Fire Research Report

The Adequacy of Existing House Foundations for Resisting Earthquakes: Effect on Service Reticulation and Ignitions

Victoria University of Wellington

August 2007

This research assessed the adequacy of a sample of 80 dwelling's foundations in Wellington against the current "Light Timber Framed Construction Standard" NZS3604:1999 (including amendments 1 & 2). The study also attempted to quantify the expected reduction in fire losses due to remedial work on foundations, installation of flexible gas connections and seismic shut-off valves. It is currently understood that large earthquakes, most often overseas, have shown that many dwellings falling off their foundations due to inadequate bracing, also severed the reticulated gas connection between the ground and dwelling. Estimated reduction in losses was compared with the costs of carrying out the remedial work.

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VICTORIA UNIVERSITY OF WELLINGTON
Te Whare Wānanga o te Ūpoko o te Ika a Māui

SCHOOL OF ARCHITECTURE
Te Kura Waihanga

The Adequacy of Existing House Foundations for Resisting Earthquakes: Effect on Service Reticulation and Ignitions.

a Report Submitted to the New Zealand Fire Service
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EXECUTIVE SUMMARY

The poor performance of residential foundations in past earthquakes prompted a practical investigation to quantify the adequacy of Wellington timber dwellings' foundations, focussing on bracing adequacy. The adequacy of a sample of 80 dwelling's foundations was assessed against the current "Light Timber Framed Construction Standard" NZS3604:1999 (including amendments 1 & 2). NZS3604 was introduced in 1978 and has been subsequently tested by many New Zealand earthquakes, most significantly being the Edgecumbe earthquake in 1987. The most current 1999 edition of NZS3604 is therefore considered to have seismically appropriate detailing and provisions to withstand design earthquakes; so for the purposes of this study, NZS3604:1999 is assumed to be the residential benchmark for seismic adequacy.

The study also attempted to quantify the expected reduction in fire losses due to remedial work on foundations, installation of flexible gas connections and seismic shut-off valves. It is currently understood that large earthquakes, most often overseas, have shown that many dwellings falling off their foundations due to inadequate bracing, also severed the reticulated gas connection between the ground and dwelling. This gas source may be ignited by any source, due to either earthquake damage or continued occupancy and activities in and around the dwelling. Estimated reduction in losses will be compared with the costs of carrying out the remedial work. This damage mitigation strategy is consistent with the Fire Service Commission strategic objective, the Focus on fire prevention, fire safety and fire outcomes.

The results for the study of seismic adequacy of foundations suggest that 39% of the sample had inadequate sub-floor bracing. Overall, 16% of the sample relied solely on the strength of ordinary piles, while 11% relied entirely on large concrete anchors. 76% of dwellings had some form of fixing deficiency, ranging from degradation to incorrect or non-existent fixings. After identifying the common deficiencies both in the sample and also from similar studies, remedial measures were costed and applied to different foundation types based on the required strength and suitability to the existing foundation system. The remedies were sourced from NZS3604:1999 and also the BRANZ document: *Strengthening Houses against Earthquake: a Handbook of Remedial measures*, written by Russell Cooney (1982). The remedies, to upgrade bracing, fixings and the overall general condition, including labour, ranged between \$19 per m² and \$72 per m², depending on the level of average remedy and size and weight of the dwelling.

In order to formulate an overall cost to Wellington City, these costs were then projected to all Wellington City foundations, which totalled over \$250 Million. It was assumed that each dwelling should be remedied to comply with the standards in NZS3604:1999 and applied based on the average condition of the sample. To understand the anticipated losses and therefore

benefits of upgrading, the estimated damage cost to residential dwellings was calculated using an Earthquake Loss Modeller, which was developed by Dr Jim Cousins and supplied by the Institute of Geological and Nuclear Sciences. The cost was calculated by assuming an earthquake of Magnitude 7.5, at a depth of 7.5km centred on the Wellington fault line, near Kaiwharawhara. In order to formulate a cost saving, or economic benefit from upgrading foundations, the cost of specific damage and collapse to residential dwellings was calculated to be $2.1 Billion, assuming no remedial measures had been applied. The cost of damage to dwellings following remedial measures was calculated at just over $1.1 Billion. Therefore, the total savings were anticipated to be around $950 Million. These results were considered as a ratio of cost over benefit which is commonly utilised in business to understand whether the associated economic benefit is greater than the anticipated cost of remedy. The cost/benefit ratio for dwellings likely to collapse is less than 10%, while extensively damaged dwellings have a higher cost / benefit ratio of less than 25%. The highest benefit was seen in Piled dwellings, where savings upwards of $500 Million were projected.

The application of remedial gas measures include two systems, which commonly solve many of the problems associated with post-earthquake fires. A Seismic Shut-off Valve [SSV], which will block to flow of gas into a dwelling during severe shaking and flexible couplings between the ground and the dwelling, so that a dwelling may deflect significantly without rupturing the gas service. Both remedial measures were applied as requried, with all dwelling with reticulated gas service requiring a SSV and all dwellings likely to deflect significantly, or with rigid connections requiring flexible couplings. Flexible couplings were priced around $100 per metre including installation and SSV's ranging from $300-$433 per unit installed. The costing for SSV's was based on US figures, which could reduce if there was a guaranteed market and supply in New Zealand. Overall cost/benefit ratios for SSV installation ranged from 0.53-1.4 and flexible couplings ranged from 0.11-0.27. Including these costs into foundation costs/benefit ratios found cost/benefit ratios of between 0.18 and 0.32 depending on the foundation type, with most of the remedial gas costs being overwhelmed by the significantly higher volume and costs of upgrading the foundations.

The application of remedial measures to foundations has consequences that directly benefit the EQC and emergency services such as the Fire Service, however the indirect benefits are likely to be far more significant during post-earthquake restoration. The direct benefits include an immediate reduction in post-earthquake recovery and reconstruction efforts which will reduce pressure on emergency management systems, hospitals and organisations involved with evacuations. The indirect benefits include less requirements for the erection, cost or location of temporary housing and accommodation for the proportion of the population that own or occupy a dwelling that has sustained serious foundation damage and require structural inspections and repairs before the dwelling can be safely re-inhabited. Minimising the number of people requiring evacuation or temporary accommodation will mean less psychological distress resulting from the destruction of one's property and the relocation into a temporary shelter, less personal cost if paying for rented or temporary accommodations (personal insurance doe not cover this cost) and less insurance claims to the EQC from a large volume of extensively damaged dwellings, which will inevitably also take many months to process.

For the results of this study to be beneficial to New Zealanders, the proper dissemination of this information is important. Society must understand the benefit of the preventative measures and the costs they may be faced with if the foundation is not securely braced, or gas system is not prepared for an earthquake.

TABLE OF CONTENTS

INTRODUCTION

New Zealand's housing stock consists mainly of light timber frame dwellings. These perform well in earthquakes due to their inherent flexibility with wall linings and claddings providing a high degree of bracing. However, damage from the moderate earthquake in 1987 at Edgecumbe, revealed that foundation bracing and connections between framing were weak points in conventional residential construction (BRANZ 2003). Many of the houses that were considered 'weak' were built prior to the introduction of formal construction standards and were consequently required to have little or no foundation bracing. A common occurrence for these dwellings that had no foundation bracing was collapse, usually seriously damaging the superstructure, trapping occupants and severing any service connections to the dwelling, including sewer lines, electricity and reticulated gas. Furthermore, observations from the 1923 Kanto earthquake suggested that around 40% of the post-earthquake fires were the result of collapsed buildings (Inoue 1925 cited Kobayashi 1984). The combination of trapped occupants, leaking gas and ignition sources such as arcing electrical currents or broken appliances make the situation even more pressing for the New Zealand Fire Service ("NZFS").

This is significant for the NZFS as they will be expected to rescue trapped occupants, extinguish any fires that ignite and limit conflagration between buildings and vegetation in a time when there will be an extremely high demand for NZFS resources. Therefore, limiting the number of dwellings collapsing due to weak foundations, fitting flexible gas connections and seismic shut-off valves will all mitigate the burden on the NZFS during the post-earthquake period.

The project report will be split into two distinct analyses; firstly to determine what type of dwelling is most at risk from falling from their foundations and secondly; to analyse the flexibility of the gas reticulation in the sample dwellings. The two analyses will then be combined to understand the relationship between inadequate dwellings and non-flexible gas reticulations and therefore the likelihood of ignitions following an earthquake. This data will then be projected to the whole of Wellington in order to formulate the cost of remedial work and thus the actual benefit of undertaking such remedial measures, both in terms of work load for the NZFS and cost to New Zealand.

BACKGROUND

On average in New Zealand we experience a large earthquake (one that exceeds Magnitude 7) every ten years. Many of our recent great earthquakes have been remote from densely populated areas and there has not been significant widespread damage. New Zealand's two first earthquakes recorded after European settlement, occurred in 1848 and 1855 in the Wairarapa region (Slade 1979). Due to common use of heavy un-reinforced stone masonry, many dwellings suffered major damage, forcing colonialists to consider alternative building practices and materials more suitable to New Zealand's unique seismic conditions. The destruction witnessed after the 1931 Napier earthquake (Dixon 1931), suggested that non-legislated building practices had been the reason for much of the destruction. However, post-earthquake fires and significant conflagration also caused much of the destruction seen in the inner section of town (Cousins et al. 2002). Damage from later earthquakes (Adams et al. 1970), such as Seddon, Murchison and Inangahua, in the mid 1960's, continued to suggest that there were significant deficiencies in our foundation building practices, however did little to enforce better bracing standards in formal legislation. The 1987 Edgecumbe earthquake proved that modern residential construction methods had generally improved since 1931, with many dwellings receiving negligible damage to the superstructure and many dwellings avoiding collapse (BRANZ 2003).

Although, many New Zealand earthquakes have occurred in unpopulated regions with limited post-earthquake fires; overseas earthquakes provide examples of what might happen in cities with densely built inner areas, such as in Wellington. The 1906 San Francisco and 1923 Kanto, Japan earthquake showed that post-earthquake fires commonly occurred due to the electrical short circuiting and overturning of heating or cooking appliances (Williamson and Groner 2000). More modern earthquakes, such as the 1994 Northridge, California earthquake, showed that fires originated from ruptured reticulated gas lines into buildings that had experienced excessive foundation deformation or had severely shaken gas appliances on the inside of the dwelling (Trifunac and Todorovska 1997). Moreover, many fires started because a leak was not directly apparent until the electrical and gas services were reinstated, which caused accidental ignitions (Park et al. 1995). Although flexible gas connections into dwellings and appliances may have prevented a number of unnecessary gas leaks in the past; it is the poor seismic awareness that constantly endangers the continued occupancy and restoration of dwellings following an earthquake. And although in many historic circumstances fire was prevented, this was usually due to a utility company, neighbour or other person that manually shut off the gas valve limiting the flow of gas into a dwelling (Williamson and Groner 2000).

FOUNDATION REACTIONS IN PAST EARTHQUAKES

Different foundation systems react to and resist seismic loading in different ways. In the 1929 Murchison earthquake (Henderson 1937), timber dwellings fell easily from their piled foundations, whereas dwellings built on concrete foundations resisted lateral loading and maintained the structural integrity with negligible damage to the superstructure. Following, the Gisborne earthquake in 1966, the movement of repiled dwellings from their foundations showed a lack of bracing and fixings to the sub-floor (Hamilton et al. 1969). Dwellings affected in the Seddon earthquake reacted badly due to poor soil conditions and the asymmetry of bracing systems (Adams et al. 1970). In the Inangahua earthquake, piles overturned and jack studding collapsed due to the lack of bracing (Shepherd, Bryant, and Carr 1970). The specific combination of sloping ground and uneven foundation heights in the area accentuated rotations about the more squat bracing elements. This vulnerability of dwellings with irregular plans was also illustrated by the torsional racking at the extremities of dwellings in the Edgecumbe earthquake (Pender & Robertson1987). The connection of R6 (6mm diameter) steel reinforcing bars between slab-on-ground and foundation wall was also seen as inadequate, as it failed to prevent the slab moving relative to the foundations. In overseas earthquakes, such as the 1971 San Fernando earthquake (Jennings & Housner1971) many split level dwellings and other asymmetric configurations, where floor diaphragms were not continuous, collapsed due to differential movement of the superstructure.

The following sections document each foundation type observed within the sample of dwellings in the study. Each foundation type reflects different construction preferences over predominately different aged dwellings, which results in varying strengths, weaknesses and sometimes inherent flaws within the design, usually the result of the construction legislation under which the dwelling was built.

1.1.1 Piled Foundations ______________________[FPF] and [IPF]

The Piled Foundation relates to two similar foundation types, the Internally Piled Foundation [IPF] and Full Piled Foundation [FPF] differing only by the age and method of exterior piling. Both systems use concrete or timber piles to resist vertical loads, which is a common method of foundation construction, most predominant at the turn of the 20th century (Harrap 1980) [Figure 3.1]. Timber piles were most often Totara or Puriri and in more recent constructions concrete, due to the ease of fabrication and resilience to rotting. Modern dwellings also use this foundation system especially where the topography is unsuitable for other foundation types. The older Piled Foundation relies heavily on the strength of the soil surrounding the piles for lateral resistance, usually relying on the overturning resistance of the shorter more squat piles.

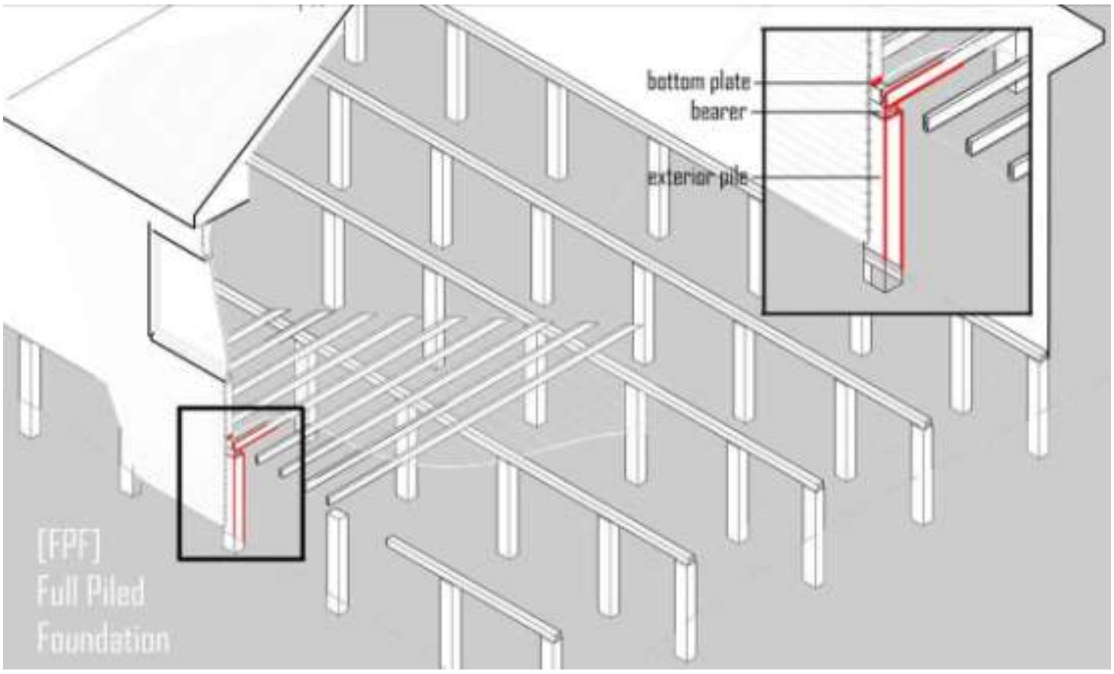

Figure 0-1 Detail of Full Piled Foundation

In past earthquakes, these dwellings often swayed sideways, especially if a dwelling had been repiled and replaced with only shallow pile footings [Figure 3.2]. Many dwellings of this age bracket usually have weatherboards covering the sub-floor area, however this form of cladding cannot be assumed to provide any significant sub-floor bracing potential.

Figure 0-2 Corner of Foundation showing Piles swayed to one side ***(Source: BRANZ 2003)***

Observations of Piled Foundations with sheet bracing attached to exterior piles have shown good bracing performance in past earthquakes (Norton et al. 1994). However, much of the extensive damage to dwellings during the 1989 Loma Prieta earthquake was attributable to pre 1940's piled dwellings with unbraced exterior piles (Norton et al. 1994). Similarly, dwellings with walings or weatherboards on exterior piles also performed poorly and slipped from piles, which can result in the piles being punching up through the floor [Figure 3.3].

Figure 0-3 Example of Piles punching through the Floor due to Sub-floor Framing slipping off Piles ***(Source: BRANZ 2003)***

Anchors such as concrete steps, chimney bases and porches are commonly integrated into the piled foundation sub-floor, which provide a significant amount of lateral resistance [refer Section 5.1]. However, if these 'anchors' are not adequately connected to sub-floor framing smashing between the piles and concrete could also potentially occur damaging the vertical load sustaining system (Norton et al. 1994) [Figure 3.4].

Figure 0-4 Full Piled Foundation slipped off Foundations, with Concrete steps remaining in place ***(Source: Cooney 1979)***

1.1.2 Concrete Foundation Wall____ _[FFW] [PFW] and [FFW/IP]

The concrete foundation wall dwelling covers three distinctly different forms of foundation: the Full Foundation Wall [FFW] the Partial Foundation Wall [PFW] and the Full Foundation Wall / Internally Piled [FFW/IP] foundation. As the names suggest the first has a full reinforced concrete perimeter wall between the superstructure and the ground [Figure 3.5], while the PFW has shorter lengths of concrete foundation wall, usually on the perimeter corners of the dwelling, making it somewhat weaker than the FFW. The FFW/IP also has a ring foundation, however uses reinforced concrete block instead of in-situ concrete. The specification of the concrete foundation wall system was used predominantly during the 1939 and 1964 State House Specification (Schrader 2005), and tended to be used in conjunction with the palette of state materials including heavy brick cladding and concrete tile roofs (Slade 1979).

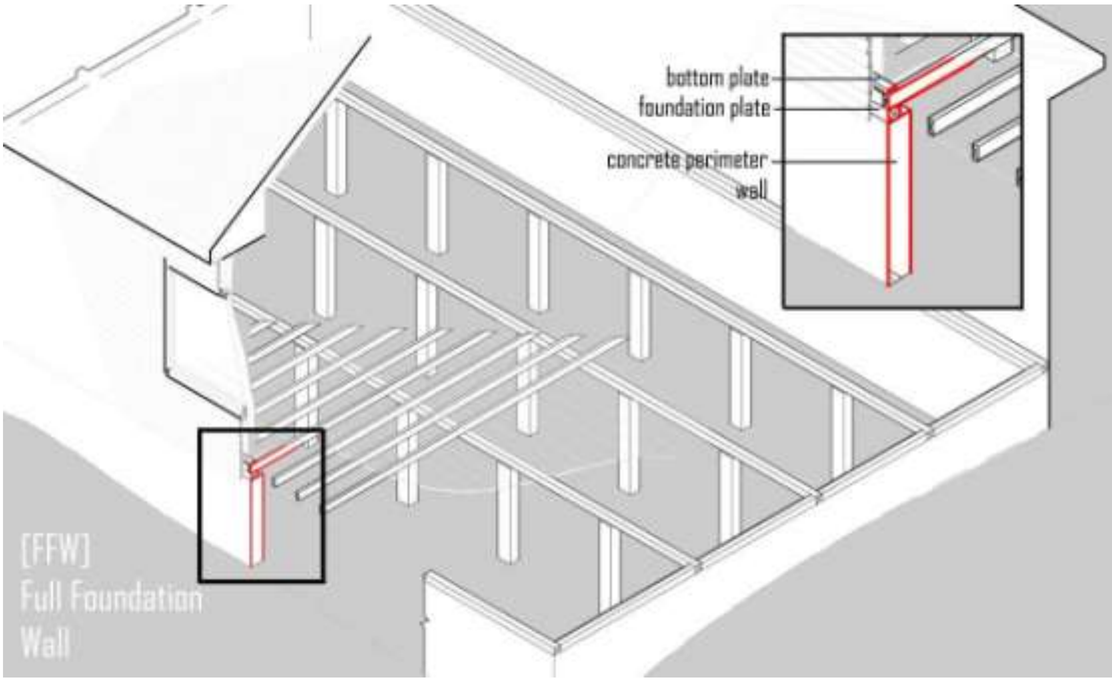

Figure 0-5 Detail of Concrete Foundation Wall

The concrete foundation wall system has been tested extensively by many earthquakes in the last 50 years, showing to sustain only light or moderate damage to the superstructure (Adams et al. 1970). Damage to the foundation area was usually limited to small cracks or subsidence (Pender and Robertson 1987) [Figure 3.6]. In many cases the concrete foundation wall system is necessary due to the use of heavier wall cladding, such as brick veneer. Although these dwellings have more weight to resist in earthquakes, the bracing provided by the concrete ring foundation is often more than adequate

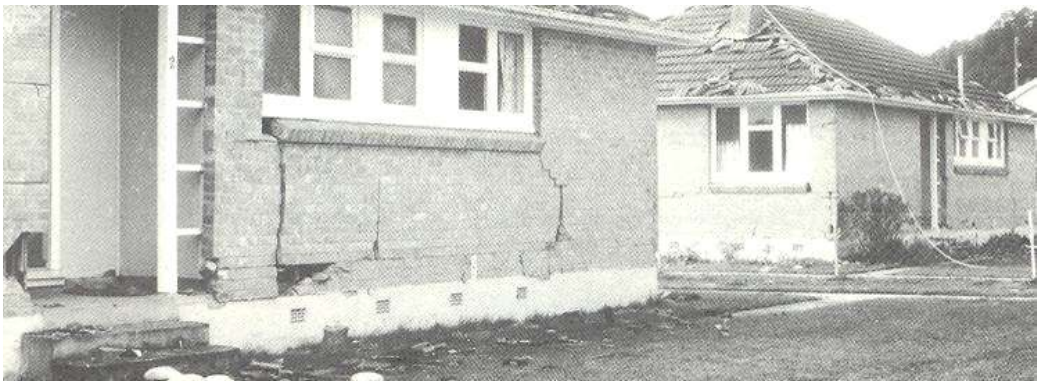

Figure 0-6 Superficial Damage to brick veneer on State Dwellings, however no damage to the Foundation Wall is evident ***(Source: Eiby 1980)***

Other foundation types that are also considered as Partial Foundation Walls are foundations with jackstudded sub-floor walls, where short timber studs span between the wall bottom plate and the concrete foundation wall below. As evidenced in past earthquakes, unbraced jackstudding can cause full or partial collapse to the foundation and therefore requires sheet bracing fixed to the interior or exterior of the jackstudding (Norton et al. 1994) [Figure 3.7].

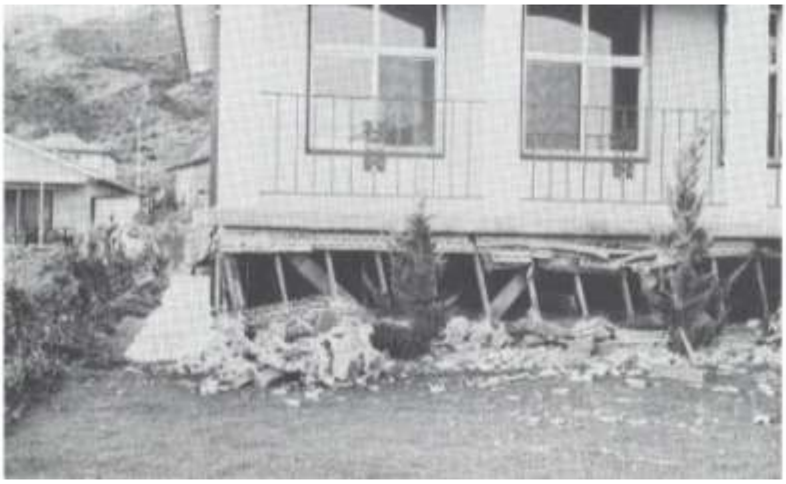

Figure 0-7 Jackstudded Sub-floor showing Cladding broken off and a slumping to one side *(Source: Jennings and Housner 1971)*

The FFW/IP was most prevalent in 1970's and 1980's dwellings and can be assumed to be as strong as the Full Foundation Wall, depending on the adequacy of reinforcing within the block sub-floor wall. However, in-plane bending of exterior walls, was seen in Edgecumbe and was most probably due to the poor integration between the dwelling superstructure and the sub-floor framing (BRANZ 2003) [Figure 3.8 & 3.9].

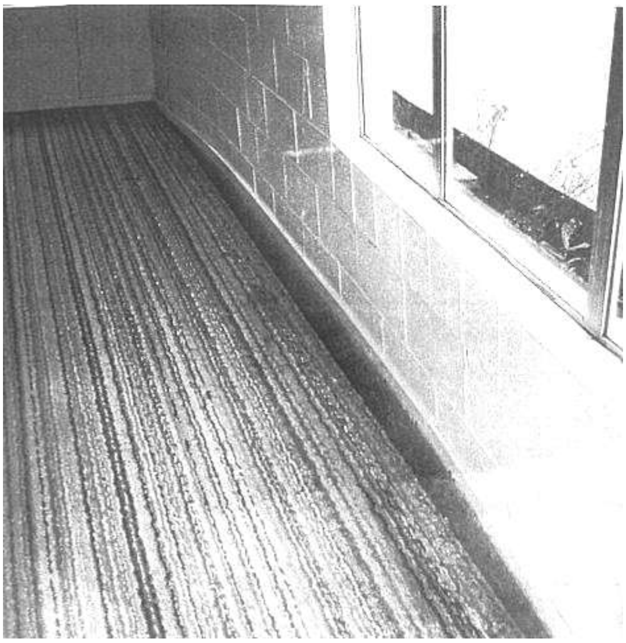

Figure 0-8 Wall separating from Exterior Foundation wall *(Source: BRANZ 2003)*
Figure 0-9 Extensive damage on the Lower Courses of Block in a Full Foundation Wall / Internal Piled Foundation *(Source: BRANZ 2003)*

This type of damage could also cause cracking to appear in mortar lines and blocks if the movement is severe. However, this damage can usually be easily repaired and would not cause the collapse of a dwelling.

1.1.3 Slab on Ground ______________________[SLAB] and [ENG]

The slab-on-ground is assumed to 'float' above the soil, meaning that loads are distributed from the superstructure to the slab diaphragm and into thickened areas of the foundation [Figure 3.10]. Since the connection from the superstructure to the foundation is the most important for the transfer of forces, this area could be a problem for dwellings with inadequate or non-existent fixings. The slab construction requires extensive reinforcing on internal corners and a reinforcing mesh over the entire slab to stop cracking resulting from movement and shrinkage.

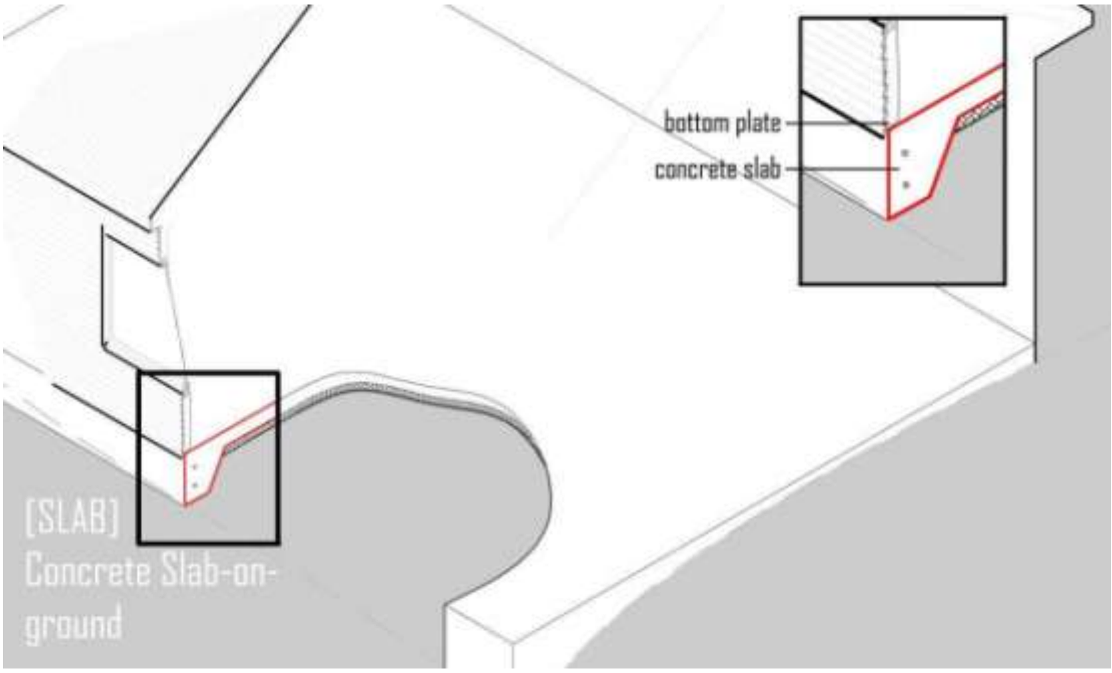

Figure 0-10 One variation of Detail for Slab on Ground Construction

The strength of slab-on-ground construction has proven to be sound in past earthquakes (Cooney and Fowkes 1981). However, a common failure see in Edgecumbe was the top slab sliding relative to the lower wall, causing extensive damage to the foundation of the dwelling [Figure 3.11]. Also, since a slab foundation floats on the ground, differential settlement of the soil can cause foundations to move laterally and vertically [Figure 3.12], crack and possibly separate causing disruption to services. It is for this reason that slab constructions suit reasonably flat consistent sites with gentle and flat topography.

 

Figure 0-11 Slab on Ground showing relative sliding difference between the Dwelling and Ground; note the prior location of Services ***(Source: BRANZ 2003)***
Figure 0-12 Severe Cracking through a Concrete Slab ***(Source: BRANZ 2003)***

1.2 Sample Spread of Foundation Type

The sample of dwellings was obtained from the Wellington City Council rates database which provided a random selection of dwellings, from which a sample of 80 dwellings was taken. Each dwelling was assessed by the foundation type and it was found that most dwellings have either a Full Piled Foundation or Full Foundation Wall, usually dictated by the architectural style of the dwelling [refer Appendix A]. Piled dwellings were most common prior to 1940, where as Full Foundation Wall dwellings were common between 1950 and 1990 [Figure 3.13].

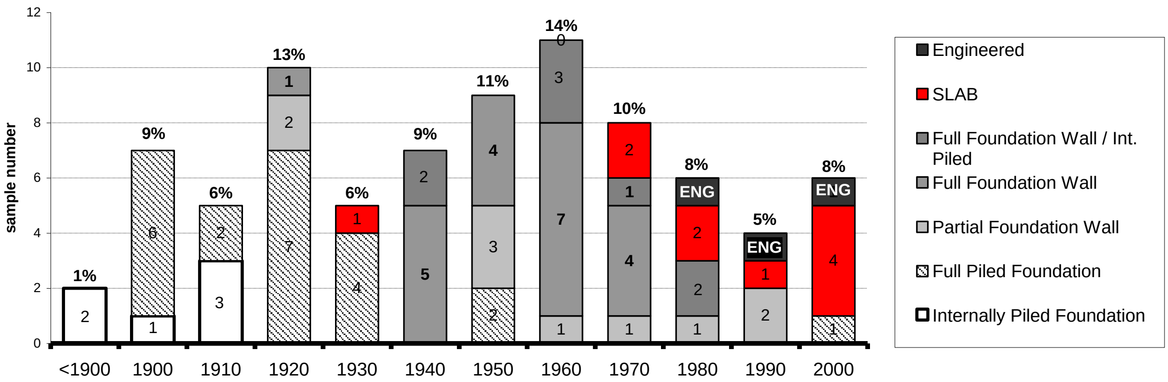

Figure 0-13 Foundation Type for Age of Dwelling, Percentages of the Total Sample.

The sample aimed to include dwellings built in each decade from the beginning of the 20th century with the number of houses from each decade proportional to the number of houses built within that period. A site visit was conducted for each dwelling with permission from the owner. In each case, the bracing, connections in the foundation was assessed against the requirements of NZS3604:1999 in light of the site conditions, age and overall weight of the dwelling.

GAS RETICULATION AND FIRES IN PAST EARTHQUAKES

Throughout history fire has followed most major earthquakes, however the extent of the destruction usually depends on the rapid shut-off of services or response from local emergency services and individuals. In examining the interrelationship between the main foundation elements and the flexibility of gas reticulation, one can determine where foundations are likely to fail and therefore whether gas connections are likely to rupture.

1.3 Rupture or Failure of Gas Reticulation

Many fires from past earthquakes, usually overseas, have occurred due to the toppling of water heaters and other gas appliances subjected to strong ground movement. This movement can break the gas service connection from the wall, resulting in the release or ignition of natural gas into buildings (Chung et al. 1995). Many gas reticulation leaks and rupture were the direct result of overturning or breakage of gas appliances due to excessive structural deflections and buildings sliding off foundations, which can rupture both gas and electrical mains. If these services enter the dwelling in close proximity, ignition of leaking gas can occur (Scawthorn 1987). These types of fires have been known to ignite immediately following an earthquake and also some time later when utilities, such as electricity, are restored (Scawthorn 1985).

Another development and significant cause of post-earthquake fires, is the rupture of reticulated gas services between the dwelling and the gas mains in the street, which are usually buried. These failures were common where ground deformations were larger than a few inches. A rupture of such a pipe may not be immediately obvious, however may still cause fires in and around dwellings (Chung et al. 1995). Natural gas piping on the customer side of the pipeline showed that service connections and meter sets are more vulnerable when a structure falls off its foundation and crushes or shears the attached service connection (Chung et al. 1995) [Figure 4.1].

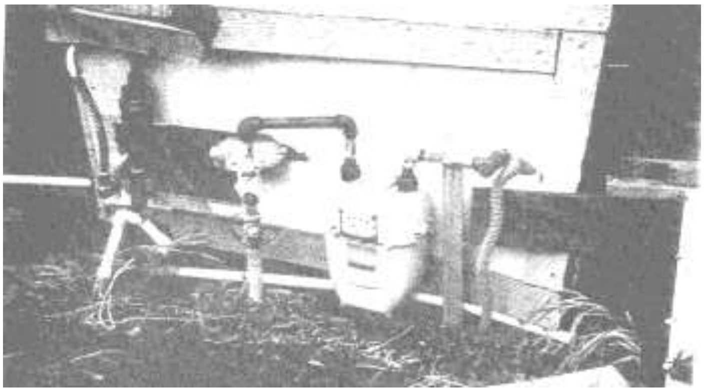

Figure 0-1 Damaged reticulated Gas meter next to a dwelling with distorted foundations *(Source: Todd et al. 1994)*

According to the gas utility supplier in the 1994 Northridge earthquake, other than failure of natural gas mains in the street, most other sources of gas leakage came from damaged structures falling off foundations, and failure of natural gas appliances inside dwellings (Chung et al. 1995). Although not directly applicable to New Zealand (due to differing uses of gas services), 2500 gas water appliances were damaged in the Northridge earthquake, which caused 47 natural gas-related fires, equating to around 35%-40% of all ignition sources (Chung et al. 1995).

1.3.1 Reticulated Gas Entry into Dwelling

The entry of gas into the dwelling (depending on the where the gas actually enters the dwelling) will largely determine the flexibility of the connection. Many dwellings have gas meters and therefore pipe connections through sub-floor walls [Figure 4.2], meaning that if a dwelling was to move significantly and the pipe had rigid fittings [Figure 4.3], the pipe may rupture at this connection. This type of connection usually differs between foundations type and also often when the reticulated gas was installed in the dwelling.

Figure 0-2 Flexible Gas Connection into Sub-floor Wall
Figure 0-3 Rigid Gas Connection into Brick Veneer

Other dwellings tend to have the gas connection at or near the street or nearer to the mains location, with a single pipe extending underground into the dwelling. For these dwellings the connection directly into the flooring an appliances is the most critical connection [refer Section 4.1.3].

1.3.2 Gas Distribution in the Sub-floor Space

The gas distribution system may also be at risk if the gas network in the sub-floor space is connected over major structural joints which could move excessively or deflect beyond the ductile capacity of the gas pipe work. This could be an issue where pipe work is directly connected to structural framing members, which could potentially move off their supports [Figure 4.4] or move prying apart pipes and breaking electrical cabling [Figure 4.5].

Figure 0-4 Structural Connection likely to move apart in an Earthquake
Figure 0-5 Pipe work interweaving within the Structure

The likelihood of breaking of piping is also increased if the pipe material is of low grade steel with threaded connectors that do not behave in a ductile manner (Williamson and Groner 2000). This would be a common situation in older dwellings. However, often in older dwellings, pipe networks are laid on the ground [Figure 4.6], underground or have flexibility and reserve capacity in the length of pipe work not connected to any part of the foundation [Figure 4.7]. Both of these factors increase the flexibility of any reticulated gas system.

Figure 0-6 Gas Pipe work laid on the Ground under Dwelling
Figure 0-7 Copper Gas reticulation with reserve flexibility of tubing

1.3.3 Entry into Flooring and Gas Appliances

Perhaps the most crucial connection for all dwellings is the connection into the flooring [Figure4.8] and whether or not flexible connections exist between the gas mains and the appliance it is serving [Figure 4.9]. If this connection is not flexible, any significant movement of the foundations, including even slight swaying, could shear off the gas connection into the dwelling causing a gas leak (Scawthorn 1987).

Figure 0-8 Rigid Gas Connection into Flooring of dwelling
Figure 0-9 Flexible Gas Connection into Gas Appliance

On the interior of the dwelling, many of the fires in past earthquakes have resulted from severely shaken gas appliances (including ovens and gas water heaters), not adequately secured to the wall (Williamson and Groner 2000). Furthermore, gas mains with no seismic shut-off valve can break and continue to supply gas to the broken area, which then only requires a spark to be ignited.

1.4 Spread of Fire and the Direct Consequences

The consequences of gas rupture and therefore fire loss following a major earthquake is influenced by three main factors, ignition frequency, conflagration potential and fire loss suppression (Kobayashi 1984). These factors will determine the number of fires following an earthquake, the likely spread for the given weather and post-earthquake conditions and the overall loss of property. In addition, the effectiveness of the Fire Service may be hindered by extended reporting and travel times due to fallen debris and damaged roads, and a lack of water mains pressure (Cousins, Dowrick, and Sritharan 1990). Therefore the chance to save a single dwelling from fire or to evacuate trapped people from dwellings fallen off foundations will be severely limited. If dwellings are in close confines conflagration and branding may increase the extent of the fire spread. Combine this with coverings and claddings that may be distorted from the earthquake, and non-combustible roof and wall coverings may be less effective to limit this spread (Scawthorn 1985).

1.5 Sample Spread of Gas Pipe Flexibility

As observed from the sample dwellings, gas connections tend to differ between ages of dwellings and when the gas installation was made [Figure 4.10]. The graph below shows a number of dwellings in the 1940-1970 bracket with no reticulated gas connected, which is consistent with mass constructions of new subdivisions during this time. The graph below also suggests that pre-1940's dwelling have the most varied forms of gas connections installed into dwellings.

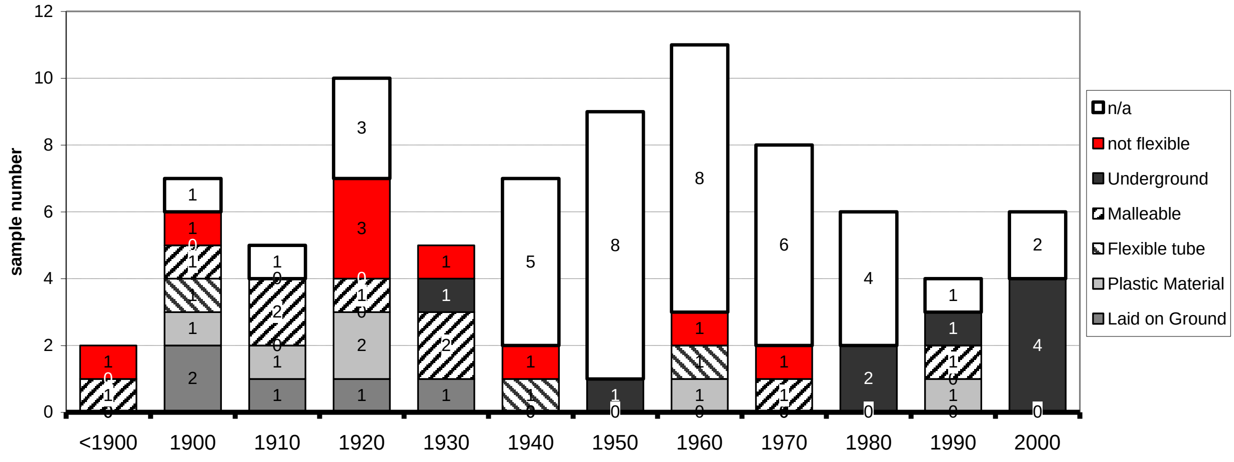

Figure 0-10 Number of Dwellings with Flexible Gas Pipe Material into Dwellings

Almost half of the dwellings surveyed had no gas connections, usually because the suburb did not have a reticulated gas service, or the owner had chosen not to install it. Some owners had bottled gas; however, this was seen in only 4% of dwellings, and all of which had flexible fittings into the dwelling. Most of the rigid gas connections tended to be in either the very old piled dwellings or newly constructed slab foundation dwellings built after 2000. These rigid connections accounted for nearly 20% of all gas connections surveyed.

PROJECT METHODOLOGY

The foundation and gas reticulation flexibility are both separate analyses and require determination on the level of strength or flexibility of each before one can determine the number of dwellings that may be at risk from a gas leak due to weak foundations. For the first part the methodology of determining the strength of a foundation is discussed, then the determination of flexibility is discussed with respect to foundations. Overall this will provide the bench mark to determine at risk dwellings, which may be at serious risk from foundation collapse, and also significant gas leaks, which could lead to further widespread fire damage and conflagration.

1.6 How do we determine the Adequacy of Foundations?

For a sub-floor to be adequately braced, it must be able to transfer the induced forces in an earthquake from the superstructure, such as the weight from the wall and roof claddings, to the ground. This is affected by the house geometry, materials and live loads on the floors. The existing bracing mechanisms must be appropriate for the induced loading. A dwelling must meet the current requirements in NZS3604:1999 (SNZ 1999), including all connection methods contained within the document. For the purposes of calculating bracing in the sub-floor, pile spacings and bearer lines are considered to be lines of bracing, or where bracing may be applied [Figure 5.1]. To assess whether each dwelling has adequate bracing, the data collected onsite, was entered into a spreadsheet, which calculates the bracing requirements up to the current version of NZS3604:1999 (Winstones Wallboards Limited 2006).

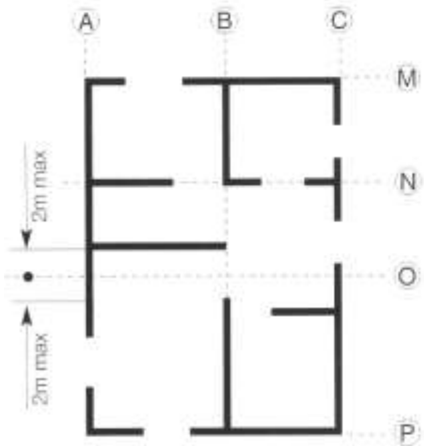

Figure 0-1 The method of Bracing Lines used for all Foundation Calculations ***(Source: Winstones Wallboards Limited 1999)***

The spread sheet compares the dwelling weights and bracing with the calculated existing bracing capacity. For each dwelling, an original calculation of bracing capacity was made and then another with remedial bracing applied (if required), in order to assess whether each dwelling has achieved minimum bracing requirements.

Although, not specifically noted in NZS3604, for the purposes of this study, anchors such as chimney bases, additional concrete slabs (common in renovations) and concrete porches were deemed to assist in the lateral bracing of a dwelling [Figure 5.2]. The relative dimensions of these concrete volumes were noted and used in bracing calculations mentioned above [refer Section 5.1].

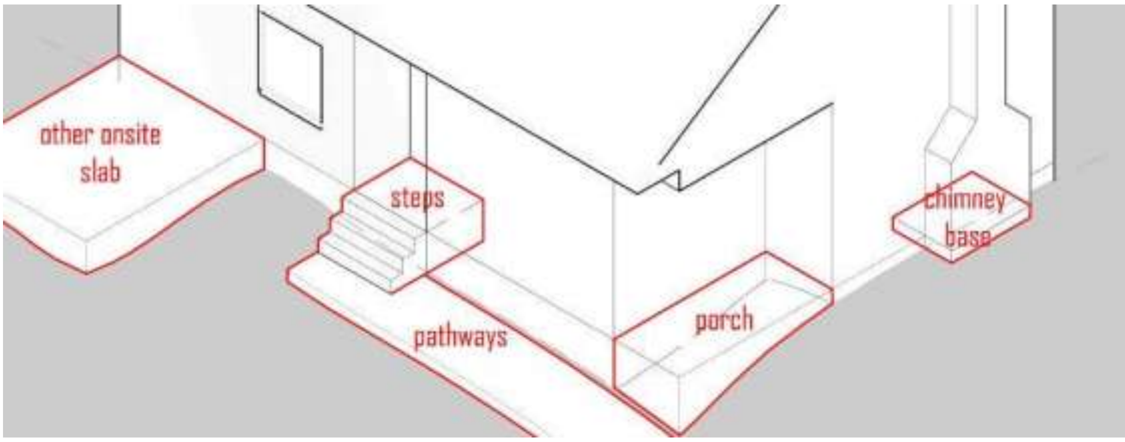

Figure 0-2 Bracing showing Different Non-designed Anchor types in a Foundation

For the purposes of this study, a dwelling will be assumed to collapse if the bracing capacity of the sub-floor is less than 50% of the required strength as prescribed in NZS3604, and from information obtained from calculations.

1.6.1 Sub-floor Fixings

In assessing the adequacy of the connections between timber framing in a foundation, it is necessary to consider the adequacy in two ways. The first is the overall adequacy of connections to transfer the induced loads through a foundation, this relies on the integration of material interfaces, quality of material, the configuration of the fixings and the construction methods used to connect the different framing members. Each connection is assumed to take a proportion of load from the entire superstructure [Figure 5.3].

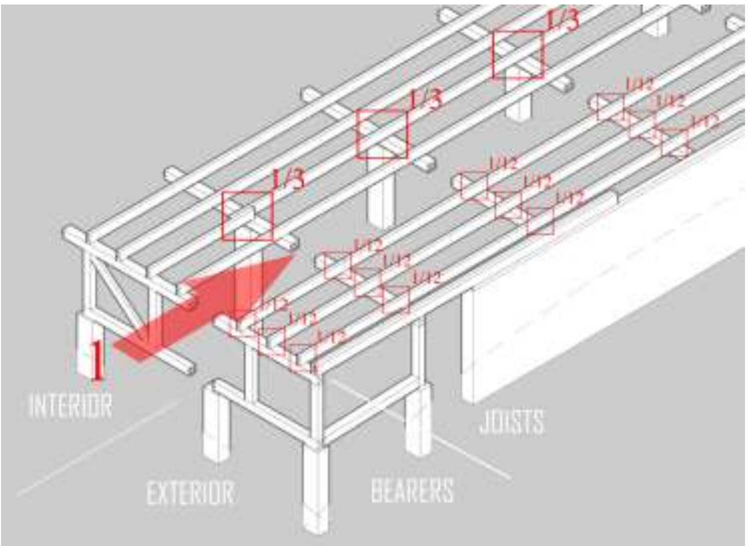

Figure 0-3 Proportion of Force relative to the Number of Connections in the Foundation

1.7 How do we determine the "Flexibility" of Gas Connections

The flexibility of gas connections is a rather subjective determination, however would usually constitute a Corrugated Stainless Steel Tubing ["CSST"] between exterior gas lines and the dwelling exterior. In many dwellings this connection to the dwelling occurs in two places, the exterior sub-floor wall and then the flooring of the dwelling, which runs to the gas appliances. Also the material flexibility may affect the performance of reticulated gas describing whether pipe work is likely to rupture. Thus, the determination of flexibility is described on these three individual levels [Figure 5.4].

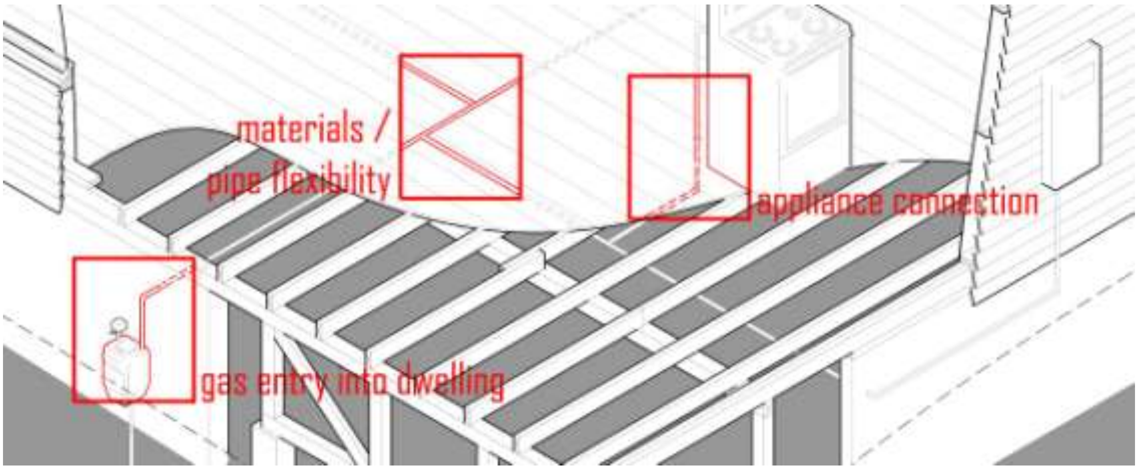

Figure 0-4 Locations in the Sub-floor where Gas Rupture may Occur

1.7.1 Entry into the Dwelling

For this study, it is assumed that the mains gas line should be appropriate to withstand seismic movement without breakage up to the point of entry into the dwelling. However this may differ depending on the amount of deformation of the soil and severity of shaking (Williamson and

Groner 2000). Rupture at the point of entry to the dwelling will most often be the result of severe displacement or collapse of a foundation relative to the entry of the gas. The rupture of this service may occur despite the foundation type, shearing the piped connection especially if the pipe material is brittle. Therefore, for the purposes of this study, if a dwelling collapses or moves significantly on a foundation, and the gas connection is rigid, it will be assumed to break causing a leak. Similarly, if the gas coupling is malleable (copper or plastic tube) or fully flexible, but the fall from the foundations is further than the flexibility in the tubing, this connection will also be assumed to sever.

1.7.2 Pipe Line Flexibility / Materiality

Once the gas line is on the interior of the dwelling, the location and length between the entry point and the gas appliance becomes a factor which will determine whether any rupture could be possible. Malleable pipe work laid on the ground may be able to move freely about during shaking and may possibly sustain little damage even of the dwelling sways heavily, and so can be assumed to be flexible. The material of the gas connection is an important property when discussing the rigidity of the entire gas system. It has been described that older type steel tubing may exhibit brittle failure between pipe connections during movement (Williamson and Groner 2000). Similarly, materials such as copper, polyethylene and unplasticised PVC piping [refer section 4.3] are inherently more malleable, however if they are connected over structural joints likely to move in an earthquake, they will be considered rigid and likely to rupture.

1.7.3 Connection to Gas Appliances

The final stage for the gas pipe work is the connection up to the floor of the dwelling and the connection into the gas appliance. If the pipe work is flexible, then this connection is less likely to rupture. However, many dwellings usually have metal pipe work and a rigid connection into the flooring, which means that this area could cause rupture especially if the appliance is unrestrained within the dwelling. For the purposes of this study, all dwellings with rigid connections to this area, and experiencing collapse will be assumed to have a gas rupture. Malleable tubing such as copper or plastic will be assumed to be adequate against this type of movement.

RESULTS OF ONSITE OBSERVATIONS

The results all refer to the dependency of foundations to be strong in order to maintain gas reticulation into a dwelling. Thus results will be discussed in terms of the effect of bracing, connections and materiality or rigid connections. Overall, an average of 39% of foundations, were below acceptable requirements for bracing adequacy. The majority of houses that failed to meet the required standards had piled foundations that were commonly used in dwellings prior to the 1940's. Weak connections in repiled dwellings also accounted for a large proportion of the sample built prior to 1940, usually occurring between the Ordinary Pile to Bearer connections. The poorest connection observed in all dwellings was the Bearer to Bearer end connections over piles. 69% of the sample failed to meet the minimum bearing distance and nail plate connection requirement, which could result in bearer ends separating and moving off the supporting piles during an earthquake.

1.8 Bracing Inadequacies

Although 39% of dwellings failed to meet the prescribed bracing requirements, some of those dwellings relied (unintentionally) on non-prescribed bracing anchors such as concrete porches and chimney bases to enhance the overall bracing potential of a dwelling. By far the most common types of foundations that were sub-standard are the Full Piled Foundation and Internally Piled Foundation dwelling [Figure 6.1].

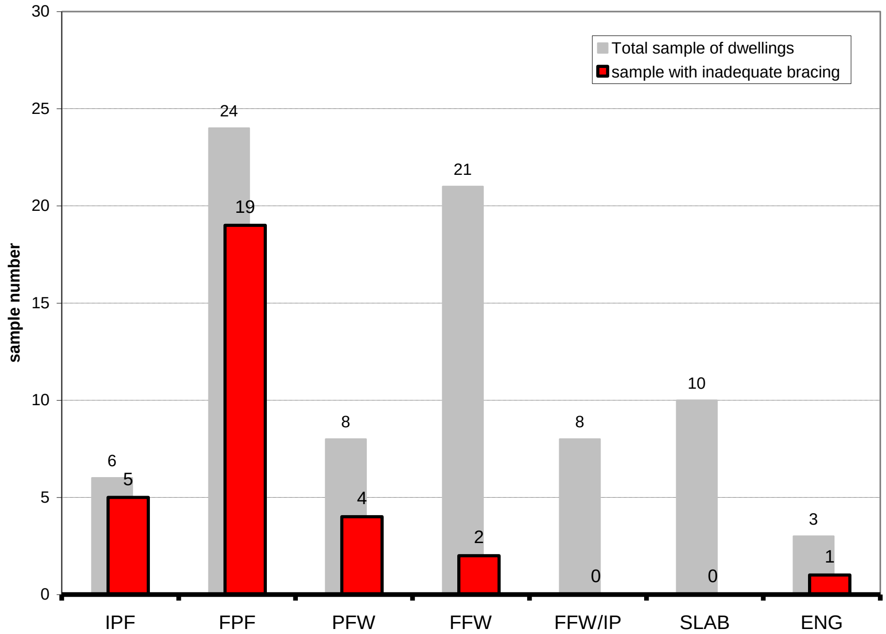

Figure 0-1 Total number of Dwellings failing Bracing Requirements per Foundation type

16% of sample dwellings had little or no bracing and a further 33% used non-prescribed, non-designed bracing methods to brace such as anchors. Other forms of un-braced dwellings relied on the strength of Ordinary Piles for lateral resistance. Twenty percent of the total sample relied entirely on this calculated resistance, commonly in piled dwellings built prior to the 1940's.

1.9 Gas Connections and Methods of Flexibility

The flexibility of gas fittings was assessed in 3 parts of the gas reticulation, the entry point of the pipe to the dwelling, the connection to appliances and the rigidity of materials and fixing to the sub-floor structure. From Figure 6.2 below, it can be seen that the number of dwellings without gas is highest in the concrete foundation wall type, however the piled dwellings tend to have a number of points of rigidity within the gas system and a generally higher number of dwellings with gas.

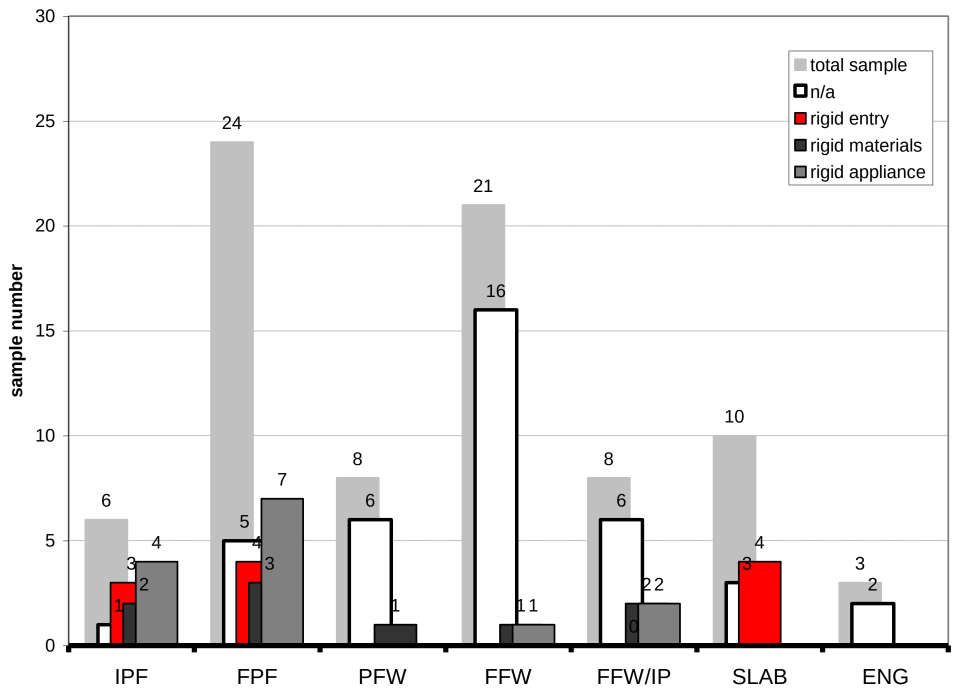

Figure 0-2 Number of Dwellings with Rigid Gas Connections over each Foundation Type

Overall 49% of dwellings have no gas attached. If this is projected to a Wellington sample, only about 34,000 dwellings have gas attached as a reticulated service. This will be used later to discuss the overall costs and benefits of applying remedial measures applicable to all Wellington dwellings. Dwellings with either a rigid entry or a rigid appliance connection are at significant risk. The material rigidity is usually not a problem, however indicates the high use of problematic or dated methods to piping gas around a dwelling.

1.10 Summary of Results

The summary of results combines the data totalling the number of dwellings likely to collapse with the number of dwellings with rigid gas connections. As expected, older dwellings had a lower bracing capacity and weak connections within the sub-floor. The number of dwellings, which are predicted to collapse, show higher proportions of dwellings with rigid gas fittings, either on entry or attached to the gas appliances.

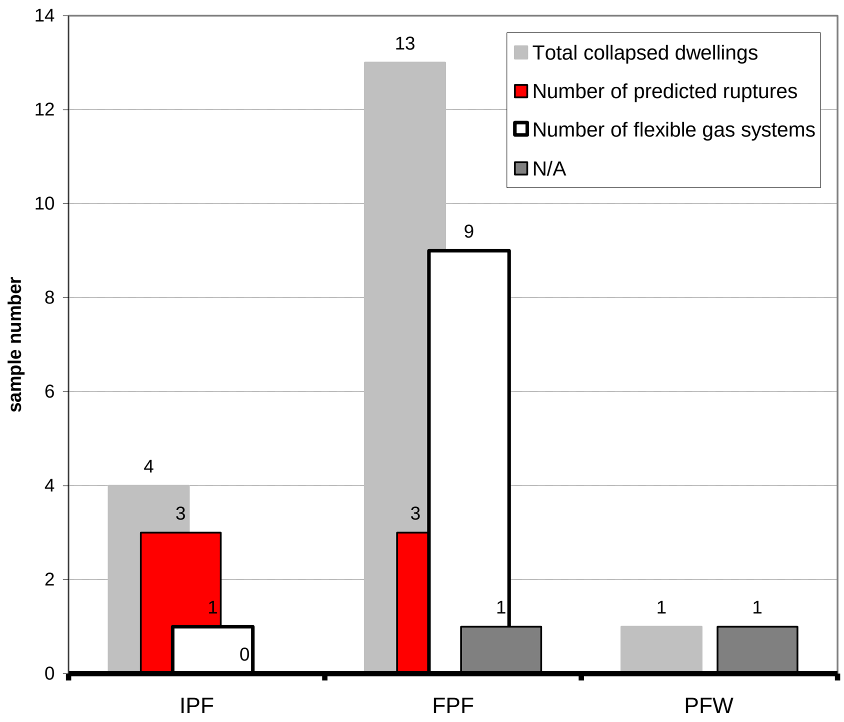

Figure 0-3 Number of Predicted Collapsed Dwellings with Rigid Gas Connections

Compared with the actual sample of dwellings in each foundation type, the dwellings that are anticipated to collapse have a higher percentage of rigid connections, than the overall sample. This is significant as the relationship describes a trend that older piled type dwellings tend to have rigid gas connections and are therefore more at risk from collapse and also gas release and fire ignition. Due to the close proximity of the dwellings and commonly combustible materials within this age bracket, the chance of conflagration is also higher. However, to understand the impact of remedying these dwellings, we must first understand the overall cost and benefit of the remedial action and the potential risk of not undertaking any action. Only then we can estimate the economic cost of remedial action to the individual and the direct economic savings for society.

Found. Type	% of Dwellings in the Sample	Total No. Dwellings in each foundation type	No Dwellings with rigid gas fitting	No. Collapsed dwellings	Gas Rupture rate per Found. collapse	Total No. of dwellings with gas rupture	% of ruptures in Wellington overall
IPF	7.5%	4,905	2,943	249	60%	149	50%
FPF	30.0%	19,620	4,647	863	31.5%	136	46%
PFW	10.0%	7,528	753	65	8%	8	4%
Total	**47.5%**	**32,053**	**8,343**	**1,177**		**293**	

Table 0-1 Gas reticulation rupture for all at risk Wellington Dwellings

Overall in Wellington, 240 dwellings have a combination of weak foundations likely to cause collapse and rigid gas connections. However, this number does not reflect the direct number of ignitions that will likely occur in Wellington. The number of ignitions may be significantly smaller for a number of reasons, firstly the gas may be shutoff before any of these ruptures ignite, either by the gas supplier or manually by the owner or neighbour. The gas leak may not have an ignition source such as an electrical spark or open flame, or be only minor and put out by the owner. The gas piping may be broken and leaking to a ventilated space or the break may not be significant to release large volumes of gas. Therefore, for the purposes of this study, previous research more specifically related to the ignition of gas leaks will be used to project the destruction of post-earthquake fire caused by gas leaks in Wellington City. However, it is clear that will be assumed that only 10% of ruptures result in a fire requiring the attention of the Fire Service.

REMEDIAL MEASURES

The study results identified key areas where foundations were inadequate, however the cost and application of remedy must be considered to formulate whether upgrading foundations is actually economically feasible. The end result of applying remedial measures must be considered to increase the likelihood of a dwelling remaining habitable following an earthquake, which will in turn mitigate cost and burden on emergency services and the necessity for temporary shelter and accommodation. Applied remedial measures were sourced from NZS3604:1999 (the Braced pile and Anchor pile systems) and the concrete Infill wall solution and Sheet bracing applications, both set out in the BRANZ publication, *Strengthening Houses against Earthquake: a Handbook of Remedial measures* (Cooney 1982).

1.11 The Foundation Remedial Solutions

Remedial piled solutions include the anchor pile solution [refer Appendix B1.4] and the braced pile solution [refer Appendix B1.1], both of which are prescribed in NZS3604:1999 (Standards New Zealand). Both solutions offer a 6kN [120BU] bracing element and both have different physical limitations for application into existing dwellings. The sheet bracing solution [refer Appendix B1.2] offers applications that gain their strength when the length of the bracing element is increased over the foundation. Other solutions include the infill of concrete between exterior concrete piles, in accordance with the BRANZ remedial solutions in *Strengthening Houses against Earthquake: A Handbook of Remedial Measures* (Cooney 1982).

The new bracing was applied on the basis that new system should complement existing system. Additional bracing should be of similar stiffness to the existing system, otherwise configuration issues may arise, possibly reducing earthquake resistance. Also, site factors such as height of dwelling from cleared ground level and the materiality of existing sub-floor structures were considered for the purposes of achieving the most cost-effective solution. For the purposes of calculation the cost of upgrading, bracing, connections and the labour involved would all be included. The cost of upgrading dwellings was based on values obtained by quantity surveying methods for different remedial applications and materials. Table 7.1 provides a break down of the applied remedial measures for the foundation, stating the average costs per square metre for all remedial applications. For an average Wellington dwelling (139sqm) one can assume that a Full Piled Foundation will cost $974 to apply remedial sheet bracing. Other foundation systems rate higher at around $2800 to remedy the bracing in a Partial Foundation Wall.

Found. type	Existing bracing system	% Sample requiring bracing	Remedial solution	Average cost of improvement per square metre of dwelling			TOTAL Per m2
				Fixings	Durability/ Condition	Bracing	
IPF	Pile	83%	Anchor pile	$14.04	$13.71	$19.96	**$47.71**
FPF [1]	Pile	63%	Sheet	$13.43	$13.50	$8.37	**$35.30**
FPF [2]	Pile / sheet	17%	Anchor pile	$13.43	$13.50	$39.66	**$66.59**
PFW	Pile / Conc. Wall	50%	Sheet	$21.69	$9.66	$5.98	**$37.33**
FFW	Conc. Wall	10%	Infill wall	$15.63	$8.05	$48.47	**$72.15**
FFW/IP	Conc. Wall	0%	n/a	$11.98	$7.36	n/a	**$19.34**
SLAB	n/a	0%	n/a	$0	$0	n/a	**$0.00**
ENG	varies	0%	n/a	$0	$0	n/a	**$0.00**

Table 0-1 The Remedial Measures and Costs applied to each Foundation Type.

1.12 Gas Reticulation Remedial Solutions

Two remedial solutions are necessary if reticulated gas services are rigid and likely to rupture during excessive ground movement. Seismic Shut-Off Valves [Appendix C1.1] function when shaking reaches the level of the valve's designated shut-off point (generally around 5.2-5.4 on the Richter Scale). The valve will automatically stop the flow of gas by means of blocking the gas passage in the piping. The pressure from the gas in the pipe blocks the flow until the gas line can be manually reset. This system ensures that if a rupture occurs, no large amounts of gas will be released into the dwelling. These valves are mandatory in parts of the seismically active State of California including Contra Costa County, City of West Hollywood, Los Angeles, and Marin County. Regulations in these areas usually state that all dwellings built after a certain period, usually after 1995, or those dwellings being altered above a certain cost, shall have motion or non-motion sensitive Seismic Shutoff Valves attached. The regulations often determine the placement of such valves and define the limits of what is determined a "building" and also the functioning limit of a "seismic shut off valve" (Earthquake Store.com 2007). Another variation to restrict the flow of gas is with an Excess Flow valve [Appendix C1.2]. Excess Flow Valves are designed to cut off the flow of gas when they detect a higher flow rating than the allotted maximum flow of the home. Since these valves operate on a different principle, excess flow valves will not shut off the gas to your house simply because of an earthquake. Thus, for this reason Excess Flow Valves will not be considered an adequate protection against earthquake only. All remedial measures will assume the Seismic Shutoff Valve be installed to protect against earthquake.

The second solution and perhaps the simplest is a Flexible Coupling [Appendix C1.3], which protects against reticulated gas rupture in rigid piping. This may occur when two elements move relative to each other during shaking. The most flexible connection, and therefore the most preferable tubing, is a Corrugated Stainless Steel Tubing (CSST), which is a flexible metal high pressure piping with PVC exterior. In New Zealand this is imported as PEX-AL, which has co-extruded barriers of PVC and aluminium layers. This provides a corrosion resistant barrier and semi flexible connections when used in place of traditional pipe materials. However, with fitting flexible couplings, it is assumed that if a dwelling collapses off the foundations, the flexible connection may still be severed. This system may only mitigate damage caused by excessive shaking, however may still rupture if the dwelling collapses off the foundations. Table 7.2 shows the breakdown of costs associated with remedial gas measures installed in dwellings.

	Dwelling	% Sample requiring remedy	Costs per unit installed[1]			TOTAL Per unit
			Materials	**Labour**	**Avg.**	
Seismic Shutoff Valves[2]	Existing/new	51%	$215.00	$200.00	$415.00	**$433.00**
Flexi Coupling CSST	Existing/new	12.7%	$48.00	$252.00	$100/m	**$300.00[3]**
Flexi Coupling PEX-AL	Existing/new	12.7%	$3.60	$295.00	$100/m	**$300.00**

Table 0-2 Percentages and Cost Breakdown of Remedial Gas Measures per Unit

Flexible couplings are assumed to be required for all piled dwellings with gas, as an earthquake may rupture the service into any type of dwelling. Overall this equates to 51% of dwellings, or 34,000 dwellings. Although the majority of dwellings may have some form of rigid gas fitting, for this study it is assumed that only the dwellings predicted to be extensively damaged or collapsed, will require a flexible connection [see Section 6.3]. However, for the risk of rupture to be mitigated, the dwelling's sub-floor must also be adequate, possibly requiring upgrading, otherwise the flexible coupling may still rupture during severe shaking or collapse. This equates to 12.5% of the total sample or 8,175 of Wellington dwellings.

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[1] Maximum and Minimum prices correct as at 12 July 2007 converted from USD into NZD and differ between different Counties in the United States. Differences in cost are also incurred for different gas pipe diameters to be installed.

[2] Differences in price also occur when the install is to occur in the kerb or on the dwelling – ranging min. $127NZD – exchange Prices from USD as at 12 July 2007. Exchange rate of 1 USD = 1.27181 NZD used throughout.

[3] Assuming a connection from the gas meter to an appliance or to the side of a dwelling will be on average 3m from the gas source. This value remains an average rather than a maximum or minimum.

CALCULATING A COST/BENEFIT RATIO

Determining a cost benefit ratio the scenario for post-earthquake fires and the applied remedial measures, must take into account 3 distinct scenarios, and then extrapolate information from the most beneficial scenario. Firstly the scenario which predicts a cost/ benefit for upgrading foundations against collapse; and by default reticulated gas rupture and the potential for post-earthquake fire. Secondly the gas fittings which will only mitigate against post-earthquake fire losses, namely with the fitting of Seismic Shutoff Valves and also Flexible couplings. The cost/benefit will also split fire prevention into sections, since SSV's are not commonly imported in New Zealand and will most probably skew the cost/benefit ratio beyond reasonable use. However, it is anticipated that the costs of imported goods would reduce significantly with demand. It is anticipated that the cost/benefit breakdown will allow the benefits to be directly separate and applicable on separate levels of NZFS engagement following an earthquake. Although both remedial scenarios will still require input from the fire service; the rescue of trapped occupants is anticipated to be lessened as well as the number of fires needing to be extinguished.

1.13 The Costs and Benefits of Upgrading Foundations only

The preliminary cost benefit ratio for different dwellings suggests that different fail rate factors based on historic precedents and foundation types will affect the cost-benefit ratio significantly. The foundation behaviour should remain predictable and failure mechanisms should be capable of dissipating energy through ductile yielding (SANZ1992). Using a predicted earthquake of Magnitude 7.2 at a depth of 7.5km, the Wellington earthquake is likely to result in the total collapse of over 1100 timber dwellings and cause serious damage to over 18,000. This is expected to result in the direct economic loss of $2.1B dollars in the timber residential sector claiming 930 lives and injuring 1290 people if it occurs during the night (Cousins 2005). Results in Table 8.1, suggest that the biggest cost saving will be in old dwellings with piled foundations, this is also the sample with the largest proportion of inadequate or unbraced foundations. These calculations are based on the assumption that dwellings previously assumed to collapse will only sustain light damage, however, some dwellings with serious configuration issues are still anticipated to collapse. Remedial measures are assumed to mitigate damage only in circumstances where a dwelling would have previously sustained extensive damage (e.g cracking and minor light damage may still occur).

Foundation type	TOTAL No. Dwellings affected BEFORE remedy	TOTAL Assets[4] at risk of damage and Collapse BEFORE Remedy ($M)	TOTAL No. Dwellings affected AFTER remedy	TOTAL Assets at risk of damage and Collapse AFTER Remedy ($M)	Total Cost of Remedial action ($M)	Total Saving from the application of Foundation Remedies ($M)
Internal Piled	4209	$226	3172	$80	$26.8	**$146**
Full Piled	16161	$892	13009	$368	$78.6	**$524**
Partial Wall	5285	$208	4266	$92	$26.5	**$116**
Full Wall	12149	$336	11079	$248	$105.1	**$88**
Full Wall/Intern.	5036	$140	4204	$86	$11.0	**$54**
SLAB	6944	$251	6494	$225	$0.0	**$26**
ENG	1894	$73	1698	$61	$0.0	**$12**
TOTALS	**51678**	**$2,125**	**43922**	**$1,159**	**$248**	**$966**

Table 0-1 Statistics Before and After Application of Remedial Measures to Foundations

Using the range of anticipated maximum and minimum repair costs, the cost / benefit ratios can be calculated. These values are only made for dwellings predicted to sustain moderate and extensive damage, as these areas are most likely to show the biggest savings [Table 8.2] and the collapse costs are always reflective of total dwelling replacement cost. Light damage totals are considered outside the benefits of foundation remedial measures and so are not included. The range of ratios is significant for moderate damage, and is still very beneficial for extensively damaged dwellings, considering that any cost / benefit less than 1 is still seen as a beneficial.

Foundation type	Light damage cost / benefit	Maximum Moderate damage cost / benefit	Maximum Extensive damage cost / benefit	Collapse cost / benefit	Overall Average cost/ benefit ratio
Internal Piled	-8.93	0.91	0.11	0.05	0.29
Full Piled	-7.84	1.44	0.19	0.04	0.44
Partial Wall	-7.99	0.80	0.10	0.04	0.26
Full Wall	-17.00	2.24	0.59	0.00	0.78
Full Wall/Intern.	-3.06	0.24	0.08	0.00	0.09
SLAB	0.00	0.00	0.00	0.00	0.00
ENG	0.00	0.00	0.00	0.00	0.00

Table 0-2 Maximum and Minimum Cost / Benefit Values for all Earthquake Damage to Foundations

[4] Assuming an average dwelling replacement cost of $316,004, based on valued 2006 pricing. This estimate is used for the repairing of damaged dwellings for earthquake and fire damage.

1.14 The Costs and Benefits of Gas Reticulation Upgrading only

The losses from earthquake activity and post-earthquake fires has been anticipated and calculated in many reports, documents and predictions. Institutions such as the Institute of Geological and Nuclear Sciences have produced *"Earthquake Loss Modellers*", which displays the number of casualties, total economic loss to residential dwellings and commercial properties for any given city (Cousins 2005). Reports on post-earthquake fires tend to be concerned with the number of ignitions requiring fire service attention, the source of the ignitions and the combustibility of the surrounding built environment (Cousins et al. 2002). The efficiency of each remedial gas solution suggests that for a SSV type valve, all of the gas will be shutoff to areas that have received higher shaking, however if only a flexible coupling is attached, a gas rupture may still occur from broken appliances inside the dwelling. This reinforces the importance of using both gas remedial solutions in a unified remedial system, see Table 8.3.

Remedy type	Gas rupture location	Possibility of Gas rupture at given location	Remedy efficiency at limiting Gas leaking	Overall Efficiency at stopping Gas leaking
SSV	In Dwelling	100%[5]	90%	90%
Flexi coupling	Connection to Dwelling	50%	70%	35%

Table 0-3 Efficiency of Remedial Measures

Data from overseas events, where post-earthquake fire has caused greater destruction, show a strong correlation between shaking intensity and average number of earthquake initiated ignitions. Estimates generally suggest that for each Million m² of floor area, ignitions will be 0 for MM6, 1 for MM7, up to 4 for MM10 shaking intensity (Cousins, Dowrick, and Sritharan 1990). Information extracted from estimations made in the same report, suggest that an earthquake on the Wellington fault line measuring Richter 7.5 will cause 23 ignitions and spread to 90 dwellings within the Wellington City limits[6] as described in Wellington City Council District plan maps. More recent reports (Lloyd 2001) show correlation between the number of anticipated ignitions, which are all based on collated data from past earthquakes and post-earthquake fire research (Scawthorn 1987), (Table 8.4).

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[5] Rupture may still occur on the interior of dwelling if flexible connections are attached.

[6] For the purposes of this report Wellington City limits do not include any suburbs north of Tawa or East of Horokiwi. None of the Wairarapa, Hutt Valley or any of the wider New Zealand population.

Remedy type	No. Ignitions (differing research sources)	Total number of dwellings destroyed by fire spread caused by gas leak[7]	No. dwellings requiring remedial measure	Total remedial Costs projected to Wellington dwellings requiring remedy ($M)	Total cost of destruction[8] including fire spread ($M)	Average efficiency of remedial measure	No dwellings destroyed by gas ignition following specific remedial measures
SSV	9 - 23	35-89	34,000	$14.4	$11-$28	90%	1-2
Flexi coupling	9 - 23	35-89	8,300	$2.5	$11-$28	35%	6-15

Table 0-4 Total costs for Upgrading Gas Connections

The number of ignitions in post-earthquake fires always has an effect on the spread of fire following earthquake. However, the spread is also related to contextual issues such as the density of surrounding buildings, vegetation and most importantly the wind speed at the time of ignition. Although this study does not attempt to correlate the effects of the building fabric on fire spread, it must pre-empt the likelihood of fire spread in Wellington at a given wind speed. It is also assumed that for older dwellings in older suburbs, which are usually piled and likely to collapse more readily, fire spread will be more common given the density of combustible materials. Although the location and rate of fire spread varies with the number of factors and variables, computer simulations in past research show that with no wind, each ignition consumed 8 buildings. However, when the wind was increased from 20km/h up to 50km/h the rate increased exponentially (Lloyd 2001). Wellington's average wind speed is 22km/h, so given this average there is a high chance that fires spread totals will be at least 20km/h. Although fire losses following an earthquake are anticipated to be less than losses due to shaking damage; if wind speeds are near gale, losses are anticipated to be even more severe (Cousins et al. 2002).

Estimating the number of fires in the residential sector following an earthquake is somewhat problematic as it is dependant on the reliability of the flexible coupling and SSV in a given shake intensity. It also depends on the number of dwellings that uptake the required remedial measure. As it stands no information is available which readily describes the efficiency of such remedial measures in the most recent earthquakes. Also, the cost/benefit is completely reliant on a total saving from which to project the total benefit for undertaking such remedial action. For the purposes of estimating, we will assume that all dwellings that require remedial measures have had them undertaken. The efficiency of SSV's will be around 90% and flexible couplings, due to the variability of installation and difficulties onsite, will assume an efficiency of only 35% at stopping gas reticulation ruptures.

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[7] Assuming a Fire Spread per Ignition of 9.7 with a mean Wellington windspeed of 20km/h - From Lloyd, 2001. Also assumed is that ignitions caused by gas leaks equate to an ignition rate of 40%.

[8] Fire damage assumes that the dwelling is completely burned out and completely consumed by fire, which requires complete replacement

Report	No. dwellings affected By ignited gas rupture before remedy	Cost of gas ignition destruction BEFORE Gas remedial measures ($M)	No. dwellings affected after remedy	Cost of Destruction AFTER Gas remedial measures ($M)	Overall Average Saving from applying remedial measures ($M)	Overall Max. and Min. cost/ benefit ratio
SSV	35-89	$11-$28	1-2	$0.3-$0.7	$10-$27	0.53 - 1.4
Flexi coupling	35-89	$11-$28	6-15	$1.8-$4.7	$9-$23	0.11 – 0.27

Table 0-5 Maximum and Minimum Cost / Benefit Values for all Earthquake Damage to Foundations

From table 8.5 above, it is apparent that the cost/benefit for the flexible coupling is very good reasonable ranging from around 10-30% cost/benefit. The benefit of installing SSV's is less apparent, mostly probably due to the higher importing costs and US based installation costs (mandatory installation of SSV's may drive the cost of installation up). It is assumed that given the high number of installations required with the efficiency of the SSV system for stopping leaks, the cost/benefit would be well below 1.

1.15 Do we need to Upgrade?

The results above suggest that dwellings require, on average, reasonable expenditure to achieve the current standards requirements for both foundation and gas reticulation. The very low cost / benefit ratio suggests that it is economically justifiable to remedy foundation defects in dwellings and also to a certain degree upgrade our gas systems. Even if more conservative assumptions concerning the sustained damage had been made, the cost/benefit would still be less than 1. Upgrading gas connections to current gas standards shows favourable benefits, especially for the fitting of flexible connections, however overall there is very little difference between upgrading foundations only or any combination of the gas remedial measures, (Table 8.6).

Foundation type	Overall Average cost/ benefit Ratio for Foundation remedies only	Overall Average cost/ benefit ratio with SSV only and Found. remedies	Overall Average cost/ benefit ratio with Flexi Coupling only and Found. remedies	Overall Average cost/ benefit ratio with All. remedies
Internal Piled	0.29	0.26	0.19	0.27
Full Piled	0.44	0.17	0.15	0.18
Partial Wall	0.26	0.32	0.23	0.32

Table 0-6 Cost/Benefit Ratio for all Scenarios of Foundation Remedy and Gas Remedies

The overall results suggest that when all remedial measures are combined, very low cost/benefit totals result. This low cost/benefit is due to the large sample and cost of foundation remedial measures, when calculated along side the relatively small cost of installing gas remedial measures. As it stands, including the remedial measures for gas connections does not significantly alter the overall cost/benefit ratio for foundation remedies. The overall decrease in workload for the Fire Service will mean a more efficient service following an earthquake and less overall damage costs to society, the homeowner and the EQC. With foundation remedies only, the Fire Service can be expected to undertake less residential rescues, which will be a primary priority above fire suppression. This will leave more time to focus on mitigating the danger of fire spread, especially in suburbs with high conflagration potential. Furthermore, if gas remedial measures are adopted, the number of ignitions due to gas leakage decreases by about 2/3, which in turn mitigates the number of possible ignitions from a residential reticulated gas source. This workload will depend on the magnitude of the earthquake, which often determines the number of rescues. Generally, a moderate earthquake will require fewer rescues than a larger earthquake.

CONCLUSIONS

The main lesson from the 1987 Edgecumbe earthquake was that successful implementation and moderately good compliance with current construction standards has contributed overall to the mitigation of collapse and serious damage to timber framed dwellings in New Zealand. This trend was also seen in the study, which found that 39% of dwellings built prior to the introduction of NZS3604:1978 have weak and inadequate sub-floor bracing, including a majority of piled dwellings. Connections were found to be reasonably adequate however, if the predicted earthquake scenario had a proportion of vertical acceleration, only around 25% of fixings would be adequate to resist induced loading, due to a loss in frictional resistance. The Gas connections entering and supplying dwellings in past earthquakes were often the source of gas leakage, due to brittle pipe work and without Seismic Shut-off Valves connected to reticulated services. Observations showed that flexibility in reticulated gas services were often varied and usually differed due to the age of installation and also the age of the dwelling. In contrast, it was also found that almost half of the sample did not have reticulated gas connected to the dwelling; predominately in the post 1940 to pre 1980's age bracket. Of the dwellings that were assumed to collapse due to weak foundations, piled dwellings made up almost 80% of that total. Also, of these piled dwellings, almost one quarter were found to have rigid gas connections somewhere within the gas supply system, likely to cause a significant rupture.

Therefore, foundation remedial bracing measures are assumed to be necessary in almost 40% of all dwellings, and remedial fixing measures in over 75% of dwellings. The total costs for these remedial measures differed for varying foundation types and cost between $19 and $72 per square metre of dwelling. The cost/benefit of remedying foundation ranged from 26% to 44%, not including gas remedial measures. Gas Seismic Shut-off Valves, for the remedy of reticulated gas systems were calculated to cost between $300 and $433 including all installation costs. However, these costs may be conservative, considering that Seismic Shutoff Valves are not currently available for purchase in New Zealand. Installing flexible couplings to rigid reticulated gas lines cost around $100 per metre. Overall the cost/benefit for foundation remedies including gas remedies, ranged from 17% to 32% for SSV and 15% to 23% for flexible couplings. Cost/benefits for all foundation and gas remedies ranged between 18% and 32%, with Full Piled Foundations achieving the most savings and highest benefits from all foundation and gas remedial measures.

Without these remedial measures, piled dwellings built prior to 1940 are at a higher risk from post-earthquake fire due to the movement of foundations and subsequent rupture of rigid gas connections. Overall, the application of all remedial measures (foundation and gas) is anticipated to cost less than 20% of the average dwelling reconstruction bill, not including post-earthquake inflated labour and material costs. This total alone could potentially save almost $1B in post earthquake repairs and mitigate the unknown costs of fire damage, temporary shelter and evacuations for the homeowners and communities. The Fire Service will benefit mostly by being required to undertake less residential rescues from collapsed dwellings and therefore gaining more time to mitigate the danger of fire spread. Unfortunately, it is evident that the value of upgrading may not be seen as cost-effective, or necessary by the homeowner, as the EQC and personal insurance generally cover dwelling reinstatement following disaster. As it stands, no direct economic incentive currently exists for the homeowner to seismically upgrade residential foundations or reticulated gas connections.

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REFERENCES

Adams, R. D., G. J. Lensen, C. M. Strachan, and H. R. Laws. 1970. Seddon Earthquake, New Zealand, April 1966. *DSIR, Wellington* Bulletin 199.

BRANZ. 2000. Timber Pile foundations. *BRANZ Bulletin 399*.

———. 2003. Lessons from the 1987 Edgecombe Earthquake. *BRANZ Bulletin 444*.

CarterHoltHarvey. 2005. *Ecoply Bracing Manual*: CHH WoodProducts. (March 2005).

Chung, R. M., N. H. Jason, B. Mohraz, F. W. Mowrer, and W. D. Walton. 1995. Post-earthquake Fire and Lifelines Workshop. *National Institute of Standards and Technology* NIST Special Publication 889.

Clark, S., M. Jones, and I. C. Page. 2005. BRANZ Study Report 2005 House Condition Survey. In *BRANZ Study Report 142*. Wellington: BRANZ.

———. 2005. New Zealand House Condition Survey 2005. *BRANZ Study Report 142*.

Cooney, R. C. 1979. The Structural Performance of Houses in Earthquakes. *Bulletin of the National Society for Earthquake Engineering* 12(3): (12(3)):223-237.

———. 1982. Strengthening Houses against Earthquake: A Handbook of Remedial Measures. *BRANZ Technical Paper 37*.

Cooney, R. C., and A. H. R. Fowkes. 1981. New Zealand Houses in Earthquakes: What Will Happen? *BRANZ Reprint Series* (No. 21).

Cousins, J. (2005) Earthquake Loss Modeller. 14 Sep 2005 ed. Wellington, Institute of Geological and Nuclear Sciences Limited.

Cousins, W. J., D. J. Dowrick, and S. Sritharan. 1990. Fire Following Earthquake. *DSIR Physical Sciences*.

Cousins, W. J., G. Thomas, D. Heron, S. Mazzoni, and D. Lloyd. 2002. Estimating Risks from Fire Following Earthquake: Institute of Geological and Nuclear Sciences.

Davey, R. A., and R. B. Shephard. 1995. *Earthquake Risk Assessment study : Study area 1, Wellington City*. Wellington: Works Consultancy Services.

Dixon, C. E. 1931. Earthquake proves superiority of wooden buildings. *New Zealand National Review* (March 15):45-48.

Earthquake Commission, (EQC). 2000. Inspecting Earthquake Damage to New Zealand Houses: an overview for EQC inspectors. Interview by. Wellington: EQC.

———. 2003. *Earthquake Damage Assessment Catalogue*. Wellington.

———. 2006a. "What we do". *Earthquake Commission Website*, 15 May. <http://www.eqc.govt.nz/abouteqc.aspx> (12 July 2006).

———. 2006b. "Earthquake Commission Insurance Policy". *EQC Website*, 15 August. <http://www.eqc.govt.nz/insurance.aspx> (14 September 2006).

———. 2006c. *EQ-IQ*, 15 December 2006. <http://www.eq-iq.co.nz/iqhome.aspx> (18 January 2007).

———. 2007. "EQC Repair Database Composite Rates". *Earthquake Commission Building Cost Database*, 1 February. <http://www.eqc.govt.nz/claims_status/building-cost/wellington.htm> (6 February 2006).

Earthquake Loss Modeller 14 Sep 2005. Institute of Geological and Nuclear Sciences Limited, Wellington.

Earthquake Store.com. 2007. Valve Regulations. *http://www.earthquakestore.com/valve-regulations.html*.

Eiby, G. A. 1980. *Earthquakes*. Auckland: Heinemann Educational Books.

Finnis, K. 2004. *Creating a Resilient New Zealand*. Wellington: Ministry of Civil Defence and Emergency Management.

Gorst, N. J. S., and S. J. Williamson. 2003. *Friction in Temporary Works*. Birmingham: The University of Birmingham.

Hamilton, R. M., G. J. Lensen, R. I. Skinner, O. J. Hall, A. L. Andrews, C. M. Strachan, and O. A. Glogau. 1969. Gisbourne Earthquake, New Zealand. March 1966. *Department of Scientific and Industrial Research* Bulletin 194.

Harrap, N. 1980. *Buying and Restoring a House*. Wellington, New Zealand: N. Harrap.

Henderson, J. 1937. The West Nelson Earthquakes of 1929 : with notes on the Geological Structure of West Nelson. *Department of Scientific and Industrial Research* (Bulletin 55).

Inoue, K. 1925. The Imperial Capital Great Fire. *Report of the Board of Inquiry for Earthquake Disaster Prevention*.

James-Hardie. 1994. Technical Information. Review of Reviewed Item. *Subfloor Bracing Systems* (June 1994).

James-Hardie Building Products. 1994. *Technical Information: Sub-floor Bracing Systems*: James Hardie Building Products.

Jennings, P. C., and G. W. Housner. 1971. Engineering features of the San Fernando Earthquake, February 9, 1971. Pasadena, California. *California Institute of Technology, Earthquake Engineering Research* Laboratory Report 71-02.

Kobayashi, M. 1984. Urban Post-earthquake Fires in Japan. Paper read at 8th World Conference on Earthquake Engineering, at San Francisco.

Lloyd, D. 2001. The Risk of Post-Earthquake Fire in Wellington, Architecture, Victoria University of Wellington, Wellington.

Megget, L. M. 1984. Pole houses in the Wellington District - Lessons Learnt in Design and Construction. Paper read at The Pacific Timber Engineering Conference, at Auckland, New Zealand.

MiTek New Zealand Limited. 2000. *LumberLok Catalogue: Subfloor Components*: MiTek New Zealand Ltd.

New Zealand State Forest Service, (NZSFS). 1924. **Circular 14**: Section II, Recommended Minimum Requirements for Safe and Economical Construction of Small Wooden-Framed Buildings. In *Building Conference relating to the Use of Timber in Building Construction*. Wellington: Government Printer.

Norton, J. A., B. A. King, D. K. Bull, H. E. Chapman, G. H. McVernon, T. J. Larkin, and K. C. Spring. 1994. Northridge Reconnaissance report. *Bulletin of the National Society for Earthquake Engineering* (27(4)):235-345.

Park, R. 1995b. The Great Hanshin earthquake. In *Wellington after the 'Quake : The Challenge of Rebuilding Cities*. Wellington, New Zealand: Earthquake Commission and Centre for Advanced Engineering.

Pender, M. J, and T. W. Robertson. 1987. Edgecombe Earthquake: Reconnaissance Report. *Bulletin of the National Society for Earthquake Engineering* (20(3)):201-248.

PRC Mechanical. 2007. Seismic Shutoff Valve Installation. Review of Reviewed Item. http://www.earthquakestore.com/gas_shut_off_valve_installation.html.

Pryda New Zealand. 2005. *Pryda Timber Connectors, Pryda Product Catalogue 07/2005*.

Raworth, B. 1991. *Our Interwar Houses: How to recognise, restore and extend Houses of the 1920's and 1930's*. Melbourne, Australia: National Trust of Australia (Victoria).

Salmond, J. 1986. *Old New Zealand Houses*. Auckland: Reed Methuen Publishers Ltd.

Saylor, H. H. 1911. *Bungalows*. Philadelphia: The John C. Winston Company.

Scawthorn, C. Dr. 1985. Fire Following Earthquake. *Fire Engineering* v. 138 (April 1985).

———. 1987. *Fire Following Earthquake: Estimates of Conflgration Risk to insured Property in Greater Los Angeles and San Francisco, All-Industry Research Advisory Council (AIRAC)*. San Francisco, California: Dames & Moore.

Schrader, Ben. 2005. *We call it home : A History of State Housing in New Zealand* Auckland, New Zealand: Reed.

Seismic Safety Commission, (SSC). 1992. *The Homeowner's Guide to Earthquake Safety*. Sacramento, California: Seismic Safety Commission.

Shepherd, R., A. H. Bryant, and A. J. Carr. 1970. The 1968 Inangahua earthquake. *Canterbury Engineering Journal* **no.1** (1):2-86.

Slade, G. P. 1979. Domestic Detailing for earthquakes - Past and Present practice, School of Architecture, Victoria University of Wellington, Wellington.

Standards Association of New Zealand, SANZ. 1999. Code of Practice for light timber frame buildings not requiring specific design **NZS 3604:1999**.

Standards Association of New Zealand, (SANZ). 1944. New Zealand Standard Code of Building Bylaws **N.Z.S.S.95** (Part IX, Light Timber Construction).

———. 1964. New Zealand Standard Model Building Bylaw **NZS 1900:**. *Chapter 6.1, Residential buildings*.

———. 1978. Code of Practice for light timber frame buildings not requiring specific design. **NZS 3604:1978**.

———. 1984. Code of Practice for light timber frame buildings not requiring specific design. **NZS 3604:1984**.

———. 1992. Code of Practice for general structural design and design loadings for buildings. **NZS 4203:1992**.

Standards New Zealand, (SNZ). 1999. Code of Practice for light timber frame buildings not requiring specific design. **NZS 3604:1999**.

Stewart, D. 1992. *The New Zealand Villa: Past and Present*. Auckland, New Zealand: Penguin Books (NZ) Ltd.

ten Broeke, J. M. 1979. Diploma in building, Case study, School of Architecture, Victoria University of Wellington, Wellington.

Todd, D., N. Carino, R. M. Chung, H. S. Lew, A. W. Taylor, W. D. Walton, J. D. Cooper, and R. Nimis. 1994. 1994 Northridge Earthquake. *National Institute of Standards and Technology* NIST Special Publication 862.

Trifunac, M. D., and M. I. Todorovska. 1997. The Northridge, California, earthquake of 1994 fire ignition by strong shaking. *Soil Dynamics and Earthquake Engineering* Vol 17:pp. 165-175.

Williamson, R. B., and N. Groner. 2000. Ignition of Fires Following Earthquakes Associated with Natural Gas and Electric Distribution systems. Berkely, California: University of California, Department of Civil and Environmental Engineering.

Winstones Wallboards Limited. 1999. *Gib Bracing Systems*. Penrose, Auckland.

———. 2006. *Gib Bracing Systems*. Penrose, Auckland.

APPENDICES

1.16 Appendix A Domestic Architectural History

The architecture of domestic dwellings is not easily defined, nor does one foundation type represent the age of one particular dwelling. However, certain trends exist which dictate the period in which each foundation type was built. Figure A1 shows the relationship between domestic dwelling fashions relative to the age of foundation type.

Older dwellings, around 1900 tended to be ornamental and built with many different native timbers, depending on the requirement and characteristics of the timber. Ornamentation usually depended on the craftsman and popular style of the time [Fig A1 A]. Transitional styles ranging from the Bay villa to the Bungalow, in the 1920's [Fig A1 B] resulted in a mix of residential architectural fashions (Stewart 1992).

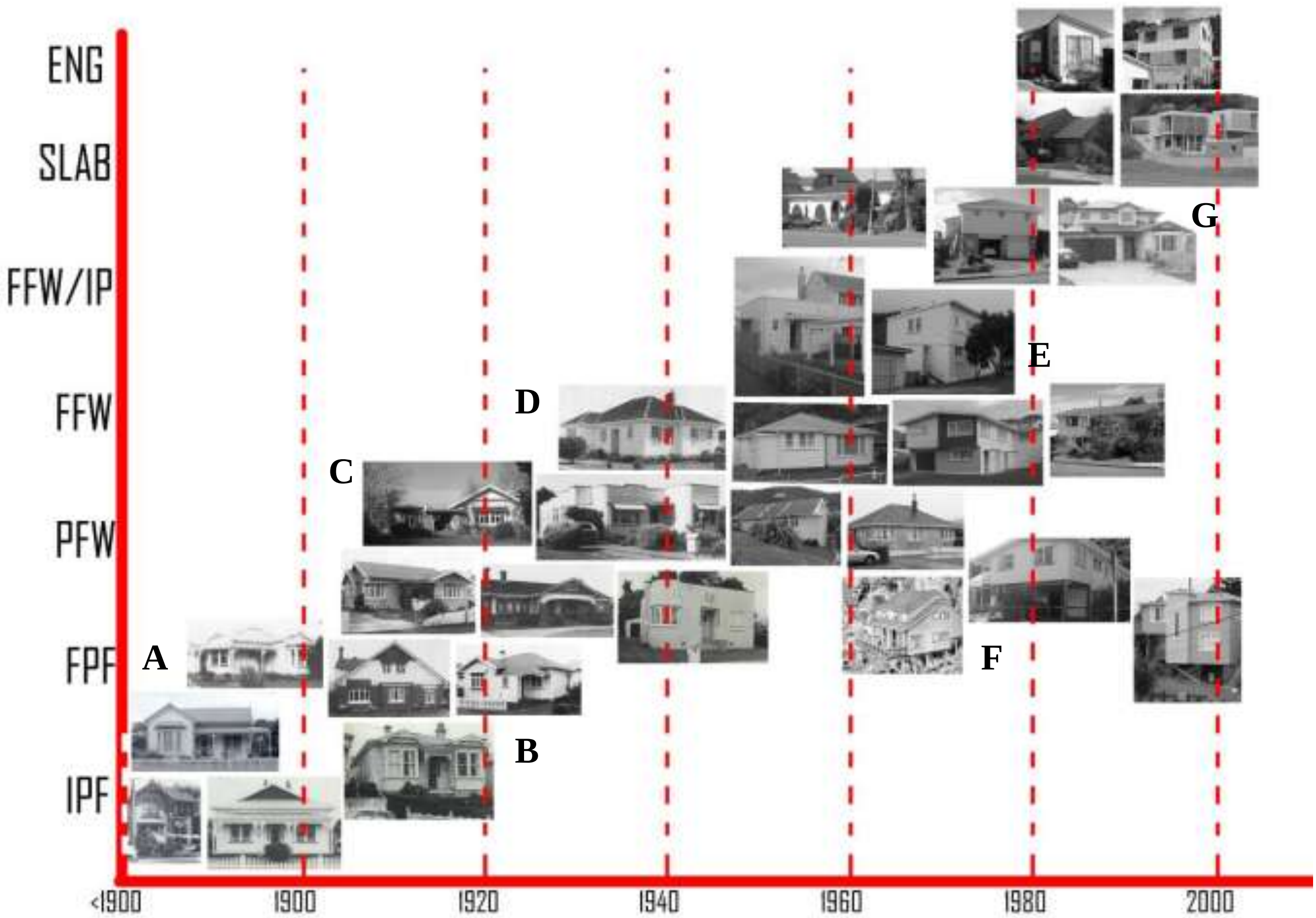


Figure A-1 Domestic Architecture relating to Foundation type and age of the Style[9].

Pre 1940's dwellings were regular in plan and sufficient to resist earthquakes, however the piles often sank over time and the sub-floor was often not braced or well ventilated.

[9] Use the Pull-Out Reference Guide at the end of this document for reference to Foundation types

Bungalow style influenced by Californian trends [Fig A1 C], often used brick in the design, either fully or partially (Saylor 1911). The Tudor and Georgian styles also used brick with reinforced concrete foundation walls to support the extra weight of the cladding (Raworth 1991). Dwellings built after the 1940's and 1950's, tended to utilise different non-traditional materials due to rations for the Second World War efforts. These were usually of a heavier nature and so dwellings required stronger foundations. This era was epitomised by the State House dwelling [Fig A1 D] and many non-state designed dwellings followed the same architectural fashion. Newer styles in the 1970's lead to integration of garages [Fig A1 E] into the dwelling envelope. Commonly adopted aesthetics of previous decades were abolished, favouring lifestyle combinations that have the potential to react poorly in earthquakes. The most critical combination is found to be rectangular split level ground floor dwelling with garage at one end and excessive roof mass (Cooney and Fowkes 1981). Pole houses [Fig A1 F] popular in the 1970's allowed previously unbuildable gradients to be infilled with dwellings, pushing foundations into an engineering realm (Megget 1984). Minimal maintenance and low cost have contributed to the style of dwellings into the modern decades after 1990, with many dwellings aiming for visual durability utilising a myriad of new materials available today. These dwellings more commonly use slab and engineered foundations for strong, simple and quick solutions to the domestic construction boom [Fig A1 G].

1.17 Appendix B The Remedial Bracing Costs

1.17.1 B1.1_________________________Braced Pile Solution

The Braced pile solution is a system of where a timber brace spans between the pile bottom and joists or Bearers at the top.

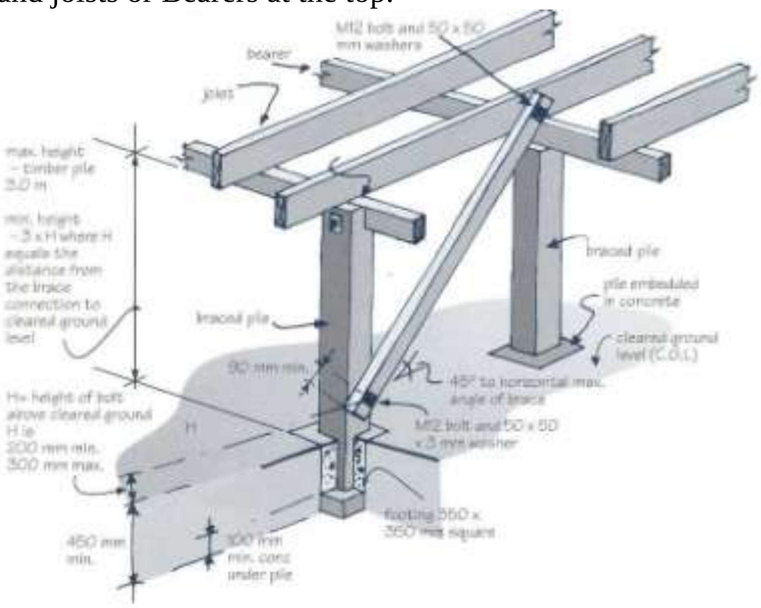


Figure B1 Braced Pile Solution, Braced from Pile to Joist ***(Source: BRANZ 2000)***

B1.1.1 Labour $175.50 per pile system

- Excavate soil around two piles
- Remove existing concrete piles and discard
- Extend existing hole to a minimum 450mm below ground
- Install two 125x125mm H5 timber piles **[cut to size]**
- Pour concrete footing
- Apply 12kN fixing from pile top to Bearer [see image below]
- Apply M12 bolt [12kN fixing] to both ends of 100x100mm H1.2 timber brace **[cut to size]**. [incl. 50x50x3mm washer one side]
- Apply 6kN fixings to 2 joists near brace ends.
- *Repeat as necessary in foundation*
- Clean up

B1.1.2 Material costs $455.00

- 2 / 125x125mm H5 timber pile **[minimum overall height 900mm and maximum height 1600mm]**
- 100x100mm H3 timber brace [maximum length 3m]
- 2 / M12 bolts galvanised including 50x50x3mm square washer
- 2 / 12kN fixings from pile top to Bearer **[refer 12kN fixing in connections section]**
- 0.050m3 concrete per pile [assume two piles]
- 2 / 6kN fixings between joist and Bearer **[refer 6kN fixing in connections section]**

B1.1.3 Total costs $612.50 per pile system

1.17.2 B1.2_________________________Sheet Bracing Solution

The sheet bracing is 7mm treated DD plywood applied to the exterior of piles with ventilation grills applied at appropriate centres. The piles if not timber [which is almost always the case] require timber framing to infill around the piles before any sheet bracing is applied. For the purposes of clarity, always assume an average case for foundation heights of 600mm [up to top side of joists]. Pile spacings will have two cases of 1.3m and 2m

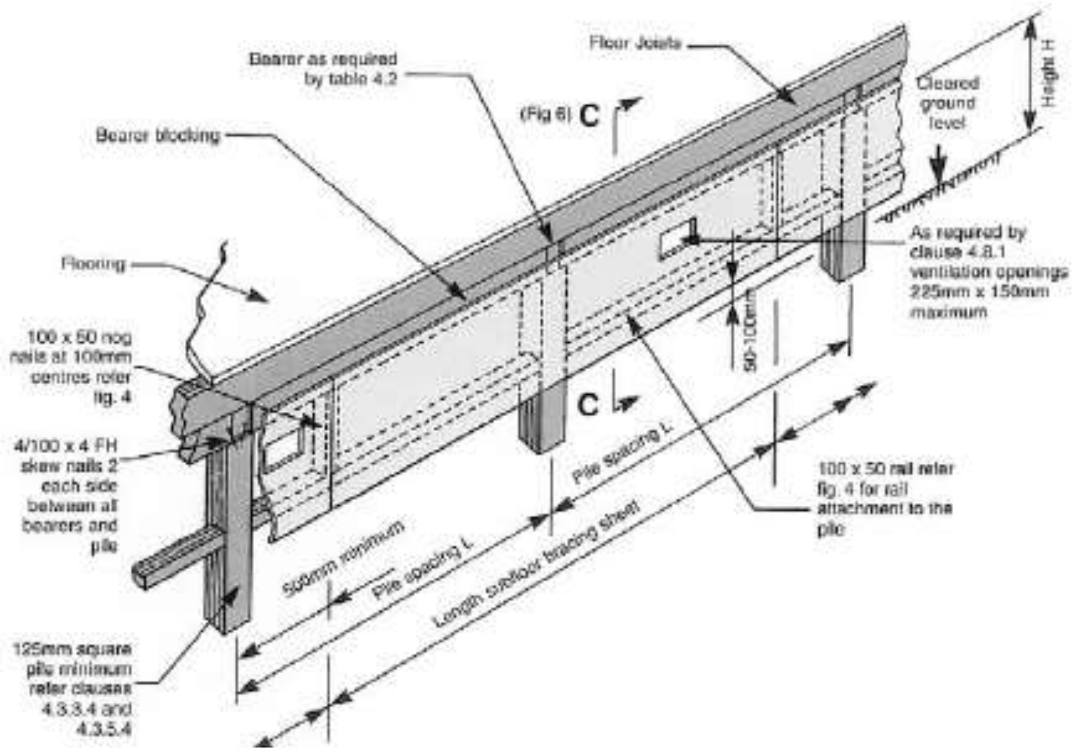


Figure B2 Sheet Bracing Remedial Solution ***(Source: James-Hardie 1994)***

B1.2.1 Labour $80.00 per linear metre

- Fill lower chord and sides between concrete piles with 100x50mm H3 timber framing **[assuming a 1.3 to 2m pile spacing]**
- Fix framing members to piles with ramset or similar power driven fixtures at 300mm centres **[assume 3 such connections per pile side]**
- Allow additional framing where sheet ends meet **[see image below]**
- *Remove lowest 2 weather boards to reveal joist or wall plate ends*
- Cut sheet width to appropriate height **[assuming average sheet of 600mm]**
- Fix sheet bracing with 30x2.5mm galvanised clouts at 150mm centres around the sheet edge **[assume 30 nails for 1.3m pile spacings and 40 nails for 2m spacings]**
- Fix ventilation grills [see ventilation in *General Condition* above]
- *Repeat as necessary around perimeter*
- Clean up

B1.2.2 Material costs $86.35 per linear metre

- H3 100x50 timber framing **[assume 3m for 1.3m pile spacings and 3.5m for 2m pile spacings]**

- 7mm exterior grade DD H3 treated plywood [maximum length 2.0 m]
- Ramset or similar power driven nail **[6 per pile bay]**
- 10 / 100x3.75mm nails for other framing applications
- 30 / 30x2.5mm galvanised nails for 1.3m pile spacings and 40 / 30x2.5mm galvanised nails for 2m spacings
- *Ventilation materials*

B1.2.3 Total costs $166.35 per linear metre

1.17.3 B1.3____________________Infill Concrete Wall Solution

The infill concrete wall is essentially a fabricated concrete wall spanning between two concrete piles and fixed to the timber framing members through fixings set in the concrete. Wall height will always be assumed an average of 900mm with pile spacings will be assumes as before, 1.3m and 2m spacings. The concrete infill wall will assume a maximum of 200mm width.

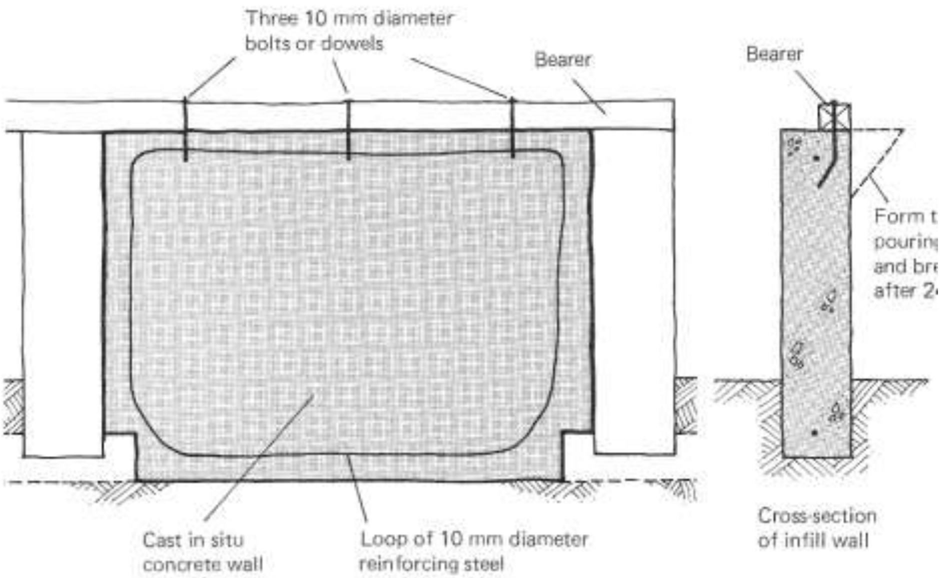


Figure B3 Concrete Infill Wall Remedial Solution *(Source: Cooney 1982)*

B1.3.1 Labour $501.25 per linear metre

- Dig out wall footing at least to the bottom of surrounding piles [always assume a 300mm depth]
- Drill and insert 3 / M10 bolts through Bearer bottom [see image below]
- Bend R10 reinforcing bar to make a loop inside the concrete **[approx. 4m length for 1.3m spacing and 5.5m for 2m spacing]**
- Box up around piles with 12mm DD grade boxing plywood, as framing as necessary for bracing while concrete sets.
- Mix concrete to appropriate 17.5MPa standard.
- Form small spout to pour concrete into boxing.
- Allow to cure for 10 days.
- Remove boxing and chip of concrete spout.
- Infill around footing with soil
- Clean up

B1.3.2 Material costs $728.75 per linear metre

- 100x50 timber framing **[assume 5 lm per boxing]**
- 3 / M10 bolts
- R10 bar **[4m for 1.3m spacing and 5.5m for 2m pile bay spacing]**
- 2 / 1000x2000 **[max]** 12mm DD grade boxing plywood
- 0.25m3 concrete for 1.3m spacings and 0.36m3 concrete for 2m spacings.
- 50 / 100x3.75mm nails for general construction and other purposes

B1.3.3 Total costs $1230.00 per linear metre

1.17.4 B1.4__________________________Anchor Pile Solution

The anchor pile is bracing measure covered in NZS3604 and is essentially a pile with a deep large footing, utilising the soil shear strength to dampen earthquake loads. It is best used in a reasonably open situation as the footing depth is 900mm.

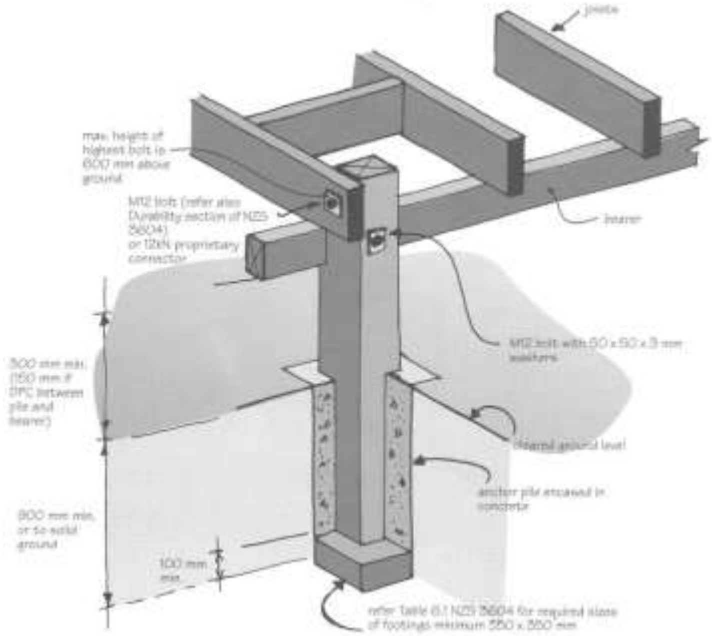


Figure B4 Anchor Pile Solution ***(Source: BRANZ 2000)***

B1.4.1 Labour $175.00 per pile system

- Excavate soil around one pile
- Remove existing concrete pile and discard
- Extend existing hole to a minimum 900mm below ground
- Notch pile side where Bearer will sit.
- Install one 125x125mm H5 timber piles **[cut to size but maximum of 1.5m overall]**
- Pour concrete footing
- Apply M12bolt fixing from pile side to Bearer side [see image below]
- Apply 6kN fixings to 2 joists near brace ends.
- *Repeat as necessary in foundation*
- Clean up

B1.4.2 Material costs $102.50 per pile system

- 1 / 125x125mm H5 timber pile **[maximum overall height 1500mm]**
- 1 / M12 bolts galvanised including 50x50x3mm square washer from pile side to Bearer side
- 0.080m3 concrete per pile
- 2 / 6kN fixings between joist and Bearer **[refer 6kN fixing in connections section]**

B1.4.3 Total costs $277.50 per pile system

1.18 Appendix C Remedial Gas Solutions

1.18.1 C1.1____________________Seismic Shutoff Valve [SSV]

The Seismic Shutoff Valve is currently supplied only in the US and by two major competitors, Koso and Little Fire Fighters, however both perform the same task of restricting gas flow in a seismic event. Note that for these items to be installed, they would need to be imported first, thus increasing the overall cost of each system.

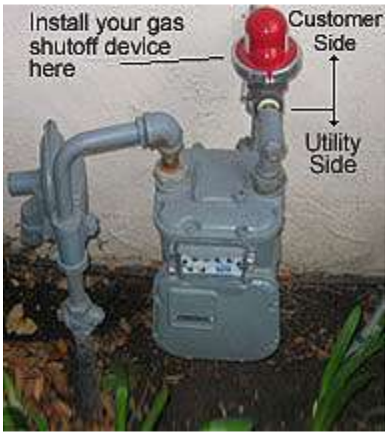


Figure C1 Koso brand Seismic Shutoff Valve ***(Source: BRANZ 2000; Earthquake Store.com 2007)***

C1.1.1 Labour $146.00 - $205.00 per SSV installed

- *Labour costs are based on current [2007] United States installation costs and for a 1 ¼ inch [40mm] diameter pipe attached to the house. Additional costs exist for any deviations of installation that do not fit inside the specific description and location of the meter (PRC Mechanical 2007). All costs are in NZD as at 12 July 2007. The following instructions from (www.LittleFireFighter.com 2007)*
- Turn off gas at mains, verify that gas is off to all appliances in the dwelling.
- Remove the pipe on the occupants side connected into the dwelling with a spanner and detach the tee from the pipe nipple.
- Measure the length of pipe nipple.
- Verify that the length of pipe removed matches the pipe length to the SSV to be installed.
- Apply pipe joint compound to the new pipe ends and screw into SSV ensuring no compound leaks into the SSV.
- Install the SSV ensuring the correct direction for operation, reconnect unit into pipe system.
- Test seals around each of the openings for any intermediate leaks.
- Attach stabiliser for the SSV to ensure no nuisance tripping of meter.
- Clean up

C1.1.2 Material costs $114.00 – $173.00

- *Either one of the following, all valves function the same, but are different in their specific method of shutoff. All are for the standard install of one Seismic Shutoff Valve with 1 ¼ inch [40mm] pipe of* *any material. Also these dollar values do not include any importing costs that may be incurred on the product, as these products are not readily available in New Zealand currently.*

- Koso – 302 [$173.00]
- Koso – VB – 302 [$173.00]
- Koso – VT – 302 [$173.00]
- Little Fire Fighter VAGV125 [$114.00]
- Little Fire Fighter AGV125 [$147.00]

C1.1.3 Total costs $320.00 - $510.00 per SSV installed

1.18.2 C1.2 Flexible Couplings

The Flexible coupling in New Zealand use Pexal tubing, however other alternatives do exist. Similar costs exist for new or existing dwelling, however the quote does not include any digging that may be involved with the installation of the tubing.

Figure C2 Flexible tubing similar to Pexal and other Corrugated Stainless Steel Tubing below

C1.1.1 Labour $84.00 per metre - $98.00 p/m

- *Labour costs are based on current [2007] United States installation costs and for a 1 ¼ inch [40mm] diameter pipe attached to the house. Additional costs exist for any deviations of installation that do not fit inside this description (PRC Mechanical 2007). All costs are in NZD as at 12 July 2007.*
- Turn off gas at mains, verify that gas is off to all appliances in the dwelling.
- Remove the pipe on the occupants side connected into the dwelling with a spanner and detach the tee from the pipe nipple.
- Measure the length of pipe required and source the appropriate length pipe to ensure no unnecessary connections. Pipe must also have enough give to ensure that during an earthquake no movement will wrench the pipe fixings apart.

- Apply brass connectors to the meter end and also to the location where the flexible pipe is to be connected.
- Attach flexible pipe to the brass connectors with a spanner and ensure no leaks by applying jointing compound around threaded areas.
- Test seals around each of the openings for any intermediate leaks.
- Clean up

C1.1.2 Material costs $1.79 per metre – $16.00 p/m

- *Either one of the following, all valves function the same, but are different in their specific method of shutoff. All are for the standard install of one Seismic Shutoff Valve with 1 ¼ inch [40mm] pipe of any material. Also these dollar values do not include any importing costs that may be incurred on the product, as these products are not readily available in New Zealand currently.*
- PEX-AL-PEX ½" Tubing (SAFE-1/2X1000)-1000ft (305m) [$547.00] $1.79 per metre of tubing.
- Corrugated Stainless Steel Tubing ½" Tubing (Gastite S93-8A4-1000) – 1000ft (305m) [$4,922.00] $16.00 per metre of tubing
- Corrugated Stainless Steel Tubing ½" Tubing (10A WARDFLEX 1000) – 1000ft (305m) [$4,320.00] $14.15 per metre of tubing

C1.1.3 Total costs $100.00 per metre

Appendix

D___________________________________Terminology

Anchors______________ Large objects such as concrete chimney bases or steps that are likely to provide lateral strength to a sub-floor in an earthquake.

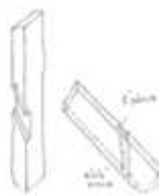
Anchor piles__________________ Piles which rely upon the soil bearing pressure and depth of footing to provide lateral resistance prescribed as 120BU. The depth and width of footing is greater than a cantilever pile.

Braced Pile_____________ Two piles with a diagonal brace spanning from the lower part of one pile to the higher of the other. The braced pile system relies primarily on the strength of the brace in compression and the ductility of the fixings for lateral bracing, with prescribed resistance of 120BU.

Bracing Line_____________ A line along or across a building, usually the bearer of joist directions, for controlling the distribution of bracing elements.

Bracing Unit ["BU"]__________________ A unit measure used for the purposes of describing bracing capacity, where 20BU equals approximately 1kN.

Cantilever piles________________ Piles which rely on soil bearing pressure and timber bending strength for lateral resistance, with prescribed bracing potential of 60BU, in NZS3604:1999.



Checked in Bracing_________ A timber member used to brace studs, usually checked into faming and nailed into side of framing over every support.

Cleared Ground Level ["CGL"]__ A level taken after topsoil is removed from site.

Configuration Issues___________ Issues regarding the design of a dwelling which will ultimately induce torsion and twisting under lateral loading. Configuration issues are the result of asymmetrical, discontinuous plans or elevations in a dwelling.

Concrete perimeter wall_____ A concrete wall which resists lateral loads in shear.

Connections___________________ A connection refers to the whole *joint* between sub-floor elements, including the specific fixings and members being pinned together.

Cut Between Brace_____________ A discontinuous timber member that diagonally spans between two studs, common in timber dwellings built before 1964 and used as a form of lateral bracing.

Damage ratio _________________ The damage ratio is described as the cost of repairing an earthquake damaged building to the condition it was in before the earthquake, divided by the replacement cost of the building.

Designed Bracing______________ Bracing specified during the design process with a particular lateral strength capacity, stated in NZS3604:1999.

Design load strength_______ The capacity or characteristic strength of an element, within a particular limit state design which assumes that the failure mechanism is predicted.

DPC____________________________ Damp Proof Course, a bituminous impregnated paper product laid between timber and concrete interfaces to limit timber rotting.

DPM___________________________ Damp Proof Membrane, usually black polythene sheeting used to limit water penetration into the sub-floor space or concrete slabs.

Fixing__________________________ Refers to the actual element that is used in the connection of members, such as a nails, bolts or other proprietary elements.

Footing ________________________A concrete pad foundation under piles or vertical elements, which bears and distributes forces into the ground.

Friction Co-efficient ________A factor which is multiplied into the strength of a connection, which considers that friction contributes a proportion of strength in a connection depending on the specific interface material properties.

Full Split Level __________________ Usually a two storey dwelling where the lower level has less floor area than the top level, and is usually been a renovation which has dug into the hillside under the dwelling, see image to right

Half Split Level __________________A dwelling which has a proportion of the top half level above the lower, see image to right

Herringbone strutting _______Diagonal timbers used to limit joist overturning and forming an 'X' pattern and arranged in rows running at right angles to joists.

House Condition Survey _____ The current report ["HCS 2005"] released by BRANZ at 5 year intervals, which collates the specific condition and health of a sample of dwellings throughout New Zealand.

Intensity ________________________The relative ground movement in a specific area, zone or region, commonly scaled using felt intensity scales such as the Modified Mercalli scale.

Irregular plan ___________________A layout of a dwelling that is asymmetrical or irregular.

Jack Studs ______________________Jack studs are less than full height studs spanning vertically from plate to plate, usually used where normal piles or elements are too tall as prescribed by standards

KiloNewton ["kN"] ______________The unit of measure to describe Force.

KiloPascals ["kPa"] _____________The unit of measure to describe a Force per unit area, or kN per square metre.

Limit state design ________________The assumed strength of a material based on ultimate strength testing from the applicable manufacturers, after a Factor of Safety has been applied. The Factor of Safety relates to the type of building or dwelling and number of occupants the constructed building is likely to hold.

Liquefaction _____________________ The reaction of shaking in soil which causes water to be suspended in soil with fine particles. This results in a loss of soil shear strength and slumping of structures above the soil.

Magnitude ______________________The size of the earthquake at the source and calculated from amplitude measurements, usually using the Richter scale to quantify the shaking.

Mean Damage Ratio ["MDR"] _____A calculated ratio for the damage of dwellings which defines the cost of the repair of the dwelling divided by the total cost of the dwelling. These are usually based on observed past losses and so are a mean product of the relative shaking and other parameters involved in shaking.

Microzoning ______________________ The differing reactions of subsoils within a smaller area of the local geography.

Moisture Content ["MC"] _________Abbreviated term for 'Moisture Content' usually of timber.

Non-Designed Bracing _________Large heavy elements that provide lateral bracing potential despite not been designed as such.

Notch scarfing ____________________A joint between timber ends which is cut, so that notches accept each end of timber, in order to create a longer length of timber.

Notch ___________________________Cuts into upper timber members which slot over lower timber members.

NZS3604:1999 ____________________The most current version of the Light Timber Framed Construction standard, which prescribes structural timber sizes, fixing methods and detailing light timber construction. All terms and definitions regarding timber construction used in the text can also be found in the definitions of NZS3604:1999.

Ordinary Piles___________________Piles that support only the vertical weight of a dwelling and have no prescribed lateral stability.

Period of a Dwelling_______________The frequency with which a dwelling will shake in an earthquake depending on the material weights in a dwelling. Also referred to the Frequency of Shaking, and Natural Resonant Frequency of a dwelling.

Redundancy_____________________Strength capacity of elements which can be considered to contribute to the design strength of a dwelling, but may be removed without affecting the dwelling's overall bracing and strength capacities.

Remedial Measures__________Solutions to problems in a foundation that will result in a foundation being assumed adequate when assessed against NZS3604:1999

Residential______________________Residential refers to one unit or dwelling, in which a family or individuals will sleep and generally inhabit.

Risk _____________________________Risk is the product of (natural) hazard and the resulting consequence. Risk can be rated for a specific local environment, a structure or to an individual.

Shallow Cantilevered Pile______A shallow founded pile with footing depth less than 450mm, allowable as a means of bracing until 1999, with an assumed bracing capacity of 12BU.

Soft Storey_______________A story in a dwelling which has load transfer issues due to either a lack of bracing, a larger stud height or heavier materials in the upper story increasing the loads to be transferred to the ground.

Splayed joint_____________________A 45º to 30º angled joint used to connect timber ends, usually in bearers, to allow the increase in the overall combined length of timber.

Sleeper Plate____________________Historic term referring to a bearer, wall plate or other horizontally laid bearing member.

Standards________________________Standards refer to the formal construction codes, usually issued and controlled by a governing body with an overall interest or controlling influence over construction and building requirements.

Torsion__________________________Torsion refers to the twisting of a structural member loaded by torque, or twisting couples, where one end turns about a longitudinal axis while the other is held fast or turned in the opposite direction.

'U nail'________________________A 4mm diameter U shaped nail with parallel ends. The nail is best to connect timber parallel members.

Ultimate strength ______________The maximum strength capacity that can be anticipated from an element, with no limit states applied.

Waling__________________________A horizontal timber framing member secured to the face of vertical framing timbers to stiffen or tie the vertical framing or piles.