LESSONS FROM THE PERFORMANCE OF HOUSES IN THE CANTERBURY EARTHQUAKE SEQUENCE OF 2010-11*

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ABSTRACT

The February 22nd and other Canterbury earthquakes resulted in substantial damage to many houses, but from a life safety perspective, performance was very good. Much damage to houses was due to lateral spreading and liquefaction, but in the hill suburbs and Lyttelton substantial shaking damage to houses occurred. With about one and a half million light timber frame houses in New Zealand, good seismic performance is essential to ensure accommodation is available to the majority of residents in the aftermath of an earthquake affecting an urban area. Damage to houses by the Christchurch earthquakes was assessed in a comprehensive randomised survey by BRANZ, reported on previously. Poor construction, such as unreinforced and poorly built foundation walls, lightly reinforced concrete block walls and poor connections was observed to result in increased levels of damage. Poor layouts such as houses with dominant openings on one side, foundations that were higher or more flexible on one side than the other and eccentricities common on hillside sloping sites resulted in increased levels of damage. A detailed multi-variable analysis quantifies the effects of these variables. The analysis determines whether there is sufficient cause to restrict the scope of the non-specific light timber frame design standard, NZS 3604 to structures with more vertical and horizontal regularity and/or recommend other changes. The effects of the common practice of engineers designing a small part of the bracing for a predominantly NZS 3604 design without considering the whole building will also be investigated.

1. INTRODUCTION

This paper is based on a survey of damage to houses in the Christchurch area carried out by BRANZ in August and September 2011 after Christchurch and the surrounding areas were subjected to major earthquakes on 4th September 2010 and 22nd February 2011 with a large number of aftershocks, the largest of which were two that occurred on June 13th 2011. Most shaking damage to houses in this area occurred during the February 22nd earthquake with more damage during the 13th June event. The survey and initial analysis is described in more detail in Thomas & Shelton (2012) and Beattie & Liu (2012), but will be outlined briefly below. A qualitative assessment of house damage was also described in Buchanan *et. al.* (2011).

The majority of houses in New Zealand are light timber frame construction. These generally perform well in earthquakes, with their inherent flexibility, low mass with resultant low inertial forces and good bracing in the superstructure provided by internal gypsum plasterboard linings. Known weaknesses are unreinforced brick chimneys, poorly secured brick claddings, unsecured hot water cylinders and header tanks, and poor foundation bracing. The cost of damage to houses in these events, has exceeded $10 billion, hence research into the performance of houses in earthquakes, and methods to improve it is critically important.

2. SURVEY METHODOLOGY

Randomly selected blocks of houses within randomly selected census mesh blocks were surveyed for their type of construction, size, geometry, claddings, external openings and other salient features. Type and extent of damage to the foundations, claddings, wall linings, structure and other features of the property were recorded. The survey was focused on getting an overall picture of damage, rather than concentrating on the worst damage. A total of 314 houses were surveyed in an area ranging from Redwood and Marshland to North New Brighton and south to Halswell, Lyttelton and Taylors Mistake, with the survey blocks shown in Figure 1.

The survey was carried out by BRANZ staff and contractors, and staff from Victoria and Canterbury Universities. As with any survey there is some inconsistency between surveyors and as much

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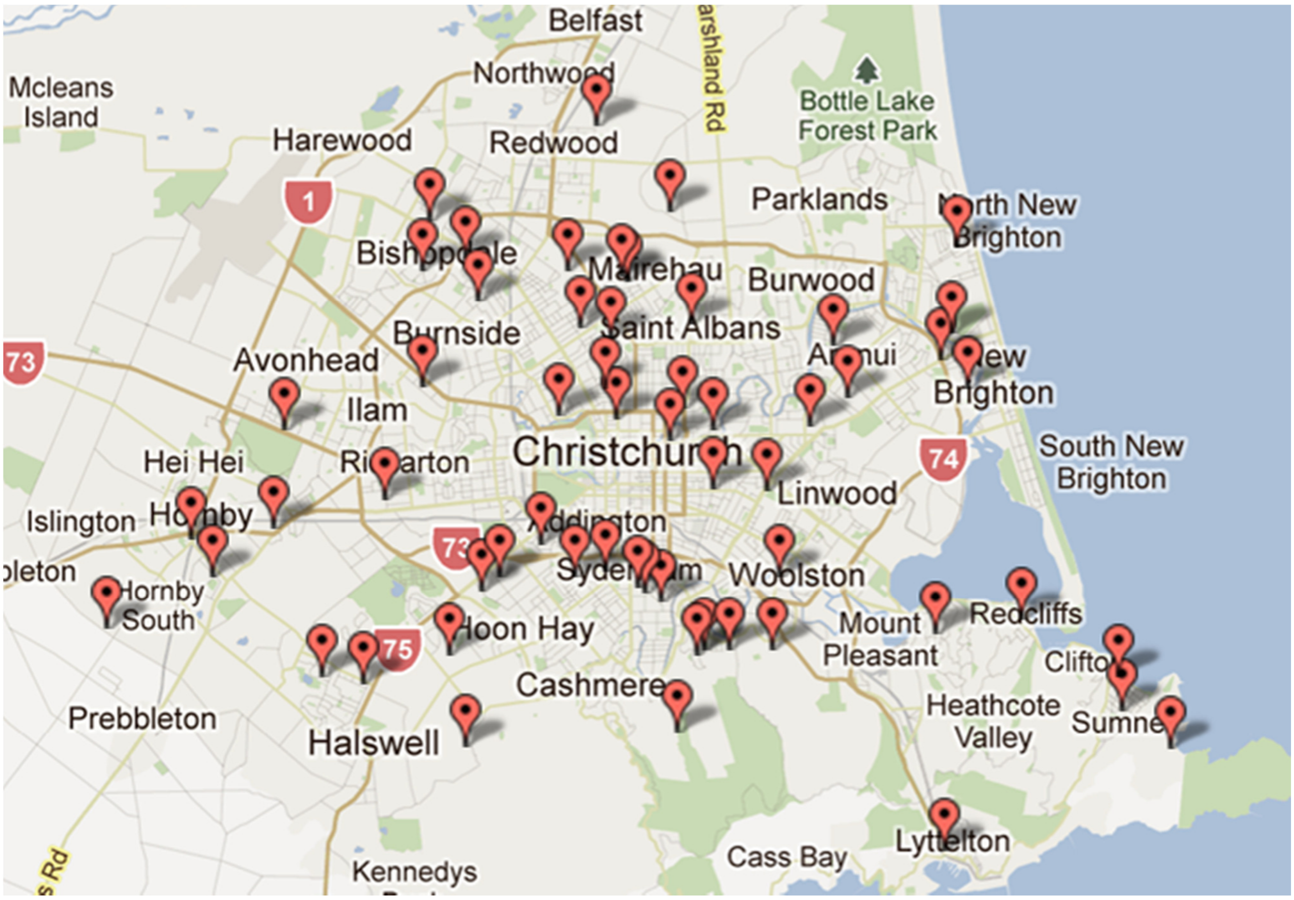

Figure 1. Extent of survey area.

information had to be gleaned from house occupants, many of whom were distressed by the damage to their houses, individual records may contain some inaccuracies but this is not thought to affect the overall results. Due to pressure of time and difficulties of access, concealed spaces such as sub-floors and roof spaces were not always checked and reasonable assumptions about type of structure were made. It is likely that damage in these area was underestimated when it was not apparent from outside. Some more severely damaged houses were not surveyed as they had been demolished by the time the survey took place, which will reduce the overall extent of damage in the sample.

Qualitative analysis of damage to linings and claddings and effects of horizontal and vertical irregularities had been carried out and previously reported on [1,4].

The two previous papers using the data concluded:

- almost all houses in the survey area had damage to linings;
- most houses with masonry, stucco or monolithic claddings had at least some damage to claddings;
- good modern workmanship appears to have helped to limited damage;
- low foundation heights and the preponderance of concrete perimeter foundation walls in Christchurch, appear to have limited damage to foundations;
- wide stiffness incompatibilities between the front and rear of houses resulted in more significant damage;
- stiffness incompatibilities between foundation elements resulted in more significant damage;
- floor deformation needs to be considered if there is a stiffness incompatibility.

This paper builds on previous work and summarises work extended to the quantitative statistical analysis using the commercial statistical software package SPSS. Also three additional data fields have been added to the database, additional information on sites subject to liquefaction and peak ground accelerations from the 22nd February and 13th June earthquakes.

3. ANALYSIS METHODOLOGY

3.1. SUMMARISING DAMAGE

The damage categories in the survey were to identify numerous features, such as claddings, linings, framing, and foundations and so on. In many categories, for example roof cladding, few houses had damage and for some types of construction there were few houses in the sample, for example monolithic cladding. Hence it was decided to concentrate on the two largest groupings of damage in terms of sample size for that type of material and range of damage, that is wall linings and masonry cladding (brick, concrete block, Summerhill stone (split concrete blocks similar in size to bricks) or stone veneers as external cladding).

Internal wall lining damage was categorised as joint cracks, diagonal cracks, and fallen sheets. They were further classified into seven levels of the extent of damage, <10%, 10-24%, 25-49%, 50-79%, 80-89% and 90 -100%. A single value for overall damage was necessary for statistical analysis, so these levels of damage were assigned values of 0-6 respectively. A decision on the extent of damage, based on the level of damage observed in the test of wall linings, was made to assign a four-fold increase in values. The integer value for diagonal racking is therefore multiplied by four and for fallen sheets by 16, and the three values added together to give an overall value score, which can vary from 1 to 126. The set of final scores was analysed and cut-off points for the damage levels given as shown in Table 1. As most of the sample had limited damage the cut-off points are biased towards the bottom end of the scale to give similar numbers in each group. A similar process was used for masonry veneers, where damage was classified as cracking, unstable or detached. The cut-off points for the damage levels for masonry veneers are also shown in Table 1.

Table 1. Summary of the damage categories.

Category	Interior Lining Damage	Exterior Damage
Undamaged	0	0
Minimal	1	1
Minor	2	2
Moderate	3-6	3-10
Major	7-72	11-126

With a single value for damage, the overall damage could be assessed against a number of variables.

4. RESULTS

The peak ground accelerations (pga) for each group of houses has been input into the database in values of increments of 0.1g based on the maps produced for the main 22nd February and 13th June earthquakes, based on the pga contour maps from the Canterbury Geotechnical Database (2013). It was intended that the damage be compared against the highest pga from either event, however none of the house groups surveyed underwent a higher pga in June than February, so only February values have been used for comparison. Figure 1 compares peak ground acceleration against damage to internal linings and external veneer claddings

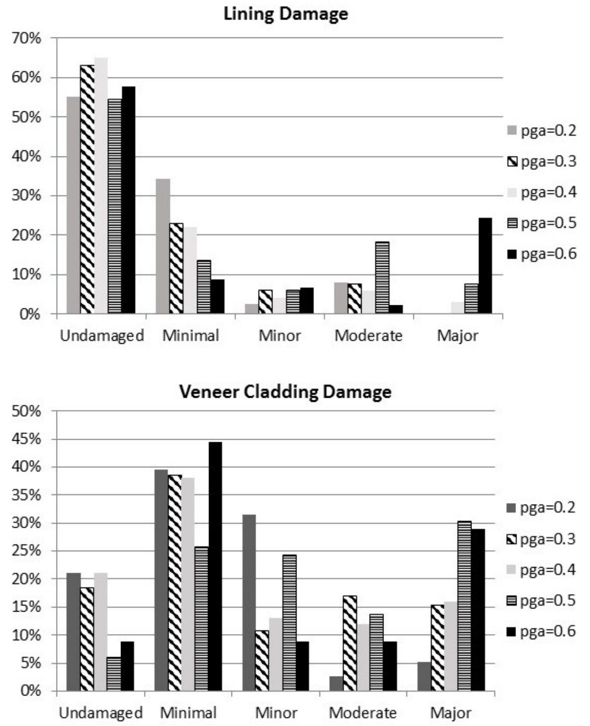

Figure 1. Lining (a) and veneer (b) damage as a function of peak ground acceleration.

respectively. The expected result is that damage would generally increase with increased peak ground acceleration for both linings and claddings. This expectation is met, which gives confidence in the accuracy of the survey, but there are some anomalies. There are a slightly lower proportion of houses subjected to a pga of 0.2 and 0.3 in the undamaged category, than those subjected to a pga of 0.4, and more in this category from pga of 0.6 than a pga of 0.5. There is obviously some variation due to statistical variation, but an obvious reason for this discrepancy is the effect of liquefaction on damage to houses on sites that experienced lower pga's.

With a single value for damage, the overall damage could be assessed against a number of variables. In the survey data a number of variables were divided into numerous categories. In many cases this resulted in categories that had so few data points that the comparisons were not statistically significantly when analysed using a Chi-square test in SPSS. The classifications were therefore grouped based on significant cut-off points in order to provide meaningful results. The first example is house age which was divided into pre-1980 and post-1980 which corresponds with the introduction of the first edition of NZS 3604 : Design of Timber Structures not Requiring Specific Design in 1978, with some allowance for uptake of the new code. Figure 2a shows a comparison of wall lining damage against house age, and Figure 2b, veneer cladding damage against house age. There are 22 houses in the pre-1980 category in the sample and 92 in the post 1980 category.

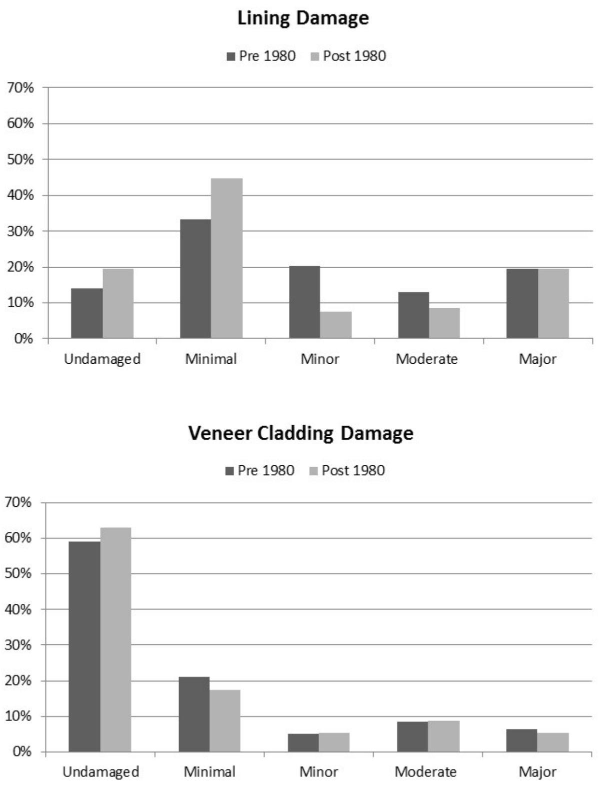

Figure 2. Cladding (a) and veneer (b) damage as a function of house age.

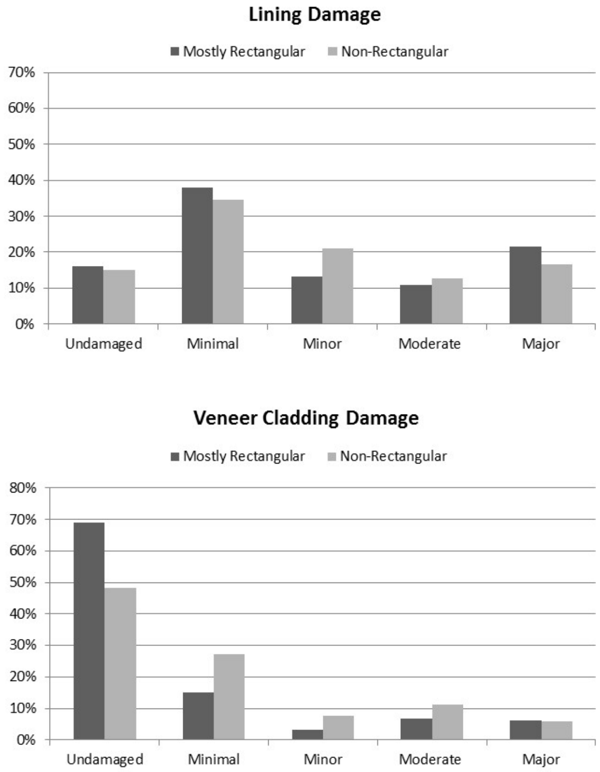

Figure 3. Lining (a) and veneer (b) damage as a function of plan shape.

Although older and newer houses had a similar proportion in the "major" category for lining damage, overall the older houses performed slightly worse, with more in the minor and moderate category. There were about the same or higher proportion of houses surveyed in every category except "undamaged" for veneer damage. Pre-1980s houses had slightly less openings, but more importantly the location of openings around the houses, as measured by the relative proportions of windows on each side is more even. Hence it can be inferred that the improvement in bracing performance that occurred with the introduction of NZS 3604 has been compensated for in a large part by a trend to having dominant openings on one or two adjacent sides of a house and to a lesser extent by an increase in the overall amount of openings. Furthermore without the improvement in lateral load resistance from designing to NZS 3604, it is likely the design trend to more, and less symmetrical layouts of, external openings would have resulted in much poorer performance.

Most houses (58%) in the sample were mostly rectangular, and non-rectangular houses had more damage overall, to both claddings and linings (Figure 3).

Mostly rectangular is defined as houses that are rectangular or square or with a slight deviation from rectangular, for example a small extension of a room a few metres outside the otherwise rectangular plan. Mostly rectangular houses are more likely to be in the undamaged or minimal categories for lining damage. Close to 70% of rectangular houses had no veneer damage compared to less than 50% of non-rectangular houses. This discrepancy between veneers and linings may be because houses are planned so that re-entrant internal corners are not common as internal walls are located at the junctions of different wings, and any damage is likely to be confined to the re-entrant corner joint anyway. On the other hand with veneer claddings, there is likely to be significant differential movement between two planes of cladding meeting at a re-entrant corner with confinement by the other plane of cladding and the wall framing limiting differential movement. Therefore the cladding can only crack, displace or fall off and this damage can propagate along the length of the wall.

The effect of topography on damage is marked. Figure 4 shows that all houses on hilly (sloping or hill top) sites had some cladding damage. Although a higher proportion of houses on the flat (271 out of a total of 314 house surveyed) were in the minimal and minor categories, over 50% of houses on hilly sites had major damage to linings. The same trend although less marked is apparent for veneer damage, with over 30% of the houses on hilly sites having major damage to veneer claddings. This finding is complicated by the fact that the level of shaking was higher in hill suburbs. The results have been separated for flat and hilly sites compared with pga's in Figure 5 for lining damage and Figure 6 for veneer claddings to ascertain whether this result is due to the level of shaking or a combination of both.

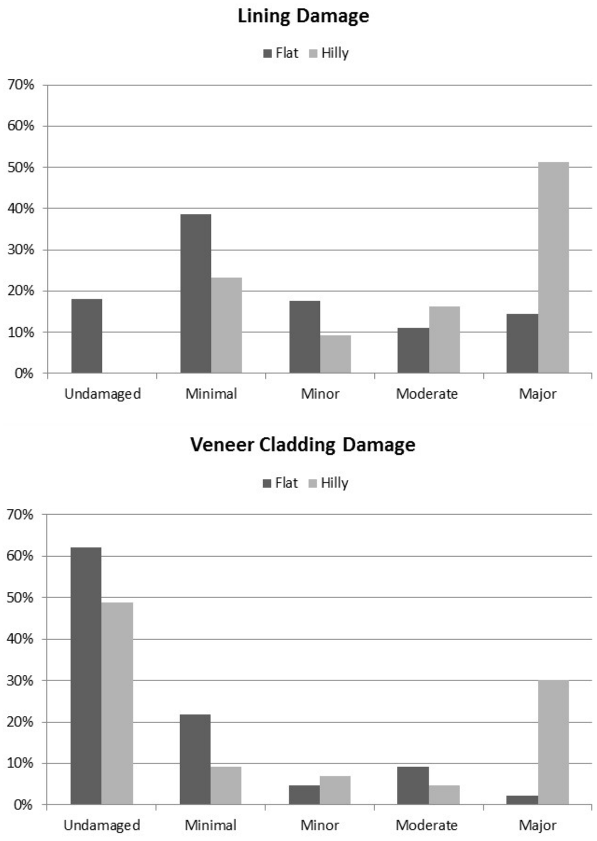

Figure 4. Lining (a) and veneer (b) damage as a function of topography.

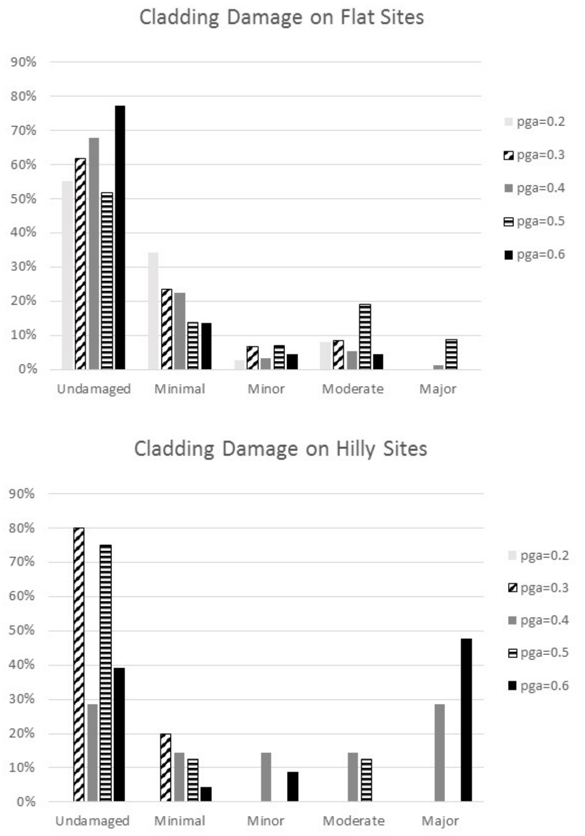

Figure 6. Veneer cladding damage as a function of pga for flat and hilly sites.

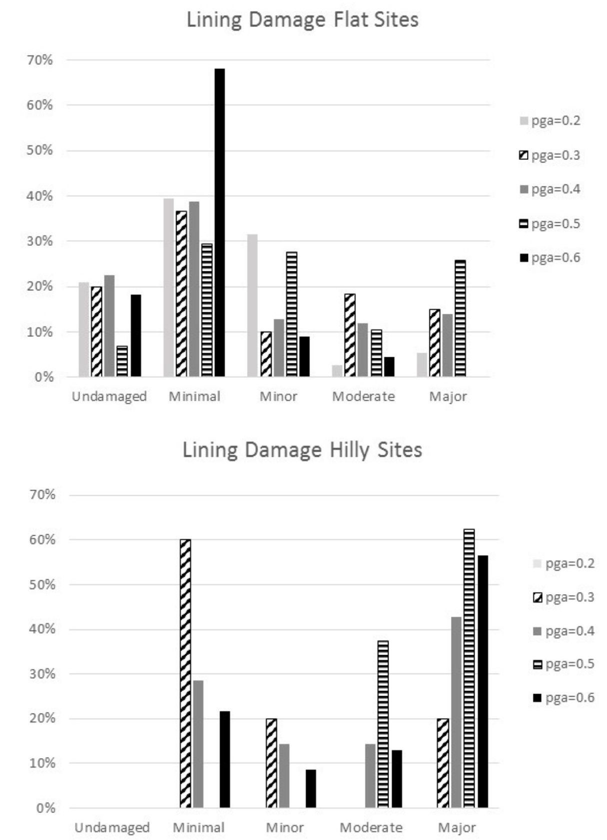

Figure 5. Lining damage as a function of pga for flat and hilly sites.

It is difficult to draw general conclusions from the middle of the range of lining damage, but at the extremes findings are more obvious. No houses on hilly sites had linings that were undamaged, regardless of the pga, but on flat sites about 17% were undamaged. In the major category there are a much higher proportion of houses in this category on hilly sites, regardless of pga. For cladding damage with a smaller sample size for both hilly and flat sites, there is more scatter in the data, but there appears to be some evidence of a trend of more damage in hilly sites regardless of pga. The increased level of damage on hilly sites regardless of pga is even more significant when the increase levels of damage on some flat sites, due to liquefaction and lateral spreading, is considered.

5. DISCUSSION AND FURTHER WORK

With the amount of data available the potential for further analysis is enormous, however when multi-variable analysis is attempted, the size of each data group can become very small limiting the validity of the results and hence the conclusions that can be drawn from them. This is particularly the case when analysing some variables such as topography, when even where sites are separated into only two categories, the flat category has more than five times the data points of the size of the "non-flat" remainder. Further analysis will be carried out on the effect of foundation height and the

Figure 7. House on sloping site with horizontal and vertical irregularities and differing foundation types.

effect of differences in foundation height, which is a more direct measure of the differences in structure that hilly sites can cause. The effect of type of foundation will also be considered. Further cross-tabulation for results between house age and plan shape versus pga will also be carried out.

Another major area of work yet to be completed is the effect of openings on damage, both the percentage of wall openings in a house and their distribution around the walls. Of particular interest is house with dominant openings on one side, or two adjacent sides which could result in significant torsional problems. This analysis is complicated by houses with dominant openings on one side, facing a view, frequently being on sloping sites and also have higher foundations on the side with large openings or even different foundation types on the higher side. They may also have horizontal as well as vertical irregularities, a good example being the house in Lyttelton shown in Figure 7, which is partly on cantilever timber beams at the front, but built into the slope on a concrete slab at the back and has vertical and horizontal irregularities.

The analysis is complicated by the large number of variables, but now that data on liquefaction and pga has been included in the data, it is intended to assess the expected levels of damage for pga and liquefaction potential, and identify outliers. The features of houses that perform much better or worse than expected will be analysed to identify trends.

6. CONCLUSIONS

Although overall levels of damage were similar in post and pre-1980 houses, houses built after 1980, tended to have slightly more openings in exterior walls but, more significantly, were more likely to have large openings on one side compared to the other sides. It appears that the effect of more rigorous design and construction of houses for bracing after the introduction of NZS 3604 is not apparent, because the trend towards more asymmetrical houses and larger windows has at the same time reduced lateral load resistance. Without NZS 3604 however, this trend in design is likely to have resulted in much poorer performance of houses with more windows and less symmetrical arrangements of windows.

The effect of plan irregularities was noticeable, more so in cladding damage, rather than internal lining damage. This is probably because damage to internal linings at re -entrant corners will be localised to joint cracks at the corner.

Topography has a significant effect, even when the peak ground acceleration is taken into account, and despite a large part of the damage on many flat sites being due, at least in part, to liquefaction and lateral spreading.

Further work is necessary to look at foundations in more detail, and the effect of extent and distribution of openings on external walls.

A qualitative analysis of houses that have significantly more or less damage than expected compared to the peak ground accelerations and liquefaction of their sites will give a good indication of combinations of features that positively or negatively affect house performance.

7. REFERENCES:

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8. IMPORTANT NOTICE

Figures 1a, 1b, 5a, 5b, 6a and 6b were produced from maps and/or data extracted from the Canterbury Geotechnical Database (https://canterburygeotechnicaldatabase.pojectorbit.com/), which were prepared and/or complied for the Earthquake Commission (EQC) to assist in preparing claims made under the Earthquake Commission Act 1993 and/or for the Canterbury Earthquake Recovery Authority (CERA). The source maps and data were not intended for any other purpose. EQC, CERA, their data suppliers and engineers, Tonkin & Taylor, have no liability for any use of the maps and data or for the consequence of any person relying on them in any way. This "important notice" must be reproduced wherever these figures (or derivatives) are reproduced.

9. ACKNOWLEDGEMENTS:

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