OBSERVATIONS OF THE PERFORMANCE OF EARTH BUILDINGS FOLLOWING THE SEPTEMBER 2010 DARFIELD EARTHQUAKE

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SUMMARY

A reconnaissance survey of earth walled buildings in the Canterbury area was carried out in mid October 2010 following the Darfield Earthquake. Fifteen earth walled buildings were inspected during the survey including historic earthbuildings and recently constructed reinforced earthbuildings.

Reinforced earth houses constructed since the 1990s performed well provided the overall wall bracing was adequate and detailing of the reinforcement and connections was generally in accordance with the NZ Earth Building Standards. Several unreinforced earth buildings constructed before 1930 (or reconstructed historic buildings) suffered significant structural damage and will require reconstruction or substantial repair. Unreinforced rammed earth buildings, and reinforced cinva ram brick buildings, constructed between 1930 and 1990 with reinforced concrete foundations and bond beams and adequate overall wall bracing generally performed moderately well given the level of shaking they experienced.

Minor cracking was observed in all but one of modern houses, performance was good where reinforcement and construction complied with the New Zealand Standards. Where buildings did not comply the damage could have been prevented by following the Standards.

INTRODUCTION

On 4th September 2010 a magnitude 7.1 earthquake occurred in Canterbury, approximately 40 km west of Christchurch, at a depth of approximately 10 km near the town of Darfield. Modified Mercalli intensities were estimated from data supplied by GNS Science. The accelerations were analysed by Gledhill *et al.* [1] and are plotted in another paper in this issue of the Bulletin, these estimates are noted for comparison with the observed damage.

Some historic and older earth buildings were damaged during the earthquake and some more recent earthbuldings suffered some minor cracking damage.

Earth buildings use heavy low strength masonry or low tensile strength monolithic walls panels, buildings in this survey were constructed using a range of earth wall techniques. These are: Adobe - sun dried brick; Rammed earth - stabilised soil heavily compacted between shutters; Cinva brick - bricks of cement stabilised soil hand pressed with a Cinva Ram mechanical press; Cob - soft soil mixture laid into a wall in layers; Sod - soil blocks cut from the ground and placed directly into the wall; and Poured earth – a cement stabilised soil mixture poured or vibrated into formwork layer by layer.

EBANZ RECONNAISSANCE SURVEY

The Earth Building Association of New Zealand (EBANZ) organised a reconnaissance survey of earth buildings in the Canterbury area following the Darfield 2010 Earthquake. This survey was carried out on 14-16th October 2010 by an engineer with research interest in earth buildings and two engineers experienced in the design and construction supervision of earth buildings. Fifteen earthbuildings were visited during the survey including several historic (or reconstructed historic) and older unreinforced earthbuildings and several more recent reinforced earth buildings and two timber framed buildings with external pressed earth brick veneer walls. A summary of the earthbuildings inspected, including their location, main construction details, and damage state are shown in Table 1.

The buildings were assessed with respect to design criteria and details within the NZ Earth Building Standards and the performance and damage criteria of the Modified EERI Methodology. This modified methodology was developed by Fred Webster and E. Leroy Tolles following the 1994 Northridge, California Earthquake and further modified by the authors for use with this reconnaissance survey [2, 3].

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Table 1. Summary of Earth Buildings inspected after the September 2010 Darfield Earthquake.

No.	Location and Type	Wall Material	Construction Date	Foundation	Bond Beam	Wall Height / Thickness	Wall Reinforcing	Sub-Soil Type	Damage State*
1	Hororata House	Rammed Earth, part timber 2nd storey	1925, addition 1960	Concrete	RC 450x250	2100/450	None	D	C1
2	Hororata Cottage	Cob	~1860	Rubble	Timber top plate	1800/400	None	D	C3
3	Cotons Cottage	Cob and Rammed earth	Reconstructed 1977	Rubble & Concrete	Timber 150x50	2500/500	None	D	E
4	Charing Cross House	Adobe	1997	Reinforced Concrete	Timber & Diaphragm	2700/275	Vertical and Horizontal	D	B1
5	Sandy Knolls House	Poured Earth, timber mezzanine	2010+	Reinforced Concrete	RC 350x200	2400/300	Vertical only to standards	D	A
6	Leeston House	Adobe	1999	Reinforced Concrete	Timber & diaphragm	2250/275 [4200/430]	Vertical and Horizontal	E	B2
7	Staveley House	Adobe, timber top storey	2008	Reinforced Concrete	280x45 timber & diaphragm	2400/280	Vertical and Horizontal	C	B1
8	Governors Bay House	Cinva Brick double skin	1978	Reinforced Concrete	RC 200x150	2250/250 2250/100 int	Vertical in conc core	B	B1
9	Camp Bay House	Rammed Earth, timber 2nd storey	1965	Reinforced Concrete	RC 200x250	2100/200	RC columns at end of wall panels	B	B1
10	Sefton House	Rammed Earth, part timber 2nd storey	2005	Reinforced Concrete	RC 300x200	2400/350 250 internal	vertical at panel ends	D	B1
11a	Spencerville House	Cinva Brick Veneer	2003	Reinforced	N/A	140 veneer	N/A	D	B1
11b	Spencerville Garage	Cinva Brick Veneer	2000	Reinforced	N/A	140 veneer	N/A	D	C3
12	Ferrymead Sod	Sod, Cob and Adobe	1860 sod, 1950 cob	None	No	2000/500	None	E	D2
13	Ferrymead Cob	Cob	1982	None	Timber top plate	2000/480	None	E	B2
14	Beckenham House	Rammed Earth	1950	Reinforced Concrete	RC 200x250	2400/200	None	D	B2

* Further detail in table 2, Estimated Site Subsoil Class based on AS/NZS 1170.5[4] Damage Subcategories 1 Low 3 Greater

NEW ZEALAND EARTH BUILDING STANDARDS

As described by Walker and Morris [5, 6], three performance based standards for earth walled buildings were published in 1998. NZS 4297 *Engineering Design of Earth Buildings* [7] specifies design criteria, methodologies and performance aspects and is intended for use by structural engineers. NZS 4298[8] defines the material and workmanship requirements of earth walls to comply with the requirements of the NZ Building Code. NZS 4299 [9] provides the methods and details for the design and construction of earth walled buildings not requiring specific engineering design. NZS 4299 is the earth wall construction equivalent of NZS 3604 Timber Framed Building. The New Zealand earth building standards are the most comprehensive in the world and have received attention from overseas and are cited by ASTM E2392 [10].

EARTH BUILDING DAMAGE STATES

The modified EERI damage state definitions are shown in Table 2 below. The damage states A through to E are shown in the first column, the EERI standard definition is shown in the second column and the definition developed by Webster and Tolles [2,3] with respect to earth walled buildings is shown in the third column. The damage states A to E were subdivided further on a scale of 1 to 3 for this reconnaissance survey with 3 being more serious than 1.

EARTH BUILDING DAMAGE TYPES

The concept of Standardised Damage Types, as defined by Webster and Tolles for earth buildings following the Northridge Earthquake, was used for the assessment of damage in this reconnaissance survey. The more important types of earthquake damage to earth buildings are as follows:

Out of Plane Flexural Damage,
Gable Wall Collapse,
Horizontal Upper Wall Damage,
Wall Mid Height Flexural Damage,
Diagonal Crack Damage,
Wall Intersection Separation,
Corner Cracks,
Crack Damage at Openings,

Table 2. Standardised Damage States used for the EBANZ Darfield Earthquake Reconnaissance Survey

Damage State	EERI Description	Commentary on damage to historic and earth buildings
A None	No damage, but contents could be shifted. Only incidental hazard.	No damage or evidence of new cracking.
B Slight	Minor damage to non-structural elements. Building may be temporarily closed but could probably be reopened after minor cleanup in less than 1 week. Only incidental hazard.	Pre-existing cracks have opened slightly. New hairline cracks may have begun to develop at the corners of doors and windows or at the intersection of perpendicular walls.
C Moderate	Primarily non-structural damage; there also could be minor but non-threatening structural damage. Building probably closed 2 to 12 weeks.	Cracking damage throughout the building. Cracks at the expected locations, and slippage between framing and walls. Offsets at cracks are small. None of the wall sections are unstable.
D Extensive	Extensive structural and non-structural damage. Long-term closure could be expected due either to amount of repair work or uncertainty on feasibility of repair. Localized, life threatening situations would be common.	Extensive crack damage throughout the building. Crack offsets are large in many areas. Cracked wall sections are unstable; vertical support for the floor and roof framing is hazardous.
E Complete	Complete collapse or damage that is not economically repairable. Life-threatening situations in every building of this category.	Very extensive damage. Collapse or partial collapse of much of the structure. Repair of the building requires reconstruction of many of the walls.

Table by Tolles and Webster [2,3]

Foundation Movement,
Horizontal Base Wall Damage,
Vertical Cracks, and
Moisture Damage.

DAMAGE TO SOME EARTHBUILDINGS

Table 3 provides a summary of the earthquake damage to the fifteen earth buildings in Canterbury inspected during the reconnaissance survey. Ground accelerations are estimated (for approximate comparison only) by interpolating from the graph by Gledhill *et al.* [1] The methodology is outlined later with buildings plotted with Modified Mercalli Intensities.

The 15 earth buildings are a small proportion of the earth buildings within Canterbury located by EBANZ members and by owners volunteering. A comprehensive survey by Allen [11] in 1991 located 46 earth houses in Canterbury this will have increased but the exact number is not known.

Table 3. Summary of Damage to Earth Buildings inspected after the Darfield 2010 Earthquake.

		Out-of-Plane	Gable Ends	Horizontal Upper wall	Mid Height Flexure	Diagonal Crack Damage	Wall Intersection Separation	Corner Cracks	Crack damage at Openings	Foundation Movement	Horiz Movement at Foundation	Moisture Damage	Vertical Cracks	Approximate Estimated PGA	Estimated MM Intensity	New Damage State*	Pre-Existing Damage State
1	Hororata House			1		1			1			2	1	0.8	7+	C1	B
2	Hororata Cottage		1	1			1	2	2			3		0.8	7+	C3	C
3	Cotons Cottage	3		2	2	3	3	3	3		2			0.8	7+	E	B
4	Charing Cross House			1					1	1			1	1	8	B1	A
5	Sandy Knolls House													0.8	8	A	A
6	Leeston House			2		1	1		1	1		1		0.35	6+	B2	B
7	Staveley House					2								0.2	6+	B1	B
8	Governors Bay House					1						1		0.5	7	B1	B
9	Camp Bay House					1	1		1			1	1	0.5	6+	B1	B
10	Sefton House	1					1		1			2	1	0.15	5	B1	B1-
11a	Spencerville House						1		1					0.25	6+	B1	B1-
11b	Spencerville Garage	3		2					1					0.25	6+	C3	B1-
12	Ferrymead Sod	2	1	2	2	2	3	2	2			2	3	0.5	6	D2	C1
13	Ferrymead Cob			1			1	1	1			2	1	0.5	6	B2	B1
14	Beckenham House			1									2	0.3	6+	B2	B1-

* Subcategories - significance of cracking, 1 low, 3 more extensive

a) Front of cottage showing corner crack at left (surface erosion is also visible).

b) Interior of same wall with the corner crack visible.

Figure 1: Hororata Cob Cottage, (Building 2) unreinforced walls with horizontal cracking and wall intersection cracks.

Historic and Reconstructed Buildings.

Hororata Cottage (Figure 1) has cob walls and Penfolds Cottage Ferrymead (Figure 3) is sod and repaired in the 1950s with cob. Both were constructed around 1860 without reinforcment.

Coton's Cottage (Figure 2) is part of a museum complex. It was initially constructed with cob walls and substantially reconstructed with unreinforced rammed earth walls in 1977.

a) North wall of cottage showing major chimney damage after initial event .
(Photos John Le Harivel Historic Places Trust)

b) South wall, east corner failure.

c) Internal view showing complex damage of south wall, east corner .

d) South wall collapse, west corner.

Figure 2: Cotons Cottage Hororata (Building 3)– largely rebuilt of rammed earth in 1977.

Both the cottages illustrated above are near Hororata, south of Darfield, where very strong shaking, with ground accelerations of approximately 0.8g and MM VIII were experienced. There was moderate cracking damage in walls of the Hororata Cottage and extensive structural damage to Penfolds Sod Cottage in Ferrymead (Figure 3) which has both sod and cob walls. Coton's cob cottage (Figure 2) had very extensive damage with all walls suffering some damage. There was major collapse of part of the end wall and several walls were damaged beyond reasonable repair.

a) Lower parts of walls made of sod, upper walls predominantly cob, cement plaster. Exterior cracking of plaster in a number of places.

b) Chimney damage from initial event. Maria Adamski Christchurch City Council

c) Interior showing end wall separation and side wall vertical crack with out-of-plane offset. The interface of the 1860s sod with 1950s cob can be seen on the right hand wall.

Figure 3: Penfolds Cob Cottage Ferrymead (Building 12); continued next page

event. One of the

d) Interior damage at the interface with the chimney.

Figure 3: Penfolds Cob Cottage Ferrymead (Building 12).

A reconstruction cob cottage in the Ferrymead historic village is shown in figure 4. It is unreinforced cob construction built in 1982, it suffered some corner cracking and other minor damage. It has a low 1.8 m walls with small window openings and a substantial chimney.

Figure 4: Ferrymead Sod Cottage (building 13) most minor damage was internal – pre-existing crack at doorway opened.

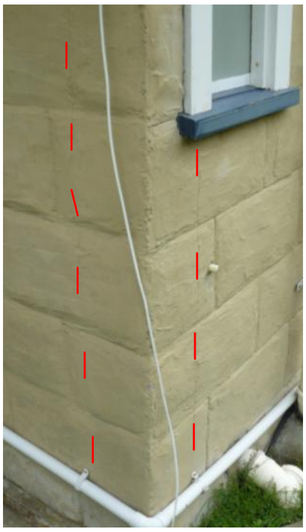
a) Detail of the displacement of the concrete bond beam relative to the unreinforced soil-cement wall.

Figure 5: Hororata Rammed Earth House , 1925, timber additions around 1960. (Building 1)

Rammed Earth Houses.

The Hororata house shown in figure 5 has unreinforced rammed earth walls and was constructed in about 1925, also in the strong shaking region near Hororata. Two pre-existing

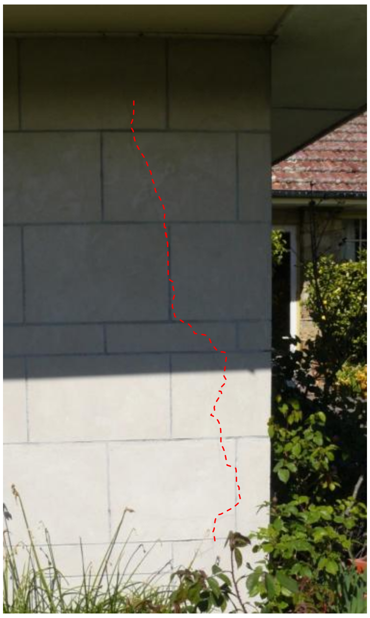
The house suffered moderate new cracking, and the bond beam, which stayed intact, moved horizontally along the walls by approximately 6mm. Movement of the bond beam relative to the wall caused diagonal cracking in the rammed earth wall adjacent to a window.



a) Lower storey rammed earth wall panels between reinforced concrete foundations, bond beams, and columns. Rammed earth walls plastered and scribed to appear as blocks.

b) Minor wall and plaster cracking at interface to the concrete column.

Figure 6: Camp Bay Rammed Earth House (Building 9) 1965.



a) Rammed earth house surface plastered – Reinforced concrete bond beam, L shape plan.

b) Fine crack full wall thickness.

Figure 7: Beckenham Rammed Earth House (Building 14) 1950.

Buildings at Camp Bay (Figure 6) and Beckenham (Figure 7) were constructed between 1950 and 1980 and have unreinforced rammed earth walls, reinforced concrete foundations and reinforced concrete bond beams that connect to lintels at the tops of walls. Both these buildings experienced strong shaking but performed quite well with slight cracking damage to the rammed earth walls particularly adjacent to window and door openings.

The house near Sefton (Figure 8) experienced moderate shaking and was constructed in stages over about ten years.

a)500 m^2 rammed earth house with second level over garage

b) Cracks adjacent to the wood faced concrete lintel.

Figure 8: Sefton Rammed Earth House (Building 10) 1995.

The Sefton house has single storey rammed earth walls with vertical steel reinforcing. The vertical reinforcing was located at each end of the rammed earth wall panels similar to the details for partially reinforced earth walls in NZS 4299[9]. There was some slight cracking adjacent to some openings. One short internal wall had some minor horizontal cracking which the owner advised occurred during construction.

Double Skin Cinva Brick House.

Figure 9 shows a house constructed in 1978 with double skin pressed earth brick load bearing external walls with a reinforced concrete core and single skin pressed brick internal walls and reinforced concrete foundations and bond beam and a timber framed upper storey. This building experienced strong shaking but generally performed well with slight diagonal cracking along mortar joints particularly near door and window openings. There was moderate cracking to two exterior unreinforced cantilever pressed brick walls and some separation of the fireplace structure from the main house walls.

Adobe Houses.

The Charing Cross house (Figure 10) was located approximately 700 metres from the Greendale Fault with very strong shaking with Modified Mercalli intensity estimated at MM8.

Figure 9: Governors Bay Double Skin Cinva Brick House (Building 8). Subject to strong shaking but with minor damage.

The damage to paving outside and tiling in the bathroom indicated significant ground movement. This single storey house was constructed in 1997 with 2700 mm high and 280 mm thick adobe walls with both vertical and horizontal steel reinforcing, reinforced concrete foundations, timber top plate and timber ceiling diaphragms.

Figure 10: Charing Cross Adobe House (Building 4) 1999. Located between the epicentre and major fault rupture. Reinforcing similar to that specified in the NZ Earth Building Standards. Minor cracking mostly due to differential ground movement.

a) Adobe house L shape plan, garage attached by timber infill, arrow shows cracking at chimney interface.

b) Evidence of liquefaction related to differential movement in foundations and cracked paths.

Figure 11: Leeston Adobe House (Building 6) 1999 - continued.

The Charing Cross house performed very well given the proximity to the fault and level of shaking and suffered only slight damage. This comprised some minor cracking adjacent to doorways and openings and lintels. There were some hairline cracks in the concrete foundations reinforced with 1-D16 bar top and bottom. NZ Earth Building Standard NZS 4299 [9] specifies 2-D16 bars top and bottom for the concrete foundations.

c) Cracking in adobe joints adjacent to windows.

Figure 11: Leeston Adobe House (Building 6) 1999.

An adobe house near Leeston (Figure 11) experienced strong shaking with ground accelerations of approximately 0.3 g and estimated MMI of VII. There was evidence of ground liquefaction at the site. This single storey house was constructed in 1999 with mainly 2,250 mm high and 275 mm thick adobe walls with both vertical and horizontal steel reinforcing, reinforced concrete foundations, timber top plate and timber ceiling diaphragms. The building performed well generally. There was some slight cracking adjacent to doorways and openings and some minor gaps at ends of lintels and more significant cracking at a very high 4.1 m high adobe wall. There was some slight horizontal cracking at the top course of adobe bricks at some locations. This was considered to be due to insufficient connection of adjacent timber top-plates and insufficient anchorage between the top course of adobe bricks and the underside of the timber top-plate.

Figure 12: Staveley Adobe House (Building 7) 2008 Structural cracking in short return walls.

The adobe house (Figure 12) near Staveley experienced moderate to strong shaking with an estimated MMI of greater than VI. This house was constructed in 2008 with adobe walls on the ground floor and a timber framed second storey. The adobe walls were reinforced. The detailing of the reinforcing and overall wall bracing was not in accordance with NZS 4299. There was horizontal cracking in the mortar joints of the adobe walls at one end of the building where the reconnaissance team considered the wall bracing and reinforcement fixing is likely to be insufficient.

Figure 13: Sandy Knolls Poured Earth House (Building 5). 2010 Vertically reinforced only but no damage evident.

Poured Earth House.

A house under construction (Figure 13) near Sandy Knolls experienced very strong shaking with ground accelerations of approximately 0.8 g and estimated MMI of VIII. This house with cement stabilised poured earth walls and steel vertical reinforcing and reinforced concrete foundations and bond beams was under construction at the time of the earthquake. All the earthwalls and roof framing were completed but the roofing was not on and the timber ceiling diaphragms were not yet installed. The building was designed by the owner in accordance with NZS 4299. The building performed well with no damage evident.

Figure 14: Spencerville Light Timber Frame House with Cinva Pressed Earth Brick Veneer (Building 11a).

Cinva Brick Veneer House and Garage.

A timber framed house (Figure 14) and timber framed garage (Figure 15) were built with 140 mm thick pressed earth brick veneer walls which underwent strong shaking. The veneer walls in both buildings were fixed to the timber frame with brick ties bedded within the mortar. The mortar for the house was sand-cement. The mortar for the garage was soil-cement. There was no positive connection with nails or screws through the tie into the top of the bricks.

The veneer walls in the house generally performed well but had some slight cracking under most of the window openings. The support timber frame for the pressed brick fireplace had separated 15 mm from the main timber framed wall for the house. This was considered to be due to inadequate connection of the fireplace to the wall.

There was a major failure of the support system for the veneer walls on the south side of the garage. This is considered to be due to the pullout of the ties from the mortar. This will be checked when the walls of the garage are demolished and reconstructed.

a) Garage with upper level timber, veneer detached adjacent to garage door, significant cracks over end wall lintel.

b) Rear wall of garage showing out of plane deformation assumed to be due to veneer ties inadequately anchored into the bricks.

Figure 15: ***Spencerville Garage Cinva Pressed Earth Brick Veneer (Building 11b).***

LOCATION OF BUILDINGS AND INTENSITY ESTIMATES

Table 4: Detail of Building Locations

	Designated Location	Longitude and Latitude
1	Hororata House	43°33’28”S, 171°59’56”
2	Hororata Cottage	43°33’ S, 171°58’ approx
3	Cotons Cottage	43°32’34”S, 171°57’35”
4	Charing Cross House	43°32’08”S, 172°22’05”
5	Sandy Knolls House	43°33’29”S, 172°42’37”
6	Leeston House	43°42’45”S, 172°25’56”
7	Staveley House	43°38’31”S, 171°25’28”
8	Governors Bay House	43°37’08”S, 172°42’37”
9	Camp Bay House	43°37’23”S, 172°46’49”
10	Sefton House	43°14’30”S, 172°39’ approx
11a	Spencerville House	43°26’06”S, 172°41’47”
11b	Spencerville Garage	43°26’06”S, 172°41’47”
12	Ferrymead Sod	43°33’29”S, 172°42’37”
13	Ferrymead Cob	43°34’03”S, 172°42’08”
14	Beckenham House	43°33’38”S, 172°38’40”

Buildings in this survey were located across the region of high intensity shaking, the longitude and latitude of the sites is listed in table 4.

The building locations are plotted in Figure 16 with approximate Modified Mercalli intensity and instrument PGA’s. The MM contours are based on more than 2000 reports recorded by GNS Science in the area of interest. There were multiple values reported at most places, an intensity value between the average and the maximum was determined for each point shown. The simplified contour plot was made using general purpose software from these intensities. The plot provides a general context with individual buildings also compared with nearby reported values.

The accelerations by Gledhill *et al* [1] are also noted on the figure, more detail is available in that paper. The general trend

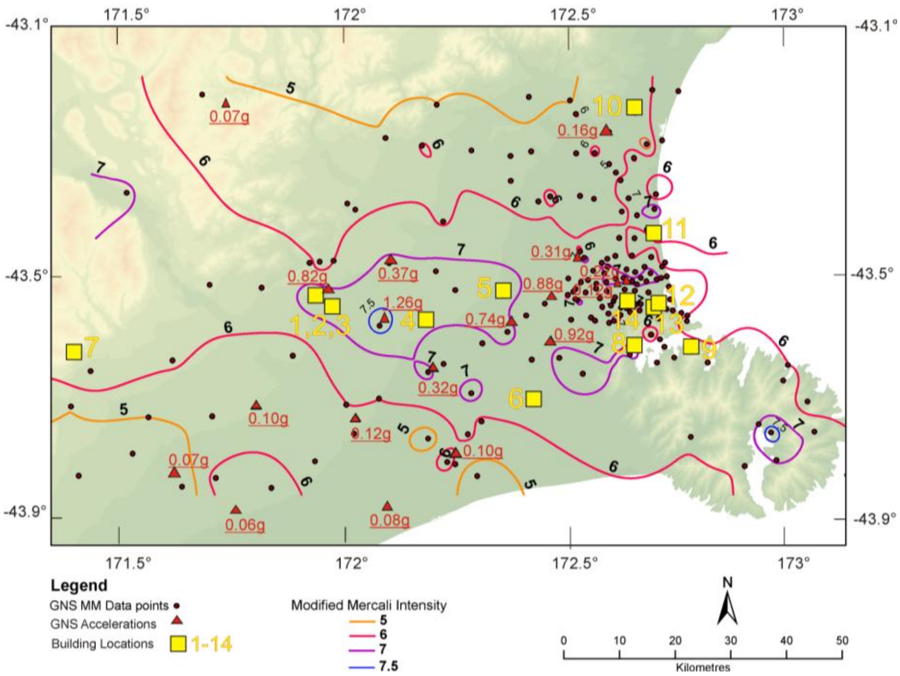


Figure 16: ***Location of earth buildings with simplified Modified Mercalli intensity contours. Instrument accelerations as reported by GNS Science [1] for 4:35AM September 4, 2010. Preliminary approximation for the purposes of this paper only.***

of accelerations was also informed by GNS Science on-line information [12] and is consistent with the intensities. Interpolated accelerations were made between recorded sites using hand drawn contours consistent with the trend. Accelerations are site dependant but these approximate indicative values will assist when comparison is made with Webster [2] and other such reports.

OBSERVATIONS AND DISCUSSION

Reinforced earth buildings constructed since the 1990s and inspected during the reconnaissance survey generally performed well during the Darfield Earthquake provided the overall wall bracing was adequate and the detailing of reinforcement and connections was in accordance with the NZ Earth Building Standards.

Some limited cracking can be expected in most earth buildings during major earthquake events, particularly adjacent to windows and door openings. This cracking is generally of no structural significance if the buildings are provided with vertical and horizontal reinforcing and the overall wall bracing provided in the building is adequate.

Cracking in a large event would be more widespread in older unreinforced earth buildings with possibly greater structural significance. For example the bond beam would need to be properly fixed along the wall length in the Hororata house to avoid in-plane cracking that would result in falling material.

Some older unreinforced earth buildings constructed before 1930 suffered significant structural damage during the Darfield Earthquake and will require reconstruction or substantial repair work.

Unreinforced rammed earth buildings and reinforced cinva brick (cement stabilised pressed brick) buildings constructed between 1930 and 1990 with reinforced concrete foundations and reinforced concrete bond beams and lintels and adequate overall wall bracing performed quite well during the Darfield Earthquake with generally only some minor cracking.

CONCLUSIONS

The NZ earth building standards deal well with key types of failure observed but need to be applied with a good understanding of the earth material characteristics.

Adequate anchoring of the top plate and full height continuous reinforcement are critical in all forms of new earth construction. Minimum bracing wall lengths must be used as specified with good intersection details. Earth brick veneers with soil cement mortar require positive connection to the ties.

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