Adequacy and retro-fitting of timber frame house foundations on slopes

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ABSTRACT

Previous studies have indicated that there are significant issues with the structural strength and stability of many existing house foundations on sloping sites. This was confirmed after the Christchurch earthquakes, where poor behaviour of such foundations was observed in the Christchurch hill suburbs.

Full scale experiments on a series of four light timber framed house foundation types, were carried out on a sloping site. The test specimens included a timber floor system of approximately 2.4m by 4.8m (downslope). Two test specimens replicated the limits of NZS 3604 foundation construction and two were examples of typical pre-NZS 3604 construction. The specimens were excited dynamically by a counter-rotating shaker with adjustable frequency and mass to simulate the effects of an earthquake.

The two NZS3604 samples performed adequately, however the other two did not, with wire ties from the piles breaking in one instance. The expected progressive downward movement of the foundations was not significant, however this is likely to be a function of excitation of the soil, where we could only excite the structure. It may also be more likely in a granular, rather than the cohesive soil on the test site. Subsequently easy to fit retro-fit solutions were installed and the performance of the pre-NZS3604 specimens increased significantly.

1 INTRODUCTION

Previous studies and observations from the Christchurch Earthquake of 2011 summarised in a previous paper (Thomas et al 2019) have indicated that there are significant issues with the structural strength and stability of many existing house foundations and other light timber frame buildings on sloping sites. Pile or poles rotate downslope as shown in figure 1, if their embedment length, footing diameter is too small, or the soil is too weak to take the imposed loads. Foundation walls may also displace downslope (figure 2.).

Figure 1: Tilting pole structure

Figure 2: Downslope displacement of uphill foundation

Under loading across-slope there is potential for large displacements on the downslope side as the building will twist about the squatter, stiffer uphill foundation. The deflections from the torsional rotation adds to the lateral displacement potentially resulting in a progressive rotational failure as described above. This is often exacerbated by the fact that the uphill foundation is of a far stiffer type, such as a foundation wall, whereas the downhill foundation will be of piles or poles. This difference in stiffness and the potential torsional problem is not addressed in NZS3604 (SNZ 1999), where only foundations strength is considered, nor in a specific engineering design if only strength is considered. These issues are likely to be of more concern in a longer duration earthquake than the 2011 Christchurch earthquake (Thomas et al 2019).

The work is not planned to replicate or model global soil instability causing landslides or subsidence. Rather it relates to the interaction between the soil and the structure for light timber framed structures during seismic excitation, concentrating on ensuring that the resilience of the structure is retained.

2 METHODOLOGY

Test were carried out on prototype foundations on a sloping site on a rural property close to BRANZ off Hayward’s Hill Rd, Judgeford, Porirua on which to conduct the experimental work. Scala penetrometer testing was undertaken at the site to establish the soil bearing properties. All four penetrometer sites indicated approximately 5 blows per 100 mm from a depth of 200 mm to 1,500 mm, thus coming close to the limit of “Good ground” defined by NZS 3604. The maximum slope at the site was measured as 1:3.6 (16^o), and the soil was described as “firm cohesive” soil.

Each test specimen consisted of a timber framed and overlaid floor of approximately 2.4m across slope by 4.8m up and down the slope. Such a size allows the inclusion of either piles at the four corners or a combination of piles and foundation walls, and the larger uphill length will allow for torsional effects from varying foundations stiffness on the uphill and downhills to be considered. Additional dead weight was added to the floors of the specimens to replicate the true mass of the superstructure associated with the supporting foundation. Figure 3 shows the setup of the specimens on the hill and details of the specimens are shown in figure 4 and in table 1.

Figure 3: Photograph of overall set-up. NZS 3604 floors on right, pre-1960 floors on left.

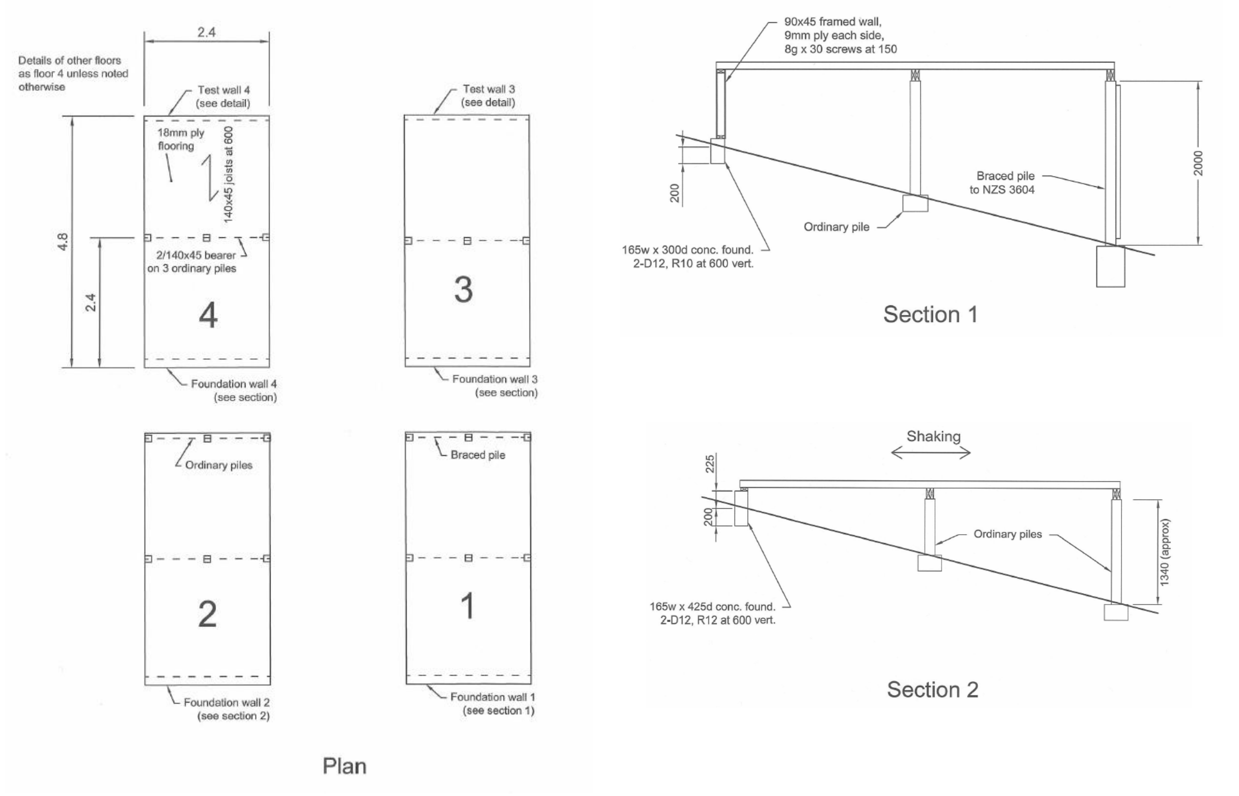
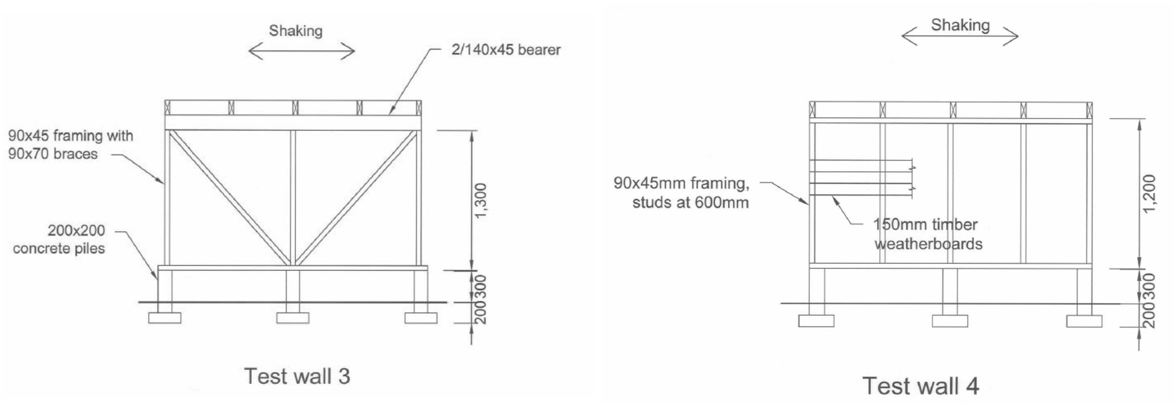


Figure 4: Layout of the four specimens (left) and sections through specimen 1 (top right) and specimen 2 (bottom right)

Table 1: Summary of Test Specimens

Test no.	Design criteria	Load direction	Up-hill Foundation	Down-hill Foundation
1	NZS3604	Across-slope	Foundation wall	Braced piles
2	NZS3604	Down slope	Foundation wall	Ordinary piles
3	Pre-1960	Across-slope	Foundation wall	Cantilever piles & jack studs & cut in braces
4	Pre-1960	Across slope	Foundation wall	Cantilever piles & jack studs & w/board cladding

The maximum pile height permitted in NZS3604 is 3.0m, but as a house width is more likely to be on the order of 6.0m, a pile on the downslope side of 2.4m high was used in specimen 1 giving the same ratio of 1:2 for a pile height of 3.0m and a building width of 6.0m, which is a slope of 30°. As the slope of the ground was less than 30°, the rear wall of specimen 1 was built up with a framed wall lined with 9 mm ply each side to provide a wall element that was significantly stiffer than the bracing on the downslope side. The four specimens will be designed to replicate the limits of NZS 3604 foundation construction (specimens 1 & 2) and also to simulate typical pre-NZS 3604 construction (specimen 3 & 4), as shown in figures 5.



Test wall 3

Test wall 4

Figure 5: Downslope end elevation of specimen 3 (left) and 4 (right)

The specimens were excited dynamically by a counter-rotating shaker to simulate the effects of an earthquake. The shaker had the capability to apply lateral inertial loads of varying size and frequency. The displacement response of the specimen was monitored along with the displacement response of the structure with respect to the ground.

After completion of the initial round of testing the two pre-1960 specimens (floors 3 and 4) were strengthened by retrofitting an infill concrete foundation wall between the ordinary piles at the front with M12 cast-in bolts fixing to the wall plate at 600 centres. In addition, floor 3 had connectors strengthening the stud to plate joints, and floor 4 had a 9 mm plywood fixed to the inside of the wall, as shown in figure 6.

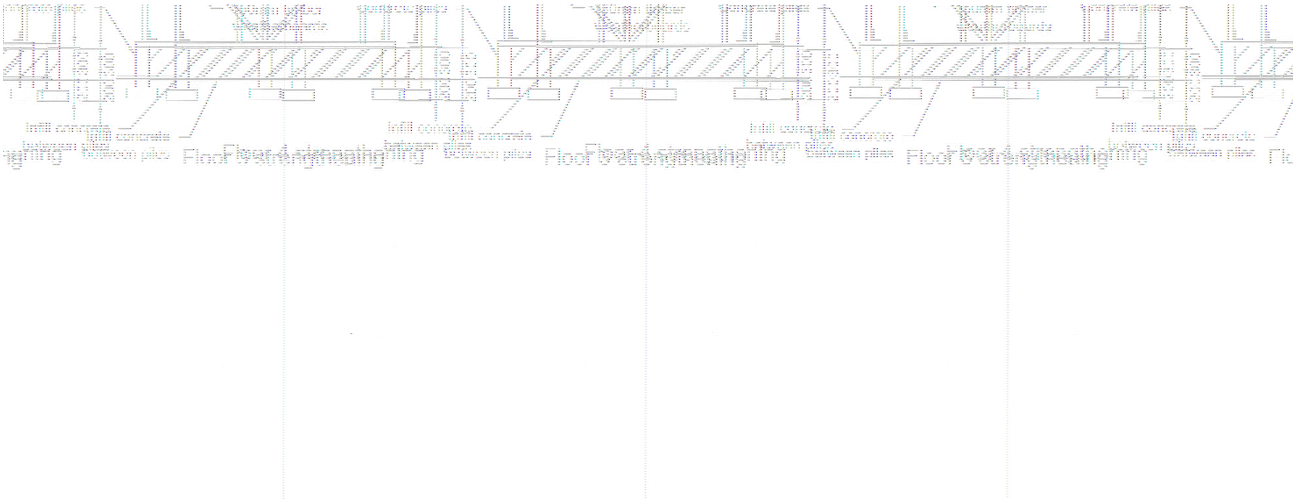


Figure 6: Downslope end elevation of strengthened specimens

3 RESULTS

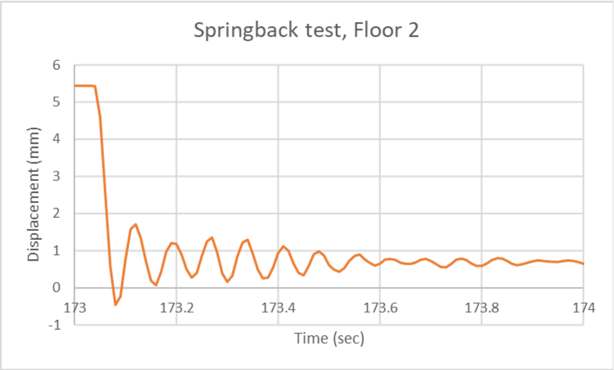
Before the shaking tests, each pair of floors was subjected to a load-deflection test by jacking the lower (taller) foundations against each other. The secant stiffness of each is presented in Table 2.

Table 2. Secant Stiffness of the test specimens

Test no.	Bracing System	Stifness (kN/m)
1	NZS 3604 braced piles	0.30
2	NZS 3604 ordinary piles	0.17
3	Weatherboards on jack studs only	0.07
4	Braced jack studs	0.30
3 (retrofit)	Weatherboards plus ply wall	2.6
4 (retrofit)	Braced jack studs strengthened	0.80

As expected, the ordinary piles and the weatherboard cladding achieved very low stiffness’s. Retrofitting of floors 3 and 4 increased the stiffness’s markedly.

Frequency testing of each pair of floors was undertaken by releasing the loading connectors after the load-deflection test. A typical plot and the measured periods are shown in Fig7. The retrofits have shortened the periods indicating an increase in stiffness, as also found with the pull-over tests. This displacement was measured across the slope at the top of the wall on the downslope slide.



Test no.	Bracing System	Period (s)
1	NZS 3604 braced piles	0.18
2	NZS 3604 ordinary piles	0.095
3	Weatherboards on jack studs only	0.16
4	Braced jack studs	0.21
3 (retrofit)	Weatherboards plus ply wall	0.04
4 (retrofit)	Braced jack studs strengthened	0.15

Figure 7: Typical Displacement plot (left) and measured period (right) for the 6 test specimens

For the floor shaking tests, the shaker was aligned across the hillslope for floors 1, 3 and 5, and up and down the slope for floor 2, so as to investigate the performance of the foundation wall under out-of-plane action. The calculated shaker output force against frequency in presented in Fig. 8 and a typical plot of measured displacement against time in Fig. 9.

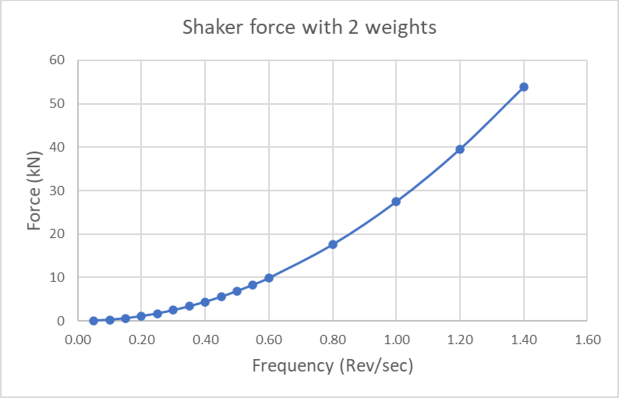


Figure 8: Typical Displacement plot

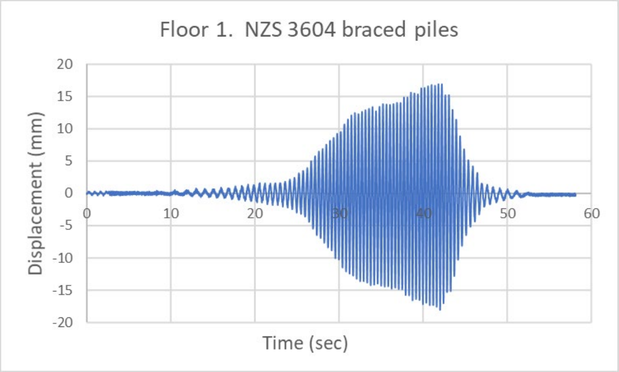


Figure 9 Typical Measured period

3.1 NZS3604 Specimens 1 and 2

Both floors performed much as expected, although the rocking of the foundation wall of floor 2 under the out-of-plane excitation was higher than expected (55 mm at a period of 0.47 sec). In practice on actual house structure, bracing would be required to resist the action in this direction. Rotation of the wall resulted in gaps between the concrete and backfill soil as also observed after the Canterbury earthquakes. Rocking of the pile foundations was also observed in floor 1 and also the pile brace deflected noticeably sideways under the eccentric axial loading from bolt connection to the piles.

3.2 Pre-1960 Specimens 3 and 4

Both floors deflected significantly, especially floor 4 because of the lack of stiffness provided by the weatherboards (76 mm at a period of 0.76 sec). The brace connections of floor 3 became very loose and the 8g wires connecting the wall plate to the end piles fractured at a low level of shaking.

3.3 Pre-1960 Retrofit.

The performance of both walls improved with the increase in stiffness provided by the retrofit solutions, especially the ply wall on floor 4, with the top deflection reduced to 6 mm at a period of 0.54 sec.

4 DISCUSSION

Progressive downslope rotation of the foundations was not noticeable in these tests, however the soil was cohesive at this site, and hence maintained its shape and did not fall into the hole behind the upslope face of the piles or walls restricting upslope displacement on the subsequent cycle.

A substantial increase in performance was achieved by the retrofit solutions undertaken. The infill foundation walls were very effective at stabilising the isolated pile foundations, although in some instances these could be difficult to construct due to limited site access. Nominal reinforcement was used in the wall, together with grouted in starters to all of the piles. In the interests of buildability this could be reduced to end piles only as the centre piles are bookended by foundation walls on each side. The ply sheeting was very straightforward to install, as were the extra connectors on the jack stud braces. All solutions would be inexpensive for most residential foundations.

5 CONCLUSIONS

This study demonstrated that NZS3604 foundations performed adequately in what was a soil that was on the lower limit of acceptable as “good ground” in NZS3604. Rocking of the shallow pile foundations in the softer soil gave some concerns. A more thorough investigation of this aspect would answer the questions raised. Significant progressive rotation of the foundations was not noted, however this is more likely in a granular soil rather than the cohesive soil on this site, and may be more a function of shaking of the ground, whereas practically only the structure could be shaken. Pre-1960 style of foundations can be readily retrofitted for greatly improved performance, although the solutions tried here were not optimised. Strengthening of the structure above the piles is straightforward but installing a concrete wall between shallow piles may be problematic particularly on sites that are difficult to access.

6 ACKNOWLEDGEMENTS

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