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Progressive failure of house foundations on slopes in earthquakes

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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, will be carried out on a sloping site. The test specimen will include a timber floor system of approximately 2.4m across slope by 4.8m upslope allowing a combination of piles and foundation walls and is sufficiently long upslope to induce significant torsional effects under cross-slope loading. Additional load will be added to the floors to represent applied live loads and superstructure. The test specimens will replicate the limits of NZS 3604 foundation construction and some examples of typical pre-NZS 3604 construction. The specimens will be excited dynamically counter-rotating shaker with adjustable frequency and mass to simulate the effects of an earthquake. The acceleration response of the specimen will be monitored along with the displacement response of the structure with respect to the ground.

This work will result in a better understanding of how foundation systems for houses on sloping sites perform under earthquake load, potentially leading to changes in NZS 3604 and an assessment of possible retrofit options for existing houses. If NZS 3604 is subsequently modified, and/or houses retrofitted then houses built on slopes will be more resilient reducing the need to find alternative housing after earthquakes and reducing remedial costs.

1 INTRODUCTION

A large part of the experimental work for this project was expected to be completed by the submission date for the paper, however due to intermittent wet weather in Wellington in the spring of 2018 vehicular access to the sloping site was unsafe so experimental results were not viable at the time of writing of this paper. They are expected to be available by the conference date.

Previous studies (Irvine and Thomas 2007, Beattie et al 2017, Thomas & McGowan 2011, Thomas and Shelton 2012 Thomas et al 2013, Brunsdon et al 2014, Horspool et al 2016, Drayton et al 2017,) 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. These structural issues may lead to consequential losses such as fire following earthquakes (Thomas and Irvine, 2007, Thomas 2017). This was confirmed after the Christchurch earthquakes, where the authors observed poor behaviour of some house foundations in the Christchurch hill suburbs when undertaking safety assessments in the declared state of civil emergency. Analysis of the data gathered in the BRANZ random survey of houses following the Christchurch earthquakes (Beattie et al., 2015, Thomas et al 2017) also confirmed that some house foundations on sloping sites demonstrated poor performance. 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.

Figure 1: Tilting pole structure

Foundation walls also rotated or slide downslope as shown in figure 2. In both types of foundations, as the foundation oscillates up and down-slope, there is more resistance to uphill motion as the soil is deeper on the uphill side and loose soil is more likely to fall into the gap left behind the foundation as it moves downslope, whereas as it moves upslope the loose surface soil is less likely to fall behind the foundation as it moves as some if it may have fallen downslope away from the foundation, and the soil height is simply less on the downslope side. After many cycles this is expected to result in the foundation rotating and/or sliding downslope as shown in figures one or two. If the rotation is sufficiently large, with the centre of load application outside the footing, then the weight of the structure above will cause the foundation to rotate further resulting in an uncontrollable progressive failure. The magnitude of this affect is highly dependent on the number of load cycles, so will be more parent in a long duration earthquake. This behaviour was observed to some extent in the Christchurch earthquake sequence of 2010-11, but no instance of catastrophic failure are known. Although the Christchurch earthquake of 22 February 2011 caused high levels of shaking, and definitive references for the duration of shaking are hard to find, its duration of shaking was short at about 10s, (Bradley et al 2017). In contrast the Kaikoura Earthquake on 14 November 2016 had a significant duration of about 25 seconds (Bradley et al 2017). This is significantly shorter than the duration of shaking expected from a large subduction zone earthquake (Bradley et al 2017).

Figure 2: Downslope displacement of footing on uphill side

Under loading across-slope there is potential for large displacements on the downslope side as the building will twist about the shorter 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.

This work will result in a better understanding of how foundation systems for houses on sloping sites perform under earthquake load, potentially leading to changes in NZS 3604, design guidance for engineered house foundations and an assessment of possible retrofit options for existing houses. This work is relevant to current Wellington City Council and EQC work on housing vulnerabilities. If NZS 3604 is subsequently modified, and/or houses retrofitted then houses built on slopes will be more resilient reducing the need to find alternative housing after earthquakes and reducing remedial costs.

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

It is proposed to conduct full scale experiments on a series of four light timber framed house foundation types, with each of these installed on a sloping site. The tests will be carried out on a sloping site on a property close to BRANZ off Hayward's Hill Rd, Judgeford, Porirua on which to conduct the experimental work (figure 3 and 4). Scala penetrometer testing and post-hole augers will be undertaken at the site to establish the soil bearing properties and the description of the soil. The soil is expected to be representative of most hillside sites in the Wellington region.

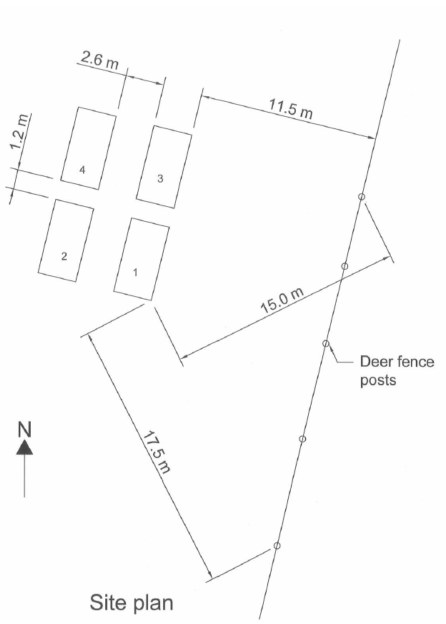

Figure 3: Surveying hillside site and Figure 4. Site Plan

Each test specimen will consist of a timber framed and overlaid floor of approximately 2.4m across slope by 4.8m up and down the slope. 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 is to be used 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 is less than 30°, the rear wall will be built up with a framed wall lined with 9mm ply each side to provide a wall element that is significantly stiffer than the bracing on the downslope side. 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 will be added to the floors of the specimens to replicate the true mass of the superstructure associated with the supporting foundation. 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 Table 1 and figures 5-6. The specimens will be excited dynamically by a counter-rotating shaker to simulate the effects of an earthquake. The shaker has the capability to apply lateral inertial loads of varying size and frequency. The acceleration response of the specimen will be monitored along with the displacement response of the structure with respect to the ground.

With regard to the NZS 3604 specimens, these responses will be compared to expected behaviour and recommendations will be made to the NZS 3604 committee for amendments/additions to the standard to improve behaviour if necessary. For the specimens modelling construction from before the introduction of NZS 3604, it is expected that the performance will not be satisfactory. Testing will be halted before irreparable damage occurs and retrofit solutions will be developed and added to the specimens. The dynamic testing will be repeated on the retrofitted structures.

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

As it is important to establish approximate costings for the implementation of the retrofit solutions for the older foundation styles. BRANZ building economists will be used to provide cost information for each retrofit solution.

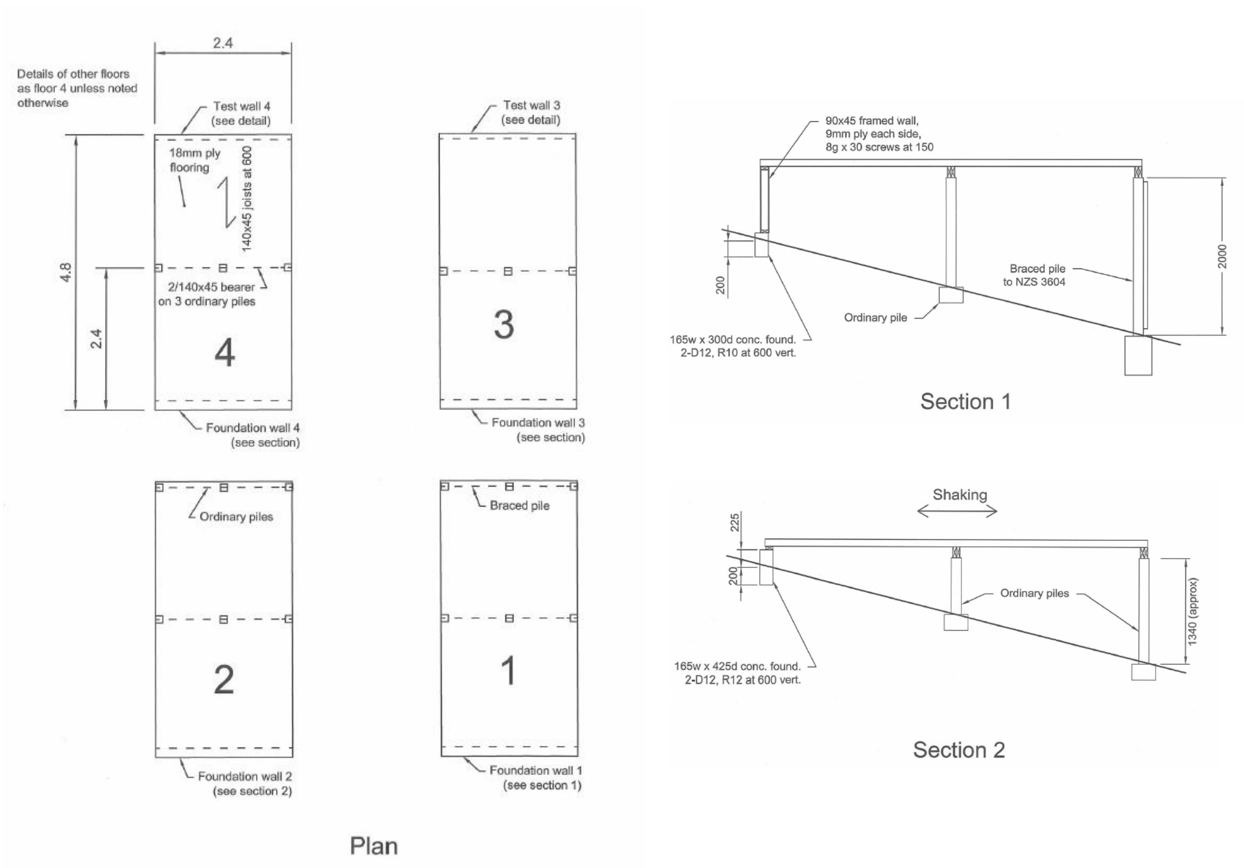

Figure 5: Layout of the four specimens (left) and sections through specimen 1 (top right) and specimen 2 (bottom right)

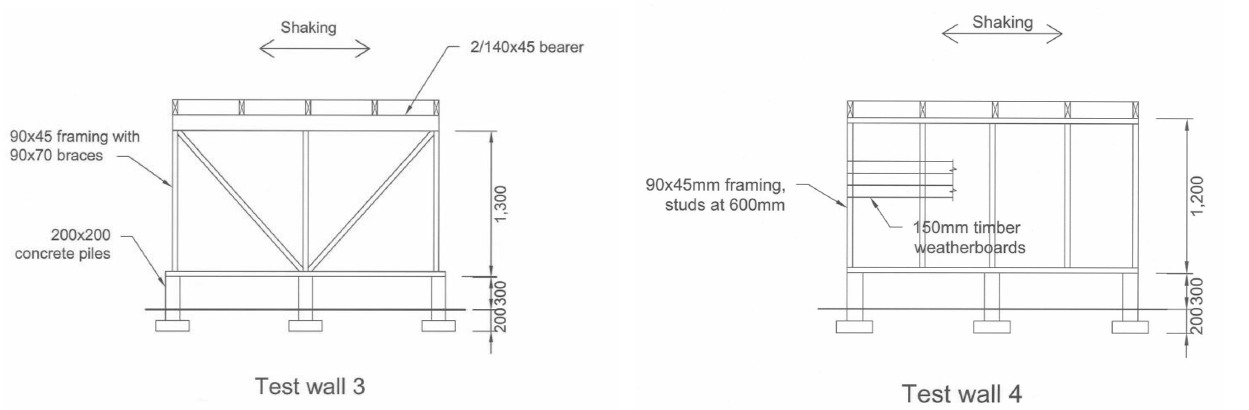

Figure 6: Downslope end elevation of specimen 3 (left) and 4 (right)

3 CONCLUSIONS

The completion of this testing program and subsequent analysis will give a better understanding of how house foundations perform on slopes in earthquakes and ascertain if more restrictive limits on slopes and using multiple foundation types need to be incorporated in NZS3604 and provide guidance for specific engineering design of house foundations.

Acknowledgements

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