The Performance of Residential House Foundations in the Canterbury Earthquakes

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ABSTRACT: During the Canterbury Earthquake sequence from September 2010 – December 2011, a number of significant seismic events affected Christchurch. These earthquakes produced significant and widespread liquefaction in the eastern suburbs of Christchurch to varying degrees.

The liquefaction caused significant damage to a large number of residential dwellings, due to the ejection of sand and water at the surface, loss of bearing strength, ground settlement and lateral spreading. The performance of four different common foundation types that had suffered varying levels of liquefaction severity during the five major earthquake events was assessed. The examined foundation types were: Slab-on-grade (NZS:3604), Concrete perimeter with short 'pier' supports (NZS:3604), RibRaft^{TM} slab foundations (Firth 2003) and deep piled foundations. Around 40 houses of each foundation type were inspected, as well as an additional 20 houses that suffered no liquefaction effects for purposes of comparison.

The results of these inspections have been analysed and a number of conclusions drawn. This paper outlines typical damage to each foundation type, explains the inspection methodology used and presents the results of the data analysis. There is clear evidence that the performance of the foundations was closely related to liquefaction severity.

1 INTRODUCTION

During the Canterbury Earthquake sequence from September 2010 – December 2011, a number of significant seismic events affected Christchurch. These events produced widespread liquefaction in the eastern suburbs of Christchurch with varying degrees of severity.

The liquefaction caused significant damage to a large number of residential dwellings, due to the ejection of sand and water at the surface, loss of bearing strength, ground settlement and lateral spreading. Residential houses with four different foundation types common in Christchurch and New Zealand, suffering varying levels of damage, were inspected across a range of liquefaction severities.

The examined foundation types were: slab-on-grade (NZS:3604), concrete perimeter with short 'pier' supports (NZS:3604), RibRaft^{TM} slab foundations (Firth 2003) and deep piled foundations. Around 40 houses of each foundation type were inspected, as well as an additional 20 houses that suffered no liquefaction, 10 concrete perimeter and 10 slab-on-grade, for purposes of comparison.

The inspections involved recording levels of ground damage (liquefaction and lateral spreading), corresponding damage to the structure (foundation levels, slopes and cracking; superstructure damage in a range of categories) and damage to the surrounding property.

This paper focuses on the performance of the four different foundation types under varying levels of liquefaction severity, and draws conclusions on their performance based on trends discovered in the inspection data.

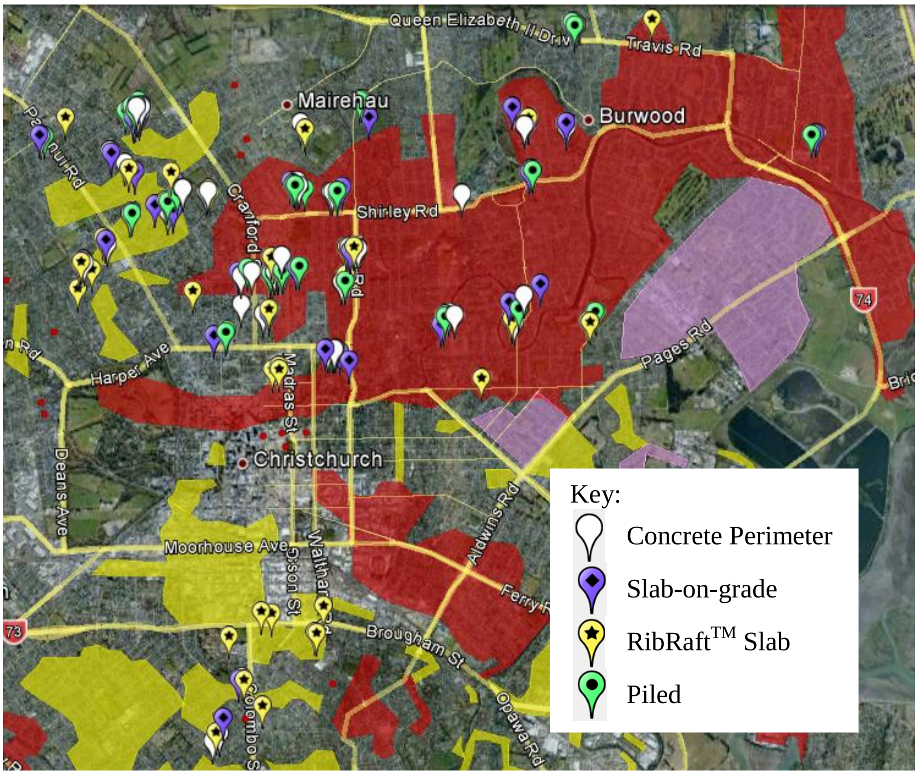

Figure 1. Locations surveyed overlayed on the UC Liquefaction Map (Cubrinovski & Taylor, 2011), where red is moderate to severe liquefaction effects, yellow is low to moderate liquefaction effects and purple is liquefaction effects on roads only.

2 IMPACTS ON HOUSES FROM LIQUEFACTION

2.1 Concrete Perimeter

Concrete perimeter foundations range from pre-1930's unreinforced concrete made with materials such as loose bricks, to newer foundations reinforced with multiple D12 bars. The short supports ('piers') can be timber or concrete, and usually are not rigidly connected to the floor. The concrete perimeter supports the walls and roof of the house, and so bears most of the structural dead load of the house, concentrating the load on these narrow perimeters.

These construction characteristics result in some very particular deformation modes for concrete perimeter houses and usually involves humping of the interior floor (Fig. 2a, b). This can be caused by the settlement of the perimeter due to the loss of bearing capacity caused by liquefaction, piers being pushed up by sand ejecta, or a combination of both.

This deformation mode varies from room to room and house to house, and is often accompanied by cracking in the concrete perimeter, overall tilting of the structure, and racking and twisting of the superstructure which causes cracking in the walls and jamming of doors and windows (see Figs. 3, 4).

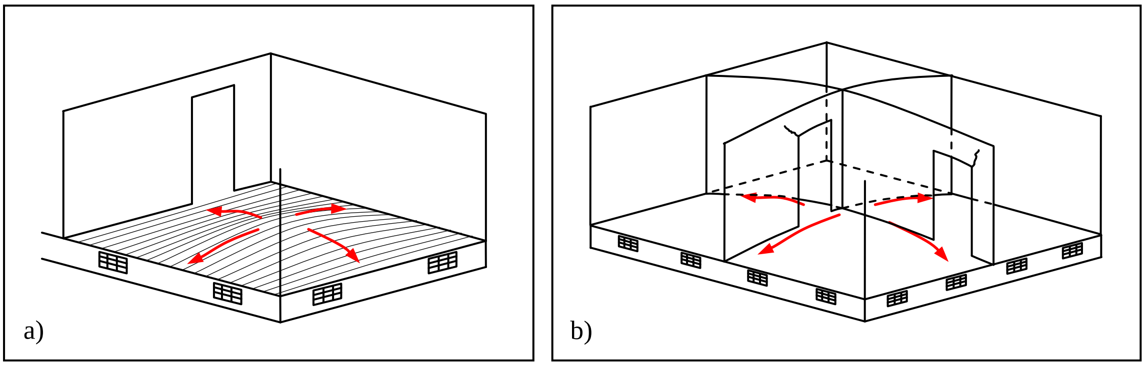

Figure 2. Typical deformation modes of concrete perimeter foundations, a) by room and b) whole floor.

Figure 3. Damage caused by racking in a house, showing door mis-alignment.

Figure 4. Typical crack in concrete perimeter foundation.

Figure 5. Cracking in floor slab.

Figure 6. Differential tilting of garage of slab-on-grade house.

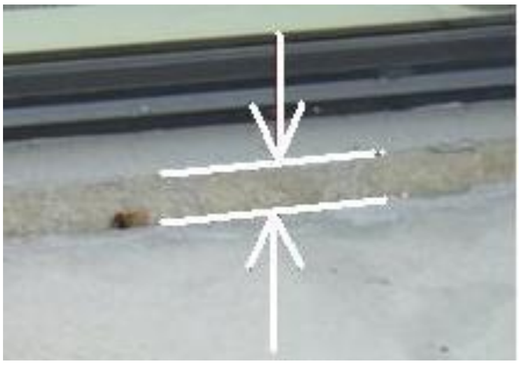

Figure 7. Piled foundation unaffected by global settlement of ground due to liquefaction.

2.2 Slab-on-grade

Typical concrete slab foundations constructed under NZS3604 are around 100mm thick (except under load-bearing walls), cast-in-place over a river-run gravel base and reinforced with 665 or 668 wire mesh. This is generally a weak arrangement when subjected to the large vertical and horizontal ground forces caused by liquefaction and lateral spreading.

Damage seen in slab-on-grade buildings is generally caused by cracking and non-uniform tilting of the slab, combined with low levels of racking and twisting. Tilting can occur uniformly, but also differentially, with irregular parts of the floor plan, such as attached garages, or rooms extending from the main floor plan being more affected by tilting (Fig. 6). This can cause large structural damage in some cases, and results in cracking in slabs (Fig. 5). The racking caused similar damage to doors and windows as shown in Figure 3 but generally to a lesser extent than for concrete perimeter foundations.

2.3 RibRaft™

A RibRaft™ slab consists of a standard slab-on-grade underlain by a square grid of reinforced concrete beams, spaced at 1.2m. The foundation is cast as a whole (i.e. slab and beams together) and is situated above the ground, with no foundation walls cast into the ground. This construction has more strength and stiffness than ordinary slab-on-grade foundations.

RibRaft™ floors generally exhibited similar damage modes to standard slab-on-grade foundations, as the structural form is still a slab. However, the damage was generally to a lesser extent, due to the added stiffness and strength. This provides better distribution of the non-uniform vertical load arising from soil liquefaction. The raising of the floor above the ground can also help to reduce the effect of lateral spreading.

2.4 Deep Piles

Driven pile foundations use either H5, 150mm diameter round timber piles, or square, reinforced concrete piles with dimensions varying from 90x75mm to 150x150mm, reinforced with wire strands along their length. The latter is more common in new houses, and the piles are generally topped with a standard slab-on-grade floor with mesh-reinforcing, which is cast-in-place over the concrete pile caps to provide a rigid connection. These foundations generally performed well in all areas of liquefaction except where severe liquefaction and lateral spreading occurred.

In areas of lower liquefaction severity, piled foundations were often relatively un-damaged, sometimes only experiencing minor tilting. These houses were unaffected by the small levels of global ground settlement caused by the liquefaction, due to the end-bearing capacity of their piles, which allowed them to keep their level until the liquefied ground had hardened again. Figure 7 shows ground settlement of around 35mm while the house has remained level.

However, in areas of more severe liquefaction severity, or significant lateral spreading, the piles were not sufficient to prevent damage, and damage similar to the ribraft foundations was found. The piles, particularly the concrete ones, have very low lateral strength, so cannot provide significant resistance against lateral spreading forces. The piles still provided sufficient support to the slab to out-perform basic slab-on-grade foundations however.

3 INSPECTION METHODOLOGY

3.1 Pre-Inspection Preparation

There were a number of preparations required before the inspections could be carried out. Areas of interest within the city were first identified, based on liquefaction maps prepared by Cubrinovski & Taylor (2011), as a range of liquefaction severities was required. Once these were identified, the next step was the selection of houses. Where possible, one house of each type of foundation was inspected close to one another (i.e. preferably within a 100m radius of each other). This was to ensure that properties of different foundation types that experienced the same seismic demand and liquefaction severity were inspected together.

3.2 Equipment

Table 1 shows the key pieces of equipment that were used in the inspection process.

Table 1. Equipment used during inspection process.

Equipment	Use	Accuracy
Tape Measure	Measuring crack widths and distances	+/- 1mm
Digital Spirit Level	Measuring floor slope and wall tilt	+/- 0.1°
Zip Level	Measuring floor levels	+/- 2mm
Camera	Recording evidence of damage	N/A

3.3 Inspection Process

The inspection of each property followed the same overall process, which included the following steps:

- Recording details of the house.
- Recording the land damage (both liquefaction and lateral spreading) suffered by the property in each major seismic event. See Table 2 for the ratings used.
- Recording the level of damage to any decks, steps, paving, fences and walls.
- Recording the level of damage to external and internal cladding, windows, doors and the roof.
- Sketching of the floor plan (ground floor only for 2-storey) on which is recorded locations and sizes of any cracks in the foundation.
- Tilt angles are taken with the Digital Spirit Level at multiple points throughout the house, in two directions at each point, with an average of at least four readings per room. Even if the house is totally un-damaged, these levels are still taken. These are recorded on the floor plan sketch also.
- Floor levels are taken with the Zip Level throughout the house, at least one point close to each corner of each room, and at least one in the middle of each room. These levels are also recorded on the sketched floor plan.

3.4 Data Indices

Table 2 shows the ratings and values given to the different damage severity levels for liquefaction, overall foundation damage and structural damage.

Table 2. Damage indices.

Damage Level	#	Liquefaction	Foundation Damage	Structural Damage
None	0	No surface effects of liquefaction visible.	No discernible damage to foundation. Floor levels construction tolerance or less.	No damage to structural components. Minor hairline cracking in plaster at corners of windows/doors
Low	1	Small sand boils (<2m in diameter & <200mm depth).	Low levels of tilting &/or cracking. No separation.	Cosmetic cracking to interior, hairline cracks in any brickwork. No doors or windows jamming
Moderate	2	Large sand boils (>2m in diameter &/or >200mm depth) not full coverage.	Moderate levels of tilting or cracking or low levels of both. Some minor separation possible	Significant cracks interior, cracking in brickwork up to 10mm wide. Doors and windows jamming but not visibly.
High	3	Near full ground coverage with ejecta, 50-200mm thick.	Moderate – high levels of cracking and/or tilting. Separation in foundation structure.	Large cracks interior, 10-20mm cracks in brickwork. Racking resulting in visibly distorted doors and windows
Severe	4	Full ground coverage with sand ejecta, >200mm thick.	Significant tilting, uniform or differential. Large cracking and separation, break-up of foundation structure.	Large structural cracks, separation of structural components. Jammed &/or broken doors &/or windows due to racking.

3.5 Data Processing

The data collected for each house was then entered into a spreadsheet, and the photos sorted into folders for each individual house. The data was scrutinised to identify any outliers. These outliers were then looked at in detail to determine whether or not there was any explanation for their different performance. If not, or if these outliers were found to be houses with significantly unusual characteristics, then they were excluded from further analysis. For example, there were very few properties inspected that suffered serious lateral spreading. As a result, these were excluded from analysis, to avoid them affecting the results. Data was also sorted based on year of construction, number of stories and external cladding type in order to determine if there were any trends in these features that would affect the overall trends in the data.

4 RESULTS

A number of interesting trends were discovered between the different foundation types when the collected data was analysed. This section outlines some of the observed results.

4.1 Overall vs. Local slopes

Three different floor slopes were recorded in the inspections. In order of increasing localisation, these were:

- *Equivalent Slope*, based on the maximum elevation difference over the foundation, taken from the Zip Level floor level measurements.
- *Maximum Slope*, based on elevation difference over the foundation, taken from the Zip Level floor level measurements.
- *Maximum Local Slope*, over 1.2m, which is the maximum slope angle measured on the floor with the Digital Spirit Level.

In all four foundation types, for the same liquefaction severity, as the measurements became more local, the slope increased. An example of this is shown in Figure 8, which shows the trend lines for each of the three slope indices against maximum liquefaction severity experienced during the Canterbury Earthquakes for concrete perimeter and slab-on-grade foundations. The trend lines for ribraft and piled foundations are very close to those for slab-on-grade. The trend lines for maximum slope and maximum local slope for concrete perimeter have very poor R^2 values, as the data was highly scattered for these indices, and affected by a large number of houses constructed with weak foundations before standards were introduced. The trend line however is mostly meant to show the overall difference in the three slopes, which it is sufficient to do.

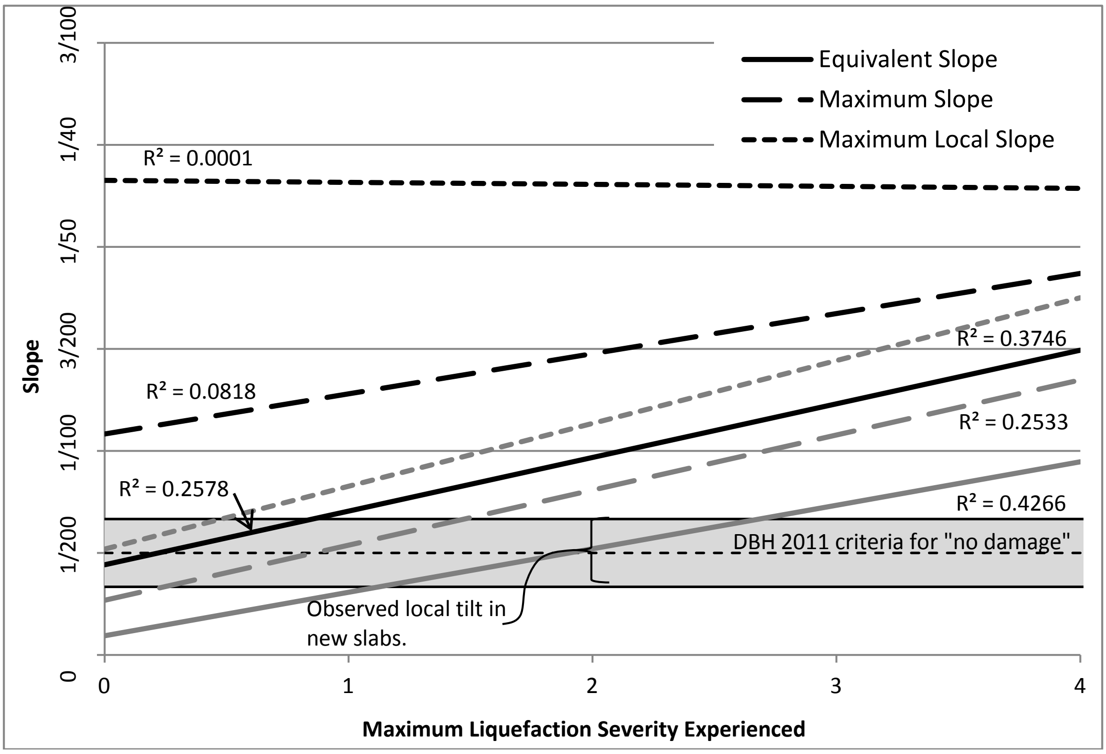

Figure 8. Trend lines for each of the three slope measurements for concrete perimeter (black) and slab-on-grade (grey) foundations.

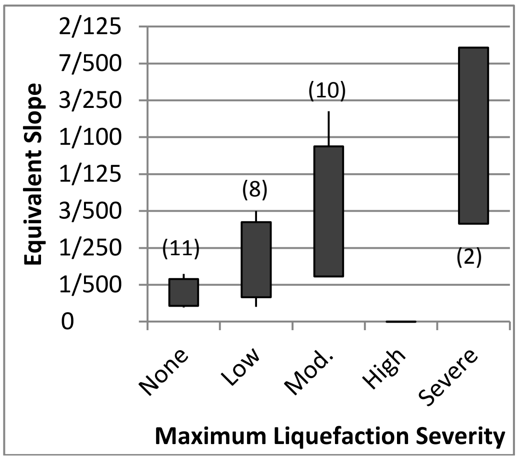

Figure 9. Equivalent Slope of slab-on-grade foundations for increasing liquefaction severity. The number of data points for each severity level is shown in brackets for each box.

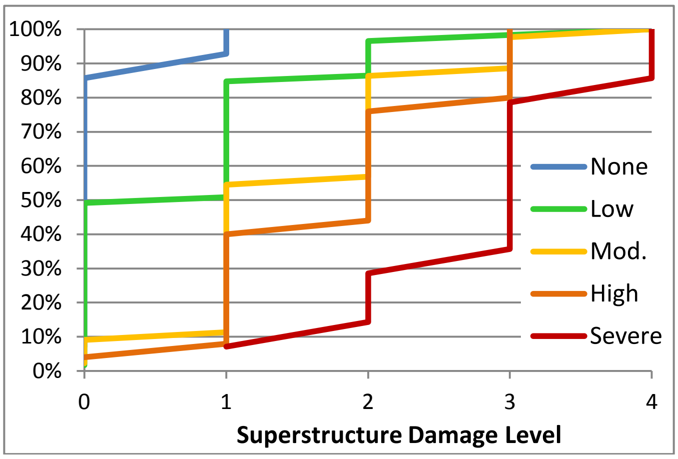

Figure 10. Distribution of Structural Damage for the different levels of Foundation Damage (each colour) for all four foundation types.

4.2 Foundation Damage vs. Liquefaction Severity

All four foundation types showed a consistent trend in their performance when floor slope was plotted against liquefaction severity. Figure 9 is a box and whisker plot of the equivalent slope for slab-on-grade foundations for each different liquefaction severity. It shows clearly that as the liquefaction severity increases, the range of equivalent slopes of the foundations also increases. Although there were only two data points for severe liquefaction, and none for high liquefaction, the trend is still evident.

4.3 **Structural Damage vs. Foundation Damage**

Figure 10 is a percentage-based plot of the distribution of superstructure damage level for the different foundation damage levels. It shows that, as the level of foundation damage increases, the distribution of superstructure damage becomes worse. Loading caused by liquefaction is often displacement-based, causing uplift or sinking of all or part of the foundation, and stretching in cases of lateral spreading. These permanent displacements put large loads on the structure, and cause plastic deformation and distortion in the superstructure.

4.4 **Concrete Perimeter vs. Slab-based Foundations**

The three slab-based foundation types behaved very similarly. Both the RibRaft™ and piled foundations had very similar trend lines for each of the three slope indices to those of the slab-on-grade foundations shown in Figure 8. This is emphasised by Figure 11a, which shows the three slab-based foundations having almost identical trend line values for all three slope types for ‘no liquefaction’, and very similar values for the two global slope measures at severe liquefaction levels.

The concrete perimeter foundations behave very differently. In Figure 11.a they have much larger values for all three slope types, and the difference increases further for the more localised slope measurements. This suggests that perimeter foundations (of the type used in Christchurch and inspected for this research) are more susceptible to damage, and illustrates the effect of their damage mode, with the high local slope caused by local humping of the interior floors (Fig.2a, b). In Figure 11.b it can be seen that the difference between the perimeter and slab-based foundations is considerably less, and the slab-on-grade even exceeds the perimeter for the maximum local slope. The maximum local slope for perimeter foundations between those that suffered no liquefaction, and those experiencing severe liquefaction is almost identical (the trendline for local tilt for the perimeter foundation in Figure 8 is basically flat). This shows that the local humping damage to perimeter foundations occurs very early, with only small losses in bearing capacity, and does not generally worsen under higher levels of ground damage and liquefaction. Further damage to these foundations occurs on a more global scale. It must be noted that these points may also be affected by the high percentage of pre-standard concrete perimeter foundations that were inspected. These performed quite poorly in the earthquakes, due to their lack of proper construction and reinforcement. These results do not necessarily represent the performance of new concrete perimeter foundations.

4.5 **Slab-on-grade vs. RibRaft™/Piled Foundations**

It can be seen in Figure 11.a that for ‘no liquefaction’, the three slab-based foundation types have very similar and satisfactory performance in all three slope measurements, which are all considerably better than the perimeter foundation performance. This is because, at lower liquefaction levels, the slab-based foundations are likely to be still fully in-tact, without any serious structural damage, with any floor slope likely to come from minor changes in level.

Under severe liquefaction (Fig. 11.b) the performance of the three slab-based foundations is somewhat different. The equivalent slope at severe liquefaction is still very similar for all three foundation types. Piled foundations have performed slightly better in equivalent slope than the other two, as the end-bearing capacity of the piles provides a mechanism to resist the overall settlement and loss of bearing capacity in founding soils subject to severe liquefaction. The piled foundation performance is not hugely better however, as most piled residential buildings only have piles to a depth of 3-7m. In severe liquefaction, as happened in Christchurch, liquefaction and loss of bearing capacity can extend throughout and well beyond this depth, rendering the extra vertical support from the piles useless. The equivalent slope of RibRaft™ foundations was also very similar. This is to be expected, as a RibRaft™ foundation does not provide any extra ability for the foundation to resist global settlements.

The difference between the three slab-based foundations grows as the slope measurements become more localised in Figure 11.b. When it comes to the maximum local slope, the most localised measurement, slab-on-grade is far worse than the other two foundation types. This is because slab-on-grade foundations are relatively thin, lightly reinforced slabs, and do not have the capacity to distribute loads and deformations across the footprint of the building, resulting in larger local slopes and differential movement. In comparison, RibRaft™ and piled foundations have higher stiffness and strength, and better load-transferring mechanisms and so sustain less damage.

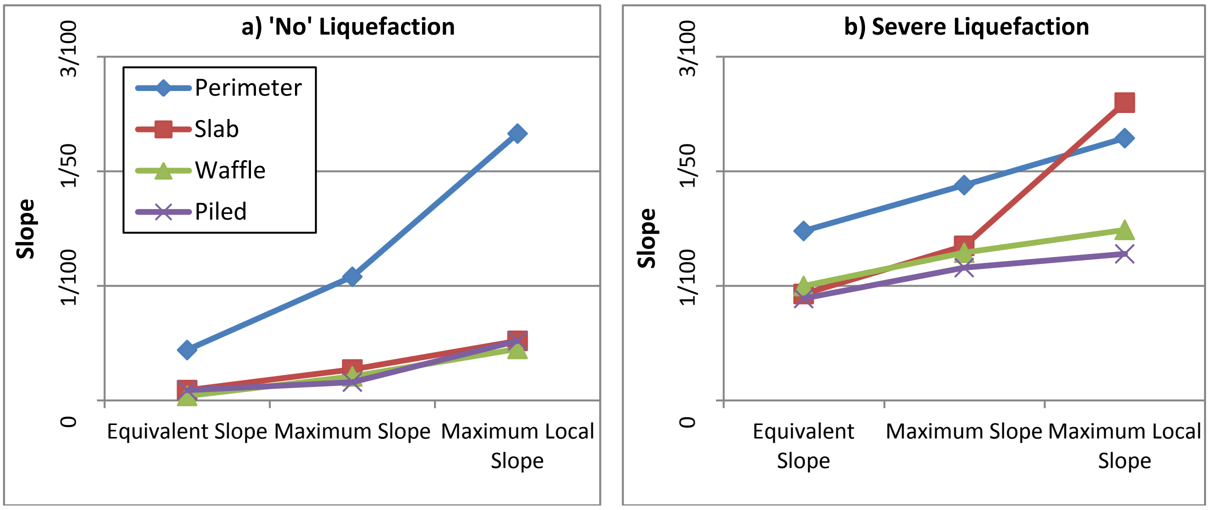

Figure 11. The trend line values for each foundation type for each of the three slope indexes. Note: 'no' liquefaction only means there was no surface manifestation of liquefaction.

5 CONCLUSIONS

Damage to residential house foundations is clearly linked to the severity of liquefaction. This extends to all types of residential house foundation, though some perform better than others.

Superstructure damage is linked to foundation damage, and therefore also to liquefaction severity level.

Perimeter foundations were much more easily damaged by the effects of liquefaction, even at low levels, than the slab-type foundations. This can be both a negative and positive. The negative being that for low levels of liquefaction severity, there is likely to be higher damage to perimeter foundations, requiring more costly repairs than for slab-based foundations, which may not need any major structural repairs. However, once the liquefaction severity level increases enough that both perimeter and slab-based foundations are seriously damaged, having a perimeter foundation can be an advantage. So long as the superstructure is not irreparably damaged, the house can be (relatively) easily lifted up and the foundation replaced. For slab-based houses though, once a certain level of damage is reached, re-laying of the foundation becomes quite difficult, as the superstructure is attached directly to the foundation.

The specialised slab-based foundations, RibRaft™ and piled, performed better than standard slab-on-grade foundations. At very low levels of liquefaction severity this is not necessarily an issue, as slab-on-grade foundations aren't very damaged either. But at moderate levels of liquefaction severity, it is advantageous to make the extra investment of a specialised foundation, as they will not need such a high level of repair. At very extreme levels of liquefaction severity it does not really matter which foundation type is used, as all will be damaged severely enough to require major repairs.

6 REFERENCES

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