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THE COST OF STRONGER AND STIFFER BUILDINGS IN NZ – COST ESTIMATION TOOLS, DATABASE DEVELOPMENT, INITIAL RESULTS AND FUTURE WORK

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SUMMARY: Structural engineers, building owners/developers, and society have reservations about the seismic performance of buildings designed in accordance with current standards, many of which have been shown in recent severe earthquakes to be uneconomical to be repaired after a major earthquake event. The option of achieving increased performance levels by designing stronger and stiffer buildings is also perceived as an expensive solution. The objective of this research is to produce a comprehensive database on a wide range of buildings and their associated structural construction cost and seismic capacity to understand the cost difference between current practice and stronger, stiffer buildings. The motivation is to test the hypothesis that a step change in increasing the seismic resilience of the structural design of a building does not necessarily equate to a significant step change in the overall cost of designing and constructing the building. This research also has the potential to support cost/benefit analyses that may need to be undertaken if more formal consideration is given to changing building regulations, requiring more robust and resilient buildings. An additional objective is to develop a predictive tool for engineers, developers and policy makers to help in the decision-making process. This paper summarises the progress to date, consisting mainly of:

1) a systematic literature review on construction costs of buildings, the cost drivers, and the best predictive tools for cost estimation,

2) the methodology to be used in the development of the costing database and the various parameters to investigate such as lateral load resisting mechanism, type of diaphragm, section size and reinforcement ratio, and

3) the advances made on the first building typology – reinforced concrete frames with pad foundation and 3 types of floor typology.

A brief synopsis of future work is included at the end of the manuscript, such as expanding the database to shear wall structures and steel frames. Additional desirable objectives to be investigated include the soil/earthworks/foundation system, non-structural elements and various facades and roof types.

INTRODUCTION

Legally-binding earthquake performance requirements as set out in the Building Act (New Zealand Parliament 2004) and in the Building Code (Department of Building and Housing - Te Tari Kaupapa Whare 2004) 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 (Ministry of Business Innovation and Employment (MBIE) - Hikina Whakatutukī 2019) 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 (NZS (New Zealand Standards) 2004)). Thus, the legal definition of earthquake performance is to prevent collapse. 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 (Structural Engineering Association of California (SEAOC) - Vision 2000 Committee 1995).

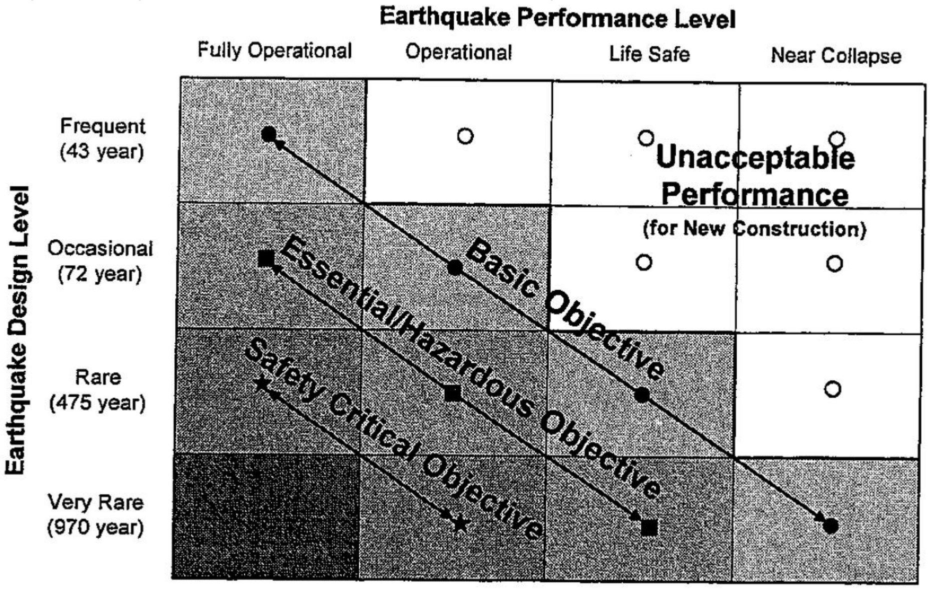


Figure 1 Recommended Performance Objectives for Buildings, according to (Structural Engineering Association of California (SEAOC) - Vision 2000 Committee 1995)

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 (Canterbury Earthquakes Royal Commission (CERC) 2012). Non-engineering aspects often determined the outcome of the demolition decision. For example 42% of the decisions were owner initiated (Marquis et al. 2017), which suggests that it was more economically beneficial to collect high insurance pay-outs, demolish 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 (Parker and Steenkamp 2012). 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 (Dorahy and Kannis-Dymand 2012; Kuijer, Marshall, and Bishop 2014; Rowney, Farvid, and Sibley 2014), and more importantly the loss of 185 lives. Society does not want a repeat of this – the societal expectations have now shifted towards a desire that a building is operational immediately or shortly after an earthquake. This expectations were defined in the Canterbury Earthquake Royal Commission Report (2012), as well as in the University of Canterbury Research Reports, the so-called "Dhakal report" (2011) and "Buchanan report" (2011).

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 (more commonly known as PRESSS technology) 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.

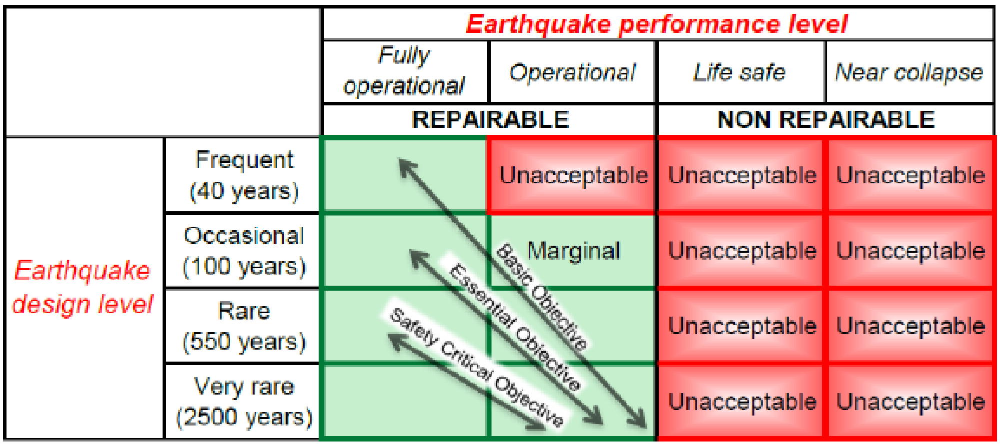


Figure 2 Performance levels as proposed in the "Buchanan report"

A simpler and, in our opinion, 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 risk than New Zealand, such as Japan and 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. The research motivation of this project is to understanding the true cost of building stronger and stiffer buildings that do not suffer significant damage and can be operational shortly after an earthquake. The literature review, the proposed methodology, some preliminary results and future work is presented in this document.

LITERATURE REVIEW

Construction costs in New Zealand

Zhao (2018) 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 most influencing factors are in the middle of the circle based. An interesting finding is that the vast majority of the experts thought that construction costs were the largest cost drivers, but the actual data shows a diametrically opposed outcome. 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, we can still exert our influence to reduce the complexity of the project, streamline procurement and stakeholders' relationships, and mitigate the elevated costs from statutory and regulatory factors.

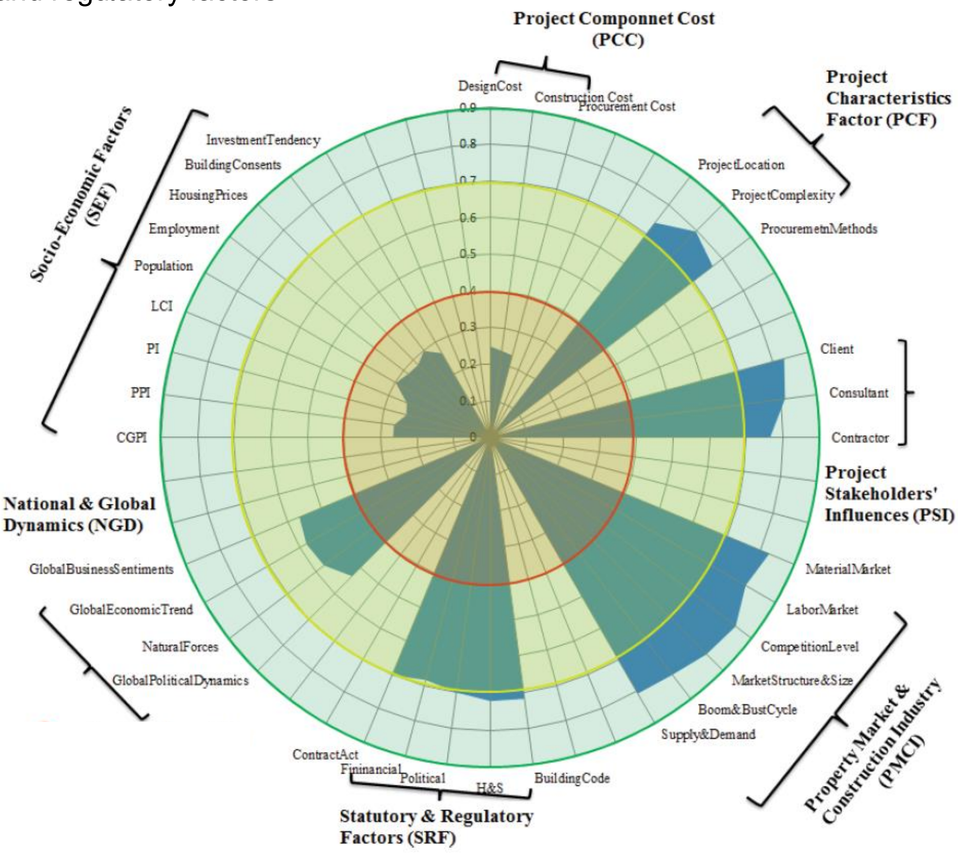


Figure 3 Relative importance of influencing factors

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 (Quotable Value Ltd. 2021). 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 (Rawlinsons Ltd. 2013). Undergraduate research studies undertaken at the University of Canterbury corroborate this finding (Figure 5), 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. Prof Sullivan (Haymes, Sullivan, and Chandramohan 2020; Sullivan 2020) has done some excellent work on the effect of earthquakes on non-structural elements, but the influence of higher seismic demand on the installed cost of these elements has not been investigated yet, to our knowledge.

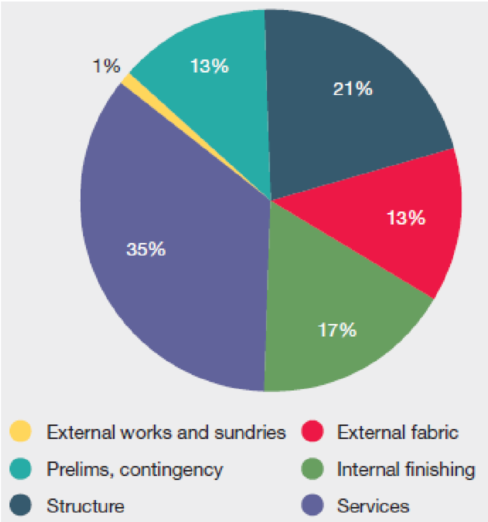
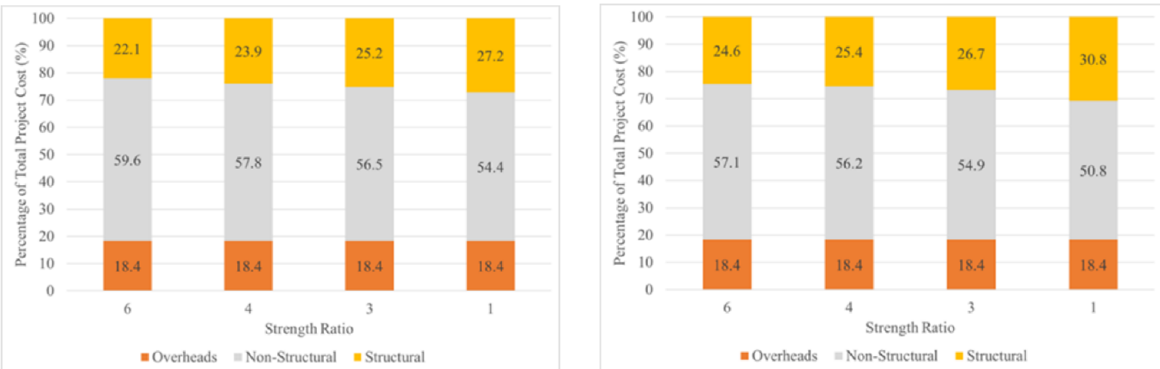


Figure 4 Elemental cost of a typical 6 to 15 storey office building



(a) Project costs for medium-rise buildings (b) Project costs for low-rise buildings

Figure 5 Estimated project costs for various strength ratios

In summary, if the construction costs have the least influence on the building development costs, and if the structural costs are between 20% and 33% of the construction costs, maybe the increased cost of having stronger building is not that significant.

Construction costs overseas

A systematic literature review using the Kitchenham methodology was completed (Kitchenham and Charters 2007). An initial screening of 133 documents was conducted, before narrowing the in-depth analysis to 43 documents. The objectives of the literature review were to 1) understand the various cost estimation methods and their reliability/accuracy, 2) identify and categorise/rank cost drivers in the construction industry, and 3) identify the best predictive tool for high accuracy cost estimation methods in the early stage of development.

1) Early stage cost estimation methods such as the floor area method (floor area multiplied by the cost per area unit) give an average error with respect to the final cost of between -15% and +25%, but the difference can be as high as -50% to +200% (AbouRizk, Babey, and Karumanasseri 2002). The maximum error of final estimates is ±5%, but more often in the ±2% range (Ashworth 2002; Ashworth and Perera 2015).
2) A total of 73 parameters were identified, 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 structure type and especially the foundation system have a significant effect on construction costs. 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

3) Several predictive tools were investigated, from relatively simple multiple regression analysis to complex neural networks. The conclusion is that all existing techniques are similarly accurate, but a large database that can capture all possible permutations is critical. Large database in this case means thousands of datapoints.

METHODOLOGY

The methodology was designed under the premise that a large database (thousands of buildings) is necessary for an accurate cost estimation at the early stages of the building development process. Thus, it was considered unrealistic to use real buildings, because it would not be possible to produce such a large database. Instead, industry practice using highly accurate, late stage cost estimation methods was used, facilitated by Revit/Dynamo and Matlab/Python as further described below. We are in the process of developing the database, and once this has been completed a predictive tool will be developed to achieve high accurate cost estimation in the early stages of the development process.

Building Information Modelling (BIM)

BIM was used to develop the models of the buildings and produce the quantity take-off. Dynamo is a relational database application programming interface (open source visual parametric programming plug-in on Revit), and enabled us to rapidly produce the buildings. An example of what Dynamo looks like is shown in Figure 6. The database of concrete frame buildings have been completed as of May 2021, and we are working on steel frames and concrete wall buildings.

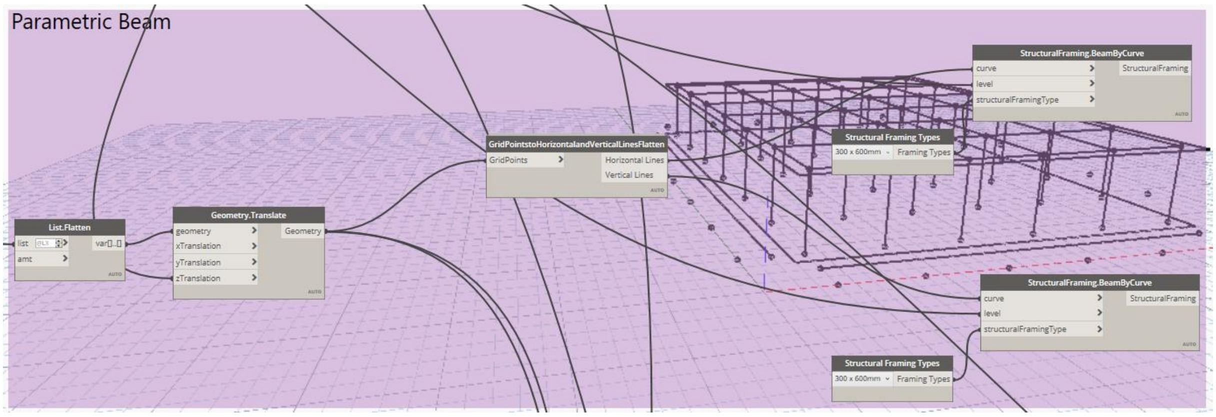


Figure 6 Parametric design of a beam using Revit and Dynamo

Cost estimation

The cost estimation was produced on MatLAB, using the quantity take-off from Revit and the costing database from QV Costbuilder (2021). A more detailed costing database was produced for some critical structural elements, such as the floors (precast, cast-in-place and composite floors) and the shear walls (to investigate the influence of various reinforcement configurations).

Structural (seismic) capacity

A comprehensive seismic capacity calculation of the BIM buildings will take place in the next 12 to 18 months, but a preliminary design of a limited number of buildings (~75) has been completed using RESIST. RESIST is a NZSEE computer programme that allows for preliminary design of lateral load resisting elements to withstand earthquake loads. All the buildings have a hazard factor of between 0.1 and 0.7 (for soil C conditions and no near-fault factor).

PRELIMINARY RESULTS

Only preliminary results on RC framed buildings have been produced at the time of publication. The main parameter investigated so far is the influence of column size on construction cost for buildings of various sizes (3, 5 and 10 storeys and floor size from just over 100 m^2 to just over 10,000 m^2. The seismic capacity has been determined in terms of hazard factor Z, leaving all other parameters fixed (soil C and no near fault effect). The foundation was assumed constant for buildings of the same size, for example the 10-storeys buildings had 5.4 m pads 1.2 m thick, but are not considered in the costs. The influence of column size, floor area and number of storeys is reported in Figure 7. The difference in cost is minuscule, usually ranging from 0.5% to 1.5%. The largest difference is for the largest building, as can be expected. The difference in this case was 2.4% for buildings within the current seismic hazard. In other words, the construction costs of designing the building for a hazard factor of 0.5 (close to the maximum) instead of 0.13 (the minimum) is only 2.4%. We acknowledge that there are numerous and significant caveats in this analysis: i) only the structure is being considered, not roof type or the foundation and related earthworks, ii) non-structural elements have not been considered, although it can be assumed that the design (and therefore the cost) of these elements would not change significantly), iii) only one reinforcement ratio has been considered thus far, iv) only one floor type is included in these results, and v) only one price per element has been considered but different cities and towns will have different prices of up to 15% in some cases. These are preliminary results that will most likely change as the project progresses, but they already point out that the influence of seismic hazard level on total construction cost is likely to be minor.

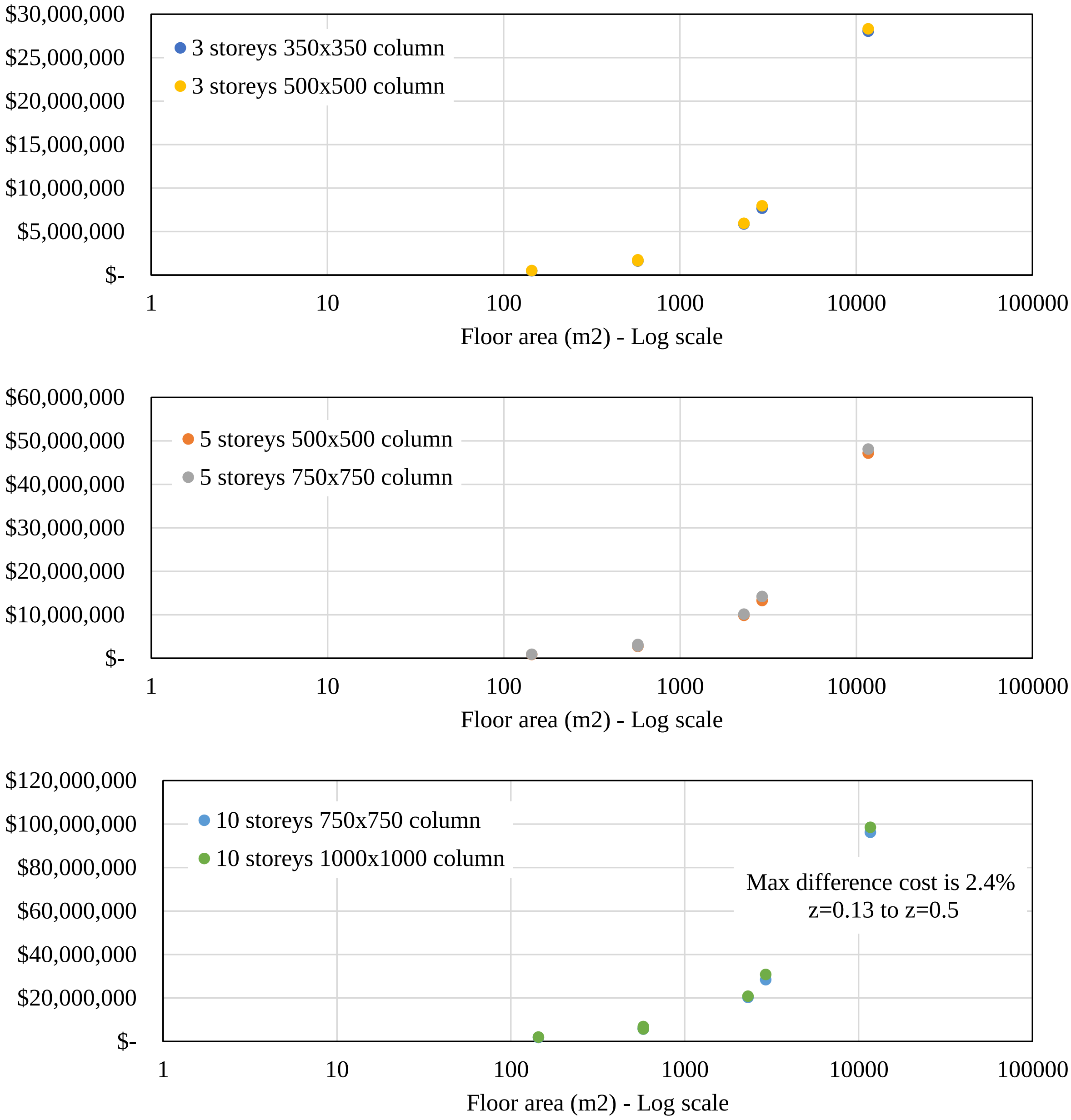


Figure 7 Cost of 3-, 5- and 10- storey buildings for various floor areas and column sizes

FUTURE WORK

The most challenging part of this project was to create a methodology that would allow us to develop an extremely large database relatively quick and labour-free. This phase has almost been completed, and we are now focused on creating the database of buildings for cost estimation and seismic capacity calculation. The databases on RC frames, RC shear walls, moment resisting steel frames and braced steel frames are being compiled, including 3 types of floors. The influence of a) foundation and related earthworks, b) facades and roof types, and c) non-structural elements will be investigated next year. The ultimate objective is to create an user-friendly tool that will allow for highly accurate cost estimates at the early stages of design.

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