CHARACTERISATION AND SEISMIC VULNERABILITY ASSESSMENT OF UNREINFORCED MASONRY BUILDINGS IN DUNEDIN CBD

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SUMMARY

The need for Territorial Authorities (TA) to compile an earthquake-prone building register has been highlighted by the Canterbury Earthquakes Royal Commission and with this in mind the following research was undertaken to enable the characterisation and assessment of potentially earthquake-prone historic unreinforced masonry (URM) buildings in Dunedin. To achieve the research goals, associated technical literature was reviewed and an earthquake-prone building register containing data on 226 URM buildings located in the Dunedin central business district (CBD) area was compiled. Additionally, structural performance of these buildings was also assessed using both the literature suggested initial evaluation procedure and the proposed risk based assessment method. It was estimated that 680 of the existing 750 Dunedin URM buildings are likely to be earthquake-prone and merit detailed assessment. It was also established that the earthquake risk in the city is primarily based on the fact that it has a significant number of URM buildings built prior to the introduction of building code, of which a large proportion is concentrated in the CBD. These not only pose a safety risk to their users but also to pedestrians on the adjacent footpaths.

INTRODUCTION

It is well established that unreinforced masonry (URM) buildings perform poorly during large earthquakes and therefore are deemed to be the most earthquake-prone class of buildings. In view of this, the use of URM in new construction was restricted to non-load bearing walls. Sections 131 and 132 of the New Zealand Building Act 2004 [1] require Territorial Authorities (TAs) to implement a risk reduction policy for earthquake-prone buildings. The seismic risk associated to URM buildings was further highlighted during the 2010/2011 Canterbury earthquake series. To this end, the Canterbury Earthquakes Royal Commission (CERC), as the first step in such policy implementation, recommended the preparation of an updated earthquake-prone building register and to bring these up to date, where they already exist [2].

Dunedin, like many other large New Zealand cities, has a large number of potentially earthquake-prone historic URM buildings and the majority of these have not yet been seismically strengthened. Dunedin City Council (DCC) estimated that there existed roughly 750 URM buildings in the region including low-risk residential URM buildings [3]. Since the 2010/2011 Canterbury earthquake series, local media and TAs has paid notable attention to the potential effects should a similar earthquake occur in Dunedin. These reports have touched on the fact that Dunedin has a significant number of pre-1930 buildings and that parts of Dunedin are likely to be susceptible to liquefaction [3-5]. DCC in fulfilling its responsibility has introduced an earthquake-prone building policy, requiring building owners to have their building assessed and if the assessed capacity is less than one third (< 34%) of the strength required by current design standards for new buildings (also referred to as %NBS) then to strengthen it. However, owners are encouraged to strengthen their buildings to a minimum of two thirds (> 67%) of new building standard [6]. The policy outlines a three stage approach including the identification of potential earthquake-prone buildings, detailed assessment of identified buildings, and then strengthening of earthquake-prone buildings (refer to Figure 1). Buildings undergoing a 'change of use' are also required to undertake seismic upgrade to 67% NBS at the time of this change of use.

The study reported herein was therefore undertaken to facilitate the first stage of DCC earthquake-prone policy i.e. identification of potential earthquake-prone URM buildings. The key objectives of this study are to firstly identify and record the characteristics of the URM buildings in the Dunedin central business district (CBD) and then to establish their seismic vulnerability, which will aid in updating the existing DCC earthquake-prone building register as per the CERC's recommendation. The area posing the highest seismic risk was selected for this investigation based on the following criteria.

1. the population and value of URM buildings.
2. the geotechnical details and liquefaction potential.
3. the number of potentially affected people that include both users and pedestrians on adjacent footpaths.

The selected area covers the Dunedin CBD that runs along Princess Street, through the Octagon and along George Street and some of the historic precinct between Princess Street and Cumberland Street (see Figure 2).

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Policy stage	2012		2013		2014		2027		2032		2037		2042	
Identification of earthquake-prone buildings	■													
Initial assessment of identified buildings		■	■	■	■									
Detailed assessment of identified buildings		■	■	■	■									
Seismic retrofit of buildings having current structural performance score of 15% or less			■	■	■	■	■							
Seismic retrofit of buildings having current structural performance score of 15% - 20%			■	■	■	■	■	■	■					
Seismic retrofit of buildings having current structural performance score of 20% - 25%			■	■	■	■	■	■	■	■	■			
Seismic retrofit of buildings having current structural performance score of 25% - 33%			■	■	■	■	■	■	■	■	■	■	■	

*Although this is the minimum required, building owners are encouraged to upgrade to the highest economically viable level possible.

Figure 1: Overview of DCC's earthquake-prone building policy and associated time frames.

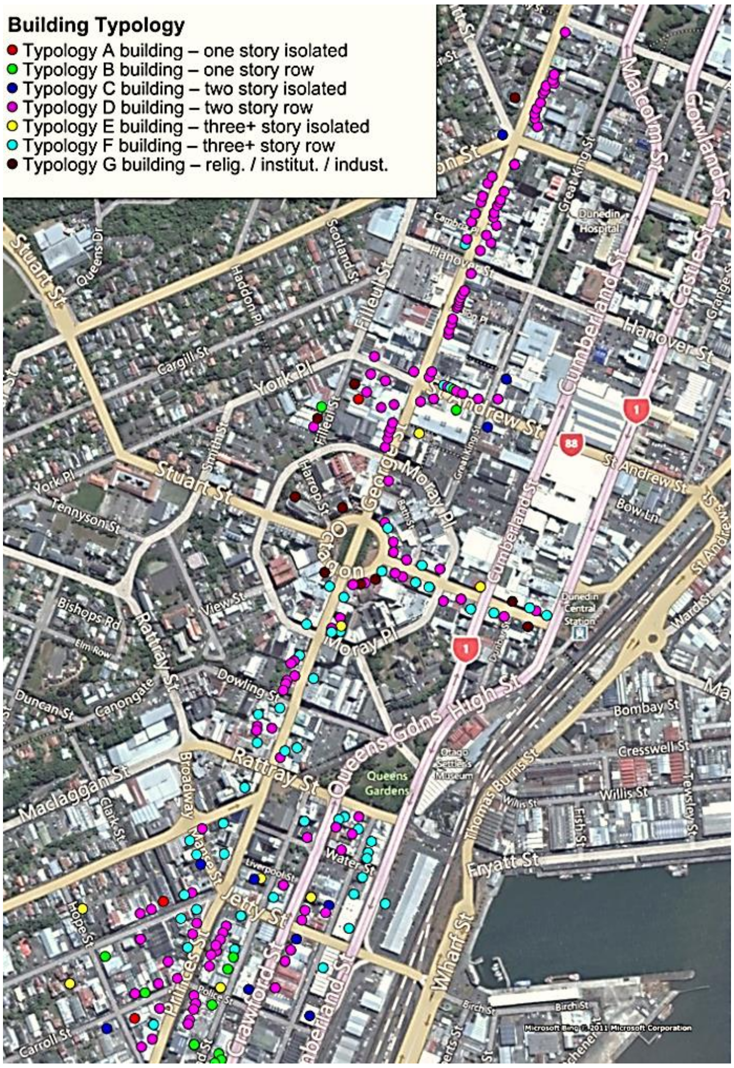
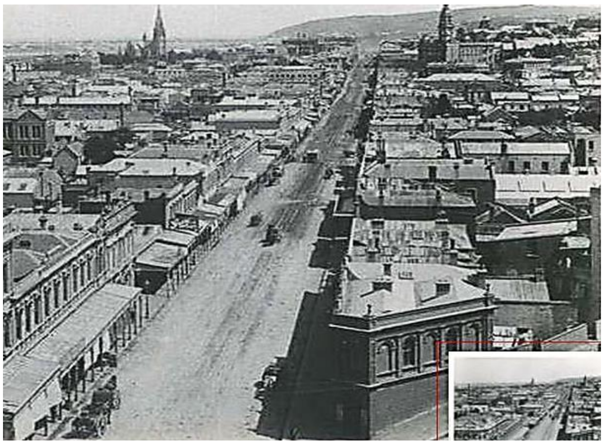


Figure 2: Definition of Dunedin CBD region and spread of different URM building typologies in the region.

The results of this research are crucial to formulate an effective and comprehensive earthquake-prone building policy, which is a first step in seismic risk reduction process. This investigation not only provides a template for similar research to be undertaken for other areas/regions but also provides useful data/statistics that later can be compared with observations made in other areas to establish any location variation in national context and can be used for future research on social, economic, historical or architectural aspects.

HISTORY OF DUNEDIN URM BUILDING STOCK

The early foreign settlers arrived in Otago harbour to found the Dunedin settlement in 1848, with first retail shops established in the area around Princes Street and Manse Street. Dunedin's current main commercial and retail area runs north-east along Princes Street through the Octagon and along George Street to North Dunedin. This area was once low lying swamp and was rapidly developed during and after the gold rush of the early 1860s [7]. Development of Auckland in the 1900s as the largest city in New Zealand and the relocation /closure of local Dunedin industry caused a reasonable decline in city's development. Since then construction and redevelopment in the Dunedin CBD has been limited (see Figures 3a and 3b). Many subsequent developments have involved only renovation of existing buildings [7] that may or may not include any strengthening intervention, leaving the city with a significant number of URM buildings built between 1860s and 1900s (i.e. built prior to the introduction of seismic building codes) . This has seen the city left with a legacy of Victorian architecture that still provides the city much of its character today and has become one of the famous tourist attractions.. Typical examples include, the Former Excelsior Hotel building (see Figure 4a) and Bendix Hallenstein's Drapery and General Importing Company building, that has now been adapted for the Dunedin Public Art Gallery (see Figure 4b).



(a) George Street in 1904

(b) George Street in 1994

Figure 3: Panoramic views from Knox Church (Source: Hocken Collections).

(a) Former Excelsior Hotel (1862)

(b) Bendix Hallenstein's Drapery and General Importing Company building (1884)

(c) URM buildings in Caversham

(d) URM buildings in South Dunedin.

Figure 4: Photographs of some example URM buildings.

Early settlements built during the gold rush in outlying areas around CBD (including South Dunedin, Mosgiel, Port Chalmers, Green Island and Caversham) all have groups of URM buildings that are typically single or double storey and used for retail businesses (see Figures 4c and 4d). These surrounding areas developed shops as part of an economic and social infrastructure to cater for the needs of residents without them having to travel in to the city center. This development in South Dunedin resulted in the city's second major retail area, along King Edward Street, around the intersection with Hillside road (formerly known as Cargill Street) towards Caversham.

GEOLOGY AND SEISMICITY OF DUNEDIN

The geology of Dunedin is varied across the region, with several different types of underlying strata (see Figure 5a). The industrial and commercial areas and the port around the head of the harbour are built on low-strength alluvial deposits and reclaimed land. The hills surrounding the harbour basin are predominantly basalt, whereas the areas around Caversham and Kaikorai Valley are overlain by sandstone and mudstone that extends through to Burnside and Green Island.

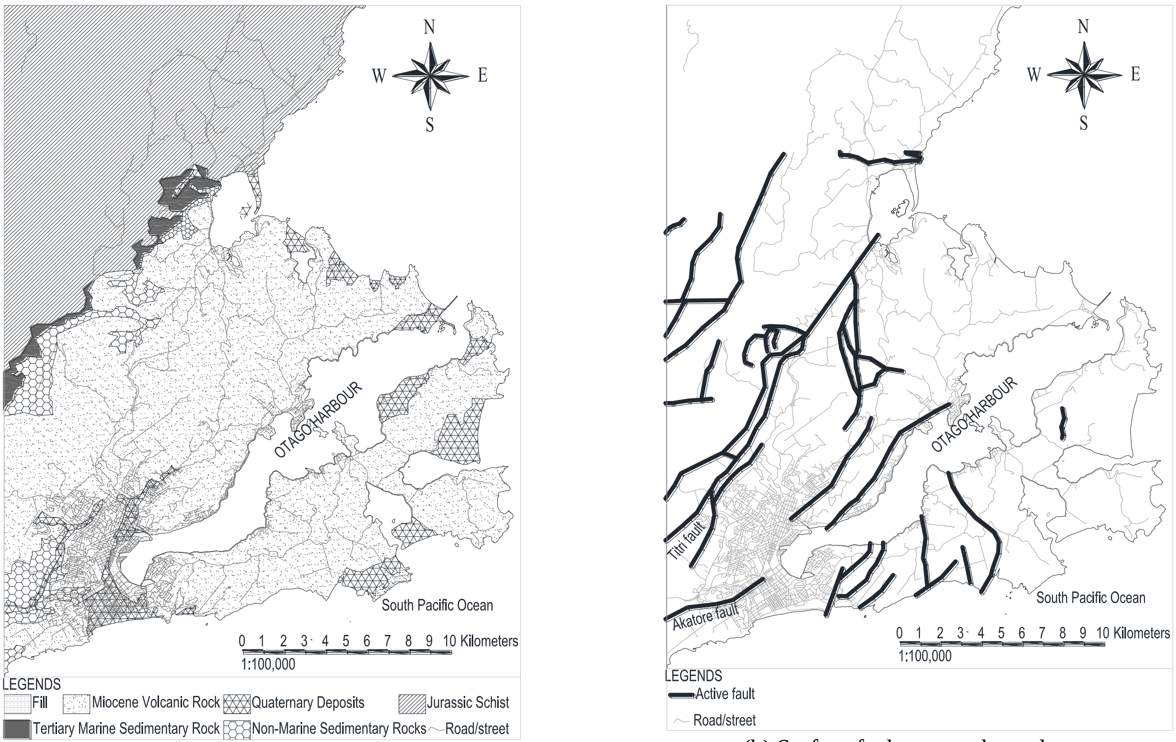
South Dunedin is built on low laying alluvial deposits, which lie between the Otago Peninsula and the hills of Saint Clair and is underlain by estuarine silts, sands and clays that are potentially susceptible to liquefaction [8, 9]. The Dunedin CBD is founded on rock on the west side and around the Octagon and alluvial deposits on the other side of the George Street [9].

The 1974 Dunedin earthquake is the only seismic activity recorded to have caused any significant damage in the city. Adams and Kean [10] reported the earthquake as magnitude 5.0, which was centered approximately 7 km off the south coast of Saint Kilda at a depth of 20 km. It has also been reported that the earthquake induced a shaking intensity of VII on Modified Mercalli Intensity (MMI) scale in the worst affected areas, whereas the peak ground acceleration recorded in Saint Clair was 0.27 g in the North-East direction [11]. The damage caused by the earthquake included damage to chimneys, cracking of external masonry and plaster, plumbing, tile roof damage and breaking of household contents. The minimal damage was reported as widespread in the suburbs on the alluvium deposits between the Otago Peninsula and Saint Clair, with relatively less damage reported in the rest of the city and hill suburbs [3].

Studies of the Alpine fault (not shown in Figure 5b) by Sutherland and Norris [12], estimated lateral displacements along the Alpine fault of up to 8 m, at the time of its next significant movement. This surface fault rupture on the Alpine fault would result in a shaking intensity of approximately VIII on MMI scale and have an estimated recurrence interval of about 300 years, with literature suggesting the high probability of such a seismic event [3]. Table 1 gives an overview of the expected shaking intensities for Dunedin along with corresponding probabilities and the surface fault rupture hazard map shown in Figure 5b.

Table 1. Probabilities for various shaking intensities in Dunedin (adapted from [9]).

MMI Intensity	Approximate expected effect	Average return period
VI	Minimal property damage	30 Years
VII	Some property damage, loss of life unlikely	100 Years
VIII	Significant property damage, loss of life possible	450 Years
IX	Extensive property damage, some loss of life	In excess of 2,500 Years
X	Catastrophic property damage, major loss of life	Very small probability



(a) Geological map

(b) Surface fault rupture hazard map

Figure 5: Geological and seismological details of Dunedin (adapted from [3]).

Glassey *et al.* [8] reported that the largest credible earthquake event for Dunedin could result from a ground rupture on the Akatore fault (one of the local faults). This rupture could be expected to produce an earthquake of magnitude 7.0 and a ground shaking intensity of IX on MMI scale, with this level of shaking estimated to have a recurrence interval of about 3,000 years. McCahon *et al.* [9] and Glassey *et al.* [8] both suggested that the city can expect one earthquake of felt intensity VII every 100 years (analogous to a peak ground acceleration of 0.3g for a 100 year return period), which is more onerous than the seismic loading that current New Zealand loading standards [13] would produce for a 1/500 event.

PREVALANCE AND CHARACTERISATION

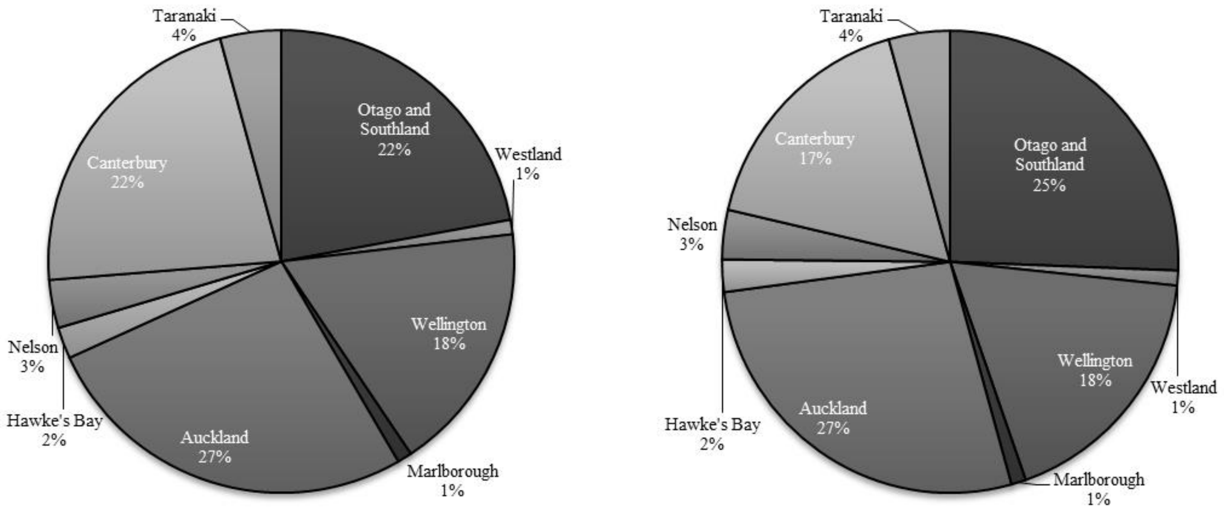
The prevalence of URM buildings in New Zealand is well documented and URM buildings appear in the majority of city's and small towns across the country. Due to their age, only limited information can be found about the construction details and physical characteristics of the materials used to construct these historic buildings. The limited information also means that the exact number of URM buildings in New Zealand is also not known.

Russell and Ingham [14] estimated a total of 4,000 URM buildings to exist in New Zealand prior to the 2010/2011 Christchurch earthquake series, with their population distributed across the New Zealand as illustrated in Figure 6a. Recently, an updated recommendation on the number of URM buildings in Otago and Southland was presented at the Canterbury Earthquakes Royal Commission [15] based upon recalibration after better data was obtained on the number of URM buildings in Christchurch (see Figure 6b). The same research identified seven typologies to represent the non-residential URM building stock in New Zealand). One photograph of a representative building for each of these seven typologies are shown in Figures 7a to 7g, along with their description and their prevalence rank in a national context (RNZ) and in Dunedin (RDN) noted in the captions.

In order to achieve the research objectives, a significant volume of data was obtained through several primary and secondary resources. DCC provided data from their geographic information system that included information about the buildings' unique identifier, address, year of construction, floor area, wall type, wall condition and plans. However, the information was incomplete and required supplementary information from other sources to be obtained. Therefore, missing information was gathered by interrogating DCC rating information, real estate websites and by undertaking field surveys/ building inspections. The register complied consisted of a data set on 226 buildings in and around the main streets of Dunedin CBD. The sample of Dunedin buildings assessed have been characterised into the typologies identified by Russell and Ingham [14], the location and spread of the surveyed buildings can be seen in Figure 2.

Overall, it was observed that the buildings fitted well in the typologies described in the aforementioned study, although it was often found that buildings of different storey height were built directly adjacent to one another thus not completely fulfilling the definition of a row type building. However, for practical purposes it was decided that buildings were deemed to be part of a row when situated directly adjacent to one another. It can be seen in Figure 8a that typology D is the most prevalent type by a large margin and that row buildings (typologies B, D, and F) are far more common than isolated buildings (typologies A, C and E). It can also be established that Dunedin appears to have a greater number of larger, three or more storey high buildings than the numbers reported for other parts of New Zealand. This might not be true for the overall city because the buildings assessed were situated in the city centre and those located in the suburban areas are mostly low-rise (i.e. one or two storeys high).

It was also estimated by interrogating the council's rate information that the 226 buildings assessed have a total value of improvements (capital value less land value) of approximately 159 million dollars, representing a large proportion of the value of Dunedin building stock as the further outlying URM buildings have a relatively lower land value. Not only are these URM buildings of considerable financial value, but 103 of the 226 buildings surveyed have also some form of historic significance, while others may have townscape significance related to their location in groupings and collections. Figure 8b shows the number of buildings and their historic places listing category, where CAT I HP = category one historic place, CAT II HP = category two historic place, and Façade = places having a protected historic façade only.



(a) Prior to the 2010/2011 Earthquakes [14]

(b) Recalibrated after the 2010/2011 Earthquakes [15]

Figure 6: URM building distribution in New Zealand.

(a) Typ. A: single storey isolated (RNZ =4 & RDN =7)

(b) Typ. B: single storey row (RNZ =3 & RDN =3)

(c) Typ. C: two storey isolated (RNZ =2 & RDN =4)

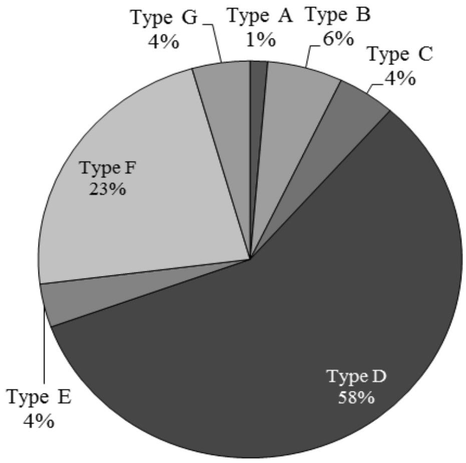
(d) Typ. D: two storey row (RNZ =1 & RDN =1)

(e) Typ. E: three+ storey isolated (RNZ =7 & RDN =6)

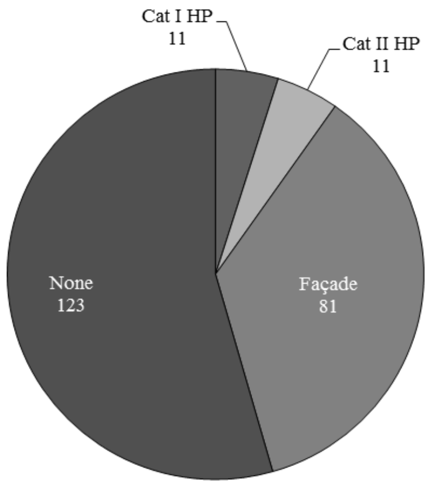
(f) Typ. F: three+ storey row (RNZ =6 & RDN =2)

(g) Typ. G: religious institutional, or industrial (RNZ =5 & RDN =4)

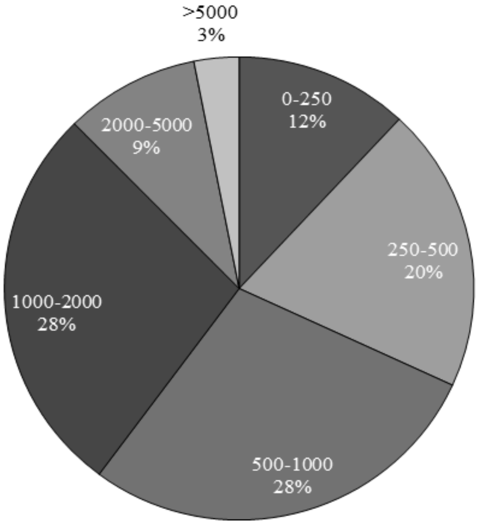
Figure 7: Typologies representative of non-residential URM buildings in New Zealand, where RNZ = prevalence rank in New Zealand and RDN = prevalence rank in Dunedin.



(a) Typology distribution



(b) Historic significance



(c) Covered area

Figure 8: Characteristics of Dunedin URM building stock.

It was also found by interrogating the building register that 211 of the total 226 buildings have an unrestrained parapet, which owing to the short return period and cantilever boundary conditions pose the largest safety risk.

EARTHQUAKE-PRONE BUILDING POLICY

The Initial Evaluation Procedure (IEP) for existing buildings is described in the chapter 3 of NZSEE guidelines [16], with Attribute Score Assessment based IEP for URM buildings built prior to 1935 detailed in Appendix 3B of the guidelines. IEP is intended as a coarse screening assessment to identify potential earthquake-prone buildings and it is noted that the IEP results would not be relied upon as a definitive assessment of a building's strength relative to the percentage of New Building Standards (NBS) but only be used to identify buildings that warrant a further detailed assessment. However, the IEP provides a preliminary score for a comparative risk grading of buildings to establish priorities for improvement. The guidelines recommend that a detailed assessment be performed for a buildings having an IEP score of less than or equal to 33% and be strengthened to satisfy the local building control requirements, if need be.

Strengthening to one-third of NBS is the current minimum requirement adopted by the majority of councils across New Zealand to satisfy the requirements of the New Zealand Building Act [1]. It should be noted that whilst this level of strengthening may reduce the seismic risk and may avoid/minimise damage in earthquakes of lower intensity but the risk remains that this level of strengthening is not high enough to withstand a potential large magnitude earthquake. It is a well-debated topic in recent times that the minimum strengthening requirement should be lifted to two-thirds of NBS. Perhaps, if this was to be considered, it should be adopted sooner rather than later before the inevitable strengthening work has already been carried out. To this end, some territorial authorities recommend strengthening to 67% NBS or more, as a result of the damage observed during the 2010/2011 earthquakes. Moreover, the overall score allocated to a building would not effectively represent the seismic risk associated to critical individual components e.g. parapets, chimneys, and wall-diaphragm anchorage.

SEIMSIC VULNERABILITY ASSESSMENT

As the first step for establishing the seismic vulnerability of Dunedin URM stock, a building register was populated details related to all eight attributes (also referred to as risk items) required for IEP. Indicative IEP scores were calculated for 216 buildings of the total 226 URM buildings located in Dunedin CBD by performing an IEP on one representative building from each typology (A to F) and by applying this score across all buildings of that typology. It is noted that typology G (institutional, industrial and religious) buildings were discounted owing to their complex/unique nature that does not conform to trends, like the other typologies and each requires specific investigation.

During the second stage of this research, actual IEP score for each of the 216 buildings was calculated using the information recorded in the building register and the information collected by conducting external visual assessments. Both IEP scores indicated that the majority of the buildings assessed are "likely to be earthquake-prone", with very little or no difference in their IEP scores. The results of the existing URM IEP, which tended to yield very similar results for all of the different types of buildings, highlighted the need for more criteria and or a larger scale to help differentiate between the different buildings. To attempt to accomplish this, the following scale based risk assessment scheme is proposed. The scheme draws on the basis of the existing URM IEP, and supplements it by including more assessment criteria and a newly devised scoring scale. This will provide a greater range or results while still containing the key risk items which contribute to the failure of URM buildings. In this proposed assessment procedure, buildings are scored against a total of 10 risk items and then these scores are summed and used to infer a NBS score. This enabled identification of the most likely at risk buildings and to further prioritise the buildings for further action/detailed assessment. The proposed risks and judgment criteria for scoring are given in Table 2.

Table 2. Proposed risk categories and scores

Construction period risk						**Scoring justification/ description**
Period	Pre 1880	1880-1899	1900-1919	1920-1935	Mixed	It was observed from the building inspection that the construction quality was quite variable between the 1880s and 1930s. Therefore, a risk score has been assigned to each period to account for weakness in the older material, both at the time of construction and due to its age.
Risk scores	2	1.5	1	0.5	1.25	

Floor area risk							**Scoring justification/ description**
Area (m^2)	0-250	250-500	500-1000	1000-2000	2000-5000	>5000	To account for the size of the building, with this inherently representing the diaphragm spans, presence of cross walls, and number of users of the building.
Risk scores	0.5	1	1.5	2	2.5	3	

Number of stories risk						**Scoring justification/ description**
No. floors	1	2	3	4	5	The more stories the building has the more risk because it will attract more seismic forces even when it does not have structural regularities in vertical plan. This can also be put down to the higher buildings having a higher period and therefore experience higher displacements under earthquake load, thus the more risk of damage.
Risk score	1	2	3	5	5	

Foundation soil risk			**Scoring justification/ description**
Foundation soil type	Rock	Alluvial	This scoring is based on the fact that foundation details of existing URM buildings is almost similar irrespective of the foundation type but the seismic demand will vary based on soil profile type. (Note: This is assuming the structures also have the same period.)
Risk score	1	1.58	

Diaphragm continuity risk	**Scoring justification/ description**
Same as existing IEP	Same as existing IEP

Wall condition risk					**Scoring justification/ description**
Condition	Sound	Good	Fair	Poor	This risk scores have been based on the IEP attribute score for material condition applied to the wall condition, collected during the building survey.
Risk score	0	1	2	3	

Pounding potential risk			**Scoring justification/ description**
Pounding potential	N	Y	The risk of pounding is not just based on separation from the adjacent building as per the existing URM IEP but taking into account the height of diaphragms as well.
Risk score	0	3	

Plan regularity risk					**Scoring justification/ description**
Ratio W/L	1 > 0.75	0.75 > 0.5	0.5 > 0.25	< 0.25	As the majority of URM buildings inspected had walls at perimeter and the weight of the building was largely due to these walls as well, therefore ratio of building dimensions was used to account for horizontal regularity.
Risk score	0	1	2	3	

Wall out –of-plane failure risk				**Scoring justification/ description**
h/t_w	< 10	10 < 14	14 <	Same as existing IEP but with wider interpolation.
Risk score	0	1	3	

Wall in-plane failure risk					**Scoring justification/ description**
A_p/A_w	< 10	15 < 10	20 < 15	>20	Same as existing IEP
Risk score	0	1	2	3	

Where: W = shorter side of the URM building; L = longer side of the URM buildings; h = height of URM walls between restraints; t_w = thickness of URM wall; A_p = plan area of the storey of interest; and A_w = cross-sectional area of all walls.

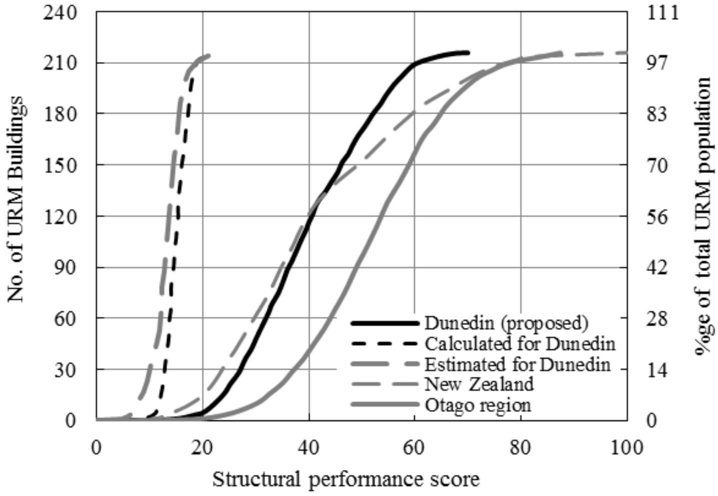


Figure 9: Seismic vulnerability of URM building stock in local and national context.

The results of the proposed risk index based analysis are also shown in Figure 9. It could be argued that the IEP process has little value for URM buildings, given it is unlikely to deliver results in excess of 33% for any URM building, even where this performance could be higher. However, it is also important to remember that the IEP is a course screening tool and is intentionally conservative. Therefore, there is value in IEP assessments, as they are the first step along the path to ensuring that the country's historic buildings are safe in the event of an earthquake. Given the experience of the 2010/2011 Christchurch earthquake swarm and the increased level of awareness in the industry perhaps it would be worthwhile to investigate and calibrate the IEP method for URM buildings.

The two IEP assessment models, although conducted quite differently, produced similar results. This confirmed that same typology buildings would behave similarly in the event of earthquake. As there is no link between the scale based risk assessment and the IEP scores these cannot easily be compared. However the results of the risk assessment may be used as a means to prioritise detailed assessments. Aspects of assessment, or at least the risk categories used in the proposed risk based scheme, may provide a useful addition to the current URM IEP, which does lack in some areas e.g. the site soil class is typically not accounted for, which as indicated above increases the design load on a structure by a factor of up to 1.58, which is a larger increase than an increase from importance level 2 to 3.

CONCLUDING REMARKS

The 1974 Dunedin earthquake is known to be the only damaging earthquake in the region, with damage mostly contained to buildings located in the southern parts of the city. This could be put down to the geology of the area and its proximity to the epicentre. Whilst Dunedin has a relatively low probability of experiencing a significant earthquake when compared to other main centres across New Zealand, the seismic risk comes primarily from the prevalence of numerous URM buildings in the CBD, with these not only posing a safety risk to their occupants but also to a large number of people on the adjacent streets.

It can be implied based on the data discussed above and the findings from the vulnerability assessments that 21 (that had have some sort of strengthening) of the 226 URM buildings surveyed for this report can be classed as not earthquake-prone, while the remaining 205 buildings are likely to be earthquake-prone. Based on these numbers it could be estimated that of the estimated 750 URM buildings in Dunedin 680 would be expected to be earthquake-prone, prior to implementation of the city's EPB policy, which is already resulting in large numbers of building upgrades. It is also noted that the majority of these earthquake-prone buildings have some sort of historic significance associated to them. In this case, should the city experience a significant earthquake, which was to damage these buildings to the extent that they were beyond repair, the architectural history of the city and the CBD environment would be drastically effected. A large number of unrestrained parapets present possibly the largest risk to life because these can fail even during medium intensity seismic events having a lower return period and can therefore be expected more frequently. Additionally, numerous adjacent URM buildings do not have diaphragms at the same height and thus exhibit pounding potential, making the design of a seismic retrofit for these row buildings more complicated.

ACKNOWLEDGMENTS

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