Impact of seismic demand on construction costs

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ABSTRACT

The legally binding earthquake performance requirements in New Zealand's Building Act and Building Code emphasise building collapse prevention and to safeguard people from injury, allowing for a certain degree of damage to resist the seismic load. However, societal expectations demand that buildings remain operational after an earthquake. The research aims to understand the true cost of building structures that remain operational after an earthquake. Our assumptions are that, 1) higher seismic demand is expected to have a limited impact in overall construction costs, and quite minimal impact on total development costs, and 2) the influence of seismic resilience on construction costs is different depending on the structural system. An extensive construction costs database was developed including the most typical structural and foundation systems. The main conclusions are that 1) the effect of location alone (i.e. without include the seismic hazard of that particular location) and floor type on construction costs is not critical, 2) the impact of a higher seismic demand on construction costs depends on the structural system, and 3) foundation type has a large influence on construction costs but seismic demand does not. Engineers should prioritise stiff lateral systems but without compromising resilience and redundancy through proper ductile detailing because the cost implications of having a stiffer structural system are minimal, especially when considering the total development costs. The cost implications of having more resilient buildings that can be readily occupied after an earthquake are negligible, and New Zealand should move towards stiff, damage resisting structures using well understood structural systems like reinforced concrete walls and steel eccentric braced frames. The society expects this from our buildings, our engineers are trained and capable to design them, and the extra cost is minuscule.

1 INTRODUCTION

The Building Act (MBIE 2004) and the Building Code (NZG 2004) state that the building has to "*withstand the likely earthquake load*", i.e. to "*safeguard people from injury* [and] *loss of amenity* [as well as] *protect other property from physical damaged caused by structural failure*". However, societal expectations have evolved, particularly after seismic events like the 2010/2011 Canterbury earthquakes, which highlighted the economic and social costs of damage. Despite adequate life safety performance in most buildings during the Canterbury earthquakes, nearly 70% of multi-storey reinforced concrete structures in downtown Christchurch were demolished (CERC 2012), influenced by factors like insurance payouts and economic considerations(Marquis et al. 2017, Parker and Steenkamp, 2012). The societal shift towards immediate post-earthquake operational functionality, as outlined in reports like the Canterbury Earthquake Royal Commission Report(Dhakal 2011), has prompted a reevaluation of design philosophies. The current approach in New Zealand allows for some degree of structural damage to dissipate earthquake energy, but there's a call, particularly in the "Buchanan report,"(Dhakal 2011, Buchanan et al 2011) for higher performance standards to minimize non-repairable outcomes. A simple method to minimise damage is to design buildings respond largely in the elastic range, but without compromising ductility and resilience. Construction cost is often used as a reason to use ductile structures but this reason has not been robustly challenged for new building construction. The research motivation of this project is to understand the true cost of building stronger and stiffer buildings that do not suffer significant damage and can be operational shortly after an earthquake.

2 LITERATURE REVIEW

We identified 73 parameters that influence construction costs based off a systematic literature review including 133 documents(Castro Miranda et al 2022). The building size, compounded by the floor area and the number of floors has the largest influence score. Only two structure driver are within the top 10 cost drives, being the foundation due to extensive excavation works and the type of structure. These results are from non-seismic countries, so the cost drivers of New Zealand are likely to be different. Zhao (2018) investigated which factors of the building development process influence the building development cost using expert elicitation (experts' opinions) and experimental, analytical and modelling data. Socio-economic factors have the highest influence, while Property market and construction industry have the lowest. Construction costs, together with design and procurement costs have the least influence on the building development cost. Engineers cannot significantly influence the most critical factors, such as the property market and construction industry, but can still aim to reduce the project's complexity and mitigate the elevated costs from statutory and regulatory factors, for example. In New Zealand, the structural costs are typically about a third of the total construction (QVCB 2021). Other sources point to the structures component of a mid-rise building being typically around 20% of the total construction cost(Rawlinsons 2013, Dhakal & Aninthaneni, 2021). Based on the admittedly scarce literature, the hypotheses are that 1) higher seismic demand is expected to have a limited impact in overall construction costs, and quite minimal impact on total development costs, and 2) the influence of seismic resilience on construction costs is different depending on the structural system.

3 METHODOLOGY

The number variables affecting the structural construction costs of buildings is too large to consider all of them, especially when final design considerations are accounted for. The design and costing of a large number of case studies but only at a preliminary design stage was produced using Resist (NZSEE 2008), a software developed and hosted by the New Zealand Society for Earthquake Engineering (NZSEE). Seismic hazard is composed of multiple variables but considering all of them would be time-consuming. The seismic hazard factor *Z* from NZS 1170.5 (NZS, 2004) was used as a simplified measure of seismic hazard given how widely recognised its values are, and to make the data analysis and discussion more intuitive and easier to follow. A higher seismic hazard factor *Z* has been used to simulate not only higher seismic demand, but also as a proxy to more earthquake resilient buildings. Specialised methods and/or software were sometimes used, including 1) NZ standards, 2) supplier documentation, 3) SCNZ and HERA guidance and software on steel design (SCNZ 2007), 4) SESOC's Gen-Wall (SESOC 2020) for RC wall design, and SESOC Soils (SESOC 2021) to design the foundations.

QV cost builder (QVCB 2021) was used to obtain the unit cost at the various locations (Auckland, Wellington and Christchurch) and multiply by the quantity take off to get total cost. The unit cost does not take into consideration the seismic hazard of the location, but other aspects such as logistics of delivery, labour market, etc. The impacts on construction costs from location alone and from the seismic hazard must be decoupled so the differences are investigated and understood. To do so, the seismic hazard was artificially changed at the various locations, as shown in Table 1. The data was collected in Excel, Python and/or Matlab, to combine the quantity take offs with the cost data and further parametrise the problem (e.g. different costs in different cities) and visualise the results.

Key shortcomings of the research are 1) floor diaphragms are considered rigid and adequate to transfer seismic loads, but not checked or designed, 2) structural connections are not designed, especially critical for steel structures as discussed below, 3) concrete columns are always rectangular and of a fixed slenderness ratio, 3) reinforcement ratios are fixed, 4) only planar walls (i.e. no enlarged boundaries, L, T, I walls, etc), 5) facades, non-structural elements and fire protection is not included, and 6) up to 8 storeys high buildings.

4 RESULTS

The results are divided depending on the structural system:

4.1 RC frame buildings

A total of 16 Resist models were created using four building sizes (432 m^2 across 3 storeys, 1152 m^2 across 8 storeys, 8748 m^2 across 3 storeys, and 23328 m^2 across 8 storeys), 2 *Z* hazard factors (0.4 and 0.7), and two floor weights. The cost parameters used to parametrise the quantity take off were 5 bar sizes for a constant reinforcement ratio (D16, D20, D25, D32 and D40), 3 cities (Auckland, Wellington and Christchurch) and 11 floor types (1 type of cast in-site, 6 composite types and 4 hollowcore types). The idea of this first costing exercise was to consider a large number of costing parameters to understand the cost drivers. The total of 1320 building costs have been summarised in Table 1 in million-dollar figures. Buildings with composite floors are 10% to 30% cheaper than buildings with in-situ or precast floors, with little difference between these two floor systems. Research has shown similar conclusions in other countries like Australia(Chan 2011). This analysis overlooks construction times and stages, which may have an effect on costs. Some precast floors performed very poorly in past earthquakes, so the little savings are not justified.

Table 1 RC Frame construction costs in $M

	Floor area (m^2)	**Hazard factor z=0.4**			**Hazard factor z=0.7**		
		Auck	**Welly**	**Chch**	**Auck**	**Welly**	**Chch**
In-situ	432	0.34	0.30	0.33	0.42	0.37	0.41
	1152	1.20	1.07	1.16	1.86	1.67	1.80
	8748	5.48	4.89	5.29	6.54	5.84	6.32
	23328	18.45	16.49	17.84	25.50	22.86	24.64

	Floor area (m^2)	**Hazard factor z=0.4**			**Hazard factor z=0.7**		
		Auck	**Welly**	**Chch**	**Auck**	**Welly**	**Chch**
Composite	432	0.26	0.24	0.25	0.35	0.31	0.34
	1152	1.00	0.91	0.97	1.46	1.30	1.42
	8748	4.01	3.66	3.87	5.07	4.61	4.89
	23328	14.55	13.22	14.04	21.60	19.58	20.84
Precast	432	0.33	0.29	0.32	0.41	0.37	0.40
	1152	1.19	1.05	1.15	1.66	1.51	1.61
	8748	5.47	4.78	5.30	6.61	5.82	6.42
	23328	17.66	15.51	17.12	22.36	19.76	21.65

The average cost increased 34% when the seismic hazard was increased from 0.4 to 0.7. This extra cost is only associated to structural elements (frames) and not foundations or non-structural elements. Location alone, when decoupled from the seismic hazard of the particular location, does not have a significant influence, as seen in Figure 1. Large buildings, and especially slender (tall and narrow) buildings incurred in a significant cost increase for a higher seismic demand, from 40% to 55% approximately, compares to 20% to 35% for small and squat buildings.

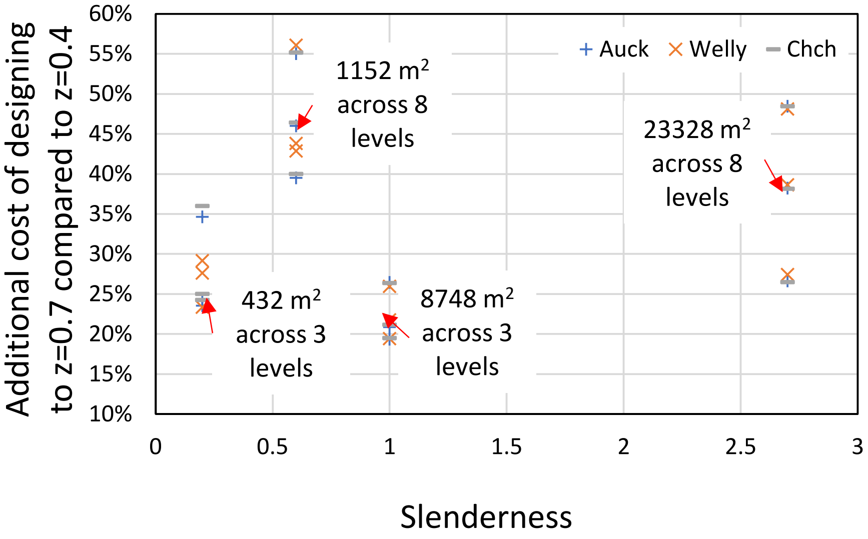

Figure 1 Effect of building slenderness on RC Frame costs

4.2 RC wall buildings

A large number of costing models were created for RC wall buildings, totalling 1472 individual buildings with two floor areas, three heights, 4 hazard factors, two floor weights across 16 floor types and three cities. The objective was to better understand the influence of middle-height buildings and more seismic hazard factors. A summary of the cost increase, normalised by the cost of the building at a hazard factor Z=0.2 is reported in Figure 2 for the three building heights. The costs include not only RC walls, but also gravity system (columns, primary and secondary beams, and floors). As for the RC Frame buildings the effect of location is minimal when decoupled from the seismic hazard, so only the Auckland values are included for simplicity. Similarly, only the values for composite floor buildings are included, as this is the most common floor method and the influence of floor types were discussed above. As opposed to RC frame buildings, the height (for a similar building size) and building slenderness have little effect on costs. The cost increase for higher seismic hazard factors is also significantly smaller than the cost increase in RC frame buildings. The reason for this phenomenon is that increasing the strength of stiff elements, that have a large lever arm, is easier (cheaper) than increasing the strength of flexible elements.

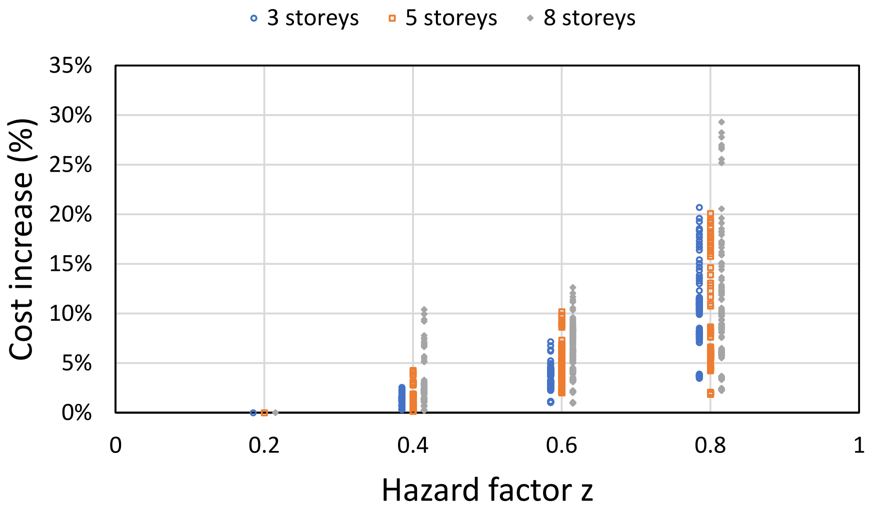

Figure 2: Effect of hazard factor on construction costs of buildings with RC walls (only Auckland and composite floors).

4.3 Steel buildings

Three cities but only composite floors (6 types) were used for the steel buildings, as it is unlikely to design a steel building with concrete floor systems. Two floor plan sizes and 3 heights were modelled, using hazard factors equal to 0.15, 0.4 and 0.7 and two structural systems (Moment Resisting Frames MRF and Eccentrically Braced Frames EBF). The fabrication costs in QV Cost Builder were found to be too crude for structural steel buildings, and the values from SCNZ's connections guide were used instead. This guide has two main limitations: 1) the lack of available data for Moment End Plate (MEP) and 2) the lack of costing guidance for bolted replaceable link, where the active link and collector beam would be priced as one continuous member. Therefore, the following was assumed for the seismic frame connections:

1. Welded moment connections were used in place of moment end plate connections for the active link and braces.
2. The collector beams were priced using MEP-S Flush connections into the column, and a welded moment connection between the brace and the beam (detail in the collector beam governs the cost).
3. The beams in a MRF use welded moment connections followed by two bolted beam splices within the span.
4. If the beam size allows, then a MEP-G connection is used to be more cost effective.
5. The foundation connection is a MEP, based on the size of the heaviest column.
6. All MEP connections are 100/50 where possible.

Similarly to the RC walls buildings, the effect of location is only 1.8%, and the effect of the various composite floors is also low (4.7%), so these parameters are not included in the results for simplicity. Similarly to RC buildings, where the increase of construction costs with a higher demand is more significant for flexible (frame) buildings compared to stiff (wall) buildings, the cost increase is extensive for MRFs but much more limited for EBFs. As seen in Figure 2 for MRFs, the effect of increasing the seismic factor *Z* from 0.2 to 0.4 is 40%, but when increasing it further to 0.7 the cost increase ranges from 40% and 130%. By contrast, for EBFs the cost increase is only between 2% and 8% when the hazard factor is increased to 0.4, and between 8% and 11% when further increased to 0.7. of increasing the

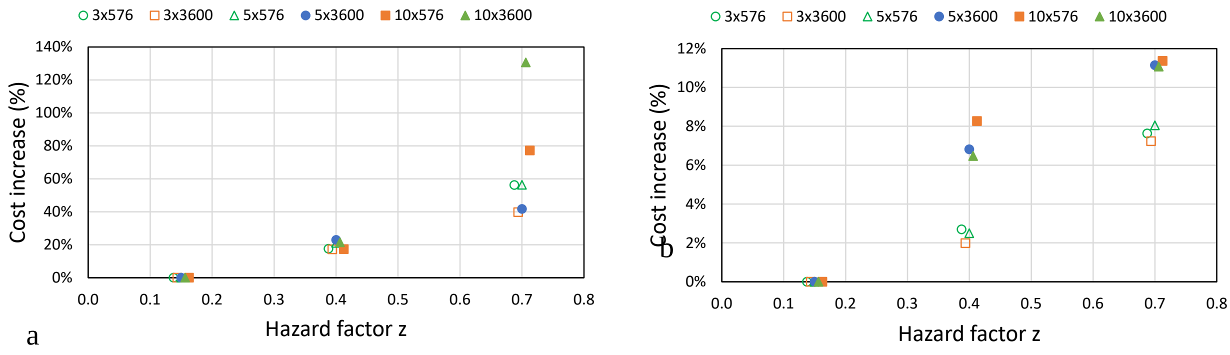

Figure 3 Impact of increased hazard factor on construction costs increase for a) moment resisting frames, and b) eccentrically braced frames

4.4 Foundations

The type of foundation (shallow pads or deep piles) have a significant impact on construction costs, as well as the type of pile or whether the pads are restrained or not. The cross-comparison reported in Table 2 shows that shallow foundations are about half as cheap as deep foundations, concrete piles are slightly cheaper than steel piles, and unrestrained strip foundation are the cheapest option. A more detailed discussion follows, divided by shallow and deep foundations.

Table 2 Impact of foundation type on construction cost

	UC97	600RC	Pad	Unrestr'd strip	Restr'd strip
UC97	1.00	1.12	1.56	2.42	1.76
600RC	0.88	1.00	1.36	2.13	1.55
Pad	0.63	0.70	1.00	1.54	1.13
Unrestr'd strip	0.41	0.46	0.65	1.00	0.73
Restr'd strip	0.56	0.62	0.88	1.36	1.00

Shallow foundations. A sensitivity analysis was performed to reduce the large number of variables involved in foundation design. Building's location, the soil shearing angle φ, the effective cohesion factor c', and the soil density γ were found to have a relatively limited effect on construction costs compared to other parameters such as building size (3, 5 and 10 storeys with 576 or 3600 m^2), shallow foundation type (pad, unrestrained strip or restrained strip), loads from the building, number of foundations and hazard factor (0.15, 0.4 and 0.7). Therefore, the first set of parameters was set at a fixed, average value, while the second set of values were considered for the analysis. The gravity / vertical loads (680 to 2967 kN) and the horizontal / seismic loads (45 to 426 kN) were calculated for the whole building and then divided by however many foundation pads, strips or piles were used. The construction costs of foundations in Wellington and Christchurch are cheaper than in Auckland, 8% and 5% respectively, everything else being equal. For simplicity, only Auckland and soil type C will be used in the following discussion. Unrestrained strip footing is the cheapest option, although not always practical, and restraining the strip increases the construction costs between 25% and 44%. Using pad footings is between 22 and 68% more expensive than unrestrained strip footings. The cost increases related to higher seismic hazard factor Z are quite significant when compared to the structural costs, especially if using pad foundations and for large buildings, as in Figure 4.

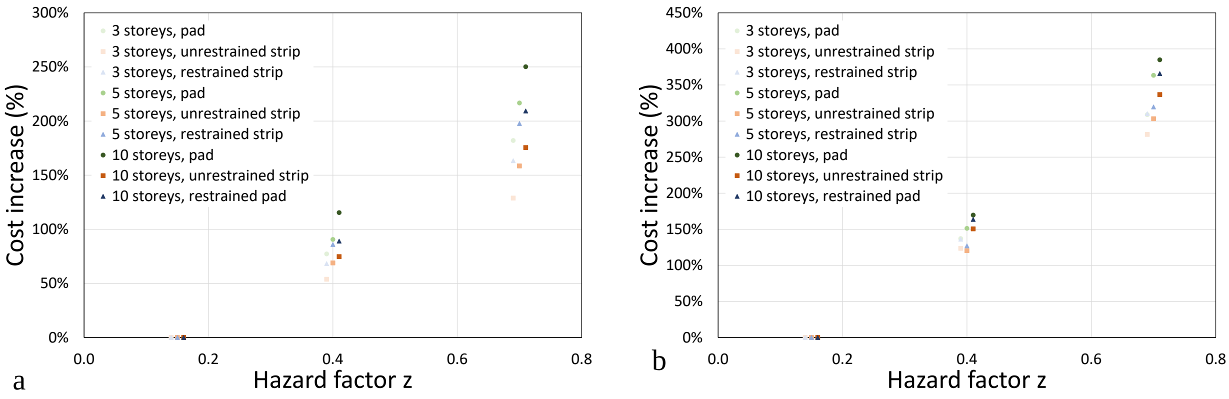

Figure 4: Impact of increased hazard factor on construction costs increase for shallow foundations in a) 576 m^2 and, b) 3600 m^2

Deep foundations. The building location, pile cap type (free or restrained) and dimensions (for pile groups), the water table depth, the site's slope and the distance from the pile to the slope, the soil layers' relative thickness, the effective cohesion c', and the soil density γ were found to have a relatively limited effect on construction costs compared to other parameters such as pile type (steel or concrete) and dimensions, number of piles (for pile groups), loads from the building and soil shearing angle φ. Therefore, the first set of parameters was set at a fixed, average value, while the second set of values were considered for the analysis. For simplicity, only soil type C and Auckland prices were considered. The impact of seismic demand on construction costs of piles is significantly smaller than that of shallow foundations, when all other aspects remain equal, as shown in Table 3. The difference in the impact of seismic hazard on costs is due to the bearing mechanism of shallow foundations (mainly through pressure of the soil underneath the pad, which is small and thus requires a large increase in pad area) compared to that of deep foundations (through pressure along the whole pile shaft, which mobilises a larger amount of soil than the pads).

Table 3 Impact of seismic demand on construction costs of piled foundations

		600 mm diameter RC pile		UC97 steel pile	
Shearing angle φ	Factor z	576 m^2	3600 m^2	576 m^2	3600 m^2
25	0.15 to 0.4	4.3%	5.6%	4.2%	7.5%
	0.15 to 0.7	5.7%	11.3%	10.4%	14.5%
40	0.15 to 0.4	2.3%	4.0%	4.0%	3.0%
	0.15 to 0.7	3.5%	15.6%	6.5%	11.7%

5 CONCLUSIONS AND FUTURE WORK

Using preliminary design and parametrising the quantity take off and costing allowed for a database of thousands of buildings to be assessed for numerous parameters and their on construction costs, while using the seismic hazard Z as a simplified proxy for seismic demand and resilience. The main conclusions are:

1. Everything else being equal (include seismic demand), the impact of building location on construction costs is minimal. Similarly, the impact of floor type on construction cost is also insignificant. The impact of building size is not linear, and the slenderness has an impact on construction costs.
2. The structural system and its stiffness have a huge impact on construction costs when increasing the seismic hazard. Stiff systems can accommodate higher demands with a relatively small construction cost increase, but flexible systems run in significant over costs implications.

3. Shallow foundations can be up to 2.5 times cheaper than deep foundations, and the type of foundation also has an influence on construction costs. However, the type of foundation is often determined by soil conditions and building size.

Engineers should prioritise stiff lateral systems as the cost implications are minimal, especially when considering the overall development project. New Zealand should move towards stiff, damage resisting structures using well understood structural systems like RC walls and steel eccentric braced frames but without compromising redundancy and resilience through proper ductile design.

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