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 total 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

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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 Gisborne 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 (SANZ, 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 150 mm 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.

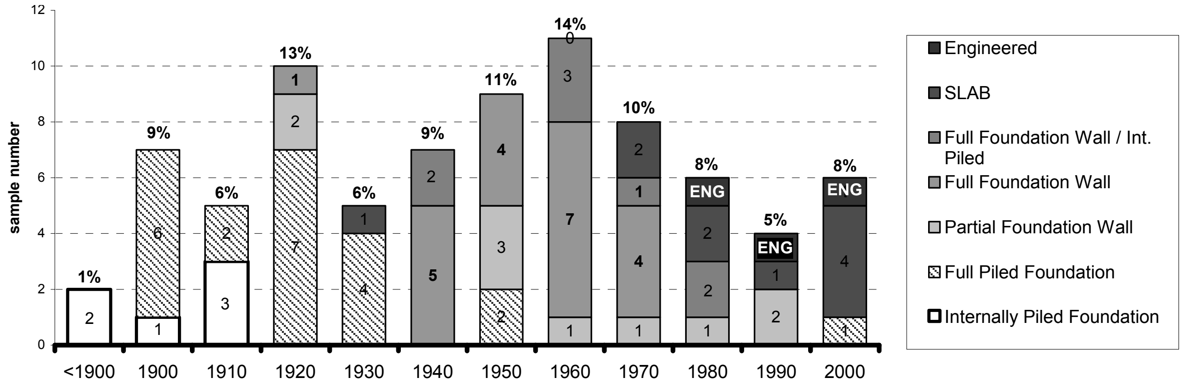

Figure 1. Foundation type for age of dwelling, percentages of the total sample.

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.

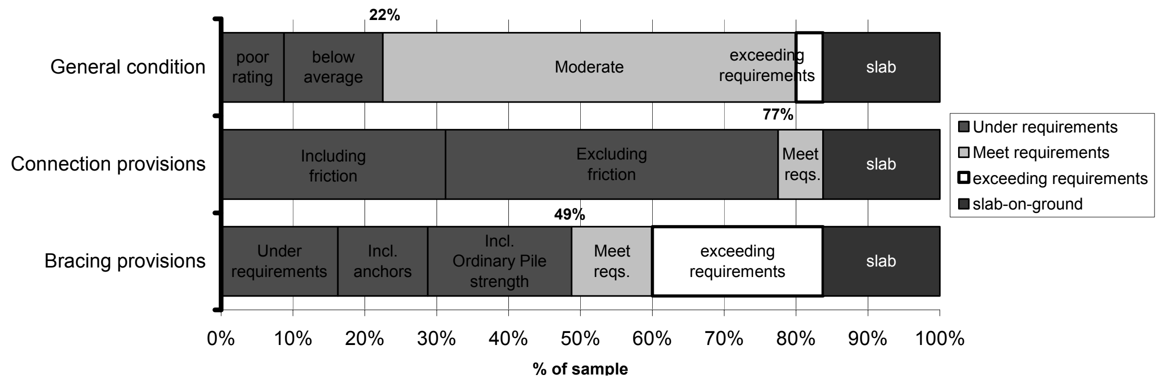

Figure 2. Overall failure for key foundation elements

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. 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.

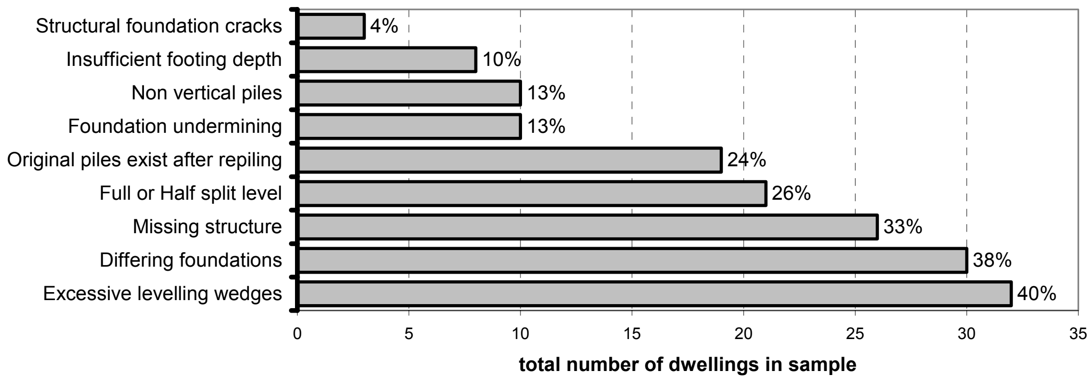

Figure 3. General conditions pertaining to good construction practice

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 2,000BU 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 kN per square metre of floor area. 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 8 km, 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 1,290 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 (139 sqm) one can assume that a Piled foundation will cost $974 to apply remedial sheet bracing. Other foundation systems rate higher at around $2,800 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 sys-tem	% Sample requir-ing bracing	Remedial solution	avg. remedy per dwell-ing	avg. fixing cost per sqm	avg. condition cost per sqm	avg. bracing cost per sqm	TOTAL
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). The remedial action on 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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