Performance of Timber, Masonry and Earth Houses in the Christchurch Earthquakes New Zealand September 2010 and February 2011

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Abstract

Two earthquakes struck close to Christchurch city in New Zealand generating high level ground excitations that caused severe geotechnical effects and widespread structural damage. This paper focuses on damage to timber and masonry that resulted from the geotechnical effects experienced including liquefaction, lateral spreading, rock fall, horizontal and vertical ground accelerations. Light timber framed construction performed well for life safety but there were a large number seriously damaged, heavy masonry caused significant problems when inadequately reinforced. Changes to the construction standards are needed to improve foundation requirements and lateral wall bracing.

Earth building damage to modern houses is discussed in reference to the New Zealand Earth Building Standards, and particularly the non-specific design clauses which specify a consistent reinforcing approach. Double skin pressed earth brick and earth brick veneers performed badly and will be excluded in a future revision. Historic unreinforced earth buildings suffered serious damage that was typical for the level of shaking

Keywords: Earthquake Performance, Seismic Resistance, Earth Houses, Light Timber Frame

The February event produced the most severe geotechnical effects and structural damage to major structures in the central city and damaged over 100,000 houses. In some areas damage was due to rock fall from hillsides cliffs. The most severe ground shaking effects were seen on houses in the hill suburbs and a large number of house foundation problems occurred in the eastern suburbs where there was an unprecedented level of liquefaction and lateral spreading of the underlying soils (Fig 3).

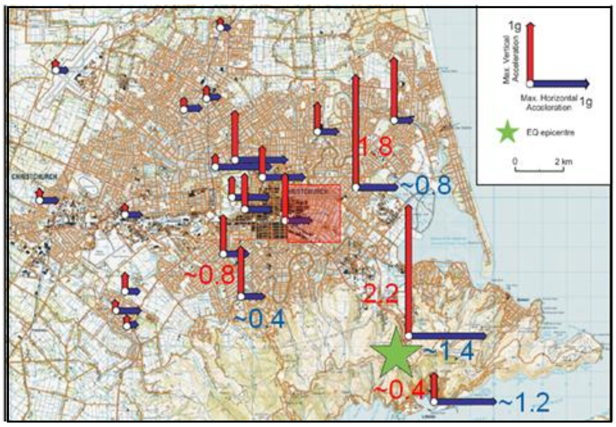

Figure 2 Ground accelerations due to the Feb 2011 earthquake with some larger values annotated

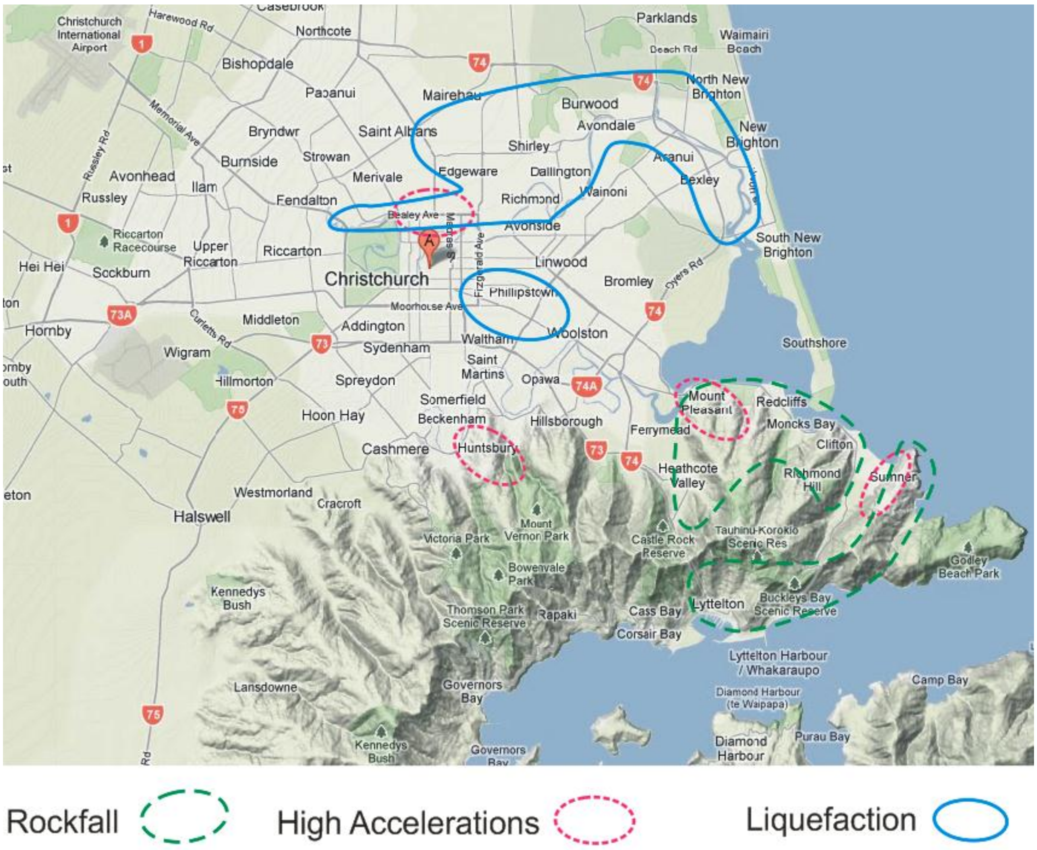

Figure 3 Approximate location of worst house damage types in February 22 Earthquake (Google map)

Rock fall damage

In areas to the southeast of the city centre houses were damaged due to landslides and boulders that broke free from hillsides during the earthquake. In some cases this type of damage was severe and resulted in large portions of houses being destroyed and rendered uninhabitable, as shown in Figures 4 and 5.

Figure 4. House damage in Heathcote due to rock fall (Carradine)

  

Figure 5a Fallen rock entry point   5b House and garage   5c Close up of fallen rock inside house and garage

Liquefaction

Liquefaction occurs when silty or sandy soils of a relatively constant grain size and moderate to low density are below the water table when an earthquake occurs. The shaking causes the particles to settle towards a more compact configuration and causes a major increase in pore pressure effectively turning the soil into a liquid for a short time. This caused house foundations to sink and pipes and manholes to float (Fig 6,7). When liquefaction occurs near rivers, estuaries or other unconstrained slopes the liquefied soil moves downhill and causes house foundations to spread laterally (Fig 8).

Figure 6 Houses that settled and have been inundated by ejected material in a major liquefaction zone

Figure 7 Masonry veneer damage due to lateral spreading and differential settlement (Buchanan) and due to differential settlement

Figure 8 Houses near rivers that have been subject to differential settlement and lateral spreading

Floor slabs are either unreinforced or reinforced with a welded wire steel mesh but in many cases the lateral spreading caused slab fractures and resulting structural house damage (Figure 9).

Figure 9 House and reinforced slab damage as a result of ground movement (Buchanan)

Horizontal Accelerations

Most common damage expected from earthquakes is due to lateral ground movement which is usually characterised by ground accelerations. As was seen earlier in figure 3 the ground accelerations were very high in many parts of the city and substantially exceeded design levels. Figure 10 shows the central city spectral accelerations with the design spectra for the 500 year design level and additionally the 2500 year maximum considered values from the most recent loadings standard. While accelerations were very large the duration of shaking in the central city was short with high accelerations occurring over about 7s. Christchurch was very well instrumented but there were no records in the hill suburbs. The nearest instruments gave the highest peak ground accelerations (PGA) of 1.4g horizontal and 2.2g vertical, it is likely that residential hill suburb accelerations were even higher.

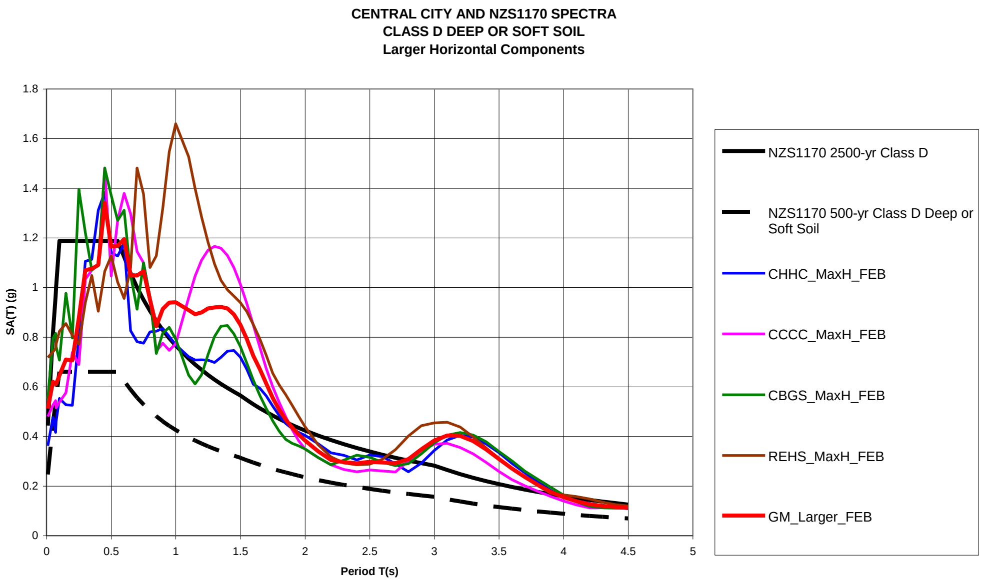

Figure 10 Horizontal spectral ground accelerations in central Christchurch and NZS1170 design levels (Bradley)

Masonry Veneers

Lightweight timber cladding systems such as weatherboards suffered less damage than heavier facades such as brick and masonry. The most commonly observed failure was where the masonry veneer separated from the frame due to inadequate tie systems and in particular the bond with the mortar. This damage was worst in the hill suburbs. Figures 11 and 12 show masonry veneer failures. Some failures were due to differential movement between systems having different structural stiffness.

Figure 11 A house that totally lost its masonry and stucco facade

Figure 12 Two examples of masonry veneers detached from the wall framing. The first example with such poor mortar that the veneer has separated into individual bricks

Internal Linings

NZS 3604 is the comprehensive “Timber Framed Buildings” standard (Standards New Zealand, 2011) includes wall bracing systems and bracing ratings. In newer houses a significant portion of the lateral load resistance of the building is based on internal linings. There have been cases of occasional severe damage to the higher grade plasterboard used as an internal bracing material well fixed at the edges and glue fixed to intermediate timber framing. A case with the board popping off after its lateral load capacity had been exceeded is shown in Figure 13.

Figure 13. Severe failure of GIB Braceline internal linings (Morris)

In most cases internal plaster damage was limited to cracks, but in some cases there was enough movement to cause the plaster to buckle, as in Figure 14.

Figure 14 Buckled plasterboard in house in Heathcote Valley (Carradine)

Figure 15. A soft storey failure of a timber framed house not resulting in collapse

Several examples of soft storey failures were observed where there was inadequate bracing capacity in the lower level as illustrated in figure 15.

Vertical Accelerations

Vertical accelerations are likely to have had a significant effect on masonry performance. The effects were most evident with heavy clay and concrete tiled roofs. These had little or no tie downs and in many cases tiles were dislodged, in the worst cases the roofs shed most tiles as shown in figure 16.

Timber house summary

Most houses were of light timber frame construction and performed very well during the earthquake. The structural integrity of timber framed houses was largely intact for the range of foundation and load conditions described. Even severely damaged houses did not collapse and saved lives although they were no longer habitable.

Figure 16 House with all roof tiles dislodged

Masonry Houses

As discussed earlier masonry facades caused significant problems however the timber frame stayed intact. Double brick houses performed much worse and many were observed to have partially collapsed as shown in Figure 17. Generally, fully reinforced and grouted concrete block masonry houses performed very well although walls constructed with partially filled cells, with only the reinforced cells filled with grout, did not perform as well. (Figure 18).

Figure 17 Examples of partial collapse of double brick houses (Carradine)

Figure 18 Ungrouted cells with reinforcing steel in place (Beattie)

Unreinforced masonry houses performed badly during the earthquake and there were many examples of exterior structural wall failures (Figure 19).

Figure 19 Left: Collapse of unreinforced masonry exterior wall (Carradine), and Right: Collapse of unreinforced masonry exterior wall (Morris)

Earth Houses and Buildings

Earth buildings form a very small part of the building stock in New Zealand but comprehensive earth building standards have been published, this paper primarily references *NZS 4299 Earth Buildings Not Requiring Specific Design* (Standards New Zealand, 1998). The NZ Standards are significant internationally and make a valuable contribution with over half the world's population living in earth houses.

A survey of earth buildings was done, with support from the Earth Building Association of New Zealand (EBANZ), one month after the September earthquake and a summary of all houses surveyed was published. (Morris et al. 2010, 2011). The damage was consistent with expectations and would have been prevented if the details were consistent with the New Zealand earth building standards. After the February earthquake a further survey was undertaken of all known accessible earth houses.

Earth buildings that are unreinforced have a number of typical failure modes as illustrated in Figure . These modes of failure were observed in two reconstructed historic cottages. Serious damage to Cotons Cottage in Hororata is shown in Figure , the horizontal peak ground acceleration (PGA) during the September earthquake was measured 0.5g just 350m away. (Gledhill et al. 2010, Cousins and McVerry 2010).

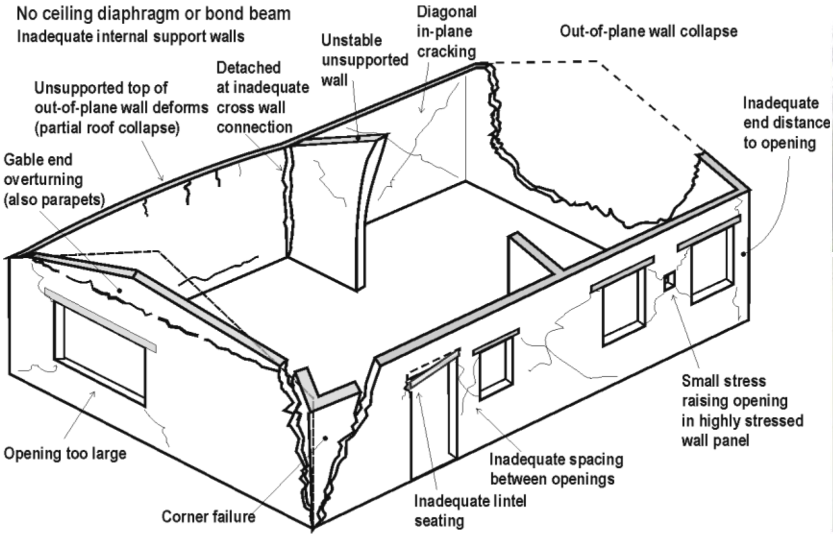

Figure 20 Typical failures of unreinforced earth construction (C) Morris

Figure 21 Cotons cob cottage extensively damaged

The adobe (sun dried brick) house illustrated in Figure and 22 was built in 1997. It incorporated many details and reinforcing that are included in the earth building standards but with a slightly weaker diaphragm and no rigid cross walls. It is 4km from the epicentre and 800m from the fault trace so is likely to have experienced 0.7g to 0.8g horizontal PGA. The walls are 275 mm thick and 2.7m high and are horizontally and vertically reinforced. Vertical reinforcing is

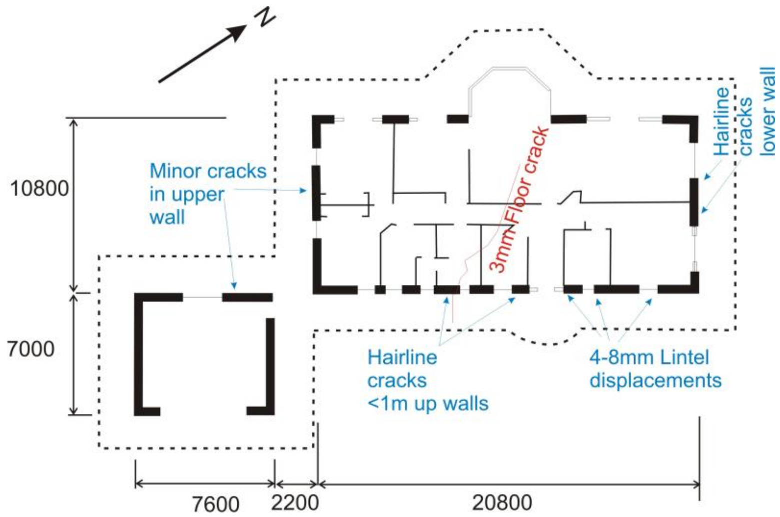

Figure 22 Charing Cross adobe house plan showing adobe walls and minor damage locations

continuous to the top plate which is additionally anchored to both the wall and the ceiling diaphragm. The most significant damage was a cracked floor slab evident from a 2-3mm crack in the floor tiles. This crack continued as a 1mm crack through the concrete foundation beam reinforced with a D16 top and bottom (two top and bottom are recommended in NZS4299). There were also hairline cracks at foundation level as shown in Figure 22. It appears that there was some differential movement at the west corner where settlement and movement of the verandah posts embedded in the concrete path caused cracking in the upper south wall (Figure 1). Lateral movement had caused movement or minor pounding of the lintels leaving gaps of 4-6mm at ends of the lintels (Figure).

This house suffered minimal damage which was primarily due to differential ground movement and while there were indicators that the building had suffered significant shaking the limited amount of damage in this significant event provides evidence for the effectiveness of the building system.

Figure 23 Charing Cross adobe house, 4km South East of the epicentre

Figure 14 Crack in wall near the west corner

Figure 25 Opening at edge of lintel beam

Three other adobe houses were investigated after the September earthquake and another at Diamond Harbour after the February earthquake. All had suffered minor damage and clearly indicated the effectiveness of the continuous full height reinforcement. Unreinforced historic buildings which relied on the strength of the earth walls for lateral load resistance all suffered significant damage.

A number of earth buildings made of stabilised rammed earth performed well but most were only subjected to moderate shaking (<0.4g PGA) and suffered minor cracking. This technology uses cement stabilised soil compacted into shutters to create a monolithic wall panel. The older buildings all had reinforced concrete bond beams and unreinforced walls, in one 1925 house subjected to higher accelerations (Estimated PGA 0.65g) the bond beam moved relative to the wall and caused significant damage which could have prevented with good anchorage.

The most significant damage to earth buildings occurred with pressed earth brick masonry cavity walls and veneers. Pressed earth bricks are made of soil-cement in a compacting press. The performance of buildings using this technology was very much the worst of the modern earth wall technologies and while not specifically covered by the NZ Earth Building Standards will need to be specifically excluded.

Figure 25 Pressed earth double skin masonry, serious wall failures were avoided because of the post and beam construction supporting the upper storey.

Conclusions

Many thousands of houses were damaged with the worst damage occurring due to liquefaction and lateral spreading in the eastern suburbs. The very high levels of lateral and vertical shaking were the main causes of damage in the hill suburbs. Lightweight and framed buildings have performed very well in preventing walls and roofs collapsing on owners and saving lives when subjected to seismic shaking and severe ground deformations. While lives were at serious risk due to rockfall, the resilience of light timber frame construction was evident with houses still standing after large sections of wall were destroyed.

These were the first major earthquakes where modern reinforced earth buildings have been tested. All known accessible earth houses were surveyed damage was minor in most of the modern buildings surveyed and able to be understood in all cases with most of the more serious damage to modern buildings due to differential ground movement. The adobe buildings all used modern detailing and confirmed the principles of the requirements of the New Zealand earth building standards. Full height continuous vertical reinforcement is critical, timber ceiling diaphragms are working well, there is a minimum length of return walls and stiff cross walls need to be provided.

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