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The adequacy of existing house foundations to resist earthquakes: Cost benefit of upgrading

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Adequacy of Existing House Foundations for Resisting Earthquakes: the Cost-Benefit of Upgrading

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ABSTRACT: The past performance of foundations in earthquakes for timber dwellings prompted a practical investigation into the adequacy of existing sub-floor bracing, connection capacity and the overall adherence to NZS3604:1999. Using information gathered from a sample of 80 Wellington dwellings and by using the results from an Earthquake Loss modeller, it was found that the cost of upgrading "at risk" foundations is almost 30 times less expensive than the complete cost of rebuilding dwellings. Potential damage mitigation saves around 5 times the calculated damage costs. This saving has the potential to reduce temporary shelter costs and other large unknown costs of post-earthquake rehabilitation and reconstruction.

1 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. The damage from the moderate earthquake, Edgecumbe 1987, revealed that foundation bracing and connections were a weak point (BRANZ, 2003). Many houses were built prior to the introduction of formal construction Standards and have little or no foundation bracing.

The number of environmental factors affecting foundation capacity means that no foundation reaction can be fully predicted, or assumed to be safe. All observations are based on past events and factors such as topography, timber type, connections, degradation, non-designed bracing and the predicted earthquake scenario. In examining the interrelationship between foundations, connections, bracing and condition factors, one can determine where foundations are likely to fail and how they can be remedied to perform better when tested by a large earthquake. However, as the reaction to the dwelling is difficult to accurately predict, so too is the efficacy of the remedy. Therefore it is important to consider the appropriateness of a remedial action when applying it to an existing structure.

2 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. The two first recorded earthquakes occurred in 1848 and 1855 in the Wairarapa region (Slade, 1979). At the time residential dwellings were influenced in design and construction by European building practices, for example, dwellings were constructed using heavy un-reinforced stone masonry. Consequently, dwellings suffered major damage, forcing colonialists to consider alternative building practices and material more suitable to New Zealand's' unique conditions. The destruction witnessed after the 1931 Napier earthquake (Dixon, 1931), suggested that building practices had not evolved uniformly due to the lack of enforceable construction by-laws and this prompted changes to the building legislation. 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 gaps in our foundation building practices. These events did little to enforce better bracing standards in formal legislation. The 1987 Edgecumbe earthquake proved that modern construction methods had generally improved since 1931, with many dwellings receiving negligible damage to the superstructure and many dwellings avoiding collapse (BRANZ, 2003). Destruction in the 1971 San Fernando (Jennings & Housner, 1971) and 1995 Kobe earthquakes (Park, 1995) further reinforced that adherence to modern building standards greatly increased the chances of a dwelling surviving a large earthquake.

2.1 *History of sub-floor construction Standards*

The first formal construction recommendation, Circular 14, was developed in 1924, by the New Zealand State Forest Service (NZSFS, 1924). Circular 14 listed recommendations relating to the sizing of foundation piers and concrete walls and the sizing of timber members in relation to dwelling height and floor loading. Following the 1931 Napier earthquake, in an attempt to improve the standard of dwelling construction N.Z.S.S.95 (SANZ, 1944) was released. N.Z.S.S.95 built on Circular 14, was limited to prescribing reinforcement requirements for concrete piles and walls and included new foundation systems such as jack-studding. Foundation bracing and construction was enhanced with the introduction of the State house Specifications in 1936 (Broeke, 1979), which included the use of intermittent and full concrete sub-floor walls. However further amendments to the Specification reintroduced piled foundations under exterior walls in order to reduce termite infestation. These amendments reduced the bracing capacity of dwellings significantly. A new Standard was developed in 1964 (SANZ, 1964) superseding N.Z.S.S.95, however due to the wording of the sub-floor bracing provisions, it was uncertain whether sub-floor bracing was actually required. In 1978, the Light Timber Framed design standard NZS3604 (SANZ, 1978), was introduced. NZS3604 endeavoured to create better sub-floor bracing systems instead of relying on "good trade practice" it focused on establishing specific construction requirements, conveying them in an easy-to-follow visual format.

2.2 *The past strength of our dwellings*

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 super structure. Following, the Gisbourne earthquake in 1966 (Hamilton et al., 1969), the movement of repiled dwellings from their foundations showed a lack of bracing and fixings to the sub-floor. Dwellings affected in the Seddon earthquake (Adams et al., 1970) reacted badly due to poor soil conditions and the asymmetry of bracing systems. In the Inangahua (Shepherd et al., 1970) earthquake, piles overturned and jack studding collapsed due to the lack of bracing. 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 & Robertson, 1987). The connection of R6 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 & Housner, 1971) many split level dwellings and other asymmetric configurations, where floor diaphragms were not continuous, collapsed due to differential movement of the superstructure.

3 HOW DO WE DETERMINE "ADEQUACY" OF FOUNDATIONS?

To determine whether a foundation is adequate, it is necessary to consider the key elements of a foundation which contribute to its overall lateral strength under seismic loading and the degree to which a dwelling remains habitable following a large earthquake. NZS3604:1999 (SNZ, 1999) sets out the minimum requirements for foundations, including the seismic bracing potential, the connections between the sub-floor framing members and the overall general condition and durability requirements of a foundation. This standard is used in this study to determine whether a foundation is seismically adequate. Requirements such as bracing requirements depend on the seismicity of the area, other geographical, architectural and topographical factors.

3.1 *Bracing*

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 inertial weight from the wall and roof claddings, to the ground. This is affected by the house geometry, materials and live loads. The existing bracing mechanisms must be appropriate for the loading. A dwelling must meet the current requirements in NZS3604:1999, including all connection methods and general condition parameters. Although, not specifically noted in the Standard, 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. NZS3604 does not take into account lateral resistance of ordinary (shallow) piles in piled foundations. Therefore, when determining whether existing piled foundations are adequate, it is necessary to estimate the approximate resistance of an ordinary pile by calculating the ability of the soil friction to resist overturning and sliding.

3.2 *Connections*

In assessing the adequacy of the connections in a dwelling, it is necessary to consider the adequacy in two ways. The first is the overall adequacy of connections to transfer 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. The second is the acceptable connection methods (including connection methods for bracing) as required by NZS3604:1999. Connections must be durable otherwise they physically degrade and lose strength over time. The effectiveness of a connection depends on the material used and the friction coefficient between different material members. Timber to timber connections, have a friction coefficient of less than 1, however the timber-concrete interface will be in excess of this. Friction between connections is observed in all materials; however as an earthquake in locations such as Wellington is likely to exhibit a proportion of vertical acceleration, this will momentarily result in zero or significantly reduced friction between members.

3.3 *General conditions*

The sub-floor requires sufficient ventilation, a minimum of 150mm ground clearance and regular structural configurations to maintain the integrity and adequacy of the sub-floor and maximise its ability to resist seismic loading. The ventilation requirements in the current Standard have not significantly changed since the requirements in the first recommendations in 1924.

4 STUDY AND ASSESSMENT OF EXISTING HOUSE FOUNDATIONS

We carried out a study which aimed to assess a wide cross section of different house foundations. The Wellington City Council provided a random selection of dwellings from their rating database, from which a sample of 80 dwellings was taken as shown in Figure 1.

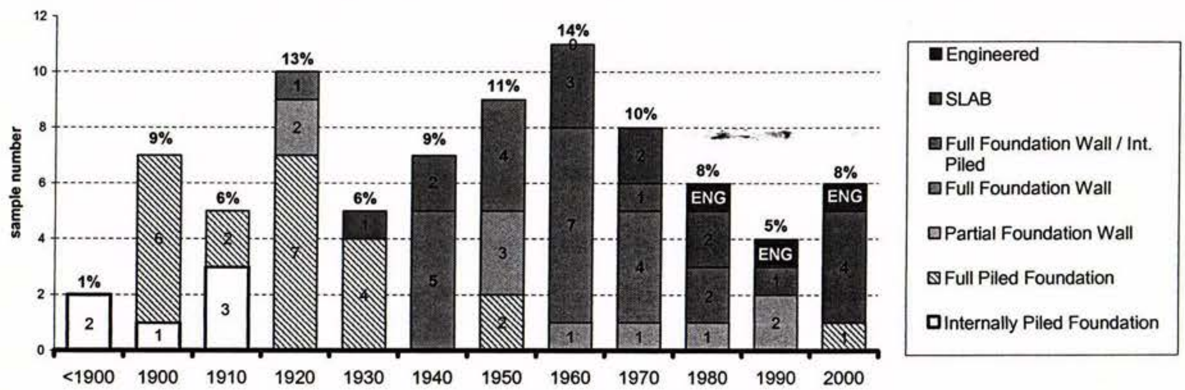

Figure 1. Foundation type for age of dwelling, percentages of the total sample.

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 in that period. A site visit was conducted for each dwelling with permission from the owner. In each case, the bracing, connections and general condition of the foundation was assessed against the requirements of NZS3604:1999 in light of the site, age and weight of the dwelling.

5 WERE THE DWELLINGS ADEQUATE?

Overall, an average of 49% of foundations, were below acceptable requirements for all key elements of foundation adequacy. As shown in Figure 2, 16% of sample dwellings had little or no bracing and a further

33% used non-prescribed methods such as anchors, to provide bracing potential. The majority of houses that failed to meet the required standards had full piled foundations that were commonly found in houses prior to the 1940's. The connections providing the load paths to the bracing members from the floor were inadequate in at least one location in 32% of dwellings. Weak connections in repiled dwellings accounted for a large proportion of the sample built prior to 1940, usually occurring between the ordinary pile to bearer connections.

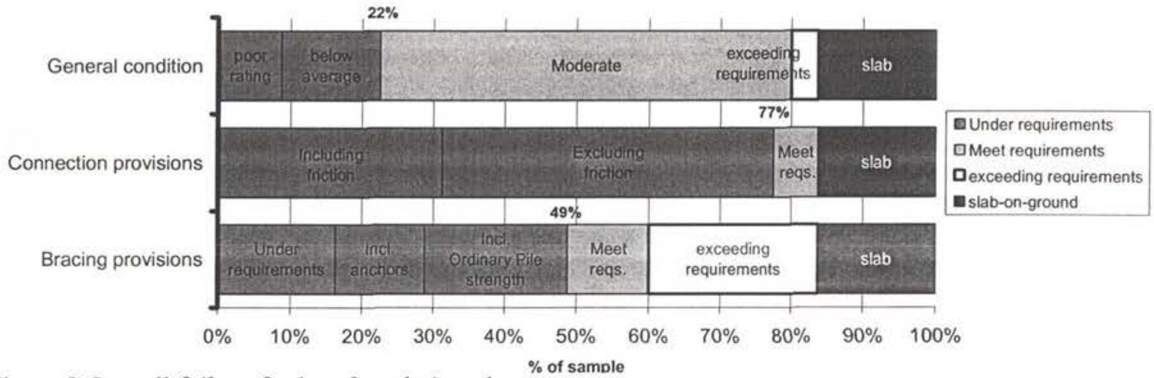

Figure 2 Overall failure for key foundation elements

The poorest connection observed in all dwellings was 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. The overall general condition of foundations surveyed was moderate and most consistent in dwellings constructed between 1940 and 1960. However, some newer dwellings from the 1970's and 1990's showed signs of premature degradation resulting in a below average condition rating. Serious ventilation issues were seen in 45% of dwellings and 54% of connections in dwellings exhibited rust or oxidisation. Determining the adequacy of foundations in this respect is subjective.

Although 49% 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 the dwelling. These systems will provide some lateral stability. An un-braced dwelling does not have zero lateral resistance, therefore it is estimated that the soil friction provides between 3BU and 15BU per pile (20 BU is equivalent to 1 kN of force). Twenty percent of the total sample relied entirely on this calculated resistance from the Ordinary piles, usually in pre 1940's piled dwellings.

5.1.1 *Friction resistance of connections*

Overall, an average of 13% of connections providing load paths to the bracing members (in four significant locations sampled), were inadequate. Excluding the effects of friction, the number of connections failing increases by 24% for the Joist to Bearer connections and 65% for connections from Bearers or Plates to the concrete Foundation wall. The Ordinary pile to Bearer connection was inadequate in 56% of the sample, so about half of connections were inadequate even after repiling. Although some connections failed due to poor construction or materials, older dwellings failed as connections used are weaker than those prescribed by modern Standards. The Plate to Foundation wall connection has had changes in most significant Standards since 1924. As the standards have developed fixing spacings have reduced. However only 5% of the Plate to Foundation wall sample would fail to transfer loads adequately. This example shows that the concept of connection adequacy evolves over time.

5.2 *Configuration issues*

The general conditions observed onsite correlated well with the 2005 House Condition Survey (Clark et al., 2005), however more issues such as excessive levelling wedges in repiled and re-levelled dwellings were observed in the sample. Figure 3 shows the percentage of the sample with general condition issues. However, overall, a number of dwellings had a combination of these issues, especially in older dwellings that have missing structure, insufficient footing depth and non-vertical piles. Dwellings that had been renovated often had full or half split level additions usually made to the lower floor by excavating the foundations, and almost half of these dwellings had differing foundations likely to cause serious configuration issues under lateral loading. Unfortunately, it was more difficult to assess the adequacy of foundations in dwellings with configuration issues, as the significance of these issues usually only becomes fully apparent after an earthquake.

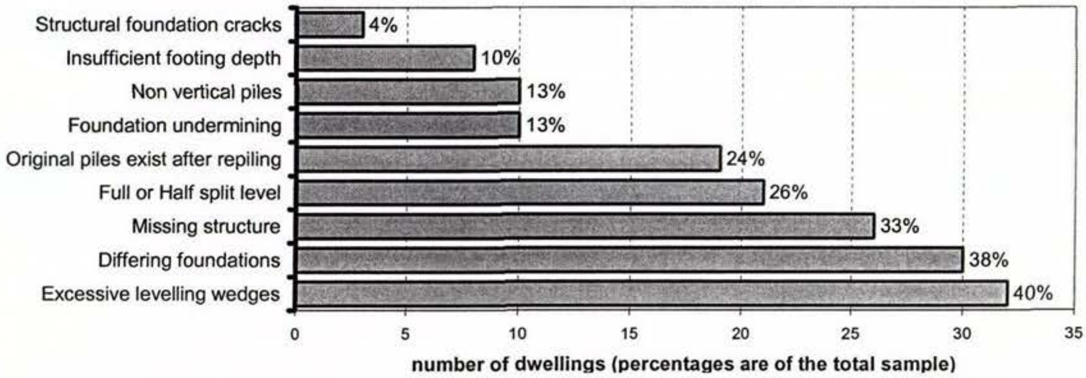

Figure 3. General conditions pertaining to foundation durability

6 DISCUSSION

29% of dwellings on average over all key foundation elements were observed as being in an above average condition. 45% of dwellings had an excess of foundation strength with 24% showing in excess of 2000BU per Bearer line, usually from full concrete foundation walls. 16% of the sample were Slab-on-ground construction or engineered foundations. These were assumed adequate, although slabs built prior to 1990 may have non-visible reinforcing deficiencies. A significant number of fixings failed to comply with NZS3604:1999 however, were still calculated to adequately transfer loads through to the bracing and other connections. Just over 25% of the sample showed adequate fixing capacity under conditions where friction cannot be expected. 18% of the sample had excellent overall general condition, usually seen in newer dwellings and 58% had only moderate condition issues.

As expected, older dwellings had a lower bracing capacity and were more likely to have deficient connections compared with NZS3604 requirements. However, some modern dwellings around the 1970's, 1980's and 1990's had an extremely poor general condition and limited connection capacity as a result of fixing degradation. The impact of dwelling mass on connections showed increased failure for dwellings with a combined roof and wall cladding weight over 4 kPa . These heavier dwellings were the most evident around the 1940's and peaked around the 1980's. The percentage of dwellings demonstrating poor conditions, weak connections and limited bracing, is comparable to the number of adequate dwellings. 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, and then we can estimate the economic cost of remedial action to the individual and the direct economic savings for society.

7 DESCRIPTION OF THE "LOSS MODELLER"

The economic costs of an earthquake hitting Wellington, was calculated using the Geological and Nuclear Sciences *"Earthquake Loss Modeller"*. The loss modeller output displays the number of casualties, total economic loss to residential dwellings and commercial properties for any given city. For the purposes of this study, the results were limited to the Wellington city suburban limits, described in Wellington City Council District plan maps. The damage costs described do not include Porirua or the Hutt valley or any of the wider affected area in New Zealand. The modeller uses Damage Ratios and values are assumed *"reasonable probabilistic fits to Earthquake Commission (EQC) losses for period 1990 to 2003"*(Cousins, 2005). Remedial measures are applied to the foundation to ensure that the dwelling may remain habitable following an earthquake. The foundation behaviour should remain predictable and failure mechanisms should be capable of dissipating energy through ductile yielding (SANZ, 1992).

Using a predicted earthquake of Magnitude 7.2 at a depth of 8km, the Wellington earthquake is likely to result in the total collapse of over 440 timber dwellings and cause serious damage to over 18,220. This is expected to result in the direct economic loss of $3.8B dollars in the timber residential sector claiming 930 lives and injuring 1290 people if it occurs during the daytime.

8 REMEDIAL MEASURES

The study results identified key areas where foundations were inadequate and to which remedial measures could be applied to increase the likelihood of a dwelling remaining habitable following an earthquake. 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). The application of bracing methods were initially applied on the basis that new systems should complement existing systems. 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. Remedial measure costing included remedying connections and existing general conditions that could affect the future strength of the foundation.

The cost of upgrading dwellings was based on values obtained by quantity surveying methods for different remedial bracing applications. Table 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 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.

Table 1. The remedial measures and costs applied to each foundation type.

Foundation type	Existing bracing system	% Sample requiring bracing	Remedial solution	avg. remedy per dwelling	Average cost of improvement per square metre of dwelling			TOTAL
					fixings	durability/ condition	bracing	
Internal Piled	Pile	83%	Anchor pile	10 piles	$4.17	$147.00	$21.42	**$172.59**
Full Piled	Pile	63%	Sheet	7m sheeting	$5.10	$96.70	$7.01	**$108.81**
	Pile / sheet	17%	Anchor pile	10 piles	~	~	$13.80	**$115.60**
Partial Wall	Pile / Conc. Wall	50%	Sheet	5m sheeting	$5.30	$52.50	$20.16	**$77.96**
Full Wall	Conc. Wall	10%	Infill wall	4m infill	$6.54	$26.30	$41.40	**$74.24**
Full Wall / Internal piles	Conc. Wall	0%	n/a	~	$5.35	$26.50	~	**$31.85**
SLAB	n/a	0%	n/a	~	$0	$0	~	**$0.00**
ENG	varies	0%	n/a	~	$0	$0	~	**$0.00**

It is apparent from the table that older dwellings will cost more to remedy than newer dwellings. However, it must be emphasised that this is the assumed average case and costs to remedy the dwelling's condition vary significantly due to the labour intensity of general condition remedies.

The other costs of earthquake repair, usually discussed as the wider implication of the earthquake on society, are concerned with the losses in production markets, the inflation and post-earthquake repair and the cost of shelter and aid to be provided to society. The losses in production markets will cause mass unemployment and produce mass material shortages, as observed after the 1995 Kobe earthquake (Park, 1995). The material shortages, destroyed transport infrastructure and increased demand for construction professionals will drive the cost of such services up during the post-earthquake repair period. This inflation has been estimated as high as 10-30% of normal construction costs (Davey & Shephard, 1995). Shelter and aid provided to the public is perhaps the biggest contributor to unknown costs (Cooney & Fowkes, 1981). Upgrading foundations aims to increase the total number of habitable dwellings, limiting evacuations and the necessary shelter and serious aid resulting from collapsed dwellings. This may decrease pressures on national insurance reserves, decrease personal insurance costs and limit residential material and labour demands on markets.

9 THE COST BENEFIT RATIO

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. Initial results in

Table 2, suggest that the cost saving between the earthquake scenario before remedial action and after remedial action is undertaken, is almost 80% for collapsed dwellings and approximately 40% for damaged dwellings. This is predicting that dwellings previously assumed to collapse will only sustain damage, however, some dwellings with serious configuration issues are still anticipated to collapse. Remedial measures are assumed to mitigate damage in only half of the sample dwellings. The foundation type does affect the damage and collapse ratio, and a preliminary assumption based on sample observations, suggests that around 70% of "at risk" dwellings are piled foundations.

Table 2. The anticipated costs for collapsed and damaged dwellings.

	Post earthquake cost before remedy $M	Post earthquake cost after remedy $M	Cost saving $M	Remedial Costs $M	Cost / benefit ratio	Benefit / cost ratio
Collapse	$257	$51	$206	$7	0.03	29
Damage	$3,523	$2,070	$1,453	$284	0.19	5.1
TOTAL	**$3,780**	**$2,121**	**$1,659**	**$291**	**0.17**	**5.7**

9.1 *Do we need to upgrade?*

The results above suggest that dwellings require, on average, reasonable expenditure to achieve the current standards requirements. The very low cost / benefit ratio suggests that it is economically justifiable to remedy foundation defects in dwellings, even if more conservative assumptions on the reduction in damage had been made. This analysis assumes that a maximum credible earthquake will occur in the lifetime of these dwellings. Assuming an average building life of 50 years and the often quoted 50% probability of a maximum credible earthquake in Wellington within 50 years, the cost / benefit ratio would double to about 0.3. Assuming the likelihood of piled dwelling collapse (over 70%), and applying information contained in the House Condition Survey, the cost of upgrading certain foundation types may be less than the total average annual expenditure currently spent on maintaining dwellings (Clark et al., 2005).

10 CONCLUSIONS

The main lesson from Edgecumbe was that successful implementation and moderately good compliance with construction standards had contributed overall to the mitigation of collapse and serious damage to timber framed dwellings. Piled dwellings assumed "at risk", cost less than 5% of the average dwelling reconstruction bill, not including inflated labour and material costs. This total alone could potentially save over $1B in post earthquake repairs and mitigate the unknown costs of temporary shelter and aid requirements for families. Unfortunately this value of upgrading may not be seen as cost-effective by the homeowner, as the EQC and personal insurance cover dwelling reinstatement. At present, no real incentive exists for upgrading residential foundations.

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ENG 344

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: the Cost-Benefit of Upgrading

EQC Non-Biennial project 6UNI/530

by Dr G.C. Thomas and J.D. Irvine

21 June 2007

EXECUTIVE SUMMARY

The poor performance of residential foundations in past earthquakes prompted a practical investigation to quantify the adequacy of Wellington timber dwellings' foundations, including the sub-floor bracing, sub-floor fixings and general condition of the foundation. The adequacy of a random sample of 80 light timber framed dwelling's foundations was assessed against the current "Light Timber Frame 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 observed damage to dwellings built to the then current NZS3604:1984, showed only negligible damage due to foundation inadequacies and as a result, the Standard required only minor amendments. The most current 1999 edition of NZS3604 is therefore considered to have seismically appropriate detailing and provisions to withstand design earthquakes. For the purposes of this study, NZS3604:1999 is assumed to be the benchmark for the seismic adequacy of Light Timber Framed buildings.

The results for the study of seismic adequacy of foundations show 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 application or simply non-existent fixings. The overall condition of the sample dwellings was compared with the House Condition Survey 2005 produced by BRANZ. Inadequacies identified in the House Condition Survey 2005 were also prevalent in the majority of sampled dwellings in the study, such as non-compliance with minimum height and sub-floor ventilation requirements. However, the House Condition Survey does not assess any rented accommodations and so the condition results may be underestimated. The study sample does, however, include rented dwellings, but the proportion of rental dwellings in the sample is smaller than the proportion in the overall population. The sample, therefore, may still be unrepresentative of the actual average dwelling, especially in terms of condition and range.

After identifying the common deficiencies both in the sample and also from similar studies, remedial measures were costed by a registered Quantity Surveyor 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. This cost depended on the level of average remedy required and size and weight of the dwelling.

The cost for upgrading foundations in light timber frame dwellings in Wellington City to resist earthquakes was estimated at $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 Mean Damage Ratio for each foundation type was then modified, based on similar earthquake damage projections based on the same Wellington earthquake scenario. Dwellings that had either significant configuration issues or were located in an area likely to experience higher earthquake shaking, were still anticipated to collapse despite applying sub-floor remedies. 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 high 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 measures to foundations has consequences that directly benefit the EQC and emergency services; however the indirect benefits are likely to be far more significant during the post-earthquake clean-up. The direct benefits include reducing pressure on emergency management systems, hospitals and organisations involved with evacuations, which will facilitate a quicker reconstruction of the post-earthquake society to pre-earthquake levels. The indirect benefits include minimising the erection, cost or location of temporary housing and accommodation for the proportion of the population that must evacuate seriously damaged dwellings. A dwelling that has sustained serious foundation damage will require structural inspections and repairs before the dwelling can be safely re-inhabited. Examples from past New Zealand earthquakes have shown that some citizens were forced to occupy 'at risk' dwellings for a number of months following the earthquake destruction, simply because no temporary accommodation was allowed for, nor was available. 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 does 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.

However, 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. Explaining the indirect costs to the homeowner may also help reinforce the necessity of applying remedial measures. Newspaper publications produced overseas have shown positive results when information of the measures one must take to mitigate earthquake damage, is coupled with understandable research facts in an easily readable format. Similarly, areas which receive numerous earthquakes, such as California have legislation in place, which greatly emphasise earthquake strengthening and securing of a dwelling and usually have an effect on the resale value of a house.

Despite the public's initial reaction to dismiss the risk and likelihood of an earthquake, the fact remains that although the likelihood of earthquake is smaller than other hazards, the consequences are far more severe. Foundation upgrading is the one area that will receive the highest economic and social benefits for capital expenditure, whether it is made by the homeowner or the Government. The economic benefits for the homeowner will most commonly result from the cost of evacuations, temporary shelter and the mitigation of injury due to securing the foundation from collapse or extensive damage. Direct costs of repairing damage are usually borne by the Earthquake Commission and other insurers. Although the predicted results of upgrading may be clear, the homeowner generally requires more rigorous information regarding the problem, clear incentives for upgrading and proactive initiatives from the authorities. These initiatives must be targeted at the homeowner in an easily understandable format, which is focussed on better performance and savings, rather than on the worst case scenario which has been shown to increase ambivalence and fatalistic mindsets within society.

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1 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. 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.

The large number of factors affecting foundation strength means that foundation reactions can be difficult to predict. Therefore, observations and areas of focus in the study are based on past events and factors that most often affect the strength of a foundation such as topography, the timber variety, condition of connections, degradation of materials, use of non-designed bracing and most importantly the anticipated magnitude and intensity of the earthquake scenario. In examining the interrelationship between these factors and the main foundation elements including existing bracing, connections, and overall condition, one can determine reasonably accurately where foundations are likely to fail and how they can be remedied to perform better when tested by a large earthquake. However, as the specific reaction of the dwelling is difficult to accurately predict, so too is the efficacy of the remedy. Therefore it is important to consider the appropriateness of a remedial action when applying it to an existing structure.

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2 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. The two first earthquakes recorded after European settlement, occurred in 1848 and 1855 in the Wairarapa region (Slade 1979). At the time residential dwellings were influenced in design and construction by European building practices, for example using heavy un-reinforced stone masonry. Consequently, dwellings suffered major damage, forcing colonialists to consider alternative building practices and materials more suitable to New Zealand's' unique conditions. The destruction witnessed after the 1931 Napier earthquake (Dixon 1931), suggested that building practices had not evolved uniformly due to the lack of enforceable construction by-laws and this prompted changes to building and construction legislation. 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 gaps in our foundation building practices. These events did little to enforce better bracing standards in formal legislation, mostly due to the small size of the affected populace. The 1987 Edgecumbe earthquake proved that modern construction methods had generally improved since 1931, with many dwellings receiving negligible damage to the superstructure and many dwellings avoiding collapse (BRANZ 2003). Destruction in the 1971 San Fernando, California (Jennings & Housner1971) and 1995 Kobe, Japan, earthquakes (Park 1995b) further reinforced that adherence to modern building standards greatly increased the chances of a dwelling surviving a large earthquake.

2.1 History of Sub-floor Construction Standards

The first formal construction recommendation, Circular 14, was developed in 1924, by the New Zealand State Forest Service (NZSFS 1924). Circular 14 listed recommendations relating to the sizing of foundation piles, concrete walls and the sizing of timber members, in relation to dwelling height and floor loading. Following the 1931 Napier earthquake, in an attempt to improve the standard of dwelling construction, N.Z.S.S.95 (SANZ 1944) was released. N.Z.S.S.95 built on Circular 14 and was limited to prescribing reinforcement requirements for concrete piles and walls and included newly introduced foundation systems such as jack-studding. Foundation bracing and construction was enhanced with the introduction of the State House Specifications in 1936 (ten Broeke 1979), which included the use of intermittent and full concrete sub-floor walls. However further amendments to the Specification reintroduced piled foundations under exterior walls in order to reduce termite infestation. These amendments reduced the bracing capacity of dwellings significantly. A new Standard was developed in 1964 (SANZ 1964) superseding N.Z.S.S.95, however due to the wording of the sub-floor bracing provisions, it was uncertain whether sub-floor bracing was actually required. In 1978, the Light

Timber Framed Construction standard NZS3604 (SANZ 1978), was introduced. NZS3604 endeavoured to create better sub-floor bracing systems instead of relying on "good trade practice" it focused on establishing specific construction requirements, conveying them in an easy-to-follow visual format.

2.2 The Strength of Our Foundations 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 super structure. Following, the Gisbourne 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 & Robertson 1987). The connection of R6 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 & Housner 1971) many split level dwellings and other asymmetric configurations, where floor diaphragms were not continuous, collapsed due to differential reaction and 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. The five foundation types listed are not completely extensive, due to the limited sample size, however, cover most variations of the major foundation systems commonly seen within the Wellington region. All foundation types are abbreviated and listed in a pull-out reference guide, which should be referred to in conjunction with the in-text abbreviations [refer Appendix E].

2.2.1 Internally Piled Foundation [IPF]

The Internally Piled Foundation is a completely piled foundation system with exterior piles supporting the superstructure and roof of the dwelling, while the interior piles support only the floor loading and internal walls. Figure 2.1 illustrates that the exterior piles usually have a jackstud type system on exterior piles. Other alternative constructions have bearers notched into the sides of exterior piles.

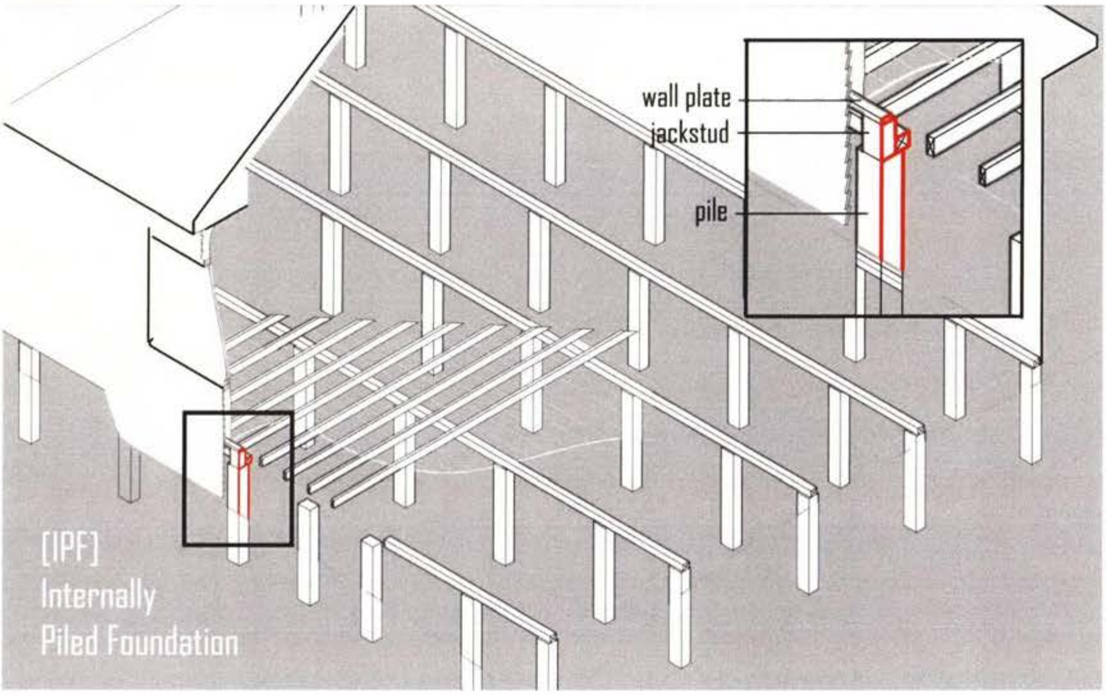

Figure 2-1 Detail of Internally Piled Foundation

This method of foundation construction is common in dwellings built around the turn of the 20th century (Harrap 1980), which may have derived from the construction of old stone cottages, where the dwelling was enclosed prior to the timber floor being laid (ten Broeke 1979). All piles in these dwellings were usually timber, most often Totara or Puriri, due to the ease of splitting and resilience to rotting. The Internally Piled Foundation relies heavily on the strength of the soil surrounding the piles for lateral resistance. This strength, combined with the overturning resistance of short, squat piles are commonly the only form of lateral resistance. In past earthquakes, these dwellings often swayed sideways, especially if a dwelling had been repiled and replaced with only shallow pile footings [Figure 2.2]. 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 bracing potential.

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

2.2.2 Full Piled Foundation [FPF]

The Full Piled Foundation is the most common form of piled foundation using concrete or timber piles to resist vertical loads. No special detailing is given to the side or exterior pile lines [Figure 2.3].

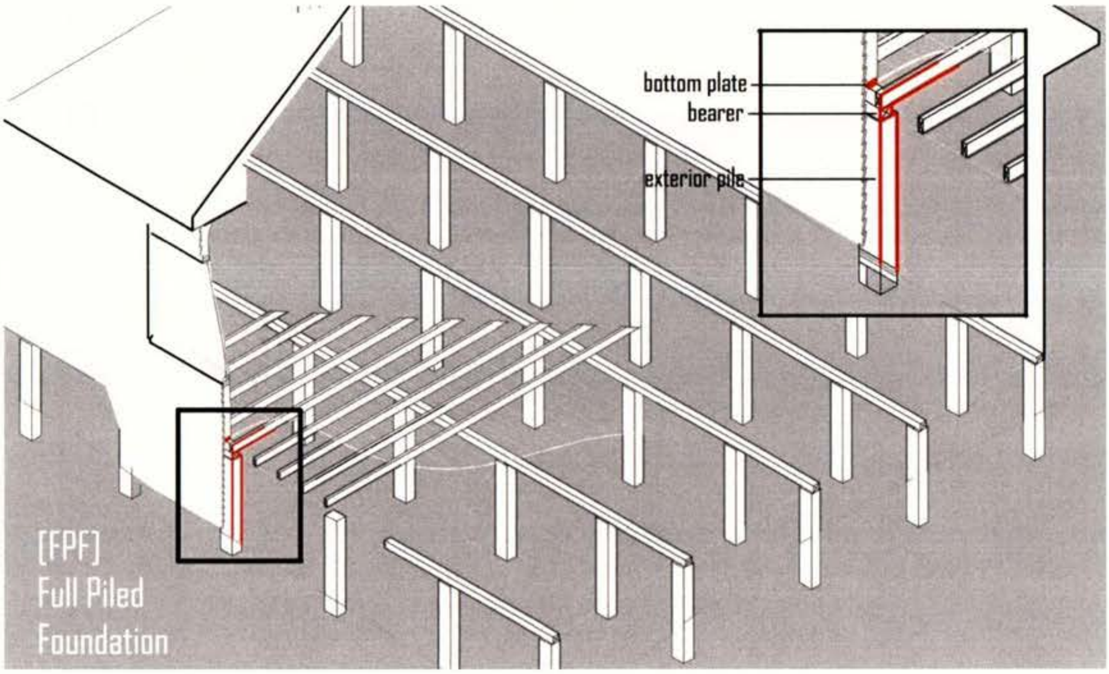

Figure 2-3 Detail of Full Piled Foundation

The Full Piled Foundation is most common in dwellings built prior to 1940 and continues to be popular for modern dwellings especially where the topography is unsuitable for other foundation types. Many dwellings built with this foundation types were constructed with native timber piles, which tend to decompose, where as concrete piles were used for dwellings built after the 1950's and in 1980's repilings. Other pile materials such as earthenware, ceramic piles or other found objects may have also been used during construction or repiling. More modern piled dwellings commonly use highly treated timber piles, which allow more reliable fixing methods to sub-floor framing.

Observations of Full 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 2.4].

Figure 2-4 Example of Piles punching through the Floor due to Sub-floor Framing slipping off Piles ***(Source: BRANZ 2003)***

Full Piled Foundation dwellings have also tended to sway heavily on piles during earthquakes, utilising the strength of the soil surrounding the piles to dampen loads. As a result many dwellings with limited soil ductility, or shallow footings have resulted in sideways collapse, especially if no large concrete 'anchors' [refer Section 3.2.2] were integrally connected to sub-floor framing (Norton et al. 1994) [Figure 2.5]. If concrete 'anchors' were present and not fixed to the framing, smashing between the piles and concrete could also potentially occur.

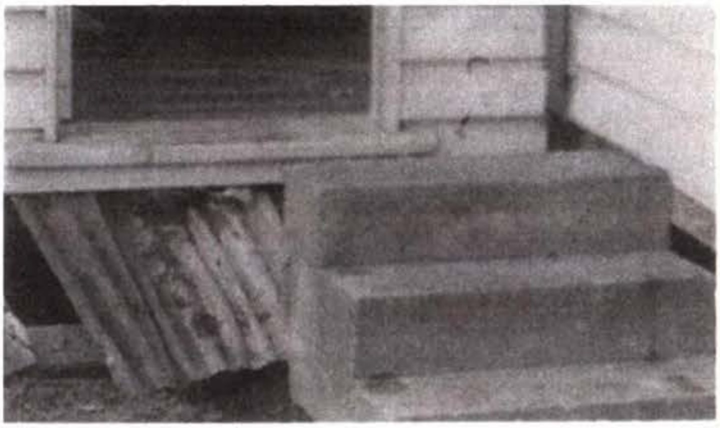

Figure 2-5 Full Piled Foundation slipped off Foundations, with Concrete steps remaining in place ***(Source: Cooney 1979)***

2.2.3 Partial Foundation Wall [PFW]

The Partial Foundation Wall, also known as an intermittent concrete foundation wall, has short lengths of concrete foundation wall, usually on the perimeter corners of the dwelling. This foundation type is most common between the 1940's and 1950's and is considered an adequate foundation type for resisting seismic loads (BRANZ 2003). The concrete section of the wall can span as much as four pile bays and is generally connected to sub-floor framing with bolts or reinforcing bars through a timber plate [Figure 2.6]. The specification of this form of foundation was used predominantly during the 1939 and 1964 State House Specification (Schrader 2005), however tended to be used only where cost and availability of materials were limited (Slade 1979).

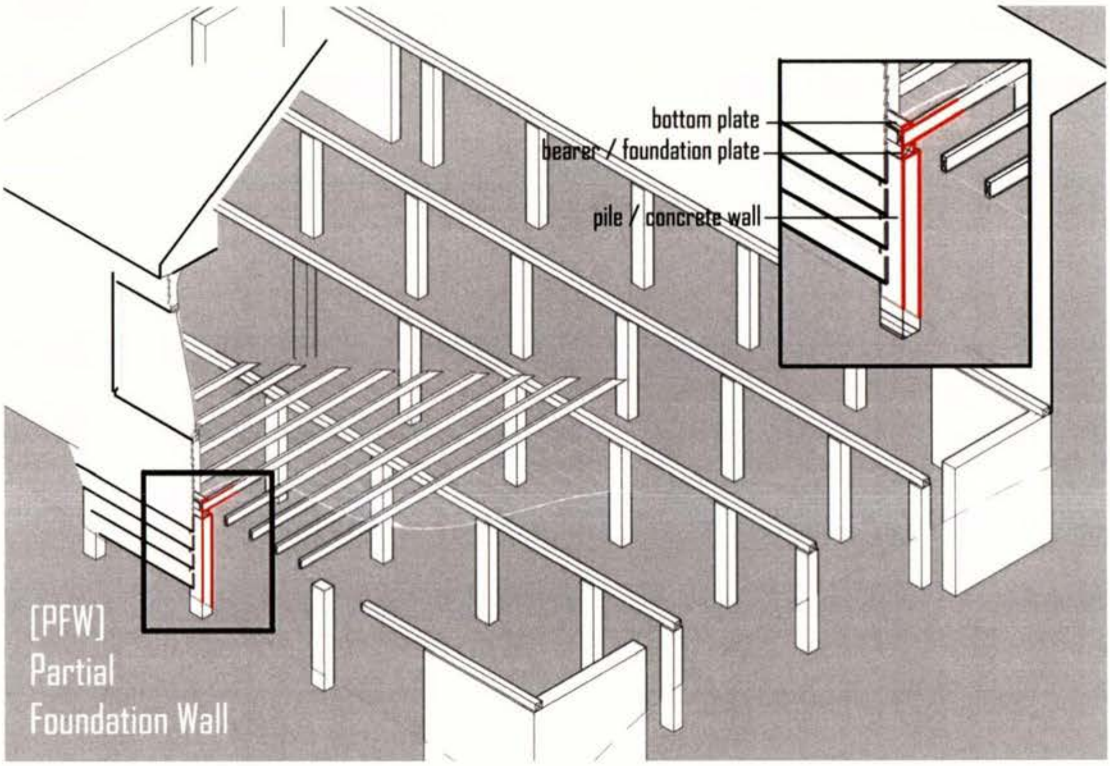

Figure 2-6 Detail of Partial Foundation Wall

This foundation type has performed well in past earthquakes, with many examples escaping with only superficial damage to cladding (BRANZ 2003). Other foundation types that are also considered Partial Foundation Walls are jackstudded sub-floor walls, where 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 2.7].

Figure 2-7 Jackstudded Sub-floor showing Cladding broken off and a slumping to one side ***(Source: Jennings and Housner 1971)***

2.2.4 Full Foundation Wall [FFW]

The Full Foundation Wall achieves its bracing potential from a full reinforced concrete perimeter wall between the superstructure and the ground [Figure 2.8]. Lateral loads are directed from the super structure directly to the concrete foundation wall and then to the ground.

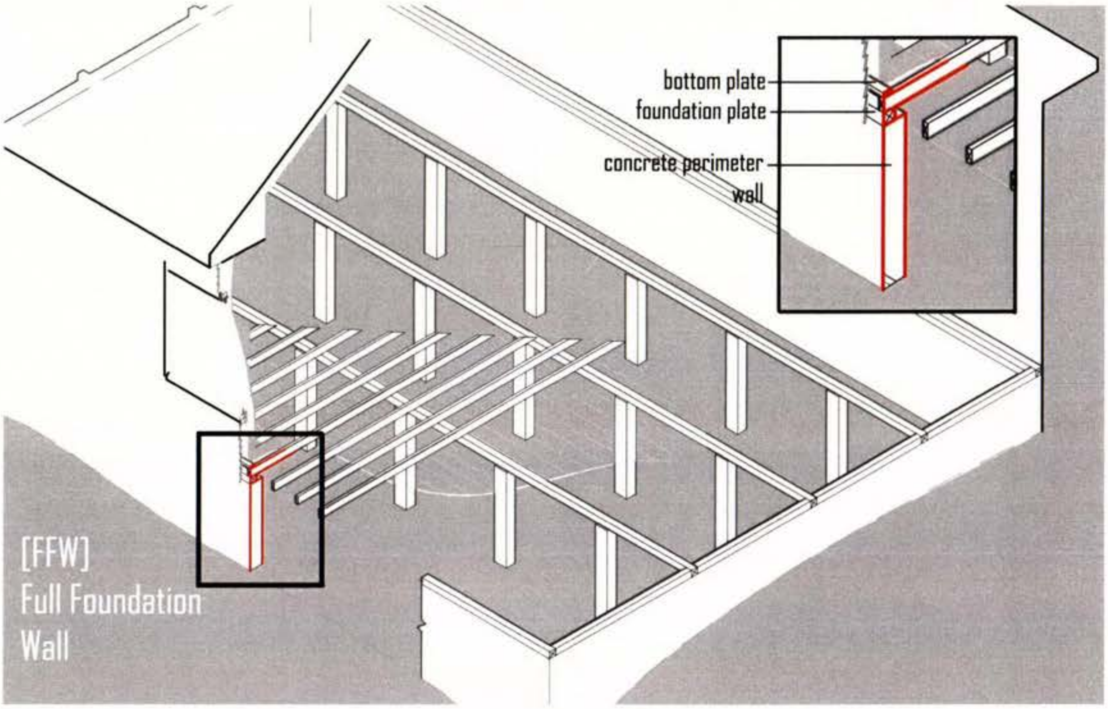

Figure 2-8 Detail of Full Foundation Wall

This method of construction found favour in post Second World War New Zealand construction and was also promoted by the State Housing Scheme, whose focus was on strength and durability. Each dwelling would be constructed using quality labour and materials, and was designed to last up to 60 years (Schrader 2005).The Full Foundation Wall 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 2.9]. A Full Foundation Wall is necessary for dwellings with heavy 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 2-9 Superficial Damage to brick veneer on State Dwellings, however no damage to the Foundation Wall is evident *(Source: Eiby 1980)*

2.2.5 Full Foundation Wall / Internal Piles *[FFW/IP]*

The Full Foundation Wall / Internal Piled dwelling is commonly constructed with a brick or block veneer from the ground to soffit level. The sub-floor wall is usually reinforced block and has integrally cast half-piles on the exterior foundation wall, on which the bearers sit. Early provisions for this type of foundation allowed the perimeter piles to be cast separately from the exterior wall, which meant that the sub-floor framing was simply sandwiched between either side of the foundation wall [Figure 2.10].

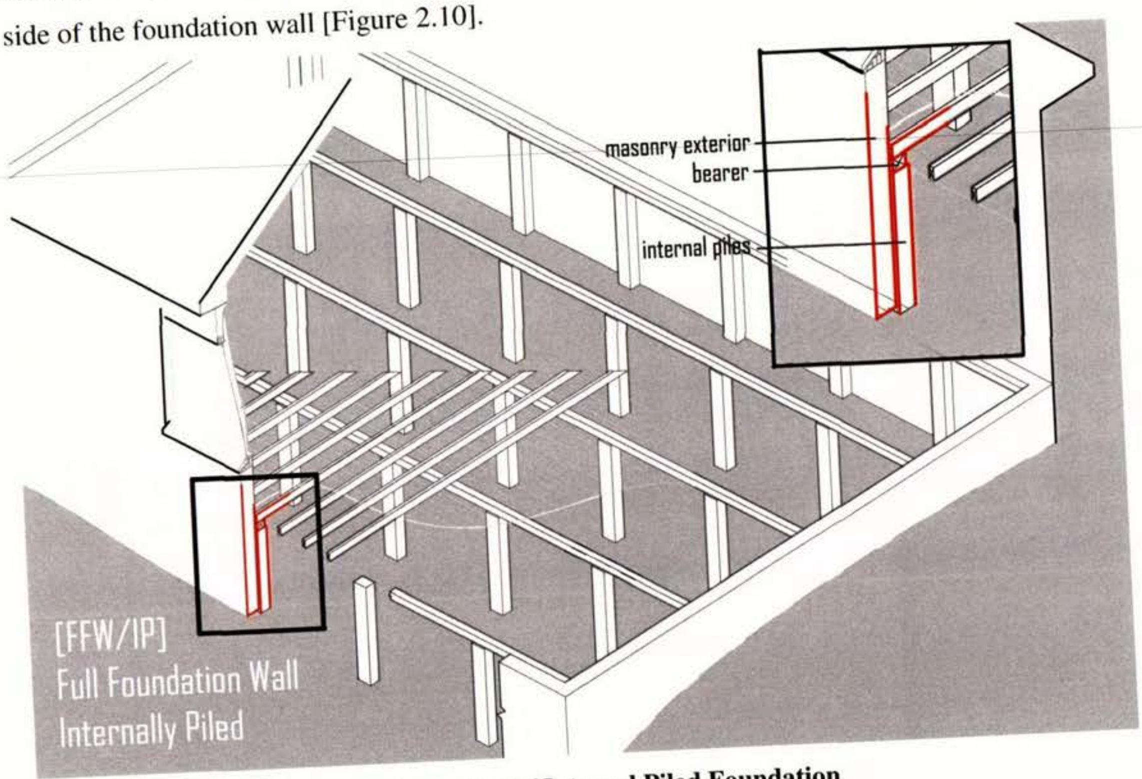

Figure 2-10 Detail of Full Foundation Wall / Internal Piled Foundation

This form of construction is 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 lack of integration between the dwelling superstructure and the sub-floor framing (BRANZ 2003) [Figure 2.11].

Figure 2-11 Wall separating from Exterior Foundation wall ***(Source: BRANZ 2003)***
Figure 2-12 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 [Figure 2.12].

2.2.6 Slab on Ground [SLAB]

The slab-on-ground foundation has revolutionised the construction of foundations in dwellings, reducing the cost and time required to build new houses and construct additions to dwellings since the mid 1980's. 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 2.13]. 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. As the fixings are normally within the wall, they can not be checked for compliance without removing internal or external wall cladding. 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.

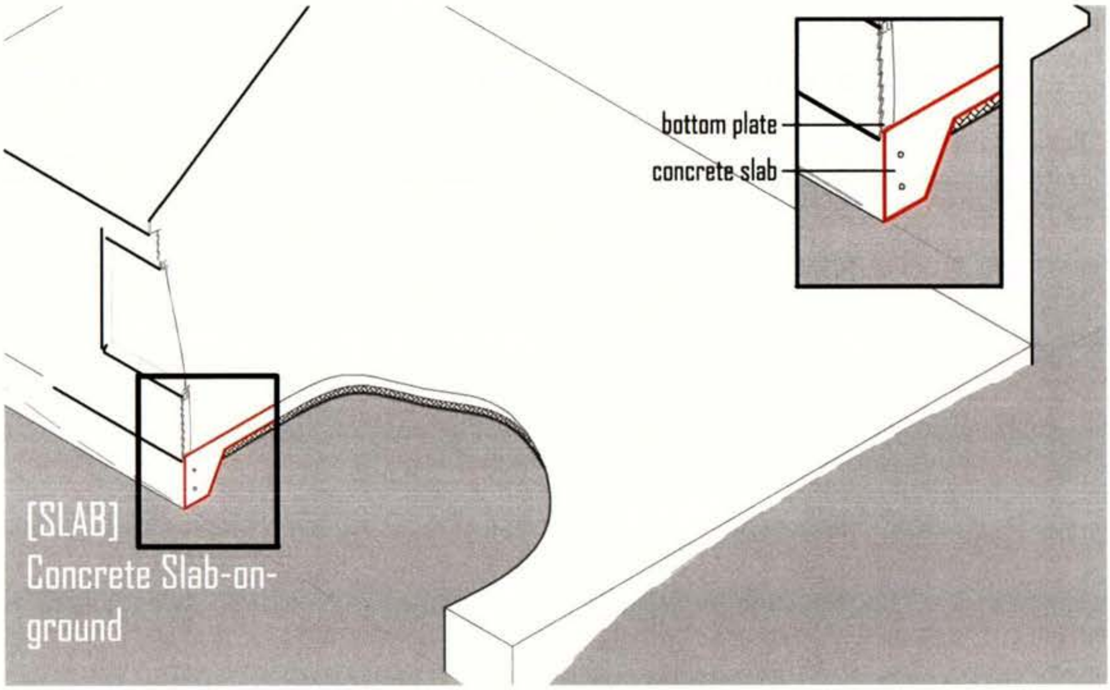

Figure 2-13 One variation of Detail for Slab on Ground Construction

Other modern foundations consist of concrete crib wall constructions, concrete column construction and other foundation constructions usually utilised only in extremely difficult situations, outside the scope of NZS3604 and required to be specifically designed by an engineer. 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. A slab foundation now requires additional reinforcing between exterior perimeter walls and the poured slab (BRANZ 2003). Irregular plans for concrete slab foundations, also require additional reinforcement across assumed cracking lines or parts of distinct change in an asymmetric layout [Figure 2.14] (Standards New Zealand 1999).

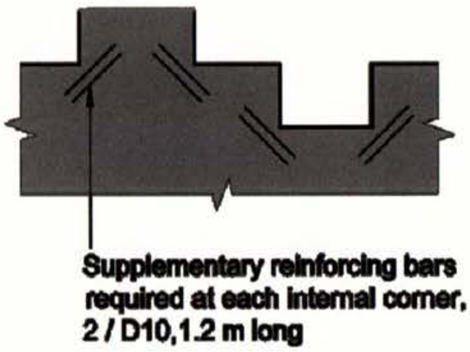

Figure 2-14 Supplementary Slab-on-Ground Bracing at Internal Corners ***(Courtesy: Standards New Zealand 1999)***

Since a slab foundation floats on the ground, differential settlement can cause foundations to move [Figure 2.15], crack and possibly separate [Figure 2.16]. It is for this reason that slab constructions suit reasonably flat consistent sites with gentle and flat topography.

Figure 2-15 Slab on Ground showing relative sliding difference between the Dwelling and Ground; note the prior location of Services ***(Source: BRANZ 2003)***
Figure 2-16 Severe Cracking through a Concrete Slab ***(Source: BRANZ 2003)***

2.3 Sample Spread of Foundation Type[1]

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 2.17].

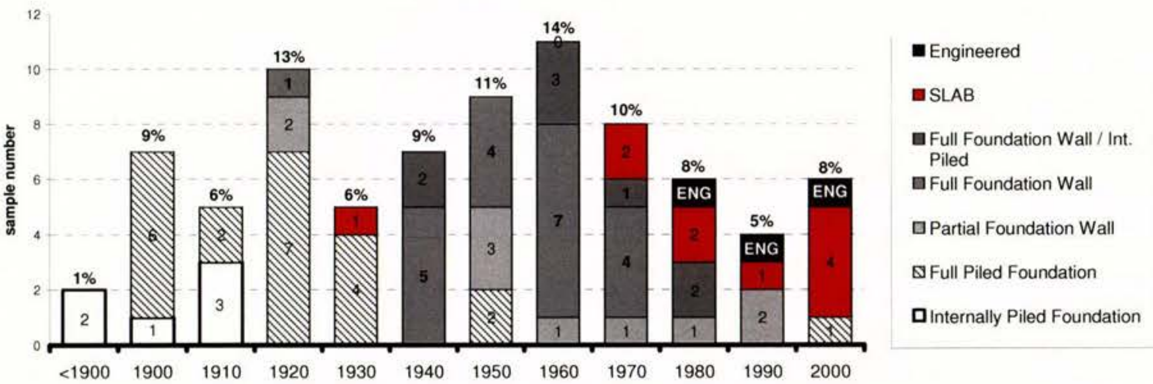

Figure 2-17 Foundation Type for Age of Dwelling, Percentages of the Total Sample.

The sample aimed to include dwellings built in each decade from the beginning of the 20[th] 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 and general condition of the foundation was assessed against the requirements of NZS3604:1999 in light of the site conditions, age and overall weight of the dwelling.

[1] Refer Appendix E – Foundation Definitions for a pull out reference guide of each foundation type

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3 PROJECT METHODOLOGY

The house inspections were undertaken over a three month period during the Wellington winter. As they were all undertaken with a single inspector, methods of standardisation were not an issue and were not required to be integrated into the survey. The survey considered 4 main areas, including the existing bracing potential, the connections and fixings between all framing members, the general condition and an overall comparison between the current standard NZS3604:1999 and the built foundation.

3.1 How do we Determine "Adequacy" of Foundations?

To determine whether a foundation is adequate, it is first necessary to consider the key elements of a foundation which contribute to its overall lateral strength under seismic loading and the degree to which a dwelling remains habitable following a large earthquake. NZS3604:1999 (SNZ 1999) sets out the minimum requirements for foundations, including the seismic bracing potential, the connections between the sub-floor framing members and the overall general condition and durability requirements of a foundation. This standard is used in this study to determine whether a foundation is seismically adequate. Prescriptions such as bracing requirements depend on the seismicity of the area, other geographical, architectural and topographical factors.

3.2 Adequacy of Bracing

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, including all connection methods and general condition parameters. 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 3.1]. 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).

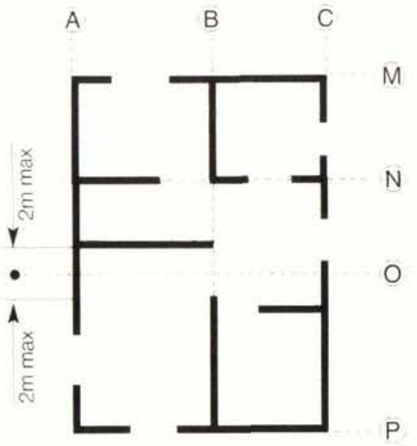


Figure 3-1 The method of Bracing Lines used for all Foundation Calculations ***(Source: Winstones Wallboards Limited 1999)***

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. However, for the lateral strength to reflect the actual onsite scenario, other volumes which contribute to the bracing also needed to be considered. Therefore, bracing was considered on two levels; 'Designed' and 'Non-designed'. The 'Designed' bracing are elements specifically described in NZS3604:1999. The 'Non-designed' bracing included all forms of lateral resistance not specifically designed or intended to resist lateral loads.

3.2.1 Designed Bracing

All elements in NZS3604:1999 with prescribed bracing potential were considered adequate to specifically withstand earthquakes. For concrete walled foundations, the bracing potential is based on the relative height to length ratio, which assumes that longer elements with less average height will be stronger than taller elements of similar length. A corresponding bracing potential of between 42-300BU per metre is then obtained from NZS3604:1999 (Standards New Zealand) [Figure 3.2].

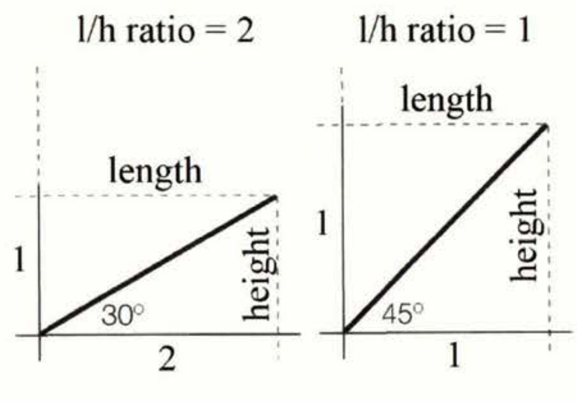


Figure 3-2 Concrete Foundation Wall and Sheet Bracing Length / Height ratio Calculation

Sheet bracing potential is calculated using manufacturers tested strengths (CarterHoltHarvey 2005; James-Hardie Building Products 1994; Winstones Wallboards Limited 1999).

3.2.2 'Non-Designed' Bracing

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 3.3]. The relative dimensions of these concrete volumes were noted and used in bracing calculations mentioned above [refer Section 3.2].

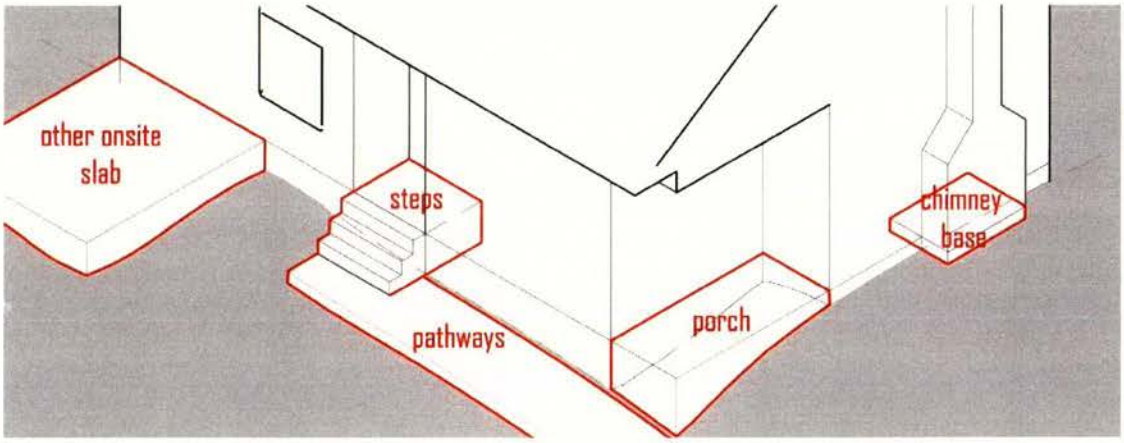


Figure 3-3 Bracing showing Different Non-designed Anchor types in a Foundation

NZS3604 does not take into account lateral resistance of ordinary (shallow) piles in piled foundations. Therefore, when determining whether existing piled foundations are adequate, it is necessary to estimate the approximate resistance of an ordinary pile by calculating the ability of the soil friction surrounding the pile to resist overturning and sliding. Using plans and bracing schedules retrieved from the Wellington City Archives, piles were considered to provide some proportion of lateral soil resistance and friction under lateral loading, otherwise a foundation would collapse under the slightest of lateral force. Calculations of ordinary pile strength showed that a pile, depending on the volume and depth of the footing, was calculated to exhibit between 3-15BU per pile [Figure 3.4].

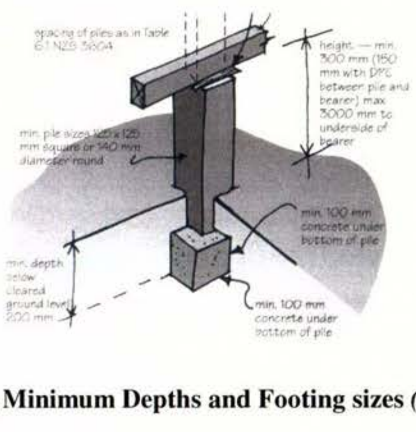


Figure 3-4 Ordinary Pile showing Minimum Depths and Footing sizes ***(Source: BRANZ 2000)***

3.3 Sub-floor Connections

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. See Appendix D for fixing definitions and abbreviations used in the text.

3.3.1 Path of Loads through Sub-floor Framing

The methodology aims to understand where a specific foundation type may be at specific risk from weak fixings, and thus where additional fixing remedies should be applied. It was assumed that each pile will take an equal amount of vertical load and lateral load from the superstructure, however this may differ for each foundation type [Figure 3.5].

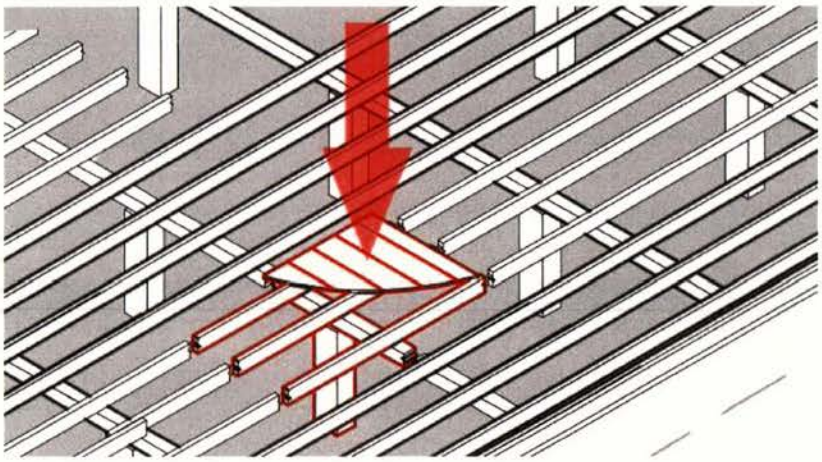


Figure 3-5 The Single Pile Load Methodology

The load is then assumed to be transferred through the framing members, and distributed equally along the length of the bearer [or joist depending on direction], to the bracing members and then to the ground [Figure 3.6].

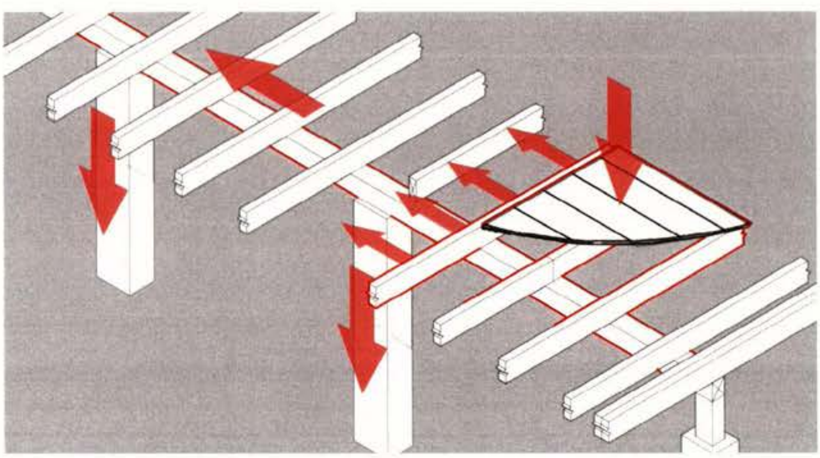


Figure 3-6 Method of Line Load Transfer through Sub-floor Framing to the Ground

Each connection is assumed to take a proportion of load from the entire superstructure [Figure 3.7]. For dwellings with load concentrations at the perimeter of the dwelling, these loads were still anticipated to travel through internal framing to transfer to exterior bracing elements over the whole foundation area.

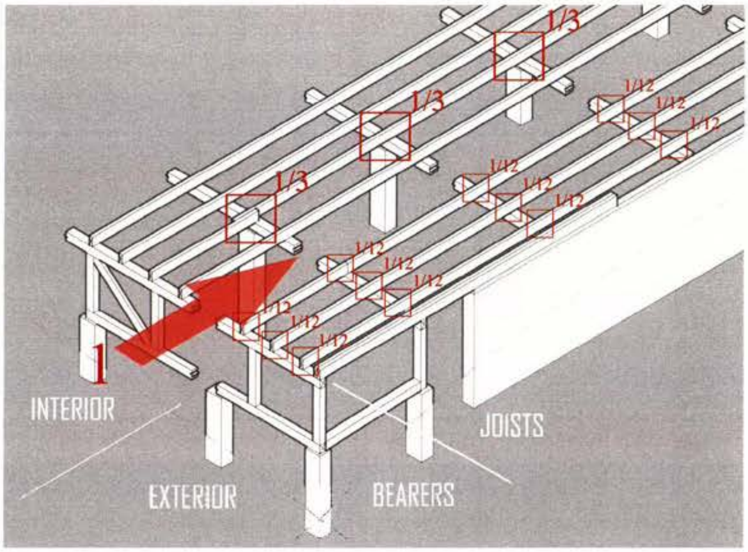


Figure 3-7 Proportion of Force relative to the Number of Connections in the Foundation

3.3.2 Adequacy of Connections to NZS3604:1999

The second method of determining connection adequacy is the acceptable connection methods (including connection methods for bracing) as required by NZS3604:1999 and stated in manufacturer's literature (Pryda New Zealand 2005; MiTek New Zealand Limited 2000). Failure of connections was assumed to occur where loads between framing members exceeded the design capacity of the fixing and therefore require additional fixings over and above prescriptions in NZS3604:1999. Also calculated to contribute to the strength of each connection, is the friction between elements that are fixed together. Differing friction coefficients are observed when different surface textures interact. This can either increase or decrease the overall observed strength of a connection (Gorst and Williamson 2003). Friction between connections is observed in all materials; however as an earthquake in locations such as Wellington is likely to exhibit a proportion of vertical acceleration, this will momentarily result in zero or significantly reduced friction between members. Four different scenarios were considered depending on the interface materials and the direction of loading [Figure 3.8].

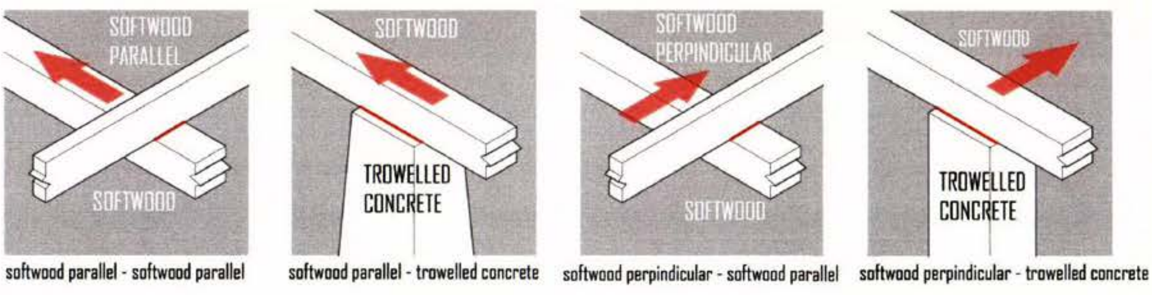


Figure 3-8 Differing Friction Material Interfaces seen in the Sample Connections

3.4 General Condition

The information collected to assess the overall condition, assessed the weight of the dwelling, the deficiencies such as the pile defects, configuration issues and poor or missing structure. Timber type and overall condition were assessed, as well as the fixing degradation. Other historic issues such as ventilation, moisture and leaking services were assessed in order to analyse the relative condition of a foundation. This information was compiled to find the overall condition of dwellings and compared against the most recent House Condition Survey 2005 produced by BRANZ (Clark, Jones, and Page 2005).

3.5 The Comparison against NZS3604:1999

The results are compared with NZS3604:1999 in three areas important to the structure and load path: the structural member compliance, the fixing provision compliance and the non-structural provision compliance [Figure 3.9]. The comparison of fixings and structural members from older construction standards can provide insights into whether foundations were constructed as prescribed, or when these prescriptions began to be enforced. With these observations, it is possible to determine whether foundations are inadequate compared with the current or superseded standards.

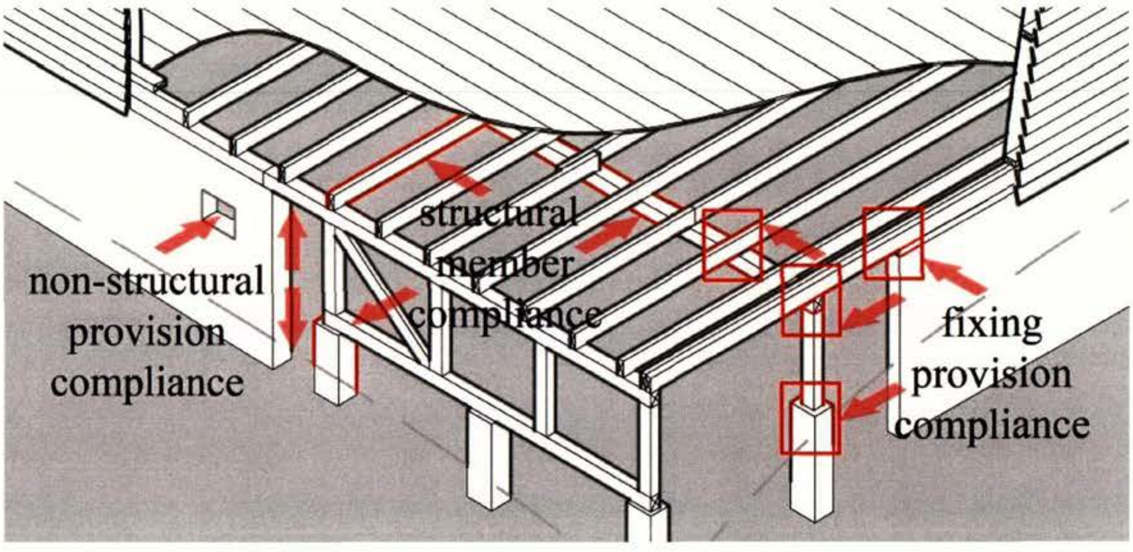


Figure 3-9 All Areas analysed in the Dwelling Comparison against NZS3604:1999

4 RESULTS OF ONSITE OBSERVATIONS

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. The overall general condition of foundations surveyed was moderate and most consistent in dwellings constructed between 1940 and 1960. However, some newer dwellings from the 1970's and 1990's showed serious signs of premature degradation resulting in a below average condition rating. Serious ventilation issues were seen in 45% of dwellings and 54% of connections in dwellings had some form of rust or oxidisation. Determining the adequacy of foundations in the respect of condition, however, remains reasonably subjective.

4.1 Reliance on Non-Designed Bracing

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. The majority of Piled Foundations (IPF and FPF) had inadequate foundation bracing. This meant that over 80% of those dwellings that had inadequate bracing had piled foundations [Figure 4.1].

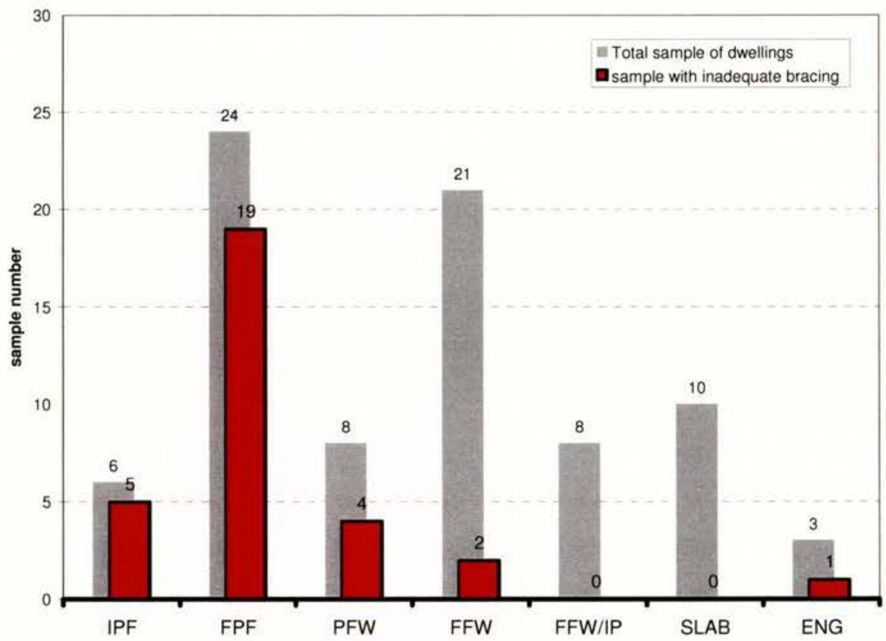


Figure 4-1 Total number of Dwellings failing Bracing Requirements per Foundation type

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.

4.2 Friction Resistance of Connections

Overall, an average of 13% of connections providing load paths to the bracing members (in four significant locations sampled), were inadequate. Excluding the effects of friction, the number of connections failing increases by 24% for the Joist to Bearer connections and 65% for connections from Bearers or Plates to the concrete Foundation wall. The Ordinary pile to Bearer connection was inadequate in 56% of the sample, so about half of the connections were inadequate even after repiling. Although some connections failed due to poor construction or materials, older dwellings failed as connections used are weaker than those prescribed by modern Standards. The Plate to Foundation wall connection has had changes in most significant Standards since 1924. As the standards have developed fixing spacings have reduced. However, only 5% of the Plate to Foundation wall sample would fail to transfer loads adequately. The Figure below show the number of dwellings with inadequate connections with and without friction included in the calculations [Figure 4.2]. It shows that all foundation types rely heavily on friction to transfer load, except the slab foundation construction. It should be noted that the earthquake scenario chosen [refer Section 6.1] may result in vertical accelerations up to 1g (gravities) or more (Cousins, Pers. Comm.). Hence, no friction between framing elements can be assumed to contribute to the overall strength of a framing connection [refer Section3.3.2].

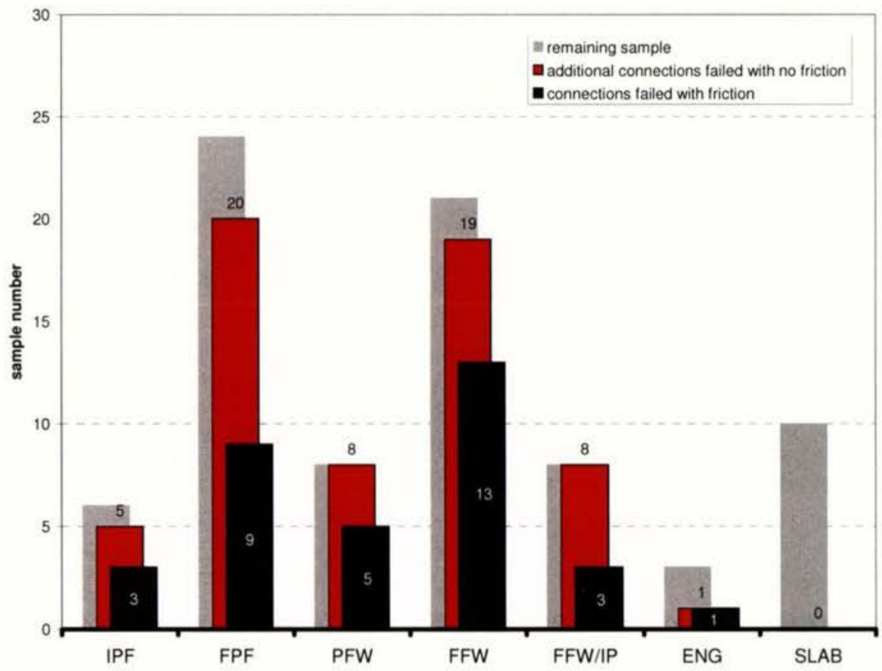


Figure 4-2 Connection failure Including and Excluding Friction compared with Foundation type

4.3 Configuration Issues and Structural Defects

The general conditions observed onsite correlated well with the 2005 House Condition Survey (Clark, Jones, and Page 2005), however more issues such as excessive levelling wedges in repiled and re-levelled dwellings were observed in the sample. Figure 4.3 shows the percentage of the sample with structural deficiencies. However, overall a number of dwellings had a combination of these issues, especially in older dwellings that have a combination of missing structure, insufficient footing depth and non-vertical piles. Dwellings that had additions were either: Full Split level dwellings where part of the lower floor is dug underneath the dwelling, Half split level dwellings where one floor level is half a storey above the other, or dwellings with differing foundation systems. All of these forms of foundation system can result in configuration issues under lateral loading. Unfortunately, it was more difficult to assess the adequacy of foundations with configuration issues, as the significance of these issues usually only becomes apparent following an earthquake.

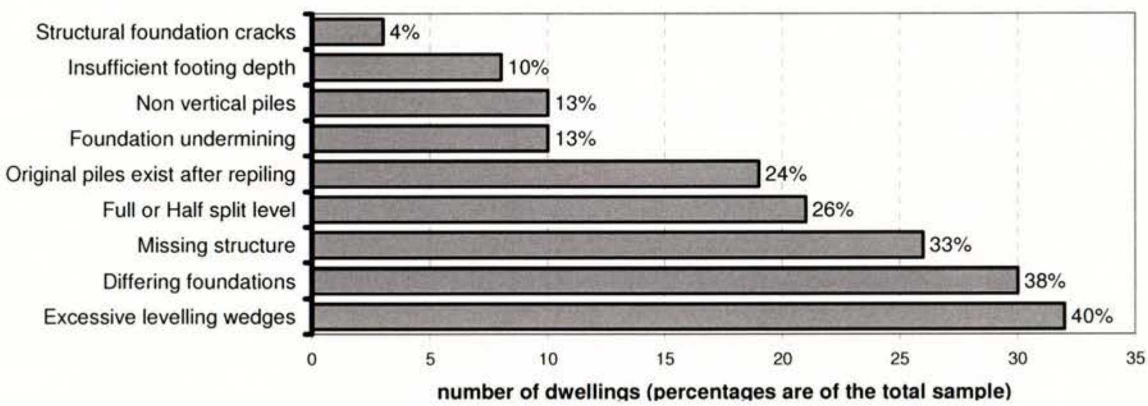


Figure 4-3 General conditions pertaining to foundation durability

4.4 Summary of Results

As expected, older dwellings had a lower bracing capacity and were more likely to have deficient connections compared with current NZS3604 requirements. However, some modern dwellings built around the 1970's, 1980's and 1990's had an extremely poor general condition and limited connection capacity as a result of fixing degradation. The impact of dwelling mass on connections showed increased failure for dwellings with a combined roof and wall cladding weight over 4 kPa, such as brick veneer dwellings and dwellings with concrete tile roofs. These heavier dwellings were the most evident around the 1940's and peaked around the 1980's. The percentage of dwellings demonstrating poor conditions, weak connections and limited bracing, is comparable to the number of adequate dwellings.

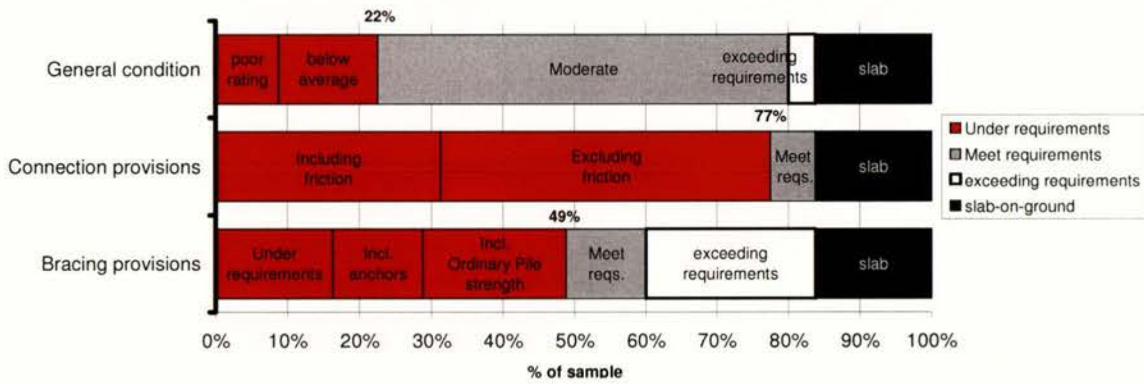


Figure 4-4 Overall failure for key foundation elements

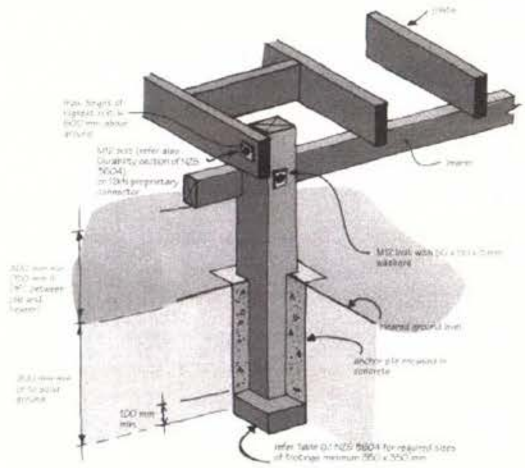
Figure 4.4 shows that overall, bracing was inadequate in 49% of the dwellings with sub-floor foundations (e.g not Slab-on-Ground dwellings) of this about half relied on the strength of Ordinary Piles and one quarter relied on large concrete anchors. A significant number of fixings failed to comply with NZS3604:1999 however, were still calculated to adequately transfer loads through to the bracing and other connections. Just over 25% of the sample showed adequate fixing capacity under conditions where friction cannot be expected. However, no dwellings exceeded minimum requirements of fixings. The condition of foundations was generally adequate, with 18% of the sample having excellent overall general condition, usually seen in newer dwellings and 58% had only moderate condition issues. 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, and then we can estimate the economic cost of remedial action to the individual and the direct economic savings for society.

5 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).

5.1 The Piled Remedial Solutions

Remedial piled solutions include the anchor pile solution, seen in Figure 5.1 and the braced pile solution in Figure 5.2, 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.



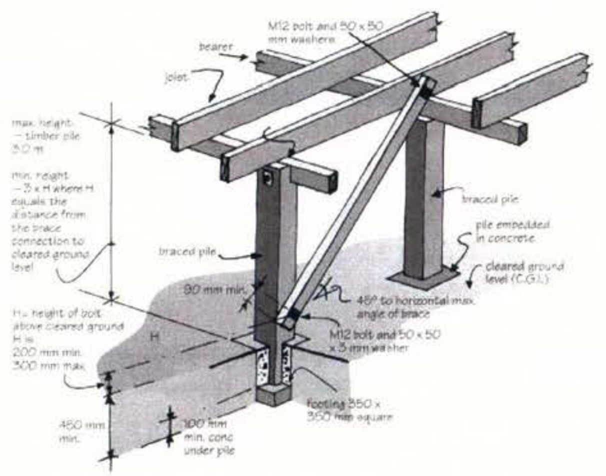


Figure 5-1 Anchor Pile Solution ***(Source: BRANZ 2000)***
Figure 5-2 Braced Pile Solution, Braced from Pile to Joist ***(Source: BRANZ 2000)***

5.2 The Remedial Sheet Bracing Solutions

The sheet bracing solutions offer applications that gain their strength when the length of the bracing element is increased [refer Section 3.2.1]. In accordance with the BRANZ remedial solutions in *Strengthening Houses against Earthquake: A Handbook of Remedial Measures* (Cooney 1982), solutions include the application of 6mm plywood to exterior piles and the infill of concrete between exterior concrete piles. The Sheet bracing solution on exterior concrete piles requires constructing framing between piles and fixing the perimeter directly to this framing. Thus, construction costs will be reduced if the exterior piles are timber. Manufacturers prescribe a strict minimum number of fixings to achieve the required bracing, as well as limitations on maximum and minimum sheet height and distance from CGL [Figure 5.3].

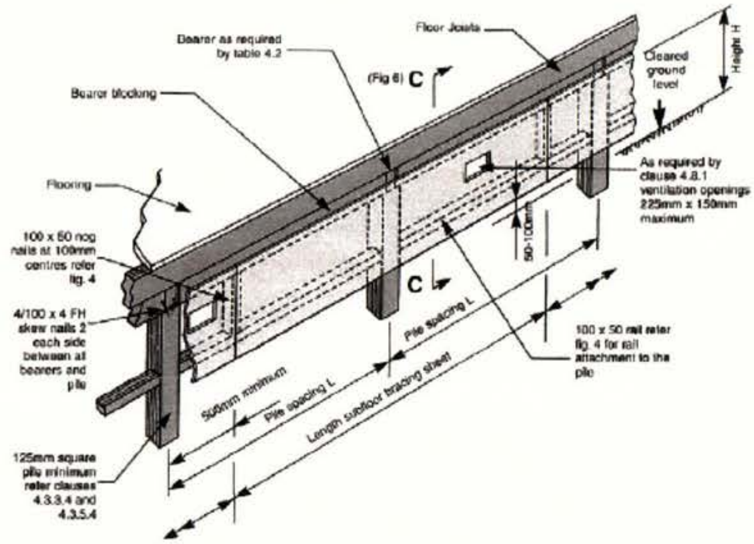


Figure 5-3 Sheet Bracing Remedial Solution ***(Source: James-Hardie 1994)***

Alternatively, the concrete infill wall solution (Cooney 1982) requires the bracing element to be integrally cast with existing footings, spanning between the two piles [Figure 5.4].

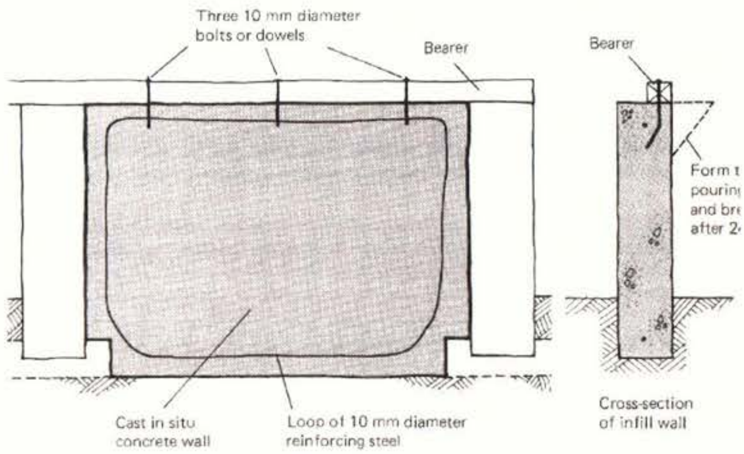


Figure 5-4 Concrete Infill Wall Remedial Solution ***(Source: Cooney 1982)***

The application of new bracing was initially 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 remedying the general condition, 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 5.1 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 5-1 The Remedial Measures and Costs applied to each Foundation Type.

It is apparent from the table that older dwellings, with piled foundations, will cost more to remedy than newer dwellings. However, it must be emphasised that this is the assumed average case and costs to remedy the dwelling's condition vary significantly due to the labour intensity of the general condition found onsite. The other costs of earthquake repair, usually discussed as the wider implication of the earthquake on society, are concerned with the losses in production markets, the inflation and post-earthquake repair and the cost of shelter and aid to be provided to society. The losses in production markets will cause mass unemployment and produce mass material shortages, as observed after the 1995 Kobe earthquake (Park 1995b). The material shortages, destroyed transport infrastructure and increased demand for construction professionals will drive the cost of such services up during the post-earthquake repair period. This inflation has been estimated as high as 10-30% of normal construction costs (Davey & Shephard 1995). Evacuation, shelter and aid necessary for people in collapsed or extensively damaged dwellings is perhaps the biggest contributor to unknown economic costs (Cooney & Fowkes 1981). This includes the erection, siting and maintaining of shelter, which is currently not governed or controlled by any formal body. Other non-economic costs, such as the psychological distress resulting from the destruction of one's property or from moving to a temporary shelter, as well as the time involved with inspections, investigations and lodging insurance claims to the EQC, all contribute to the overall indirect costs to the homeowner and society.

Upgrading foundations aims to increase the total number of habitable dwellings, limiting evacuations and the necessary shelter and serious aid resulting from collapsed dwellings. This may decrease pressures on national insurance reserves, decrease personal insurance costs and limit residential material and labour demands on over-burdened markets.

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6 CALCULATING A COST/BENEFIT RATIO

In order to justify the costs of upgrading foundations and to find the overall economic benefit to society and the individual, an Earthquake Loss Modeller is used to calculate the cost before an earthquake and then following an earthquake, with adjusted damage parameters over the whole sample.

6.1 Description of the "Loss Modeller"

The economic costs of an earthquake hitting Wellington, was calculated using the Institute of Geological and Nuclear Sciences "*Earthquake Loss Modeller*", developed by Jim Cousins. The loss modeller output displays the number of casualties, total economic loss to residential dwellings and commercial properties for any given city. For the purposes of this study, the results were limited to the Wellington city suburban limits, described in Wellington City Council District plan maps. The damage costs described do not include Porirua or the Hutt valley or any of the wider affected area in New Zealand. The modeller uses Damage Ratios and values are assumed "*reasonable probabilistic fits to Earthquake Commission (EQC) losses for period 1990 to 2003*"(Cousins 2005). Remedial measures are applied to the foundation to ensure that the dwelling may remain habitable following an earthquake. The foundation behaviour should remain predictable and failure mechanisms should be capable of dissipating energy through ductile yielding (SANZ 1992). 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).

6.2 The Costs and Benefits

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. Results in Table 6.1, suggest that the biggest cost saving will be in 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 will still occur). The foundation type does affect the damage and collapse ratio, and a preliminary assumption based on sample observations, suggests that around 80% of "at risk" dwellings are piled foundations.

Foundation type	TOTAL No. Dwellings affected before remedy	TOTAL Assets 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 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 6-1 Statistics Before and After Application of Remedial Measures

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 6.2] 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, however is still very beneficial for extensive damage, considering that any cost / benefit less than 1 is still seen as a saving.

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 6-2 Maximum and Minimum Cost / Benefit Values for all ranges of Damage

6.3 Do we need to Upgrade?

The results above suggest that dwellings require, on average, reasonable expenditure to achieve the current standards requirements. The very low cost / benefit ratio suggests that it is economically justifiable to remedy foundation defects in dwellings, even if more conservative assumptions concerning the sustained damage had been made. This analysis assumes that a maximum credible earthquake will occur in the lifetime of these dwellings. Assuming an average building life of 50 years and the often quoted 50% probability of a maximum credible earthquake in Wellington within 50 years, the cost / benefit ratio would double to about 0.3. Assuming the likelihood of piled dwelling collapse (over 70%), and applying information contained in the House Condition Survey, the cost of upgrading certain foundation types may be less than the total average annual expenditure currently spent on maintaining dwellings (see Clark, Jones, and Page 2005).

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7 DISSEMINATION OF INFORMATION

The effectiveness of the information contained in this report and the extent to which recommendations are adopted by society is completely reliant on the adequate and appropriate dissemination to society. The dissemination of this kind of information is currently supported by Government run organisations such as the EQC and the Civil Defence, who are concerned with saving the public from injury as a result of disaster. The Fix, Fasten, Forget initiative prompts people to secure the interior objects of their dwellings. Other programs focussed at informing the public of the risks of earthquake and what can be done to prepare, usually occur where people are receptive to learning such as museums and newspapers (Finnis 2004).

However, no matter the advertising, it is ultimately the homeowner's decision to prepare for an earthquake. The focus for the homeowner usually requires an understanding of what information is most relevant, what action is most important to undertake first, and whether or not any remedial action is actually required; all of which are based heavily on the psychology of disaster preparation (Finnis 2004). Thus, it is in the best interests for private and national insurance programs, as well as Local and National Authorities to ensure that people have the adequate incentives to limit damage to the home and to adequately prepare the foundation area for earthquakes. These incentives could be in the form of legislation change, residential dwelling checks for earthquake strength or other incentives which will not seem oppressive or demanding and which results in savings and benefits for all areas of the community. Third party businesses involved in making earthquake preparation easy, perhaps find a middle ground for the situation, where they provide a simple kit which is available to apply to the earthquake preparation requirement. However, this may not suit structural repairs to foundations that require professional opinion and appropriate remedy. Perhaps the best method of implementation is a brochure that 'piggy backs' current dissemination initiatives such as the 'Fix, Fasten, Forget' program. This information could also become part of a primary dwelling inspection, for pre-purchase house inspections, or alternatively a residential building Warrant of Fitness. The warrant of fitness, and therefore checks on the seismic stability of foundations, could become the prerequisite for obtaining a reasonable sale price for a house. This would then mirror legislation adopted in California that legally requires the homeowner to brace certain parts of the dwelling against earthquake (Seismic Safety Commission 1992). Overall, New Zealand society requires a proactive rather than a reactive stance, for the application and dissemination of information regarding the necessity of foundation remedial measures. It is only in a proactive society, ranging from authorities to communities, that we will mitigate the unnecessary damage to dwellings, caused by weak and inadequate foundations.

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8 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. 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. Overall, the condition of dwellings was similar to results seen in the BRANZ produced House Condition Survey 2005, with a lack of sub-floor ventilation, inadequate framing clearance and structural defects listed as the main concerns. Therefore, remedial bracing measures are assumed to be necessary in almost 40% of the 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. It was found that piled dwellings built prior to 1940 make up the large proportion of unbraced, at risk dwellings and application of remedial measures would cost less than 10% of the average dwelling reconstruction bill, not including post-earthquake inflated labour and material costs. This total alone could potentially save almost \$1Billion in post earthquake repairs and mitigate the unknown costs of temporary shelter and aid requirements for the homeowner and communities. 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 a disaster. As it stands, no direct economic incentive for the building owner currently exists for the seismic upgrade of residential foundations.

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APPENDICES

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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).

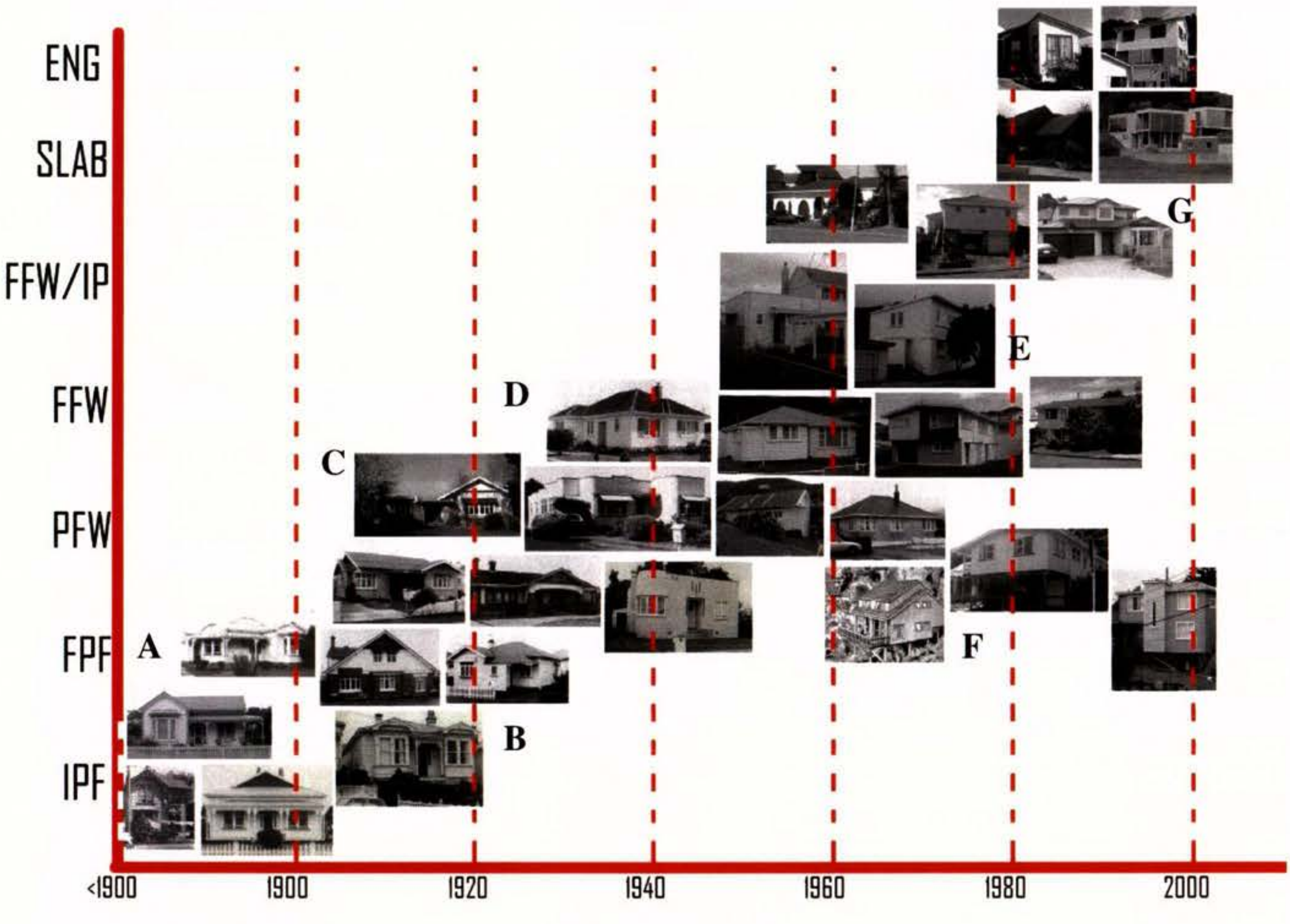

Figure A-1 Domestic Architecture relating to Foundation type and age of the Style

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. 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].

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.

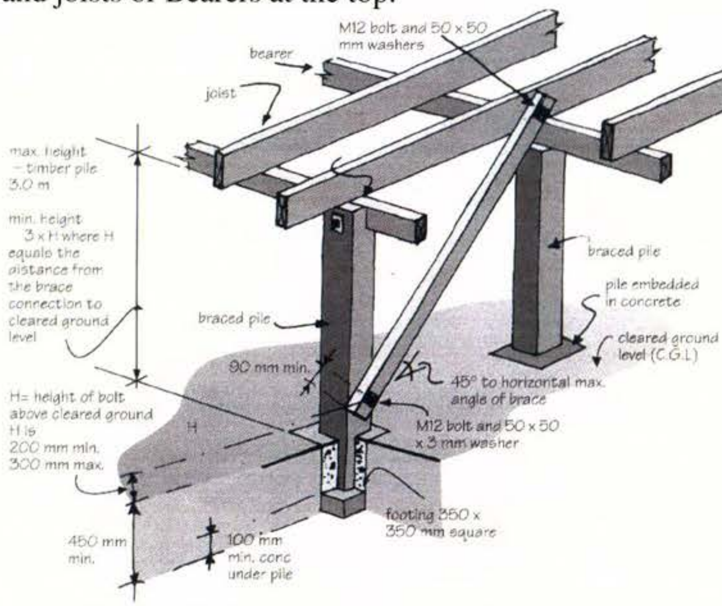

Figure B1 Braced Pile Solution, Braced from Pile to Joist ***(Source: BRANZ 2000)***

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*

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

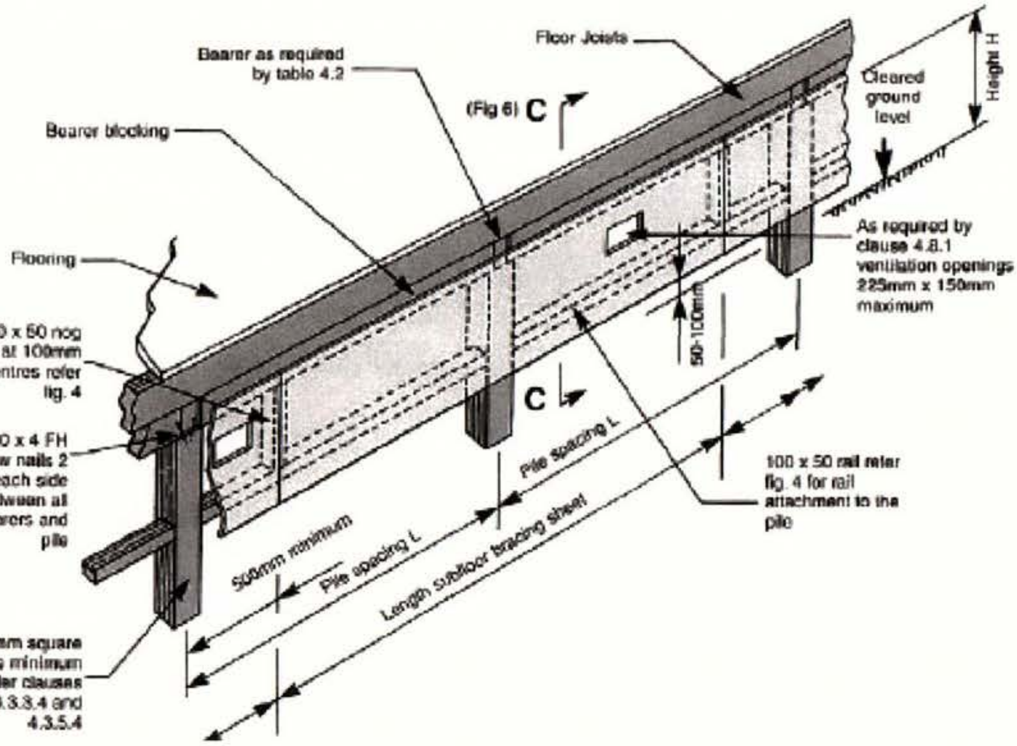

Figure B2 Sheet Bracing Remedial Solution ***(Source: James-Hardie 1994)***

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*

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.

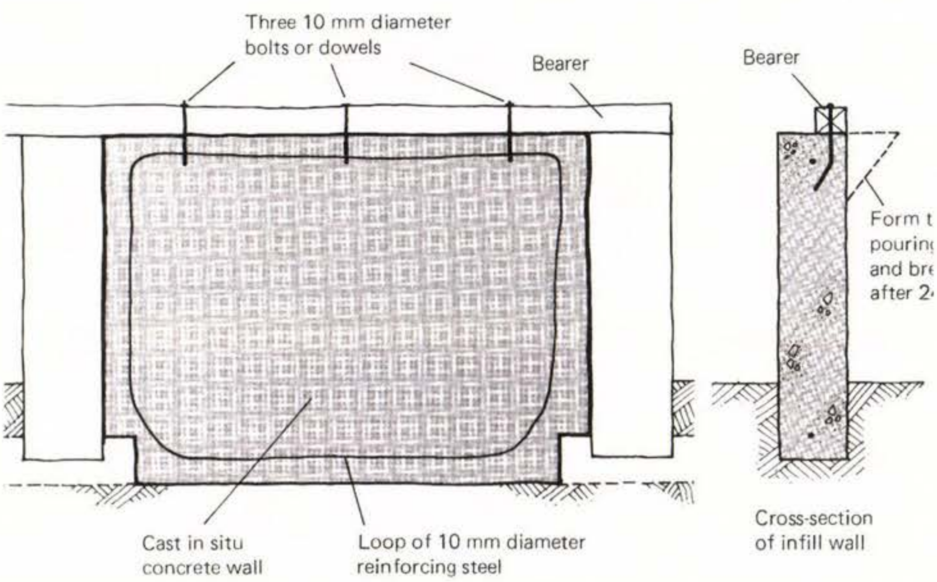

Figure B3 Concrete Infill Wall Remedial Solution *(Source: Cooney 1982)*

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

Bl.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

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Bl.3.3 *Total costs* *$1230.00 per linear metre*

Bl.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.

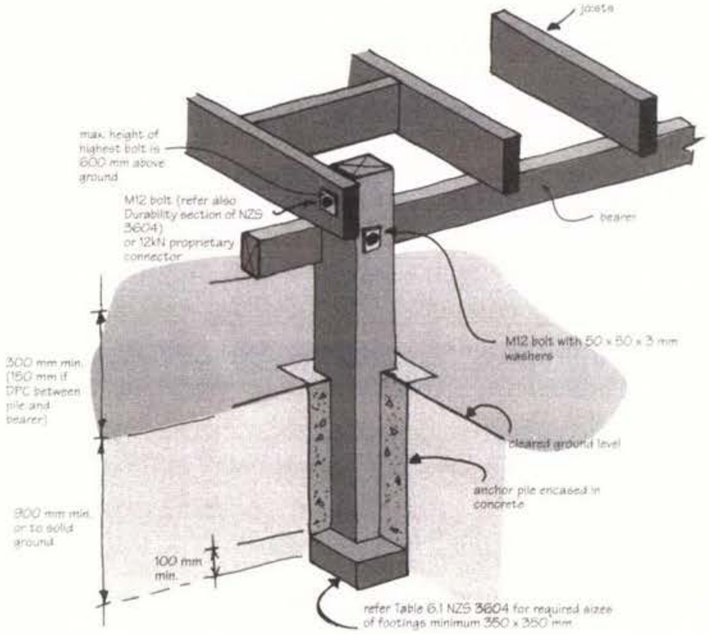

Figure B4 Anchor Pile Solution *(Source: BRANZ 2000)*

Bl.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

BI.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]**

BI.4.3 *Total costs* *$277.50 per pile system*

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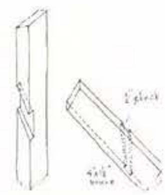
Anchor piles Piles which rely upon the soil bearing pressure and depth of footing to provide lateral resistance prescribed as 120BU. The depth and width of footing is greater than a cantilever pile.

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 cannot span required height as prescribed by the 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 45° to 30° 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.

Water Staining When water seeps into timber and a distinctive stain is left

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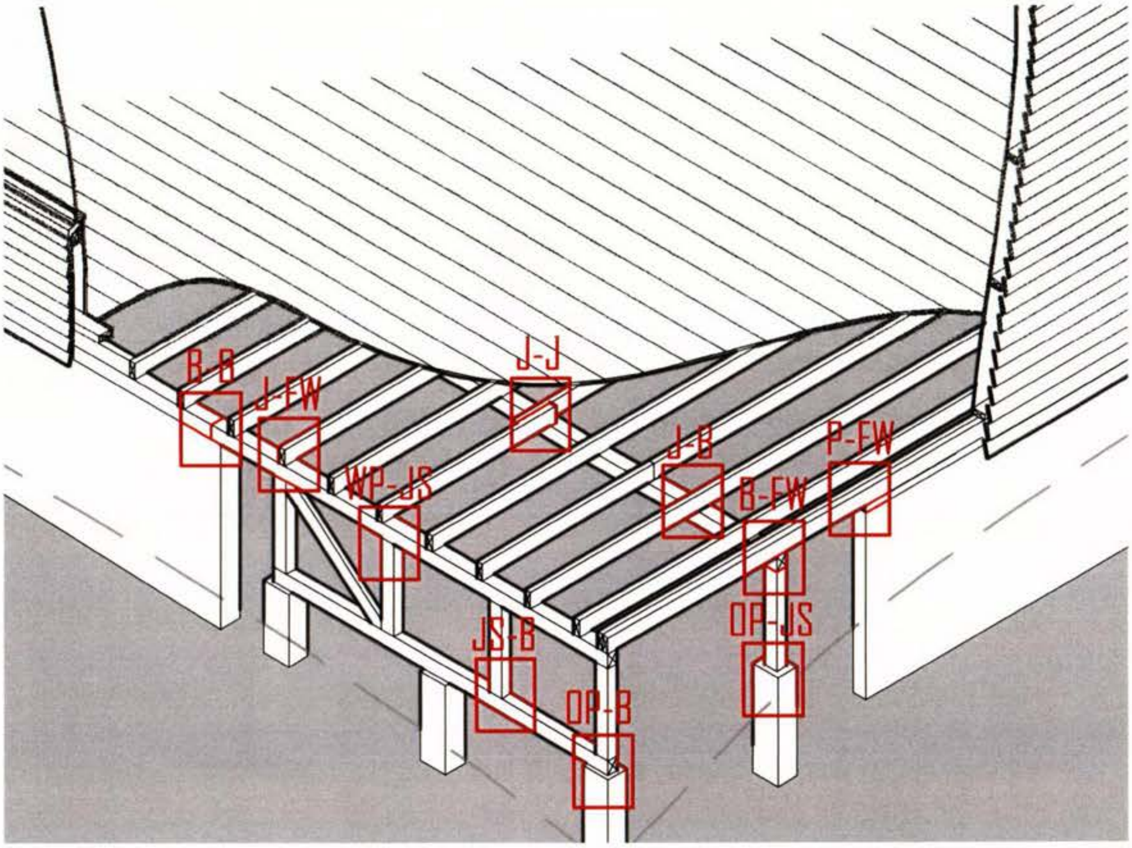
The definitions related to graphic displays are used through out the text to describe fixings and the associated connections.



[J-B]	Joist to Bearer fixing
[J-J]	Joist to Joist connection, usually flitch, butt or lapped joints
[J-FW]	Joist to Foundation wall (sleeper plate)
[OP-B]	Ordinary [or other] Pile to Bearer
[P-FW]	Plate to Foundation wall, usually bolted or fixed with R10 bar
[B-FW]	Bearer to Foundation wall, as above
[B-B]	Bearer to Bearer fixing, usually butt or flitch joint
[WP-JS]	Wall plate to Jackstud
[JS-B]	Jackstud to Bearer
[OP-JS]	Ordinary Pile to Jackstud

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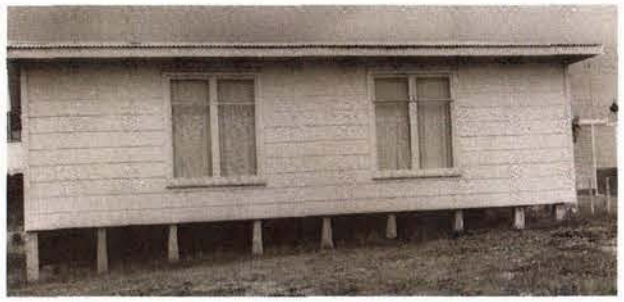
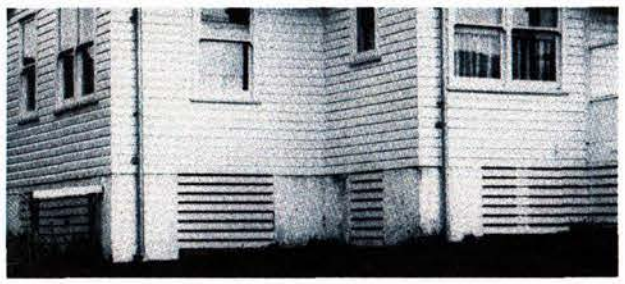
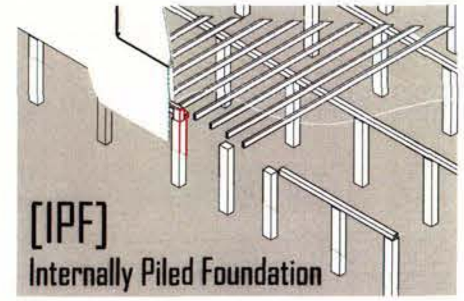


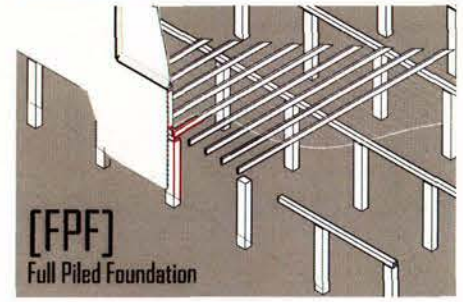


Foundation Definitions

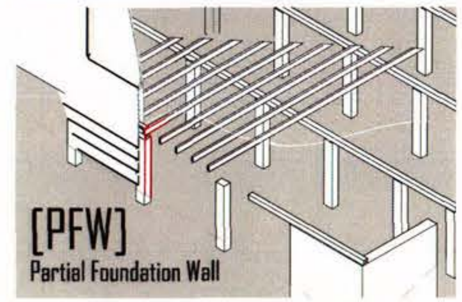
Piled foundation where exterior shell is separately piled from the internal flooring. Usually seen in older dwellings with timber cladding and generally lower to the ground



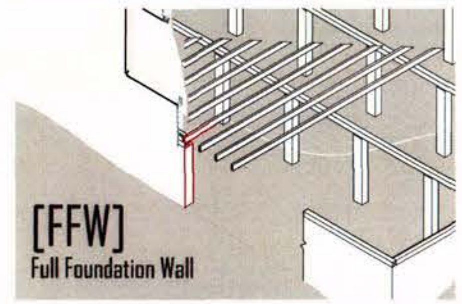
Concrete or timber piles supporting entire dwelling in unison, no special detailing given to exterior piles. Usually clad with similar material to superstructure



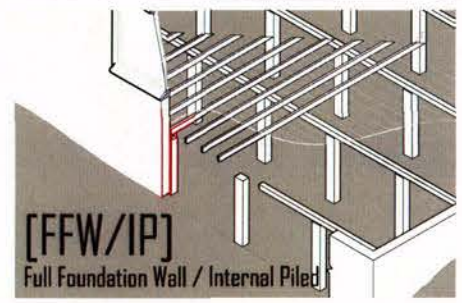
Dwelling supported on internal piles with partial concrete walls at the corners of the dwelling. Timber boards are usually used for cladding between concrete sections



Full concrete perimeter foundation wall. Bearers and joists sit on this and interior of dwelling supported by internal piles. Common with dwellings clad with masonry, brick or heavy concrete tile roofs



Dwelling with full perimeter concrete or masonry sub-floor wall supporting superstructure. Internal piles usually support interior of dwelling only



Concrete slab on ground used commonly in modern dwellings in gentle topography. Slab is usually reinforced and essentially floats on the underlying soil.