zone

People

Felt by all.
People and animals alarmed.
Many run outside.

Difficulty experienced in walking steadily.

Fittings
Objects fall from shelves.
Pictures fall from walls (H).
Some furniture moved on smooth floors, some unsecured free-standing fireplaces moved.
Glassware and crockery broken.
Very unstable furniture overturned.
Small church and school bells ring (H).
Appliances move on bench or table tops.
Filing cabinets or "easy glide" drawers may open (or shut).

Structures
Slight damage to Buildings Type I.
Some stucco or cement plaster falls.
Windows Type I broken.
A few cases of Chimney damage.
Damage to a few weak domestic chimneys, some may fall.

Environment
Trees and bushes shake, or are heard to rustle.
Loose material dislodged on some slopes, e.g. existing slides, talus and scree slopes.
A few very small ($\leq 10^{3}\text{m}^{3}$) soil and regolith slides and rock falls from steep banks and cuts.

A few minor cases of liquefaction (sand boil) in highly susceptible alluvial and estuarine deposits.

MM7 Zone

People
General alarm.
Difficulty experienced in standing.
Noticed by motorcar drivers who may stop.

Fittings
Large bells ring.
Furniture moves on smooth floors, may move on carpeted floors.
Substantial damage to fragile contents of buildings.

Structures
Unreinforced stone and brick walls cracked.
Buildings Type I cracked, some with minor masonry falls.
A few instances of damage to Buildings Type II.
Unbraced parapets, unbraced brick gables, and architectural ornaments fall.
Roofing tiles, especially ridge tiles may be dislodged.
Many unreinforced domestic chimneys damaged, often falling from roof line.
Water tanks Type I burst.
A few instances of damage to brick veneers and plaster or cement-based linings.
Unrestrained water cylinders (Water Tanks Type II) may move and leak.
Some Windows Type II cracked.
Suspended ceilings damaged.

Environment

Very small ($\leq 10^3 m^3$) disrupted soil slides and falls of sand and gravel banks, and small rock-falls from steep slopes and cuttings are common.
Fine cracking on some slopes and ridge crests.
A few small to moderate landslides (10^3-10^5 m^3), mainly rock falls on steeper slopes (> 30°) such as gorges, coastal cliffs, road cuts and excavations.
Small discontinuous areas of minor shallow sliding and mobilisation of scree slopes in places.

A few instances of non-damaging liquefaction (small water and sand ejections) in alluvium.

MM8 Zone

People
Alarm may approach panic.
Steering of motorcars greatly affected.

Structures
Buildings Type I heavily damaged, some collapse.
Buildings Type II damaged, some with partial collapse.
Buildings Type III damaged in some cases.
A few instances of damage to Structures Type IV.
Monuments and pre-1976 elevated tanks and factory stacks twisted or brought down
Some pre-1965 infill masonry panels damaged.
A few post-1980 brick veneers damaged.
Decayed timber piles of houses damaged.
Houses not secured to foundations may move.
Most unreinforced domestic chimneys damaged, some below roof-line, many brought down.

Environment
Cracks appear on steep slopes and in wet ground.
Significant landsliding likely in susceptible areas.
Small to moderate slides (10^3-10^5 m^3) widespread; mainly rock and disrupted soil falls on steeper slopes (steep banks, terrace edges, gorges, cliffs, cuts etc).
Significant areas of shallow regolith landsliding, and some reactivation of scree slopes.
A few large (10^5-10^6 m^3) landslides from coastal cliffs, and possibly large to very large ($\geq 10^6 m^3$) rock slides and avalanches from steep mountain slopes.
Larger landslides in narrow valleys may form small temporary landslide-dammed lakes.
Roads damaged and blocked by small to moderate failures of cuts and slumping of road-edge fills.

Evidence of soil liquefaction common, with small sand boils and water ejections in alluvium, and localised lateral spreading (fissuring, sand and water ejections) and settlements along banks of rivers, lakes and canals etc.

MM9 Zone

Structures
Many Buildings Type I destroyed.
Buildings Type II heavily damaged, some collapse.
Buildings Type III damaged, some with partial collapse.
Structures Type IV damaged in some cases, some with flexible frames seriously damaged.
Damage or permanent damage to some Structures Type V.
Houses not secured to foundations shifted off.
Brick veneers fall and expose frames.

Environment

Cracking on flat and sloping ground conspicuous.
Landsliding widespread and damaging in susceptible terrain, particularly on slopes steeper than 20°.
Extensive areas of shallow regolith failures and many rock falls and disrupted rock and soil slides on moderate to steep slopes (20°-35° or greater), cliffs, escarpments, gorges and man-made cuts.
Many small to large (10^3-10^6 m^3) failures of regolith and bedrock, and some very large landslides ($10^6 m^3$ or greater) on steep susceptible slopes.
Very large failures on coastal cliffs and low-angle bedding planes in Tertiary rocks. Large rock/debris avalanches on steep mountain slopes in well-jointed greywacke and granitic rocks.
Landslide-dammed lakes formed by large landslides in narrow valleys
Damage to road and rail infrastructure widespread with moderate to large failures of road cuts and slumping of road-edge fills. Small to large cut slope failures and rock falls in open mines and quarries

Liquefaction effects widespread with numerous sand boils and water ejections on alluvial plains, and extensive, potentially damaging lateral spreading (fissuring and sand ejections) along banks of rivers, lakes, canals etc. Spreading and settlement of river stopbanks likely.

MM10 Zone

Structures
Most Buildings Type I destroyed.
Many Buildings Type II destroyed.
Many Buildings Type III heavily damaged, some collapse.
Structures Type IV damaged, some with partial collapse.
Structures Type V moderately damaged, but few partial collapses.
A few instances of damage to Structures Type VI.
Some well-built timber buildings moderately damaged (excluding damage from falling chimneys)

Environment
Landsliding very widespread in susceptible terrain.
Similar effects to MM9, but more intensive and severe, with very large rock masses displaced on steep mountain slopes and coastal cliffs. Landslide-dammed lakes formed. Many moderate to large failures of road and rail cuts and slumping of road-edge fills and embankments may cause great damage and closure of roads and railway lines.

Liquefaction effects (as for MM9) widespread and severe. Lateral spreading and slumping may cause rents over large areas, causing extensive damage, particularly along river banks, and affecting bridges, wharves, port facilities, and road and rail embankments on swampy, alluvial or estuarine areas.

MM11 Zone

Structures
Most Buildings Type II destroyed.
Many Buildings Type III destroyed.
Structures Type IV heavily damaged, some collapse.
Structures Type V damaged, some with partial collapse.
Structures Type VI suffer minor damage, a few moderately damaged.

MM12 Zone

Structures
Most Buildings Type III destroyed.
Many Structures Type IV destroyed.

Many Buildings Type V heavily damaged, some with partial collapse.
Structures Type VI moderately damaged.

Categories of Construction

Buildings Type I:

Buildings with low standard of workmanship, poor mortar, or constructed of weak materials like mud brick or rammed earth. Soft storey structures (e.g. shops) made of masonry, weak reinforced concrete, or composite materials (e.g. some walls timber, some brick) not well tied together. Masonry buildings otherwise conforming to Buildings Types I-III, but also having heavy unreinforced masonry towers. (Buildings constructed entirely of timber must be of extremely low quality to be Type I).

Buildings Type II:

Buildings of ordinary workmanship, with mortar of average quality. No extreme weaknesses, such as inadequate bonding of the corners, but neither designed nor reinforced to resist lateral forces. Such buildings not having heavy unreinforced masonry towers.

Buildings Type III:

Reinforced masonry or concrete buildings of good workmanship and with sound mortar, but not formally designed to resist earthquake forces.

Structures Type IV:

Buildings and bridges designed and built to resist earthquakes to normal use standards, i.e. no special collapse or damage limiting measures taken (mid-1930's to c. 1970 for concrete and to c.1980 other materials).

Structures Type V:

Buildings and bridges designed and built to normal use standards, i.e. no special damage limiting measures taken, other than code requirements, dating from since c. 1970 for concrete and c.1980 other materials.

Structures Type VI:

Structures, dating from c. 1980, with well-defined foundation behaviour, which have been specially designed for minimal damage, e.g. seismically isolated emergency facilities, some structures with dangerous or high contents, or new generation low-damage structures.

Windows Type I:

Large display windows, especially shop windows.

Windows Type II:

Ordinary sash or casement windows.

Water Tanks Type I:

External, stand mounted, corrugated iron water tanks

Water Tanks Type II:

Domestic hot-water cylinders unrestrained except by supply and delivery pipes.

H (Historical):

Important for historical events. Current application only to older houses, etc.

General Comment:

- "Some" or "a few" indicates that the threshold of a particular effect has just been reached at that intensity.
- "Many run outside" (MM6) variable depending on mass behaviour, or conditioning by occurrence or absence of previous quakes, i.e. may occur at MM5 or not until MM7.
- "Fragile contents of buildings". Fragile contents include weak, brittle, unstable, unrestrained objects in any kind of building.
- "Well-built timber buildings" have: wall openings not too large; robust piles or reinforced concrete strip foundations; superstructure tied to foundations.
- Buildings Type III-V at MM10 and greater intensities are more likely to exhibit the damage levels indicated for low-rise buildings on firm or stiff ground and for high-rise buildings on soft ground. By inference lesser damage to low-rise buildings on soft ground and high-rise buildings on firm or stiff ground may indicate the same intensity. These effects are due to attenuation of short period vibrations and amplification of longer period vibrations in soft soils.

Discussion:

In 1992, a study group of the New Zealand National Society for New Zealand developed an "official" version of the Modified Mercalli Intensity scale for application in New Zealand. It contained definitions for the intensity zones MM1 to MM10. At the time it was felt that there was insufficient information available to provide satisfactory definitions for zones MM11 and MM12, and indeed there is quite strong support for the view that the MM10 zone damage is the worst that can arise from earthquake shaking alone. The descriptors for "environmental" effects were in some cases not well developed because of a paucity of supporting data.

In 1996, D.J. Dowrick proposed a few minor revisions of the scale and developed definitions for zones MM11 and MM12.

In 2002, Hancox et al reported the findings of historical studies on the environmental effects of earthquake shaking, and extended the environmental damage descriptors for zones MM6 to MM10.

Although neither the Dowrick nor the Hancox et al modifications have yet been adopted by a study group of the New Zealand Society for Earthquake Engineering that has been officially constituted for the purpose, they have been subjected to the normal review processes of the Society's Bulletin, and do provide useful additions to the MMI scale of 1992.

References:

Report of a Study Group of NZNSEE. "A revision of the Modified Mercalli Seismic Intensity scale." *Bulletin of the New Zealand National Society for Earthquake Engineering*, 25(4):345-357 (1992).

Dowrick, D.J. "The Modified Mercalli Earthquake Intensity scale – Revisions arising from recent studies of New Zealand earthquakes". *Bulletin of the New Zealand National Society for Earthquake Engineering*, 29(2):92-106 (1996).

Hancox, G.T., Perrin, N.D. and Dellow, G.D. "Recent studies of historical earthquake-induced landsliding, ground damage, and MM intensity in New Zealand. *Bulletin of the New Zealand Society for Earthquake Engineering* 35(2): 59-95 (2002).