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IMPACT OF SEISMIC DEMAND ON CONSTRUCTION COSTS FOR BUILDINGS UP TO 8 STOREYS HIGH

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ABSTRACT

The legally binding earthquake performance requirements in New Zealand's Building Act and Building Code emphasise building collapse prevention, allowing for a certain degree of damage to resist the seismic load. However, societal expectations demand that buildings remain operational after an earthquake. This research aims to understand the true cost of up to 8 storeys high building structures that remain operational after an earthquake. Our assumptions are: 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 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 because the cost implications of having a stiffer structural system are minimal, especially when considering the 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 RC walls. Society expects this from our buildings, our engineers are trained and capable to design them, and the extra cost is minuscule.

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INTRODUCTION

Legally-binding earthquake performance requirements as set out in the Building Act [1] and in the Building Code [2] are vague and broad. For example, the wording "*Buildings will withstand likely loads, including wind, earthquake, live and dead loads (people and building contents)*." from the Clause B1 [3] of the building code just states that the building has to "*withstand the likely earthquake load*", i.e. not collapse under what is, at the time of design, *the likely earthquake load* as defined in the pertinent code, standard or guideline (NZS 1170.5 in this case [4]). Thus, the legal definition of earthquake performance is "*safeguard people from injury* [and] *loss of amenity* [as well as] *protect other property from physical damaged caused by structural failure*". This requirement was likely to reflect the society's expectations during the 20th century, which in New Zealand was a relatively quiet time seismically, but these expectations changed as the 21st century arrived and the economic and social cost of designing for damage became starkly apparent. The Structural Engineers Association of California (SEAOC) set out an effort to "*develop the framework that yields structures of predictable seismic performance*", and in doing so developed the recommended performance objectives for buildings outlined in Figure 1 [5].

The vast majority of buildings performed adequately during the Canterbury earthquakes, when the collapse prevention requirement is the only consideration. However, nearly 70% of multi-storey reinforced concrete buildings in downtown Christchurch were demolished [6]. Non-engineering aspects often determined the outcome of the demolition decision. For example, 42% of the decisions were owner initiated [7], which suggests that it was more economically beneficial to collect high insurance pay-outs, demolish the building and re-build (or move that pay-out elsewhere). Canterbury contributed 8% of the national GDP at the time of the earthquakes, which resulted in $40B financial loss (20% of GDP), $20B rebuild excluding disruption costs, and $30B insured losses [8]. This is in addition to wide psychological effects such as post-traumatic stress disorder (PTSD), anxiety disorders such as panic attacks and depression, and sleep disturbances [9-11], and more importantly the loss of 185 lives. Society does not want a repeat of this – societal expectations have now shifted towards a desire that a building is operational immediately or shortly after an earthquake. This expectation was defined in the Canterbury Earthquake Royal Commission Report [6], as well as in the University of Canterbury Research Reports, the so-called "Dhakal report" [12] and "Buchanan report" [13].

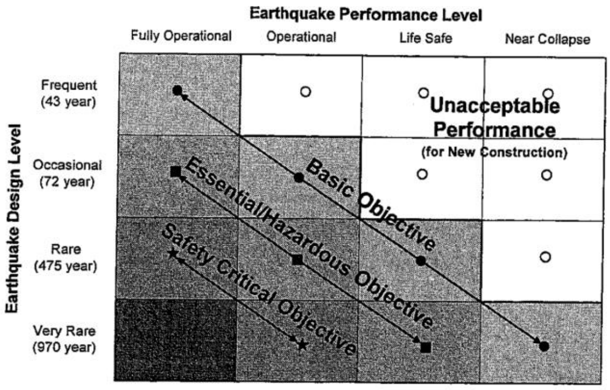

Figure 1: Recommended performance objectives for buildings, according to Structural Engineering Association of California (SEAOC) - Vision 2000 Committee 1995.

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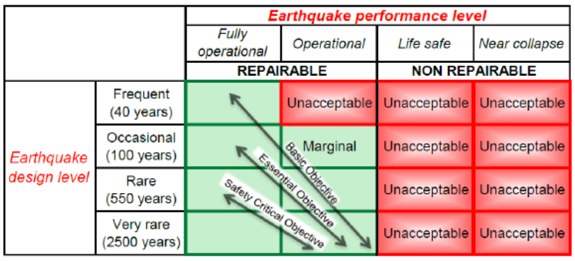
The current design philosophy for multi-storey buildings in New Zealand allows structural engineers to design buildings to suffer a certain degree of damage to dissipate the energy coming from the earthquake, rather than to resist that earthquake while remaining elastic. The "Buchanan report" suggests that the current performance levels described in Figure 1 should be increased. The report proposed that the non-repairable outcome is never acceptable, and that the structure should remain operational regardless of the level of shaking, as shown in Figure 2. Several options were proposed in the "Buchanan report" to increase the resilience of structures as per the new performance levels shown in Figure 2. The use of low damage devices such as base isolation and damping devices, rocking controlled dissipative systems and jointed ductile articulated systems are thoroughly described in the Buchanan report. Wide implementation of these methods has not materialised yet, despite decades of research and development. Potential reasons for the low implementation are complexity and cost, complex and tailor-made design, and/or safety/confidence on such systems.



		Earthquake performance level			
		Fully operational	Operational	Life safe	Near collapse
		REPAIRABLE		NON REPAIRABLE	
Earthquake design level	Frequent (40 years)		Unacceptable	Unacceptable	Unacceptable
	Occasional (100 years)		Marginal	Unacceptable	Unacceptable
	Rare (550 years)			Unacceptable	Unacceptable
	Very rare (2500 years)			Unacceptable	Unacceptable

Figure 2: Performance levels proposed in the report by Buchanan et al. [13].

A simpler and better method to reduce the damage of structures, which is also acknowledged in the "Buchanan report", is to change the design philosophy to make buildings respond largely in the elastic range. This design philosophy for buildings is successfully used in other countries that have the same or higher level of seismic hazard than New Zealand, such as Chile. Construction cost is often used as a reason to use ductile structures that dissipate the energy from the earthquake through damage instead of stronger and stiffer structures that resist the earthquake without significant damage. However, this reason may be disputable and has not been robustly challenged for new building construction. Finally, the potentially slightly construction costs are more than justified once the business disruption costs and the costs to repair the non-structural elements are considered [14,15]. 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.

The natural hazard model that determines the seismic demands used for structural design has been updated [16]. These results will be embedded into the regulatory framework through NZS 1170.5 [4], with the outcome that the seismic hazard is likely to increase in a large portion of the country, more importantly in Wellington where a lot of construction is concentrated. In our opinion we can meet the new seismic demand with the existing design tools and without a significant cost increase. Extensive work is being undertaken to provide guidance on the design of low-damage tools like base isolators and dampers. In our opinion, these are excellent tools for critical buildings like hospitals or fire stations, but we think the widespread use of low-damage technology has significant challenges. In our opinion, the use of more traditional and well-known structural systems can provide the needed strength and stiffness, and thus offer a more viable solution.

LITERATURE REVIEW

This section presents a brief summary of cost estimation methods, followed by an overview of development costs and construction costs, both in New Zealand and overseas. The objective is to guide the methodology to be used when developing the construction cost database and to estimate the proportion of structural costs with respect to other construction costs and of all construction costs with the full development costs.

Construction Cost Estimation Methods

Cost estimation is an iterative process of quantifying the cost of developing a project, with the estimates being updated depending on the information available at different design stages [17]. This process is often used to determine the feasibility of a project and potential alternatives [18], but it can be a powerful tool to understand cost drivers, i.e. the influence of various design parameters on final cost. Organisations like the Royal Institute of Chartered Surveyors (RICS) in the UK and the Association for the Advancement of Cost Engineering (AACE) in the USA lead the engineering practice by developing guidelines [19] often based on published research [20-22].

The superficial area method [20], also called floor area method, is the most commonly used method, which multiplies the total gross internal floor area (GIFA) by a cost per square meter based on historical data [19]. The low accuracy of this method (−15% to +25%) [23,24] has encouraged changes in cost estimation [25], leveraging the advances in computer hardware and software and large databases [26]. The need for innovation towards lean construction, often inspired by the Japanese industrial production processes [27,28]. has sparked new cost estimation methods, such as Activity Based Costing (ABC) [29] or Target Costing [30]. Despite these advances, the traditional GIFA method remains widely used in practice.

The recent RICS' New Rules of Measurement NRM [19] identified the Royal Institute of British Architects' RIBA Plan of Work [21] as a widely recognised model to organise design and construction projects, tightly linked with cost estimations at different stages of the project depending on the level of information available. In the inception stage, when the information about the project is limited, the statistical square area (superficial) method [18-20] is predominantly used. The objective in the design stage is to create a building within the owner's requirements, compliant with regulation, and within the cost target defined in the earlier stages. The cost plan in this stage assigns unitary costs from historical databases to the different project elements, which are then aggregated and adjusted as needed [20]. The subdivision of the buildings in elemental constituent parts, such as substructure, frame, upper floors, and roof, follow standard guidelines [19], and follows a bottom–up approach considering the necessary resources, e.g., labour, equipment, materials, and subcontractors [18]. However, this method often does not include allowances for risk or inflation, planning restrictions, legal requirements, environmental concerns, and statutory constraints, inadequate brief, aesthetics and space concerns, changes in estimating data, incomplete drawings, and a long et cetera. Despite these simplifications, the accuracy of final estimates falls within the range of ±5% as the project approaches the tendering process [23]. Therefore, this cost plan at the design stage is the method used in this project.

Construction Costs in Overseas Practice

A systematic literature review of 133 documents identified a total of 73 parameters that influence construction costs. These cost drivers were then ranked and scored using the Borda-Kendall technique, with the top 10 parameters being reported in Table 1. The building size (floor area and number of floors) have the largest influence score, dropping steeply immediately after. The foundation system has the largest influence of any structure driver, related to the various excavation works for different foundation systems. The number of elevators and roof type are not determined by structural performance, and in fact the only other structural drive is the type of structure, which has a similar influence on cost as number of units or floor area. Therefore, it is sensible to hypothesise that the structural type (and perhaps structural size) would have little influence on the final structural cost. It is important to note that most of these results are from countries that do not have the seismic hazard that New Zealand does, and thus the cost drivers or their score might be different for our country.

Table 1: Cost drivers.

Parameter	Rank	Score	Score normalised
Gross floor area	1	1287	1.00
Number of floors	2	1127	0.88
Foundation system	3	748	0.58
Number of elevators	4	546	0.42
Type of roof	5	470	0.37
Structure type	6	404	0.31
Total units	7	390	0.30
Number of unit floor households	8	353	0.27
Typical floor area	9	352	0.27
Location	10	350	0.27

Construction Costs in NZ

Zhao [31] completed a study to investigate which factors of the building development process have a more significant impact on the building development cost. Zhao used both expert elicitation (experts' opinions) and experimental, analytical and modelling data collected from published literature, grouping these data in 7 categories as shown in Figure 3. The factors with the highest influence on development costs have a shorter blue shade in Figure 3, closer to the centre of the circle. For example, Socio-economic factors have the highest influence, while Property market and construction industry have the lowest. An interesting funding from Zhao [31] is that the vast majority of experts though that construction costs were the largest cost drivers, based on interviews that Zhao conducted. However, the quantitative data obtained through this work shows a diametrically opposed outcome – the construction costs have the least influence on development costs.

Design and procurement costs have the same impact on total development cost than construction costs, but these costs have the least influence on the building development cost. The engineering community has little control over the most influential factors, such as the factors related to the property market and construction industry. However, engineers can still exert their influence to reduce the complexity of the project, streamline procurement and stakeholders' relationships, and mitigate the elevated costs from statutory and regulatory factors.

Focusing on the construction costs in New Zealand, the industry's own data shows that the structural costs are typically about a third of the total construction costs [32]. The structures component of a mid-rise building of 6 to 15 storeys is typically around 20% of the total construction cost, as can be seen in Figure 4 [33]. Research at the University of Canterbury corroborate this finding (Figure 5) [34], but there is no compelling and comprehensive evidence of the cost difference between the different design approaches and the effect of higher seismic demand on construction costs. It is important to note that the difference in design approach will have an effect on construction elements other than the structure. For example, a stiffer structure with a more limited inter-storey drift will reduce the damage to drift-sensitive non-structural elements such as gypsum plasterboard internal walls. Conversely, stiffer high-rise structures with higher acceleration on the upper levels will increase the demand on acceleration-sensitive non-structure elements such as suspended HVAC units. Profs Sullivan and Dhakal from the University of Canterbury [35-37] have done some excellent work on the effect of earthquakes on non-structural elements, and the influence of higher seismic demand on the installed cost of these elements has been recently investigated [14,15].

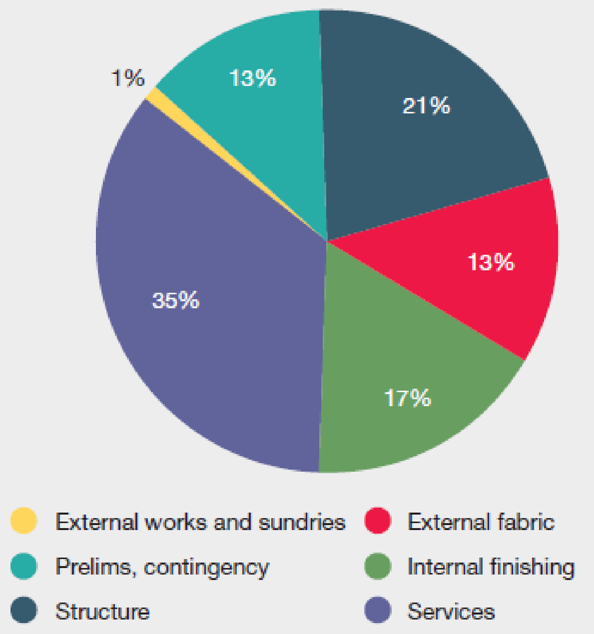


Figure 3: Elemental cost of a typical 6 to 15 storey office building from Rawlinsons 2013 [33].

Hypotheses

The construction costs have the least influence on the building development costs, with the biggest drivers being regulatory framework, market forces, and labour costs. However, structural engineers do not generally have a large influence on these factors so they will not be considered further. The structural costs are between 20% and 30% of the total construction costs. Therefore, even a relatively high increase in structural costs due to higher seismic demand is expected to have a limited impact in overall construction costs, and quite minimal impact on total development costs.

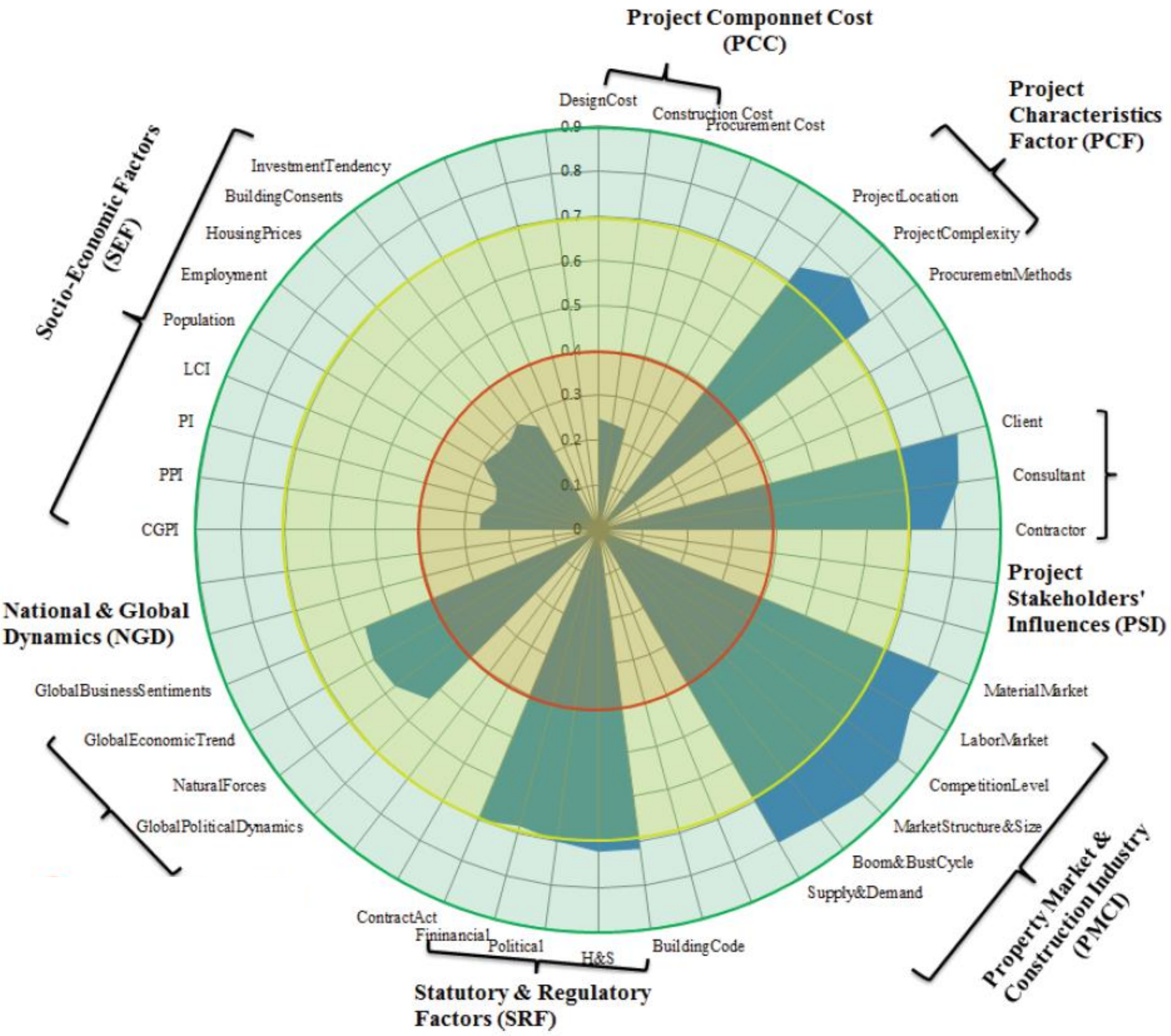
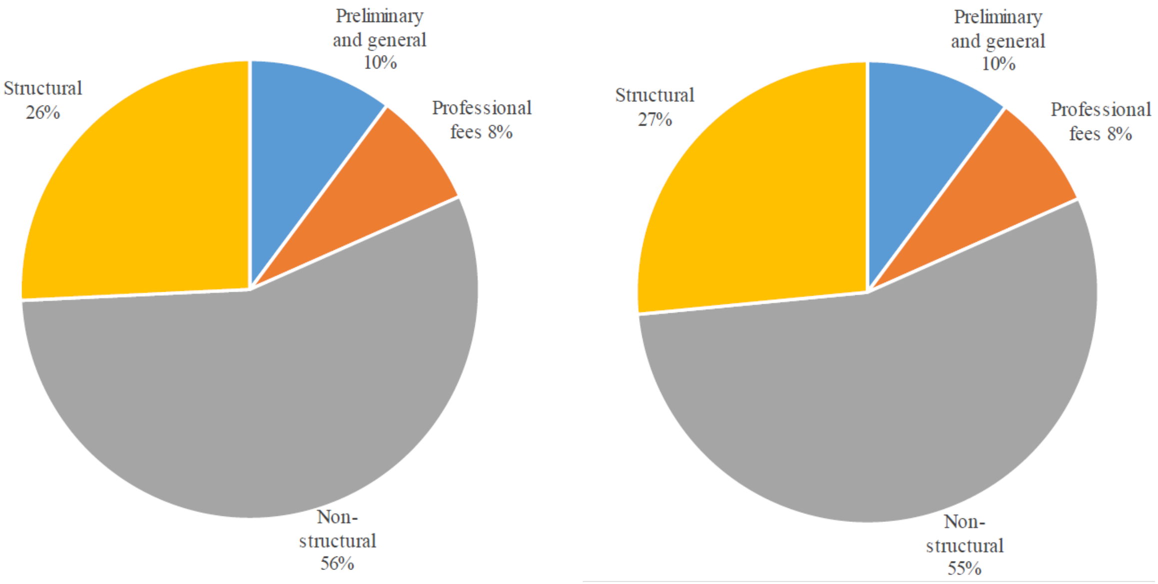


Figure 4: Relative importance of influencing factors from Zhao [31].



(a) Project costs for medium-rise buildings

(b) Project costs for low-rise buildings

Figure 5: Estimated project costs for various strength ratios from Dhakal and Aninthaneni [34].

The influence of seismic resilience on construction costs is different depending on the structural system. Increasing the seismic resilience on stiff structural systems is expected to be cheaper than doing so in more flexible systems, comparatively speaking. The effect of building stronger buildings on foundations cost is unknown as no research on the topic could be found, but changing the foundation type and especially from shallow pads/strips to deep piles is expected to have a big impact on cost.

METHODOLOGY

A myriad of variables affects the development costs of buildings, which comprise many aspects not always directly related to structural engineering, design or construction, as briefly discussed below. Even within the design and construction aspects, the number of variables is too large to consider all of them, especially when final design considerations are accounted for. Three approaches to gather the data were considered, 1) obtaining real construction costs for projects completed in the last few years, 2) design and cost a limited number of case studies at a final design stage and have high fidelity data on those, and 3) design and cost a large number of case studies but only at a preliminary design stage. Approach 1) was unsuccessful as no company was willing to share this information. Approach 2) was seriously considered, but the objective of the project is to be able to apply to a large proportion of the building stock in New Zealand, and this approach would compromise the applicability of the results. We decided to follow approach 3) mainly because it would give us a large database even if the cost calculations would not match with the final design costs. This approach allowed for a comparison of several structural systems, in three cities, with several seismic demands, different construction costs, and many other variables, as discussed below. Therefore, the methodology design was driven by the following key factors:

1. Need for a large database due to the large number of parameters and a wide range within each parameter that needs to be considered. The aim of this work was to be able to be applicable to the majority of buildings in NZ, as opposed to working only with a few case studies. For this reason, Importance Level 2 was selected.
2. The design and the cost estimation methods need to be accurate enough to limit or mitigate statistical variations within the data obscuring the interpretation of that data. Conversely, the methodology cannot be excessively time consuming, due to the wide range of parameters and the scope of the investigation
3. Sensible from structural point of view (e.g. avoid things like strong beam weak column), therefore the design methodology must be underpinned by best industry practice in all related subfields.

Structural Preliminary Design

Resist, a software developed and hosted by the New Zealand Society for Earthquake Engineering (NZSEE), was used to complete the preliminary design. Resist follows New Zealand standards to determine whether the structure defined by the user meets the requirements or not. For example, the user inputs the building properties and the RC column depth, while the width is fixed at 0.6 times the depth and the reinforcement ratio is fixed at 75% of the maximum ratio. Then Resist uses NZS 3101 to determine whether the shear, moment, and drift capacity are met or exceeded. Through an iterative process, the user can determine the preliminary design (sizing) of structural elements and compliance with NZ standards (e.g. 1170.5), but it is by no means a comprehensive design software. There is an abundance of information on the software both on NZSEE's website and on the user's guideline, but the key shortcomings are:

- Floor diaphragms are considered rigid and adequate to transfer seismic loads, but not checked or designed
- Structural connections are not designed, especially critical for steel structures as discussed below
- Concrete columns are always rectangular and of a fixed slenderness ratio,
- Reinforcement ratios are fixed,
- Only planar walls (i.e. no enlarged boundaries, L, T, I walls, etc)
- Foundations, facades, non-structural elements and fire protection is not included,
- Only up to 8 storeys high can be designed.

Despite these significant limitations, Resist is a very powerful tool that can produce an accurate enough structure within minutes. It is versatile enough that various structural systems can be considered, for up to 8 floor buildings, and with a variety of grid and wall layouts. For these reasons, the decision was made to use Resist for the preliminary design, supported by more specialised methods when needed as discussed below. Resist also allows for hazard factors significantly higher than the typical values in the main centres, which are 0.13 for Auckland, 0.3 for Christchurch and 0.4 for Wellington. Seismic hazard is composed of multiple variables such as soil types, ductility levels, drift ratios and near-fault factors, among others. However, considering all potential variables would be a very time-consuming exercise, when in reality there is a range of "seismic weight multiplier" when all of those variables are combined, such as C(T) in NZS 1170.5. A decision was made to use the seismic hazard factor Z as a simplified measure of seismic hazard given how widely recognised its values are, as detailed above. This decision makes the data analysis and discussion more intuitive and easier to follow than including all various parameters in the research. 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.

Structural Detail Design

In some cases, specialised methods and/or software were used. These additional methods mainly consisted of 1) NZ standards, mainly 3101 and 3404, to design the gravity system for wall buildings and steel buildings, 2) supplier documentation for precast and composite floors design, 3) Steel Construction New Zealand (SCNZ) guidance and software on steel connection design, 4) SESOC's Gen-Wall for RC wall design for specific cross-checking of results, 5) industry standard documentation such as HERA report P4001, Steel & Tube tables for Universal Beams (UBs) and AISC Design Capacity Tables for Welded Beams (WBs) for the design of the steel buildings, 6) SESOC Soils was used to design the foundations.

Construction Cost Estimation

QV cost builder is the most comprehensive database of construction cost rates in New Zealand, and 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 at the various locations do not take into consideration the seismic hazard of the location, but other aspects such as logistics of delivery, labour market, etc. It is therefore important to decouple the impacts on construction costs from location alone and from the seismic hazard in that location. To achieve this decoupling, the seismic hazard was changed at the various locations, so in effect a cost normalised by seismic hazard was obtained and the cost of building in a certain location due to the particularities of that location could be investigated. This phenomenon is shown in Table . Some costs were not available, such as the 50 MPa concrete, lacked enough detail, or were considered out of date by the industry. These particular cost rates were recalculated using industry standards and partners (e.g. SCNZ). Revit was used in combination with Dynamo (a parametric design plug in) to parametrise some variables such as the reinforcement layout and floor type on RC buildings and obtain the quantity take off.

Data Management, Analysis and Visualisation

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.

Variables Considered

Table 2 summarises all the variables considered in both the preliminary design and the cost estimation.

Table 2: Variables considered.

Variable	Range
Hazard factor z	0.15-0.8
Floor area	400-25000
Location	Auckland, Wellington & Christchurch
Structural system	RC Frames, RC Walls (concrete secondary system), Steel frames (MRF and EBF with steel secondary system and composite floors)
Material properties	2 concrete strengths and 4 steel grades
Foundation types	5 types: pads, unrestrained strips, restrained strips, concrete piles, steel piles
Pile condition	Isolated pile (cantilever) / group of piles (cap)
soil properties	Soil shearing angle, effective cohesion factor, soil density, soil layer thickness, water table depth

RESULTS

The results are divided depending on the structural system:

RC Frame Buildings

Reinforced concrete frame buildings of four sizes (432m^2 across 3 storeys, 1152m^2 across 8 storeys, 8748m^2 across 3 storeys, and 23328m^2 across 8 storeys) were modelled, investigating 2 hazard factors (0.4 and 0.7), and two floor weights (lightweight = composite floors and heavyweight = cast-in-place and precast), resulting in 16 structural models. The models resulted in columns between 0.5 m and 1.2 m in the largest dimension, with the smaller dimension being between 0.6 times the larger one (Resist limitation). The beams were always sizes to be weaker than the columns in the event of an earthquake. The cost parameters were 4 grade 300 (yield strength equals 300MPa) reinforcing 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 total number of buildings was 1320. The construction costs for the RC Frames (i.e. columns, beams, and floors) is reported in Table in million dollars. Two hazard factors, three cities, 4 building sizes, and the three main floor types are included in this table.

The construction costs of both in-situ and hollowcore floors are relatively similar, with a typical difference of about 1% to 4% for a hazard factor of 0.4. However, for high hazard factor of 0.7, hollowcore floors can decrease the construction costs by an average of 22% compared to the cast in-situ floors. Composite floors are between 10% and 30% cheaper than both in-situ and hollowcore floors, regardless of the hazard factor. These results align with published results from similar jurisdictions like Australia, where hollowcore floors are 30% cheaper than in-situ floors [38]. However, the construction cost of hollowcore floor in Malaysia is twice as expensive as the cost of the in-situ floor [38], potentially due to the cost of construction technologies for the manufacturing process and hiring machines during installation. In-situ construction is more labour-intensive, making it more expensive in New Zealand, but labour costs in Malaysia are extremely low, so even a labour-intensive process is cheaper. This analysis overlooks construction times, which may have an effect on costs, and structural behaviour. Hollowcore floors have been shown to perform very poorly in earthquakes, even with modern design and construction methods, so the little savings that could be achieved are not justified from a structural performance perspective.

Table 3: 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
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
Hollowcore	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 increase in hazard factor from 0.4 to 0.7 incurred an average cost increase of 34%, with this cost being related only to the frames and floors components of the construction costs (i.e. not including foundations or non-structural elements). A visual comparison of the additional cost of increasing the hazard factor is reported in Figure 6. The location does not have a significant influence on cost. By contrast, the cost increase was 34%, 38% and 29% for in-situ, composite and hollowcore floors respectively, with the extra cost probably related to the contribution of the different floor systems to the total seismic weight and its impact on structure sizes. The cost increase was significantly higher for large buildings, and especially for slender buildings (tall and narrow). For example, the additional cost of the 1152m^2 across 8 storey was between 41 and 55%, but the additional cost of the 8748m^2 across 3 storeys (much larger but shorter) was only between 19% and 26%, as seen in Figure 6. For RC frame buildings, building tall and slender buildings is not cost-effective.

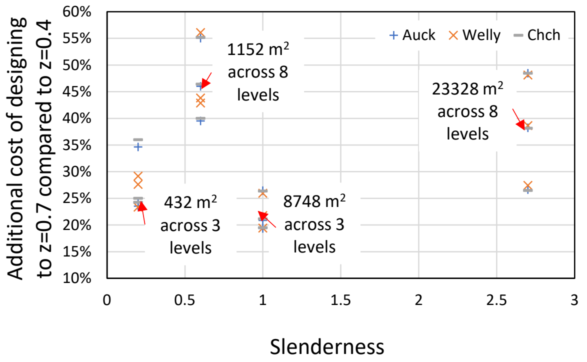


Figure 6: Effect of building slenderness on RC Frame costs.

RC Wall Buildings

Preliminary structural design considered two floor areas (900 and 2500m^2) and three heights (3, 5 and 8 storeys). We investigated 4 hazard factors 0.2, 0.4, 0.6, and 0.8, two floor weights (medium= composite and heavy = precast) across 16 floor types (including hollowcore, double tee, and composite floors), and three cities (Auckland, Wellington and Christchurch), resulting in 1472 buildings modelled. The resulting buildings had walls with a thickness between 200mm and 400mm and between 3m and 5m long. Always two walls per loading direction were considered for consistency. The aim was to have a more granular data than for RC frames and to better understand the smaller changes in middle-heigh buildings and with a wide range of hazard factors. The building location has very little effect on construction costs, and using precast floors is in average 19% cheaper than composite floors but dependant on seismic demand, as shown in Table 3. For higher seismic demands, using precast floors is only 13% to 18% cheaper than using composite floors, but for lower seismic demands the difference is between 26% and 21%.

Table 3: Average of construction costs for RC wall buildings with precast systems compared to composite floors.

	Auck	Welly	Chch
Z=0.2	0.79	0.74	0.79
Z=0.4	0.82	0.77	0.82
Z=0.6	0.84	0.79	0.84
Z=0.8	0.87	0.82	0.87

The results are too extensive to report them all, so the summary of the cost increase, grouped by the three building height and for the various hazard factors is summarised in Figure 7, using 0.2 as the baseline (construction costs at z = 0.2 equals 1 for the exact same building). These costs include structural walls, gravity columns, and primary and secondary beams as necessary (concrete columns and beams for precast floors and steel columns and beams for composite floors). Only the Auckland values are included for simplicity and because the construction cost difference is minimal. Only composite values are included in this analysis to simplify the discussion and because hollowcore are not that common these days and are discouraged by MBIE through the removal of the Verification Method B1/VM1. The values at the top of the 8-storey dataset in Figure 7 belong to the largest buildings of all with a total area of 20,000m^2, which required additional walls compared to the other buildings at z=0.4, and thus incurred additional extra costs. Buildings with z=0.6 and z=0.8 had twice as many walls as those with z=0.2 and z=0.4.

There is no distinct effect of building height or slenderness on the construction costs, in contrast to the RC frame buildings. Another difference is the minimal cost increase as the hazard factor increases, despite the significantly larger number of walls for buildings with Z=0.6 and Z=0.8. Increasing the hazard factor from 0.2 to 0.4 increases the construction cost an average of 3.5%, while going from 0.2 to 0.6 increases the costs 4% and from 0.2 to 0.8 increases the costs 7.6%. These costs increments are significantly lower than those observed on RC frame buildings, which ranged from 20% to 55%. Increasing the moment capacity of a structure primarily entails increasing the moment capacity of its individual structural members. This moment capacity consists mainly of two aspects, the internal forces within the member (compression resisted by the concrete and tension resisted by the steel) and the lever arm between those two forces. The level arm of walls is much longer than the lever arm of columns, and thus a much higher internal force (more concrete and more steel) is needed to increase the moment capacity of a column compared to a wall. Hence why the costs of increasing the moment capacity of stiff buildings are significantly smaller than that of flexible buildings. It is important to note that these are average values, and that there is a large variability in these buildings in terms of constructions methods (e.g. various floor types). The data may seem higher in Figure 7, but for example the median construction cost increase for 8 storey high buildings for a hazard factor of 0.8 is 6.2%, 140 basis points lower than the average, so a large number of the data points are concentrated on the lower end of the range.

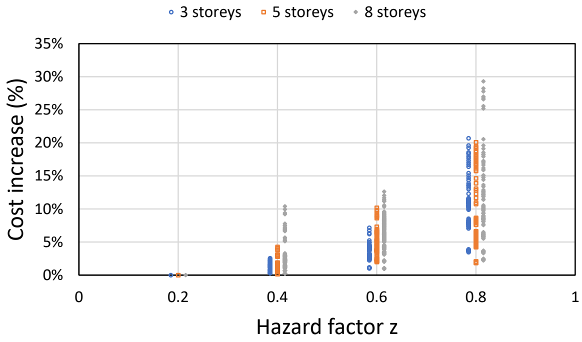


Figure 7: Effect of hazard factor on construction costs of buildings with RC walls (only Auckland and composite floors).

Steel Buildings

Buildings of 2 floor plan sizes (576m^2 and 3600m^2) and 3 heights (3, 5 and 10 storeys) were modelled for three seismic hazard factors (0.15, 0.4 and 0.7) for two structural systems (Moment Resisting Frames MRF and Eccentrically Braced Frames EBF) and one floor weight (composite floors). MRF buildings had columns ranging from 200UC to 500UC, and beams from 360UB to 900UB. EBF buildings had columns ranging from 200UC to 500 UC, and beams ranging from 200UB to 800UB. Three cities and 6 composite floor types were used for costing purposes. The fabrication costs in QV Cost Builder were found to be too crude, and the values from SCNZ's connections guide were used instead. The SCNZ's connections 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:

- Welded moment connections were used in place of moment end plate connections for the active link and braces.
- 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).

- The beams in a MRF use welded moment connections followed by two bolted beam splices within the span.
- If the beam size allows, then a MEP-G connection is used to be more cost effective.
- The foundation connection is a MEP, based on the size of the heaviest column.
- All MEP connections are 100/50 where possible.

The effect of using the various composite floor types on the construction costs is about 4.7%, and the cost difference depending on location is only 1.8%. Thus, the costs of the several buildings have been combined to simplify the analysis of the results. The construction cost increases of increasing the hazard factor from 0.15 to 0.4 and to 0.7 are reported in Figure 7 for moment resisting frames MRF (a) and for eccentrically braced frames EBF (b). The impact of seismic demand on construction cost is extensive for MRFs, with the cost increasing 20% when increasing the seismic demand to 0.4 and between 40% and a staggering 130% (for the largest building of 3600m^2 and 10 storeys) when increasing the seismic demand to 0.7. The cost increases for EBFs are much more limited, with the cost increase being between 2% and 8% for the 0.4 hazard factor and between 8% and 11% for the hazard factor of 0.7. This observation is aligned with the results from the concrete buildings, where the construction cost of increasing the seismic demand is much lower for stiff structural systems (RC walls and EBFs) than for flexible structural systems (RC frames and MRFs).

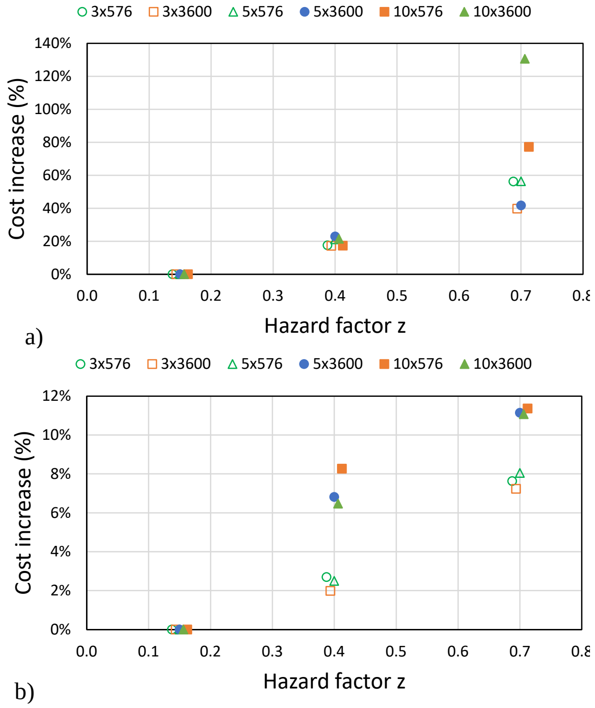


Figure 8: Impact of increased hazard factor on construction costs increase for a) moment resisting frames, and b) eccentrically braced frames.

Foundations

The impact of the type of foundation on building construction costs is significant, with the type of foundation being used for design often depending not only on soil conditions and demands but also on the type of superstructure. For example, RC walls may require more substantial foundations when compared to frame buildings due to the concentrated overturning moments at the base of the walls. Designing the foundations for each type of building considered in the previous few pages would be extremely time consuming, and the purpose of the study was for the data to be applicable to a large number of the building stock. For this reason, the cost implications on superstructure and foundations have been decoupled. The type of shallow foundation and the type of pile used also have an effect on cost, as shown in Table 4, where the comparison between various foundations are compared to each other (everything else being equal). Using shallow foundations is about half the construction costs of using deep foundations. Concrete piles (600RC) are about 12% cheaper than steel piles (UC97) and unrestrained strip shallow foundations are the cheapest (more details below). The more detailed discussion below has been divided between shallow and deep foundations for this reason.

Table 4: Impact of foundation type on construction cost.

	UC97	600RC	Pad	Unrestrained strip	Restrained 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
Unrestrained	0.41	0.46	0.65	1.00	0.73
Restrained	0.56	0.62	0.88	1.36	1.00

Shallow Foundations

Foundation design involves a large number of variables that would increase the complexity of the results' analysis significantly compared to the structural results. A sensitivity analysis was conducted to reduce the number of variables, where 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 3600m^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 from the buildings ranged between 680 and 2967kN and between 45 and 426 for the seismic (lateral) loads. These loads are for the whole building, and were divided by however many foundation pads, strips or piles were used. For simplicity, only soil type C was considered. The construction costs of foundations in Wellington and Christchurch is cheaper than in Auckland, 8% and 5% respectively. For simplicity, only Auckland will be used in the following discussion. The cheapest shallow foundation type is strip footing and unrestrained, although we acknowledge that this is not always possible in real designs. Restraining the strip foundations increases the construction costs between 25% and 44%, with the average being 33%. This option is still cheaper than doing pad footings, which are between 22 and 68% more expensive than unrestrained strip footings (the average is 49%). The effect of seismic hazard factor z on cost increase is reported in Figure 9. The cost increases are quite significant when compared to the structural costs, especially if using pad foundations and for large buildings. Foundation design is a topic that likely needs further consideration when completing detailed design, and carrying out a comprehensive geotechnical study of the soil can help save a significant amount of construction costs.

Deep Foundations

The sensitivity analysis showed that 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 construction cost implications of increasing the seismic demands for two pile types, two building sizes, and two shearing angle φ are reported in Table 5. The impact of seismic demand on construction costs of piles is significantly smaller than that of shallow foundations, when all other aspects remain equal (such as soil condition). 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). The effect of the shearing angle is also noticeable, again highlighting the importance of having a proper understanding of the soil properties. The construction costs of concrete piles are smaller than those of steel piles.

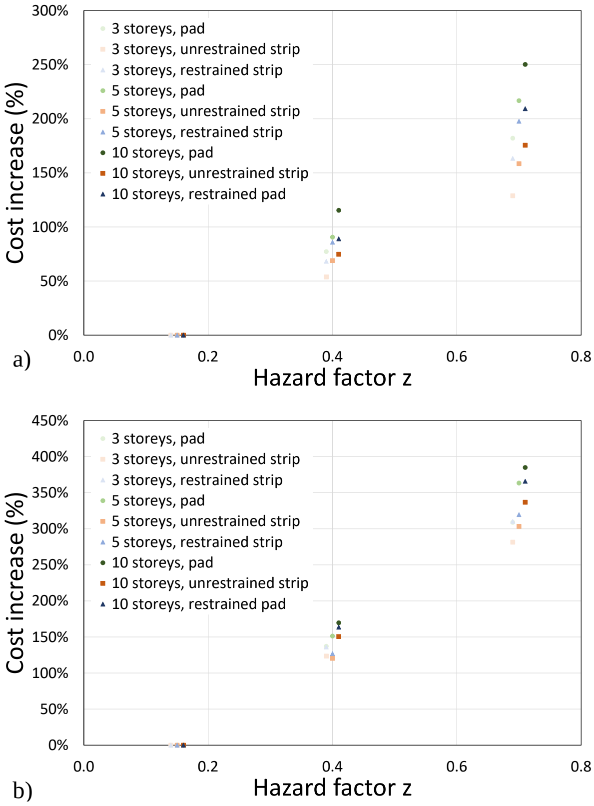


Figure 9: Impact of increased hazard factor on construction costs increase for shallow foundations in a) 576m^2, and b) 3600m^2.

CONCLUSIONS AND FUTURE WORK

We collected construction costs on thousands of buildings through preliminary design, and parametrizing of quantity take off and costing. This approach allowed for the assessment of a large number of parameters and their impact on construction costs, focusing on seismic demand, used in this work as a simplified proxy for seismic resilience. The main conclusions are:

Table 5: Impact of seismic demand on construction costs of piled foundations.

600mm diameter RC pile

Shearing angle φ	Factor z	576m^2	3600m^2
25	0.15 to 0.4	4.3%	5.6%
	0.15 to 0.7	5.7%	11.3%
40	0.15 to 0.4	2.3%	4.0%
	0.15 to 0.7	3.5%	15.6%

UC97 steel pile

Shearing angle φ	Factor z	576m^2	3600m^2
25	0.15 to 0.4	4.2%	7.5%
	0.15 to 0.7	10.4%	14.5%
40	0.15 to 0.4	4.0%	3.0%
	0.15 to 0.7	6.5%	11.7%

1. The impact of building location when the costs due to the seismic hazard changes are decoupled from the costs due to the particularities of the location are minimal. Similarly, the impact of floor type on construction cost is also insignificant as these structural elements are mainly governed by gravity loads. The impact of building size is not linear, or in other words twice the number of storeys or twice the floor area does not necessarily mean twice the cost. The slenderness of the building has an impact on construction costs, especially for RC buildings.
2. The impact of a higher seismic demand on structural costs is quite different depending on the structural system, as discussed in the RC wall buildings section. Construction costs only increased by up to 12% for steel EBF structures and up to 20% for RC wall structures, but the increase could double for steel MRF and increase by over 50% for RC frames.
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. Unstrained strips are the cheapest shallow foundation, with pads being the most expensive. Concrete piles are slightly cheaper than steel piles.

These conclusions are perhaps intuitive, especially in hindsight, but the results from this work provide quantitative proof to what many engineers already suggest through their work. Engineers should prioritise stiff lateral systems for any building that is 3 storeys or more in any area that has more than 0.15 hazard factor. The cost implications of having a stiffer structural system are minimal, especially when considering the overall development project. As an example, if the construction cost increase by 8%, but the total structural construction costs is around 25% as per Figure 3 and Figure 5, then the total increase in cost due to the structure is only 2%. But as discussed above, construction costs are about 70% of the total development costs, so the cost increase is actually 1.4% of 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 RC walls but without compromising redundancy and resilience through proper ductile design. Society expects this from our buildings, our engineers are trained and capable to design them, and the extra cost is minuscule.

Non-structural elements constitute a very high proportion of the construction costs, as shown in Figures 4 and 5. However, investigating the impact of a higher seismic demand on non-structural elements would entail a significant increase in the scope of the research, and merits a separate piece of work. In addition to non-structural elements, future works should be focused on completing full designs of several buildings for various seismic hazards and structural systems, and ideally find a real building where the construction cost can be obtained.

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REFERENCES

1 New Zealand Parliament (2004). *Building Act*. Ministry of Business Innovation and Employment (MBIE), Wellington, New Zealand.

2 Department of Building and Housing - Te Tari Kaupapa Whare (2004). *The New Zealand Building Code*. New Zealand Government, Wellington, New Zealand.

3 MBIE (2019). "*New Zealand Building Code: Clause B1 Structure - Acceptable Solutions and Verification Methods*". Ministry of Business Innovation and Employment (MBIE) - Hikina Whakatutukī, Wellington, New Zealand.

4 NZS (2004). "*NZS 1170-5: Structural Design Actions - Earthquake Actions*". Standards New Zealand, Wellington, New Zealand.

5 SEAOC (1995). "*Performance Based Seismic Engineering*". Structural Engineering Association of California (SEAOC) - Vision 2000 Committee, Sacramento, California.

6 CERC (2012). *Final Report*. Canterbury Earthquakes Royal Commission Wellington, New Zealand. https://canterbury.royalcommission.govt.nz/

7 Marquis F, Kim JJ, Kenneth JE and Chang SE (2017). "Understanding post-earthquake decisions on multi-storey concrete buildings in Christchurch, New Zealand". *Bulletin of Earthquake Engineering*, **15**(2): 731–58.

8 Parker M and Steenkam D (2012). "The economic impact of the Canterbury earthquakes". *The Reserve Bank of New Zealand Bulletin*, **75**(3): 13.

9 Dorahy MJ and Lee K-D (2012). "Psychological distress following the 2010 Christchurch earthquake: A community assessment of two differentially affected suburbs". *Journal of Loss and Trauma*, 17(3): 203–17.

10 Kuijer RG, Marshall ME and Bishop AN (2014). "Prospective predictors of short-term adjustment after the Canterbury earthquakes: Personality and depression." *Psychological Trauma: Theory, Research, Practice, and Policy*, **6**(4): 361.

11 Casey R, Farvid P and Sibley CG (2014). "I laugh and say I have 'Earthquake brain!'': Resident Responses to the September 2010 Christchurch Earthquake". *New Zealand Journal of Psychology*, **43**(2): 4-13.

12 Dhakal RP (2011). "*Structural Design for Earthquake Resistance: Past, Present and Future*". Canterbury Earthquakes Royal Commission Report, Christchurch, NZ. https://canterbury.royalcommission.govt.nz/documents-by-key/2011-09-2753

13 Buchanan AH, Bull D, Dhakal RP, MacRae GA, Palermo A and Pampanin S (2011). "*Base Isolation and Damage-Resistant Technologies for Improved Seismic Performance of Buildings*". Canterbury Earthquakes Royal Commission Report, Christchurch, NZ. https://canterbury.royalcommission.govt.nz/documents-by-key/2011-09-2377/$file/ENG.ACA.0020.pdf

14 RP Dhakal (2024). "Seismic design of buildings: Where to next?". *Bulletin of the NZ Society for Earthquake Engineering*, **57**(1): 1-17. https://doi.org/10.5459/bnzsee.1680

15 S Khakurel, RP Dhakal, T Yeow & S Saha, (2020). "Performance group weighting factors for rapid seismic loss estimation of buildings of different usage". *Earthquake Spectra*, 36(3): 1141-1165. https://doi.org/10.1177/8755293019901311

16 Gerstenberger M et al. (2022). "*New Zealand National Seismic Hazard Model 2022 Revision: Model, Hazard and Process Overview*". GNS Science Report 2022/57, GNS Science. Lower Hutt, NZ, 106 pages. https://doi.org/10.21420/TB83-7X19

17 Amos S (2004). *Skills and Knowledge of Cost Engineering: A Project of the Education Board of AACE International, 5th Edition*. AACE International, Morgantown, WV, USA.

18 PMI (2016). *Construction Extension to the PMBOK®Guide, 2nd Edition*. Project Management Institute, Newtown Square, PA, USA.

19 RICS (2012). "*RICS New Rules of Measurement*" in *NRM 1, Order of Cost Estimating and Cost Planning for Capital Building Works*. Royal Institution of Chartered Surveyors, London, UK.

20 Ashworth A and Perera S (2015). *Cost Studies of Buildings, 6th Edition*. Routledge: Abingdon Oxon, UK; New York, NY, USA.

21 Kirkham R and Brandon P (2007). *Ferry and Brandon's Cost Planning of Buildings*. Blackwell: Oxford, UK; Malden, MA, USA.

22 Potts K (2008). *Construction Cost Management: Learning from Case Studies*. Taylor & Francis: London, UK; New York, NY, USA.

23 Ashworth A (2008). *Pre-Contract Studies: Development Economics, Tendering, and Estimating*. Blackwell: Oxford, UK; Melden, MA, USA.

24 Nisbet R, Miner G and Yale K (2018). "The data mining and predictive analytic process". pp. 39–54 in *Handbook of Statistical Analysis and Data Mining Applications*. Eds: Nisbet R, Miner G and Yale K. Academic Press, Cambridge, MA, USA.

25 Fellows R (2010). "New research paradigms in the built environment". *Construction Innovation*, **10**: 5–13.

26 Brandon P (1982). "*Building cost research: Need for a paradigm shift?*" in *Building Cost Techniques: New Directions*. E&FN Spon: London, UK.

27 Egan J (1998). "*Rethinking Construction*". Report of the Construction Task Force to the Deputy Prime Minister, John Prescott, on the Scope for Improving the Quality and Efficiency of UK Construction. Department of the Environment, Transport and the Regions, UK, 40 pages.

28 Koskela L (2020). "*Theory of Lean Construction*". pp. 2–13 in *Lean Construction*. Eds: Tzortzopoulos P, Kagioglou M and Koskela L. Routledge: Oxfordshire, UK.

29 Kim Y and Ballard G (2001). “Activity-based costing and its application to lean construction”. *Proceedings of the 9th Annual Conference of the International Group for Lean Construction*, Singapore, 6–8 August; pp. 6–8.

30 Ballard G (2008). “The lean project delivery system: An update”. *Lean Construction Journal*, **1**: 1–19.

31 Zhao L (2018). “*Building Development Cost Drivers in the New Zealand Construction Industry: A Multilevel Analysis of the Causal Relationships*”. PhD Dissertation, Massey University, Albany, New Zealand.

32 Quotable Value Ltd. (2021). *QV Cost Builder*.

33 Rawlinsons Ltd. (2013). *New Zealand Construction Handbook*. Rawlinsons Publications, Auckland, NZ.

34 Dhakal RP and Aninthaneni P (2021). “Are stronger, stiffer buildings indeed costlier?: Case study of RC frame buildings”. *Proceedings of the 2021 NZSEE Conference*, Christchurch, New Zealand.

35 Sullivan T (2020). “Post-earthquake reparability of buildings: The role of non-structural elements”. *Structural Engineering International*, **30**(2): 217–23.

36 Bhatta J, Dhakal RP and Sullivan TJ (2023). “Seismic performance of a rocking precast concrete cladding panel system under lateral cyclic displacement demands”. *Journal of Earthquake Engineering*, **27**(4): 929-958. https://doi.org/10.1080/13632469.2022.2033359

37 Bhatta J, Dhakal RP and Sullivan TJ (2022). “Seismic evaluation of rocking internal partition walls with dual-slot track under quasi-static cyclic drifts”. *Journal of Earthquake Engineering*, **27**(14): 4161-4181. https://doi.org/10.1080/13632469.2022.2162629

38 Chan TK (2011). “Comparison of precast construction costs–case studies in Australia and Malaysia”. *Proceedings of the 27th Annual ARCOM Conference*, 5-7 September, Bristol, UK, pp. 3-12.