THE EARTHQUAKE HAZARD POSED BY AUCKLAND'S UNREINFORCED MASONRY BUILDING STOCK

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ABSTRACT

Following the recent Canterbury earthquakes, a renewed focus has been directed across New Zealand to the hazard posed by the country's unreinforced masonry (URM) buildings, recognising how poorly these buildings perform in large earthquakes. Auckland is the largest city in New Zealand, and because of the relative prosperity of Auckland during the period 1880-1935 when most URM buildings were being constructed in New Zealand, the city has the greatest stock of URM buildings in the country. Studied aspects of the hazard posed by these buildings include:

- The number, location and age of these buildings, and the role that these buildings play in the built heritage of the city
- Their architectural attributes and material characteristics
- Earthquake prone building policy and other public legislation relevant to these buildings
- The seismic hazard in Auckland
- The expected performance of these building by extrapolating observations from the recent Canterbury earthquakes
- Past and current activities to earthquake strengthen Auckland's URM buildings, at both an owner and regional territorial level.

Provisional recommendations developed in collaboration with Auckland Council regarding a pathway to alleviate the hazard posed by Auckland's URM buildings are also presented.

KEYWORDS: unreinforced, masonry, earthquake, hazard, retrofit, Auckland

INTRODUCTION

Unreinforced masonry (URM) buildings were a prominent form of construction across New Zealand from approximately the early 1880s to the mid-1930s. Over 1000 URM buildings are estimated to exist currently in the Auckland region alone [1], and these buildings often serve useful functions in the community in addition to encapsulating heritage and social value. Findings from investigations into URM building collapses during the 22 February 2011 Christchurch earthquake, however, have heightened the public's awareness of the unique seismic risks posed by these structures. The risk associated with URM buildings is further underscored in the final report on earthquake-prone buildings published by the Canterbury Earthquakes Royal Commission [2]. While Auckland's seismic hazard is low relative to most parts of New Zealand, the other component of risk – vulnerability – warrants that distinct attention be paid to how to best assess, retrofit, and demolish, if necessary, URM buildings across Auckland in order to protect the public's safety while best serving other interests also.

As an owner of over 3500 buildings properties, including several constructed of URM, the Auckland Council Department of Property began a seismic retrofit prioritisation programme in 2012. The intended result of this programme is a prioritisation framework which will categorise all council buildings in accordance with their seismic risk and council-assessed value in order to assign resources efficiently and effectively to both seismic inspections and future retrofit work. The programme will produce a methodology as well as a list of properties and a timeline for the construction work. Corollary outputs will include a detailed, standardised inspection programme to be used by the Departments of Property and Building Control as well as a standardised databasing index system to be used across departments to aid in data procurement on current and future property projects. Furthermore, a strategic plan for building asset priorities is expected to be delivered to the executives of Auckland Council and referenced by other departments as part of their planning processes.

Currently, the Department of Property at the Auckland Council is relying on information procured by the regulatory inspection processes administered by the Building Control Department in order to begin assessing the risks associated with the URM buildings in the Council's portfolio. Hence, the referenced Auckland URM stock includes buildings for varied owners, including but not limited to the Council.

AUCKLAND'S SEISMIC HAZARD

The islands of New Zealand sit roughly along the boundary of two of the planet's lithospheric tectonic plates – the Australian Plate and the Pacific Plate. The Pacific Plate subducts beneath the Australian Plate alongside the east coast of the North Island at an average rate of approximately 50 mm/year [3]. As Auckland resides further from this subduction zone (approximately 300 km) than most other cities and towns on the North Island, the Auckland region's seismic hazard is relatively low.

Table 1 summarises information from building standards and seismic hazard assessments relevant to Auckland's URM building stock. Most URM buildings in Auckland will likely be considered to have 50-year design working lives for assessment and retrofit design purposes, but some buildings of particular significance to the community could be considered for 100-year design working lives. For design and assessment purposes, most URM buildings in Auckland will fall into importance levels 2 or 3. Importance level 2 applies to normal structures, and importance level 3 applies to buildings containing larger crowds, valuable assets, or serving important functions as defined in the building standard [4]). URM buildings in Auckland that would most regularly be considered for importance level 3 criteria would likely include schools, libraries, and town halls. Hence, while most URM buildings would be considered for a design basis earthquake (DBE) to occur every 500 years on average, higher-profile URM buildings will need to be considered for less frequent events. The recurrence intervals listed in Table 1 correspond with ultimate limit state (ULS) design parameters to include strength, ductility, serviceability, and durability.

The Modified Mercalli (MM) scale is used to describe the damage and intensity experienced by people at a particular location. MM7 and MM8 intensities approximate the range of hazards relevant to the Auckland region as shown in Table 1. MM7 intensity is associated with slight to moderate structural damage in well-built ordinary buildings, while MM8 intensity implies considerable structural damage with partial collapse of well-built ordinary buildings [5]. The peak ground accelerations (PGA) currently used in the design standards [6] and recently proposed PGA values [7] are also included in Table 1 for shallow soils (Type C) [8]. The proposed PGA values are lower than those currently used in the standard. Note that most URM buildings in Auckland will be assessed for higher spectral accelerations than the PGA values because the hazard spectra peak at a period of about 0.2 seconds for shallow soils.

Table 1: Building design criteria and recurrence hazards for Auckland [4,7,9]

Design life	Import. level	Importance level comment	Annual prob. of exceedance for EQ ULS	Approx. MM intensity	Current PGA (C soil)	Proposed PGA (C soil)
50 years	2 3	Normal structures Crowds or valuable assets	1/500 1/1000	MM6.8 MM7.2	0.13g 0.19g	0.08g 0.12g
100 years	2 3	Normal structures Crowds or valuable assets	1/1000 1/2500	MM7.2 MM7.6	0.19g 0.26g	0.12g 0.19g

While the updated PGA values may be implemented in the next edition of the standard for most of Auckland, they will likely not be reduced for South Auckland. Figure 1 illustrates the reason for the distinction of South Auckland's higher hazard due to the concentration of historical shallow earthquakes and poor soils in the South. The most powerful recorded earthquake to affect the Auckland region was the 1891 Waikato Heads earthquake with Richter magnitude M5.5-6.0 and intensity MM6 in Auckland City (MM7 experienced on the west coast). The most recent earthquake of notable intensity was the 1972 Te Aroha earthquake with Richter magnitude M5.1 and intensity MM4 in Auckland City (MM7 experienced near Te Aroha) [10,11]. Both of these earthquakes occurred south of the Auckland region.

Much of South Auckland's geology, especially along the west coast, is comprised of Pleistocene to Holocene marine and alluvial sediments and dune sand [12]. Where unconsolidated, these soil types are prone to amplifying earthquake intensities up to two MM levels higher than intensities on neighbouring rock [11]. Fortunately, much of Auckland Central rests on volcanic and sedimentary rocks. Furthermore, liquefaction and lateral spreading are not likely to affect much of the region during an earthquake [9], although slope instability during seismic shaking could damage buildings across Auckland [11].

The only two faults near Auckland that have been active in the past 125,000 years are the Kerepehi and Wairoa Faults [10,11], labelled in Figure 1 in the South region. The Kerepehi Fault is located in the centre of the Hauraki Plains approximately 75 km from Auckland Central [10,11], displaces approximately 0.13 mm/year [13], contributes approximately 2% to the 500-year PGA determination [7], and has a mean recurrence interval of 2500 years [10,11] with moment magnitude M_w 7.2 [7] capable of producing a shaking intensity of MM7-MM9 throughout the region [10,11].

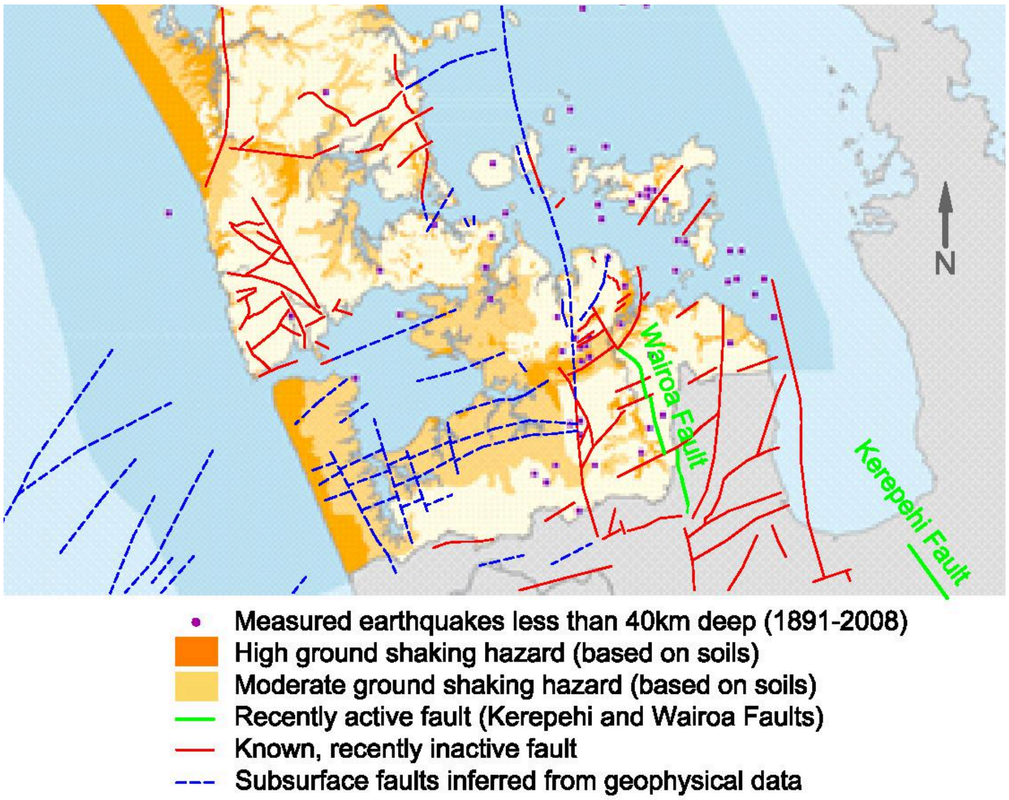

Figure 1: Mapping of the Auckland region's "ground shaking" hazard, selected fault lines, and locations of historical shallow earthquakes [11,14,15]

The Wairoa Fault (technically, North and South faults) is located near the Hunua Ranges approximately 35 km from Auckland Central, displaces approximately 0.1 mm/year (Edbrooke 2001), contributes approximately 4% to the 500-year PGA determination, and could produce a moment magnitude of M_w 7.2 [7]. Distributed seismicity sources account for the majority of contribution to the determined 500-year PGA [7], and these sources account for earthquake occurrences on currently unknown faults based on a nationwide distribution of seismic hazards [9]. Hence, the next intense earthquake in Auckland is considered more likely to come from an unknown or buried fault than from a known fault.

PLAN AND POLICY

The 2004 Building Act [16] required territorial authorities (such as Auckland Council, though it existed as multiple district councils at the time) to adopt policies on dangerous, earthquake-prone, and insanitary buildings. The Act defined an earthquake-prone building as one that "will have its ultimate capacity exceeded in a moderate earthquake (as defined in the regulations)… and would be likely to collapse causing… injury or death to persons in the building or to persons on any other property; or… damage to any other property." The referenced regulations [17] defined a moderate earthquake as “an earthquake that would generate shaking at the site of the building that is of the same duration as, but that is one-third as strong as, the earthquake shaking (determined by normal measures of acceleration, velocity, and displacement) that would be used to design a new building at that site.”

In accordance with the 2004 Building Act, Auckland Council developed a policy on earthquake-prone buildings [18] to apply to the years 2011-2016. The policy identifies the NZSEE [19] assessment guidelines as a preferred means of determining whether a building is earthquake-prone, and applies regulatory action in accordance with importance level and heritage status. URM buildings in Auckland currently deemed earthquake-prone by Auckland Council’s Building Control must be seismically strengthened within 10 years (for importance level 3), 20 years (for importance level 2), or 30 years (if deemed “heritage” per the New Zealand Historic Places Trust (2012) or district plan, by being part of a conservation area, or by having been originally constructed before 1900).

The Initial Evaluation Procedure (IEP) can be used to assign a preliminary seismic risk rating to a building, and the procedure lends itself well as a coarse screening tool applied to a large population of buildings. Hence, the IEP is extremely popular in New Zealand with building regulators and consultants managing large amounts of building infrastructure. While detailed evaluation procedures are also described in the NZSEE guidelines (2006), these procedures require a level of analysis that is not efficiently applied to a large stock of heterogeneous buildings. The IEP uses a scoring system of percent new building standard (%NBS) which indicates, in short, what seismic forces a building can withstand compared to a building designed and constructed precisely to current standards. A building with a %NBS score of less than 33 is deemed “earthquake-prone” by the national building regulations. Since an earthquake-prone building is assumed to be unable to withstand a “moderate” earthquake, the building may require further assessment and possibly structural retrofits. Calculated risk levels are not linear across the %NBS scoring range. A building determined to have a score of 33%NBS is assumed to have a collapse or partial collapse risk that is 20 times higher than a building at 100%NBS. Buildings with %NBS scores between 34 and 67 are deemed “earthquake-risk” per the NZSEE guidelines.

In addition to regulatory policy and technical guidelines, the Auckland Plan [14] was developed as the master plan for all activities within Auckland Council, with the primary goal of “creating the world’s most liveable city.” The Auckland Plan addresses the built environment and lists “build resilience to natural hazards” as one if its priorities and “increase the proportion of residents who understand their risk from natural hazards and are undertaking measures to mitigate or reduce their risk from 2011 levels to 80% by 2040” as one of its targets. The Auckland Plan directly references “ground shaking hazards” as one of these natural hazards.

URM BUILDINGS IN THE CANTERBURY EARTHQUAKES

Much has been written about the performance of URM buildings in the Canterbury earthquakes [2,20-22], but a summary is provided here in order to highlight considerations relevant to assessing risks associated with URM buildings in Auckland.

The Canterbury region of New Zealand experienced a swarm of earthquakes in 2010 and 2011, with the two most prominent events occurring on 4 September 2010 (Darfield/Canterbury earthquake, M_w 7.1) and 22 February 2011 (Christchurch/Lyttelton earthquake, M_w 6.2). The latter earthquake's hypocentre was only 5 km below the surface, and its epicentre was only 10 km south-east of the Christchurch city centre. The damage and death toll resulting from the 22 February 2011 Christchurch earthquake was substantial. 175 people were killed as a result of building failures, including 39 fatalities that were linked with the collapse or partial collapse of URM buildings at 20 different sites [2]. URM buildings represented, by far, the most building sites associated with fatalities during the earthquake.

The collapse of unrestrained falling hazards such as parapets, ornaments, gable end walls, chimneys, and loose bricks as well as the out-of-plane collapses of URM building facades put passers-by at greater risk than occupants of URM buildings [22]. In fact, 35 of the 39 people killed by URM building collapses were outside or in neighbouring buildings when they were killed, including 3 people who had run outside of a building in response to the earthquake. [2].

Researchers [22] who performed a damage survey of URM building in Christchurch after the 22 February 2011 earthquake determined that 63% of all URM buildings in the central business district (CBD) had been retrofitted in some fashion. Of those that had been strengthened to between 67% and 99%NBS (using pre-earthquake hazard values), only 24% had collapsed or been seriously damaged. By comparison, of those that had not been retrofitted in any way, 97% either collapsed or sustained heavy damage, and 90% have either been demolished or are scheduled to be demolished. It is expected that most of the buildings without retrofits would have been deemed earthquake-prone (<33%NBS pre-earthquake). Furthermore, 44% and 57% of restrained parapets and restrained gable end walls, respectively, failed while 84% and 88% of unrestrained parapets and gable ends walls, respectively, failed. In conclusion, seismic retrofits of URM buildings and their components can certainly enhance performance over a population of buildings, but further research is required in order to have confidence that restrained parapets and gable ends will perform satisfactorily in future design-level earthquakes.

The Canterbury Earthquakes Royal Commission (CERC) [2] published recommendations pertinent to seismically assessing and engaging a retrofit prioritisation programme for URM buildings. The three most prominent recommendations are listed firstly:

- Non-structural elements that may pose as falling hazards (chimneys, parapets, ornaments, and gable ends) and/or impede egress should be secured or removed.
- External facades of all URM buildings should be retrofitted, including in areas of low seismicity.
- Regulatory changes should require that earthquake-prone URM buildings in regular use be assessed within two years, strengthened globally to 34% NBS/ULS and with out-of-plane structural and non-structural components strengthened to 50% NBS/ULS within seven years, and be listed in a published schedule.
- Response spectra, particularly related to vertical accelerations, should be revised.
- Compatibility in deformation (stiffness) amongst structural components should be considered.
- "New building standard" or "NBS" is misleading, and "ultimate limit state" or "ULS" should be used to quantify expected building performance.

- Further research is needed to validate the ductility factor for URM buildings as an assumed value of 2.0 with 15% damping may not be representative of actual URM performance.
- Detailed assessments and potential retrofits of URM buildings should consider the possible need to connect all structural elements of a URM building together, so that it behaves cohesively; increase in-plane wall shear strength; and install structural systems that remove the role of lateral load resistance from the original URM structure.

Note that any amendments to the Building Act in accordance with the CERC recommendations will almost certainly apply to Auckland Council's regulatory policy and property portfolio management strategy, despite the lower seismic hazard associated with Auckland.

VULNERABILITY OF AUCKLAND'S URM BUILDING STOCK

While the apparent seismic hazards in Auckland are relatively low, especially in Auckland Central where a plurality of population and URM buildings reside, the vulnerability of Auckland's built infrastructure is high. As of 2012, Auckland's economy accounts for an estimated 37% of New Zealand's GDP, and the region's economic growth has outpaced New Zealand's national economic growth 7 of the past 11 years [23]. Auckland's regional population of about 1.3 million in 2006 [24] accounted for 32.4% of the nation's population. Hence, a major natural disaster in Auckland would be detrimental to much of New Zealand.

Russell [1] performed an encompassing review of URM buildings across New Zealand and began by cataloguing URM buildings into different typologies based on number of storeys and footprint geometry (e.g., isolated versus row building and rectangular geometry versus non-rectangular). While one-storey row buildings are deemed most prevalent across New Zealand, Auckland is likely to have more multi-storey row buildings, especially in the older parts of town, such as the central business district (CBD) and suburbs nearest the CBD. Regarding construction and materials, Russell [1] determined that most URM buildings in New Zealand were constructed of clay brick masonry (approximately 230x110x76 mm bricks) with solid walls being 3 leafs thick. Wall thickness in the base storey will typically increase by one leaf per every 2 storeys in height, such that the lower wall of a 6-storey URM building may be 6 leaves thick. Ground mortar (used between foundations and the walls) in Auckland URM buildings is likely to include red scoria ash, sand, and hydraulic lime that was ground in a mortar mill [25], and mortar between bricks is likely to include either lime or cement as the adhesive agent with a wide variety of sand particles depending on how close any given building was to ocean beaches and river banks, as the sand was usually taken from nearby the construction site Lime-based mortars do not perform as well over time compared to cement-based mortars, especially in buildings near the ocean and exposed to higher concentrations of sea salt spray [1].

In regard to seismic vulnerability, Cousins [9] suggests in a report to the Auckland Council that URM buildings are 5.4 times more fragile than are post-1980 reinforced concrete (RC) buildings. By comparison, the second-most fragile building type is pre-1980 RC at 2.3 times the fragility of post-1980 RC. Hence, as building performance in the Canterbury earthquakes has proven valid, URM buildings are over-represented in risk compared to their proportion of the building population in seismic hazard models. The results of Cousins' hazard model for Auckland are summarised in Table 2. Intensity and PGA values assume shallow (Type C) soil, importance level of 2, and design life of 50 years.

Table 2: Estimated losses and casualties (dead plus seriously and moderately injured) [4,7,9]

Return period	Loss	Casualties	Approx. MM intensity	Current PGA
100 years	$3 million	0	MM<6.8	<0.08g
500 years	$80 million	0	MM6.8	0.13g
1000 years	$200 million	0	MM7.2	0.19g
5000 years	$900 million	11	MM>7.2	>0.19g

In enforcing its policy on non-residential earthquake-prone buildings, Auckland Council's Department of Building Control has inspected approximately 639 URM buildings owned by various parties. All of these buildings to date have been identified as being constructed of unreinforced clay brick masonry (UBM), specifically, though stone masonry buildings also exist in Auckland. The proportions of building types documented thus far in the seismic assessments are illustrated in Figure 2, with approximately third parts timber, RC frames, and URM. In performing a seismic hazard analysis for Auckland, Cousins [9] extrapolated building data from Wellington to estimate that Auckland's URM stock accounted for only 5% and timber accounted for only 15%. Ultimately, it is expected that the proportions shown in Figure 2 will approach Cousins' estimates as the inspection programme progresses, and that the current disparity is indicative of the fact that older buildings in Auckland Central have been assessed firstly, which likely skews the numbers in favour of URM and timber building construction in non-residential buildings.

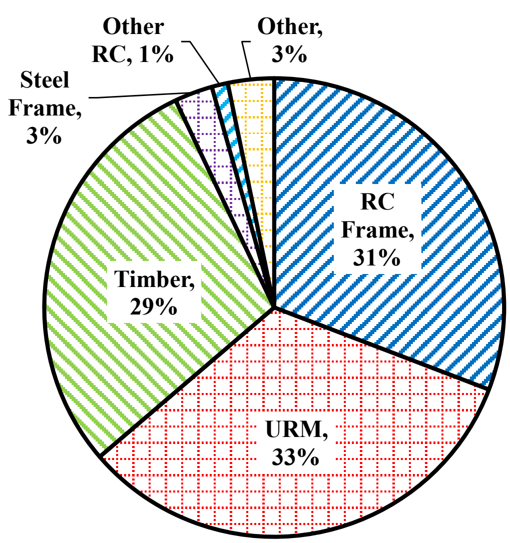

Figure 2: Proportions of non-residential building material types inspected in Auckland to date

Russell [1] estimated that a total of 1026 URM buildings exist in Auckland (which does not conflict with the current total of 639 URM buildings identified by Auckland Council's inspections given the inspectors' geographic focus on parts of the region with the highest concentrations of older buildings). Furthermore, Russell estimated construction time periods for the URM buildings in Auckland and number of storeys for URM buildings across the country. The comparative results of the Auckland Council-procured data and Russell's estimations are charted in Figures 3a and 3b. Note that the time periods of construction are fairly consistent between the two data sets. That Auckland would have taller URM buildings than most other New Zealand cities should be expected, although the multi-storey buildings may be currently over-represented due to the inspections having been performed mostly within and near the city centre.

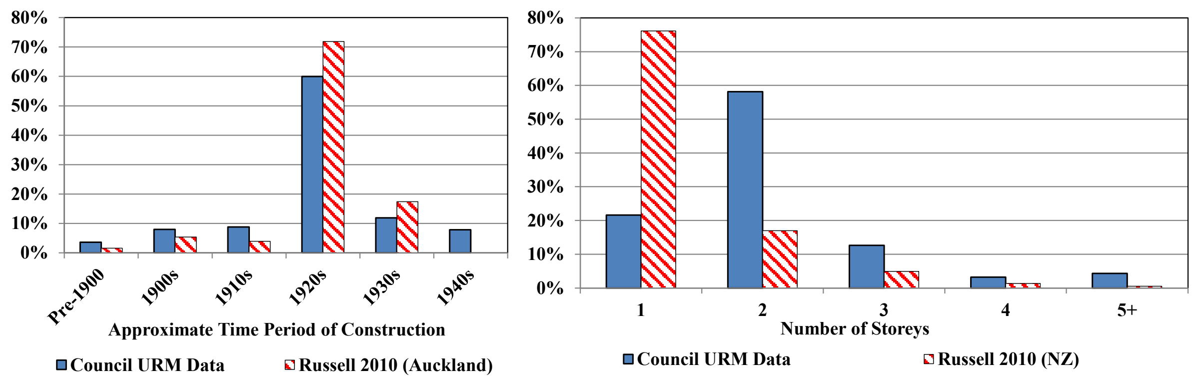

Figure 3: URM data comparisons: a) Auckland URM building construction time periods, Council data for Auckland versus CERC researcher estimations for Auckland; b) Auckland URM building storeys, Council data for Auckland versus CERC researcher estimations for New Zealand

To date, 244 URM buildings in Auckland have been assigned IEP scores through the regulatory process. Of those, 79% are considered earthquake-prone (<33%NBS), and another 15% are considered earthquake-risk (<67%NBS). Date of design, soil type, and seismic hazard are the three most consistently critical factors in determining a %NBS score per the IEP. The scoring is largely based on the assumption that a building being considered was designed to the standards of its time, and New Zealand cities other than Wellington did not have building codes prior to 1935. Furthermore, most URM buildings in Auckland will be assumed to have natural periods below 0.4 seconds, which places them within the peak spectral range of design seismic demand in the IEP. Hence, these buildings are unlikely to be assessed as anything other than "earthquake-prone" at the end of the procedure, despite the relatively low seismic hazard assumed for Auckland. The existence of seismic retrofits can be used to enhance an IEP score, but few URM buildings in Auckland thus far have been found to include such retrofits.

Cousins [9] estimates that the total values and floor areas, respectively, for Auckland buildings are \$35 billion and 17 million square metres for residential structures and \$21 billion and 15 million square metres for workplace structures. Cousins estimates that URM buildings account for 2% of the residential value/area and 5% of the workplace value/area. By assuming proportional value across all building types, Auckland's URM building stock could be valued at a combined total of \$1.75 billion and area of 1.09 million square metres, suggesting an average unit cost of \$1605/m^2. Applying URM building data from Russell [1] to the distribution of Council-determined Auckland storey heights shown in Figure 3b and assuming a total of 1026 URM buildings in Auckland, however, suggests that the financial value of Auckland's URM building stock is closer to \$0.5 billion with an area of about 0.5 million square metres, providing an average unit cost of \$1000/m^2. Despite the disparity between the interpretations of the two source estimates, it is clear that a large amount of capital is invested in Auckland's URM building stock.

FURTHER WORK AND IMPACTS

Information that can be procured through relatively simple inspections includes the building typologies (e.g., heights, building footprint geometry, isolated versus row, and the relationship of these factors to pounding potential which affected 12% of the URM building inspected in Christcurch [21]), elevation type (e.g., perforated frame versus solid wall), presence of bond beams, wall construction (e.g., solid versus cavity, number of leafs), bond patterns, basic construction material type (e.g., clay brick versus stone), and occupancy use/functional type (which will influence the importance levels and perceived community values). Further investigations into determining the architectural history, heritage status, and perceived social/community value of Auckland's URM buildings will help determine retrofit strategies and priorities.

The Canterbury earthquakes and recently released Royal Commission reports [2] have changed the legislative environment and public awareness of URM buildings. As a result, building regulators, owners, tenants, users, and heritage enthusiasts will be facing a uniqe challenge in the coming few years where improvements and demolitions of URM buildings are taking place at an unusually high rate. Auckland Council is currently developing inspection, assessment, prioritisation, and retrofit strategies that will target the risks associated with URM buildings, in particular, so as to preserve and enhance the safety, economic, and community values of these special buildings.

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