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SEISMIC BEHAVIOUR OF HILLSIDE LIGHT TIMBER FRAMED HOUSES

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ABSTRACT: A significant percentage of houses in New Zealand (NZ) are light timber-framed (LTF) hillside houses and seismic designs of LTF hillside houses are mainly informed by housing research on flat sites. The earthquake damage evidence during the recent NZ earthquakes revealed that LTF houses on flat sites performed better than similar houses on hillsides, provided that liquefaction was not a factor. There is little research available about the seismic performance of hillside houses. The objectives of the study reported are (1) to categorize the typical engineering practice in constructing LTF hillside houses historically; (2) to investigate the critical engineering issues about LTF hillside houses, in comparison with LTF houses on flat sites; and (3) to develop hypotheses for the adequate seismic design of LTF hillside houses. The study presented here revealed that, while LTF hillside houses founded directly on ground are expected to perform in a similar way to LTF houses on flat sites in earthquakes, LTF hillside houses with substantial subfloor foundation systems are expected to perform very differently from LTF houses on flat sites. The important considerations in determining the seismic performance of hillside houses with substantial foundation systems include (1) the adequacy of in-plane floor diaphragm rigidity at the ground level; (2) the connection details from the subfloor bracing systems to the ground floor diaphragm; and (3) lateral resistances (in-plane and out-of-plane) of the upper-most foundation systems.

KEYWORDS: light timber-framed, hillside houses, seismic performance, subfloor, foundations

1 – INTRODUCTION

New Zealand (NZ) is highly exposed to catastrophic earthquakes. As such, an important consideration in addressing a resilient built environment in NZ is seismic resilience of buildings. The greatest risk exposed by buildings in earthquakes is the risk exposed by residential houses because residential houses significantly outnumber non-residential buildings.

NZ has a long history of constructing low-rise (less than three storeys) residential houses using light timber framed (LTF) systems and thus the majority of residential houses are LTF buildings. Figure 1 shows the timber framing in a typical LTF residential house under construction and sheathing boards will be fixed onto the framing afterwards. LTF houses are usually constructed according to a prescriptive standard. The guideline "Carpentry in New Zealand" [1] was used prior to 1978 and the standard NZS3604 has been used since 1978. The first version of NZS3604 was very similar to the Carpentry guideline (edition in 1973) and the current version of NZS3604 is NZS3604:2011 [2] and is currently under revision.

Figure 1. A typical LTF building under construction

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NZS3604:2011, although prescriptive, has an engineering basis. According to the Engineering Basis of NZS3604 [3], the seismic bracing demand of an LTF house was derived using an equivalent static method as recommended by NZS1170.5:2004 [4], assuming a fundamental period of 0.4 seconds and a ductility of μ=3.5. This is to say, the model used is an elemental lumped mass model, as shown in Figure 2 . As illustrated in Figure 2. the seismic design basis of NZS3604:2011 was primarily developed for flat sites with no allowance for the interactions between the subfloor foundation systems and the superstructures. NZS3604:2011 is allowed to be used for constructing hillside houses on subfloor frames as long as the slopes are gentle. For a hillside house beyond the scope of NZS3604:2011, NZS3604:2011 is often used for the seismic bracing design of the superstructure but the subfloor foundation systems require special engineering design (SED).

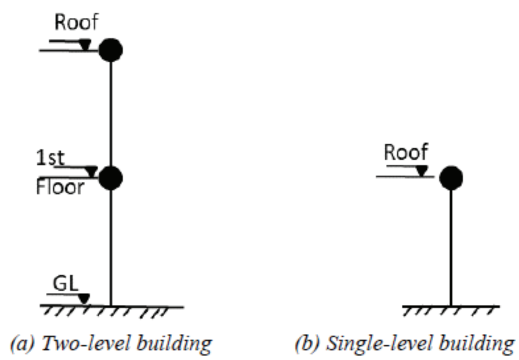
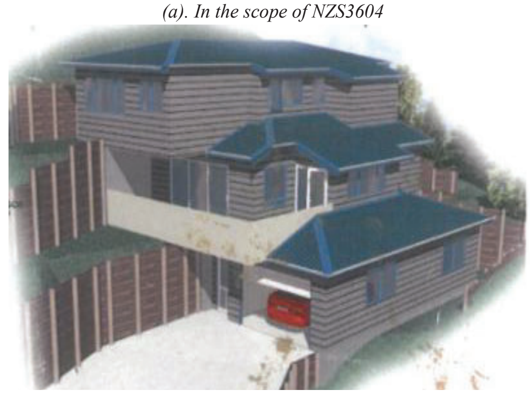


Figure 2. Model used in deriving seismic demand

Figure 3 compares hillside LTF buildings and LTF buildings within the scope of NZS3604. Clearly, the houses conceived in NZS3604 are built directly on the ground or relatively close to the ground. In comparison, hillside houses are often separated from the ground by subfloor foundation structures. There is very limited research about the interactions between the subfloor foundation systems and the main house structure "superstructure". There is no guidance available for seismically designing the subfloor foundations systems of hillside houses beyond the scope of NZS3604.

The 2010-2011 Canterbury earthquakes provided an opportunity to calibrate the seismic performance of hillside LTF houses. BRANZ conducted a seismic damage survey of about 314 houses including hillside houses. The survey [5] revealed that hillside houses are more vulnerable than otherwise identical houses but on non-liquefiable flat sites, especially when the subfloor foundation systems were substantial. The survey also revealed that seismic damage to hillside houses was often triggered by the failure in subfloor foundation systems and/or the connections between the foundation systems and the main structure, as shown in Figure 4.

(a). In the scope of NZS3604



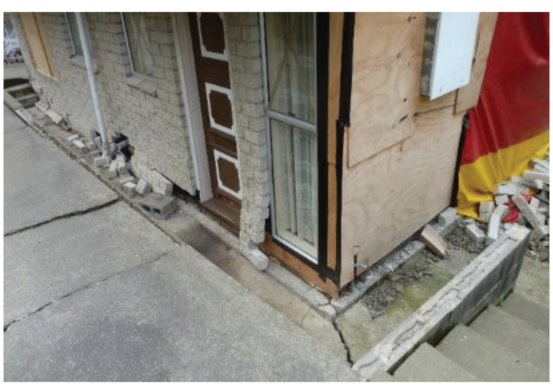
(b) Upper-slope houses

(c) Down-slope houses

Figure 3.Hillside LTF houses and LTF houses within NZS3604 Scope

a) Significant damage to brick foundation walls

b) Red-sticked after the earthquakes



c) A red-sticked down-slope house with temporary cladding

Figure 4. Damage to hillside houses in the Canterbury earthquakes

Clearly the seismic vulnerabilities in hillside houses are often associated with the subfloor bracing systems and the connections between the subfloor systems and the main house structure. The paper presented here is to characterise the subfloor system practices, to theoretically investigate the critical seismic issues around hillside houses and to develop solution concepts.

2 – ENGINEERING CHARACTERISTICS OF LTF HILLSIDE HOUSES

2.1 GENERAL

Seismic responses of building structures are affected by many building characteristics, including lateral seismic resisting systems, building configurations, interaction of subfloor foundation (subfloor bracing) systems with the superstructures, and so on. Major construction differences between hillside LTF buildings and LTF buildings constructed to NZS3604 are the subfloor systems. The subfloor foundation systems of hillside houses are the structural systems between the moving ground and the superstructure, and they are the first receivers of the ground shaking before the shaking travels to the superstructure. The responses of the subfloor foundation systems to the moving ground and the interactions with the superstructures could cause seismic behaviour of hillside LTF houses to deviate from similar houses founded on flat sites as postulated in NZS3604.

Construction techniques of subfloor foundation systems of hillside LTF buildings vary a lot, depending on the relative locations of the buildings to street access. Hillside LTF buildings can be generally classified as upper-slope houses and down-slope houses, as shown in Figure 5. Construction methods of upper-slope houses can be very different from those of down-slope houses. As a result, seismic performance of upper-slope LTF houses could be very different from that of down-slope LTF houses.

As shown in Figure 5, upper-slope LTF houses are buildings built on the ground that rises above the street. Upper-slope LTF houses are often built into the ground because their designs intend to incorporate site features to minimize the street accesses and construction problems posed by the land rising above the street. As a result, the upper-slope LTF buildings are usually founded directly on its foundations on ground. This aligns well with assumptions in the Engineering Basis of NZS3604 [3], as explained previously in Section 1.

In contrast, down-slope LTF residential houses are built on ground that drops below the street. It is common that down-slope LTF buildings are founded on substantial subfloor framing systems to minimize street access and create a ground floor platform. As a result, down-slope houses have the main buildings generally separated from the ground by a substantial subfloor foundation structure,

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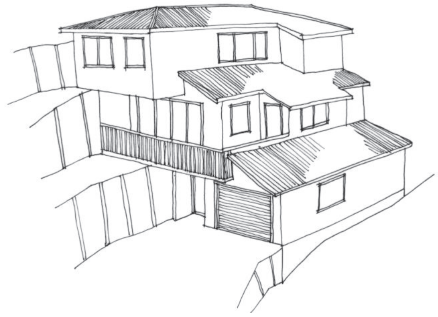
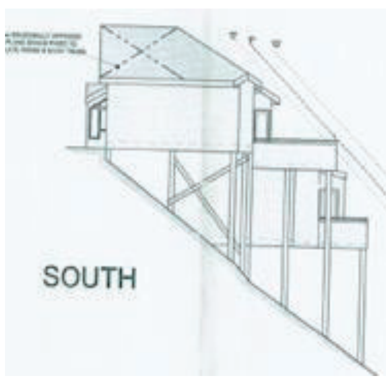
as shown in Figure 5(b). The hillside houses in this category are expected to have different performance from the houses within the scope of NZS3604.



(a) An upper-slope house



(b) A down-slope house

Figure 5 Upper slope houses versus down-slope houses

To gain insights into the engineering characteristics of LTF hillside houses, the design documentations of about 100 down-slope LTF hillside houses were reviewed, and the studied design documentation included houses constructed before and after NZS3604 was first introduced in 1978. The reason to limit the design document review to down-slope houses is because the upper-slope houses have similar engineering characteristics to houses on flat sites, as discussed later in Section 2.3. The intention of the design documentation review was to categorise the subfloor foundation systems used in the practice (as detailed in Section 2.2) and to group the arrangements of the subfloor foundation systems (as detailed in Section 2.3).

2.2 SUBFLOOR SYSTEMS AND SUBFLOOR SEISMIC BRACING PROVISIONS

The design documentation review revealed that the commonly used subfloor foundation systems and connection requirements in hillside LTF houses constructed according to modern standard NZS3604 (post 1978) are different from those in houses constructed to the guideline "Carpentry in New Zealand" (before 1978). In general, LTF houses constructed to NZS3604 have more stringent subfloor bracing requirements, more subfloor bracing system options and more stringent requirements for connections between the subfloor bracing systems and the main house structure, compared with LTF houses constructed prior to 1978. For example, the foundation walls of bricks or stones were allowed by the guideline "Carpentry in New Zealand" but were not allowed since the first edition of NZS3604 in 1978. As for the subfloor bracing systems, the options in the guideline "Carpentry in New Zealand" included stepped or unstepped foundation walls, piles with shallow footings (could be as shallow as 100 mm) and piles with diagonal braces, as shown in Figure 6. In comparison, the options in NZS3604 increased to include anchor piles with deep footings, cantilever piles with deep footings, braced piles as well as the concrete slab foundations. Figure 7 shows anchor piles and braced piles in NZS3604:2011.

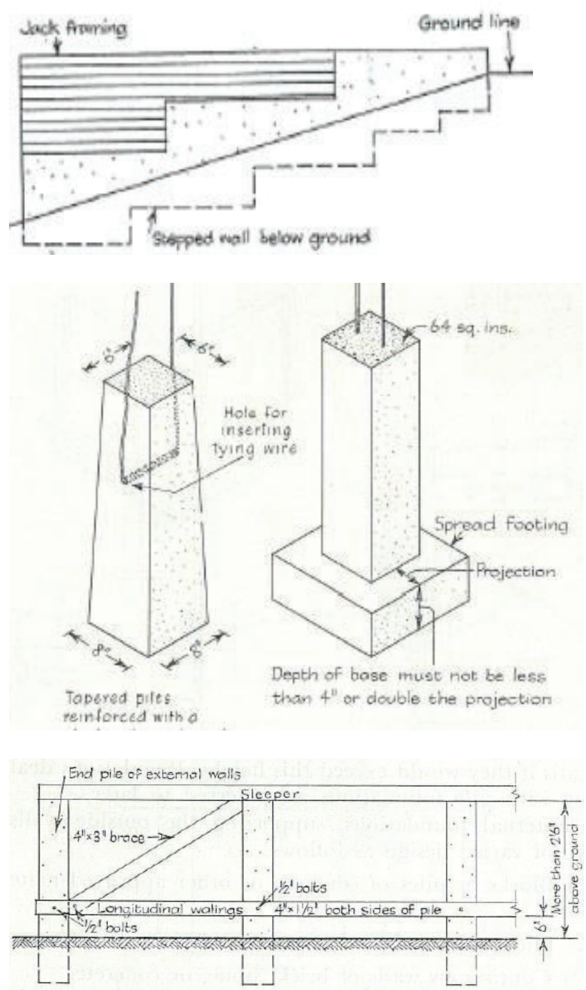
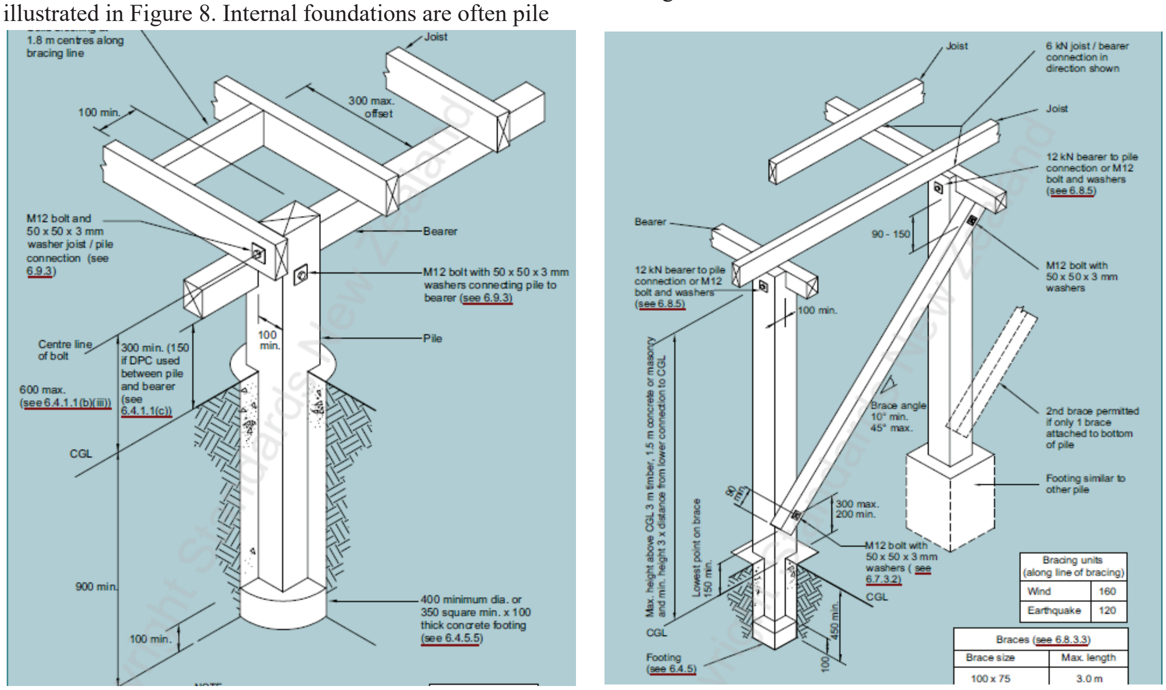


Fig.6. Commonly used subfloor foundation options (pre 1978) [1]

Hillside houses constructed before 1978 have different subfloor bracing system layouts and different connection requirements between the subfloor bracing systems and the main house structure from hillside houses after 1978.

A common practice in pre-1978 hillside houses is that external foundation systems were continuous foundation walls (stepped or non-stepped) or a mixture of foundation walls (commonly around corners) and pile foundations as illustrated in Figure 8. Internal foundations are often pile foundations. The requirement for the connections between ground floor framing to concrete ring foundation walls was by cast-in dowels of Ø9.5 mm at a spacing of not greater than 1.35 meters. According to the guideline "Carpentry in New Zealand", the internal piles were required to be braced at a spacing of 4.8 m in each direction. With regards to the connections between floor framing and piles, Ø4 mm wires were used as illustrated in Figure 6.



a) Anchor piles *b) Braced pile*

Figure 7. Common subfloor foundation options (post 1978)

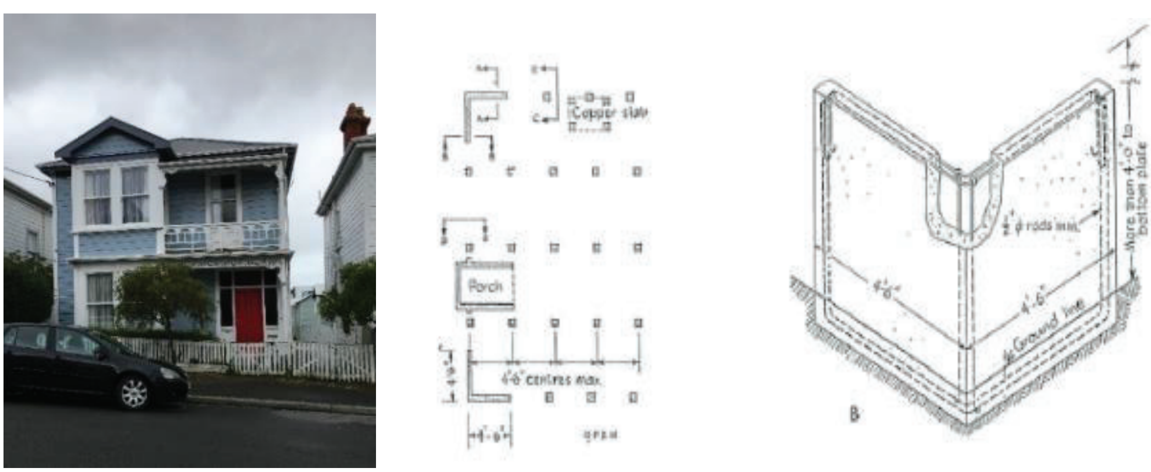


Figure 8. Bracing system arrangements of pre-1978 hillside houses

In comparison, the introduction of NZS3604 in 1978 resulted in more stringent subfloor bracing requirements for hillside houses. Furthermore, the use of concrete slab foundations became very prevalent since the 1980s. As such, it is common for the post-1978s hillside houses that

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a partial ground floor is a concrete slab foundation on grade and the rest of ground floor is supported on pile systems.

Another improvement area in NZS3604 is the connections from the subfloor bracing systems to the floor framing of the main house structure. As explained previously, the pile foundation systems in LTF houses constructed to the guideline “Carpentry in New Zealand” used Ø4 mm wires and the wire connections had negligible shear transfer abilities from floor diaphragm to the pile bracing systems. In comparison, current NZS3604 requires a minimum shear capacity of 12kN for each connection from the floor framing to the subfloor bracing system, and this enables an effective load transfer from the floor diaphragm to the subfloor bracing systems. As such, the vulnerable area for hillside houses constructed before 1978 could be the separation of houses from the foundations due to the connection failure from the floor framing to either the perimeter foundation walls or the internal pile systems. For the post-1978 hillside houses, the subfloor bracing provisions are more stringent and the subfloor bracing systems are stronger than these before 1978, creating greater demand for the ground floor diaphragms. In this case, critical considerations include the adequacy of the in-plane rigidity of the ground floor diaphragm in transferring the seismic actions across subfloor bracing systems and the stiffness compatibility issues between pile bracing systems and the concrete slab foundations.

2.3 CATEGORISATIONS OF SUBFLOOR FOUNDATION SYSTEM ARRANGEMENTS

Combinations and arrangements of subfloor foundation systems are important for understanding the engineering characteristics in terms of seismic performance of hillside houses. In this section, the hillside houses are categorised based on the combinations and/or the arrangements of the subfloor foundation systems. The engineering characteristics of hillside houses in each category are discussed accordingly.

Main House Structures Founded Directly on Ground

As described in Section 2.1, upper-slope houses are usually founded directly on their foundations on the ground, as illustrated schematically in Figure 9. The upper-slope LTF houses in this category are generally at least as stiff as similar buildings within the NZS3604 scope, and they are likely to have a fundamental period shorter than 0.4 s. According to the current seismic loading standard AS/NZS1170.5:2004 [4], seismic actions of the hillside houses in this category can be determined using equivalent static methods, which is the same as the method used by the Engineering Basis of NZS3604 [3]. As such, the houses in this category could use the same engineering principles as adopted in NZS3604.

Under lateral seismic actions, deformation profiles of upper-slope LTF buildings along the building height is similar to that of buildings within the scope of NZS3604 but the overall deformation is likely to be less than that within the scope of NZS3604, as illustrated in Figure 9. LTF houses in this category are believed to have similar resilience in earthquakes to LTF houses within the scope of NZS3604, hence similar ductility and damping capacity as houses constructed to NZS3604 can be assumed.

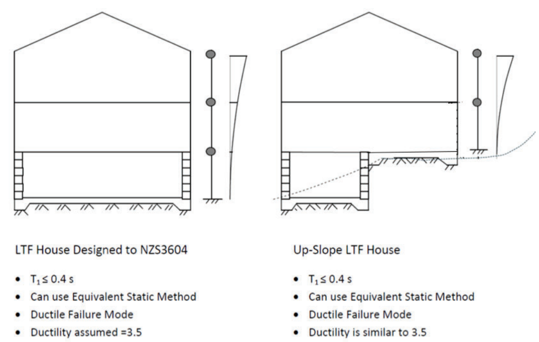
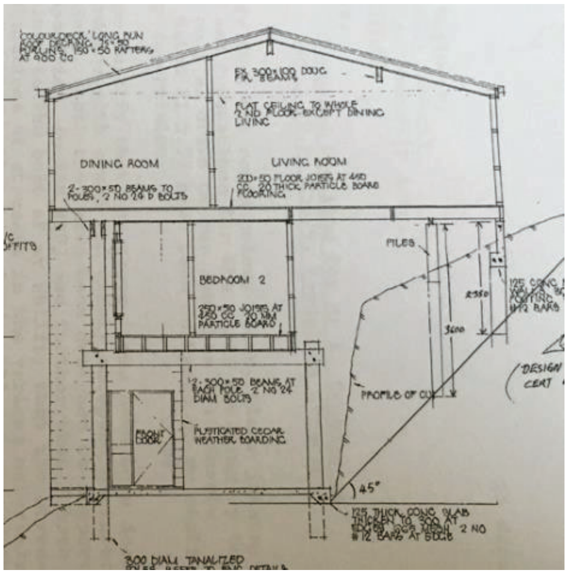


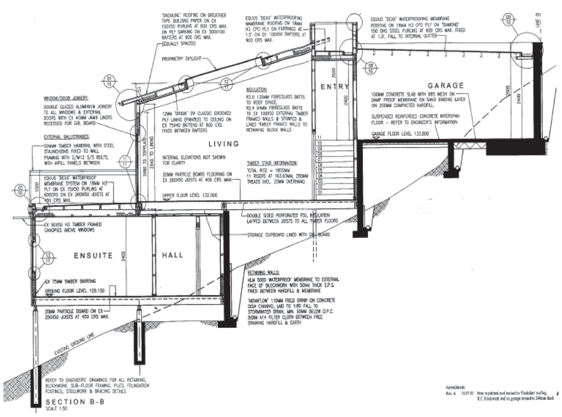
Figure 9. Comparison with LTF houses to NZS3604

Main House Structures Founded at Different Levels

A common practice of down-slope hillside house construction in the cases of reasonably steep sites is that the subfloor foundation systems are often substantial and these subfloor foundation systems follow the site slope. Consequently, the hillside houses in this category often are founded and braced at different levels, regardless of the construction ages being before or after 1978. On top founding level, the main house structure could be founded on a concrete foundation wall acting as a retaining wall, or a concrete ground beam or short piles. On the lower ground level, the structure could be founded on piles or foundation slabs. Figure 10 shows two design examples.



A) Before NZS3604 was introduced



B) According to NZS3604

Figure 10. Typical subfloor frame arrangements of down-slope houses

Potential vulnerabilities of hillside houses in this category could include irregularities in horizontal and/or vertical directions and incompatibilities of different foundation systems. As a consequence of irregularities and/or incompatibilities in the subfloor foundation systems of hillside houses, uneven load distributions and force concentrations could happen, leading to disproportionate (progressive) failures or eventual collapse.

Main House Structure Founded at the Same Level with Mixed Subfloor Bracing Systems

For a gentle down-slope site, it is more common that the main house structure of a hillside house is founded at the same level but the subfloor foundation bracing systems include mixed bracing systems.

As explained in Section 2.2, the seismic bracing requirements in the guideline "Carpentry in New Zealand" were not stringent. It is clear that the most vulnerable area for the hillside houses before 1978 is due to (1) the separation of houses from the foundations, as a result of the failures of connections from the floor framing to either the perimeter foundation walls or the internal piles, and/or (2). inadequate subfloor bracing resistance, especially when the ring foundation walls are not continuous concrete foundation walls.
For the post 1978 down-slope hillside houses in this category, the crucial considerations include the adequacy of the ground floor diaphragm to transfer the seismic actions across different subfloor bracing systems and the stiffness incompatibility issues between subfloor bracing systems and the concrete slab foundations.

3 – QUALITATIVE STUDY OF CRITICAL SEISMIC ISSUES OF HILLSIDE HOUSES

When LTF hillside houses have substantial subfloor bracing systems, their seismic behaviour becomes complicated. Seismic behaviour of LTF hillside houses founded either at the same level or at different levels are examined to investigate the critical issues in association with the substantial subfloor bracing systems of hillside houses. The examination is carried out by conducting equivalent static analysis methods using schematic models for the earthquakes in along-the-slope direction and across-the-slope directions.

3.1 FOUNDED AT DIFFERENT LEVELS

Figure 11 shows the three-dimensional (3D) schematic model of a hillside house founded at different levels. Equivalent static analyses of the 3D hillside model were conducted separately for the along-the-slope direction and across-the-slope earthquake actions. Figure 12 shows a 2D model used for the study of the seismic performance when the earthquake is along-the-slope. These exercises revealed qualitative but interesting findings, as explained in the below.

Along-the-slope earthquake results

The seismic bracing systems under the top founding level, along the earthquake direction, are made redundant, if (1) the foundation on the upper level is strong enough to resist total EQ action, and (2) the floor diaphragm at the top founding level as well as the connections from the floor diaphragm to the rest of the structure are strong enough to transfer the load to the foundation system on the upper level.

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Disproportionate (progressive) failure could potentially occur because of (1) the load concentration at the top foundation level; and/or (2) the incompatible subfloor seismic bracing systems along the slope. The top foundation systems will resist most of the actions until they fail, then the actions will go to the foundation systems at the lower level until they fail. This is a typical progressive failure example.

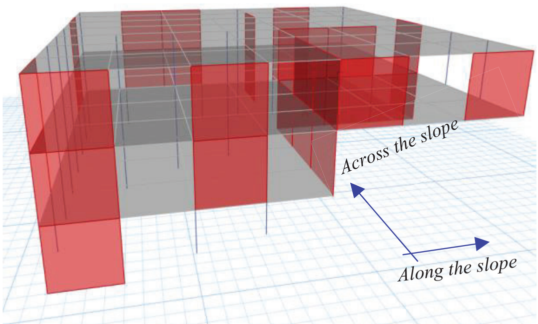

Figure 11. The 3D model of LTF houses founded at different levels

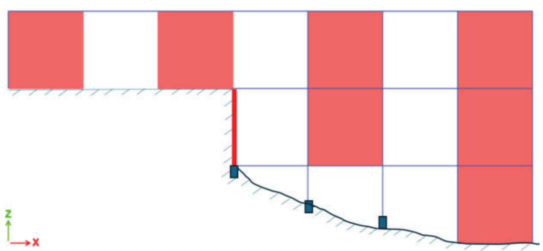

Figure 12. The 2D model of LTF houses founded at different levels

Across-the-slope earthquake results

When hillside houses are subjected to the across-the-slope earthquakes, the house structure will have translational and torsional responses. The examination reveals that seismic performance of LTF hillside houses could be very different from similar buildings on flat sites. The house performance in this case depends on diaphragm capabilities at ground level, adequacy of the connections from the floor diaphragm to the foundation (subfloor) systems at ground level, and the adequacy of the foundation on the uppermost founding level for resisting in-plane and out-of-plane seismic actions.

If the foundation on the uppermost level is adequate to resist EQ actions associated with translational and torsional seismic responses, the seismic bracing systems under the top founding level would be made redundant, provided that the floor diaphragm is strong enough to bring the seismic actions to the top foundation systems.

3.2 FOUNDED AT THE SAME LEVEL WITH MIXED SUBFLOOR BRACING SYSTEMS

When the main house structure of a hillside house is founded at the same level but the subfloor bracing systems consist of a mixture of different bracing systems, similar issues to the issues discussed in Section 3.1 need to be considered. These include (1) progressive failure/collapse in subfloor systems when the earthquake is along-the-slope direction; (2) the effects of significant torsional response when the seismic is across-the-slope; and (3). the in-plane rigidity adequacy of the ground floor diaphragm. This is discussed below.

When a hillside house has a substantial subfloor frame system, the subfloor system often has a mixture of different bracing systems including braced pile systems, concrete foundation walls, sheathed timber walls so on. Different subfloor frame systems have different stiffness/dynamic properties; therefore seismic responses of subfloor framing systems in this category often have severe stiffness incompatibility problems.

Due to the nature of slopping ground, stiffness incompatibility in subfloor system will exist when the seismic action is along-the-slope, even in the cases of the subfloor systems being the same structural system. As shown in Figure 13, the subfloor frames of a down-slope building are braced pile bents and the two pile bents, A and B, are likely to have different stiffnesses due to the height difference. When the earthquake is along-the-slope, the stiffer system, braced pile group B (bent “B”), resists more action than braced pile group “A” (bent “A”) until it fails. Subsequently the total seismic actions are redistributed to bent “A”, potentially leading to failure of bent “A”. Such a failure mechanism in subfloor systems is undesirable and special considerations are needed to prevent it from happening.

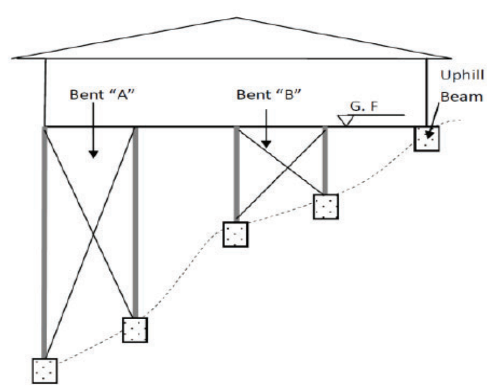

Figure 13. Progressive failure, subjected to along-the-slope earthquake

Apart from the above stated progressive failure in subfloor systems associated with stiffness incompatibility of subfloor frame systems, LTF hillside houses founded at the same level but with mixed subfloor bracing systems could also have significant torsional response when subjected to across-the-slope earthquakes. As shown in Figure 14, the uppermost foundation is a foundation wall, the subfloor bracing systems at the opposite side of the house are braced piles. Braced pile systems are usually more flexible than the ground beam. When the earthquake is across-the-slope, the subfloor structure will experience significant torsion and the ground floor will act almost as a cantilever beam. This requires adequate design of the uppermost foundation wall for out-of-plane and in-plane actions, adequate designs of ground floor diaphragm and adequate design of the connections between the ground floor and the uppermost foundation walls.

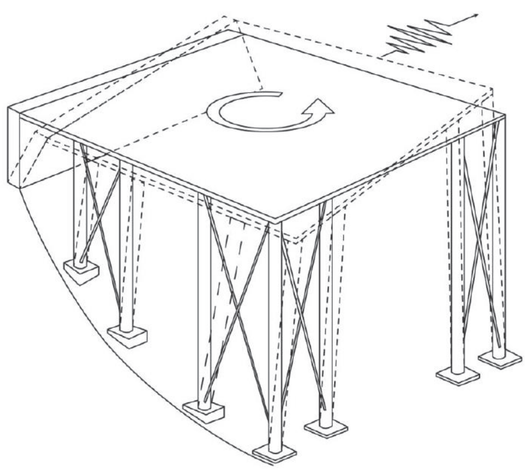

Figure 14. Torsional responses in across-the-slope earthquake

The reality is that the in-plane rigidity of the floor diaphragm in residential houses is likely to be somewhere between rigid and flexible. Hence, the effect of the flexibility of the ground floor diaphragm on the load distributions within the subfloor bracing systems of mixed stiffnesses need to be investigated to prevent out-of-control torsional behaviour.

4 - CONCLUSIONS

LTF house construction has been using prescriptive guidelines and standards for many decades in New Zealand. These guidelines and standards were developed based on the assumption that LTF houses are directly founded on ground. LTF hillside houses are sometimes supported by substantial subfloor foundation systems. In earthquakes, the subfloor foundation systems between the moving ground and the main house structure could cause the seismic behaviour of such houses to deviate significantly from the assumed performance from the guidelines and standards.

During the 2010/2011 Canterbury earthquakes, hillside houses with substantial subfloor foundation systems were observed to be more vulnerable than their counterparts directly founded on ground. There is very little research about the effect of subfloor foundation systems on the house performance in earthquakes.

A project currently under way at BRANZ is to identify the seismic vulnerabilities of LTF hillside houses and develop solutions to improve seismic performance of LTF hillside houses. The study presented here is one component of this BRANZ research effort.

In this study, historical construction requirements and construction techniques of LTF hillside houses are reviewed. Subsequently, engineering characteristics of LTF hillside houses are classified into three broad categories, namely, hillside houses directly founded on ground, hillside houses founded at different levels and hillside houses founded at the same level but with a mixture of subfloor bracing systems.

The study led to the following conclusions:

(1) Hillside houses founded directly on ground

For hillside houses founded directly on ground, the seismic designs of the houses could use NZS3604:2011 because the engineering characteristics of houses in this category aligns with the assumptions in the engineering basis of NZS3604:2011.

(2) Hillside houses founded at different levels

For hillside houses founded at different levels, the subfloor bracing systems below the uppermost ground level could be made redundant, provided that (a) the in-plane and out-of-plane resistances of the foundation systems at the uppermost level are adequate to resist total actions associated with the building; (b) the in-plane rigidity of the floor diaphragm at the uppermost level is adequate to transfer the seismic actions across the building; and (c) the connections between the diaphragm and the foundation at the uppermost level are adequately strong to bring seismic actions to the uppermost foundation systems.

(3) Hillside houses founded at the same level with mixed subfloor bracing systems

For hillside houses founded at the same level but with a mixture of subfloor bracing systems, the stiffness incompatibility will inevitably be present in the subfloor

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foundation systems. The subfloor systems could potentially develop progressive failure (collapse) under along-the-slope earthquakes and significant torsional responses under across-the-slope earthquakes. Adequate consideration to address stiffness incompatibility in subfloor bracing systems and adequate design of ground floor diaphragms become very crucial.

It is suggested that, in all seismic design scenarios of LTF hillside houses, adequate designs of in-plane floor diaphragm rigidity and the connections between floor diaphragm and the subfloor bracing systems be considered.

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