

Ground motion records for time-history analysis of URM buildings in New Zealand – The North Island

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ABSTRACT: The New Zealand Standard for Structural Design Actions, NZS 1170.5:2004, defines a criterion for selecting ground motion records for time-history analysis based on similarity between the seismological signature of earthquakes used for the analysis and those that are expected to be encountered at a given location. However, as most structural designers are not familiar with the specific details of the probabilistic seismic hazard model used to determine the design spectra, further information is currently required before designers can readily select appropriate earthquake records.

The objective of the study reported here was to integrate the seismologist's and the engineer's specialist knowledge, and to develop a method of selecting the best set of records for different locations considering the hazard level for each location and the seismological characteristic of the expected ground motions. For this purpose, New Zealand has been divided into several seismological hazard zones based on the mapping of the Hazard Factor presented in NZS 1170.5:2004, and the fault mechanism. Furthermore, a suite of records is proposed for use when conducting time-history analysis of existing New Zealand unreinforced masonry (URM) buildings, satisfying the Standard requirements. Recommendations are presented for selecting the records to be used in each zone. Preliminary results are presented for the North Island of New Zealand. A similar proposal for the South Island is still under study.

1. INTRODUCTION

In the last 10 years the use of dynamic methods in structural analysis has increased significantly. Especially interesting is the development of time-history analysis techniques. Some years ago, these methods were only applied in academic studies, but today they are widely employed by many consulting engineering firms for the seismic analysis, design and assessment of structures. That is one of the reasons why the latest version of the New Zealand Standard for Structural Design Actions, NZS 1170.5:2004 (Standards New Zealand 2004a) (henceforth referred to as "the Standard"), dedicates extended sections to this topic (Sections 5.5 and 6.4). In the Standard, criteria are defined for the selection and the scaling of ground motion records for analysis, and some considerations are suggested for modelling and analysis. However, there are several topics that currently are not fully addressed in the Standard, and more comprehensive explanations or further recommendations are required. One of these issues is the criterion defined to select an appropriate suite of records to be used in time-history analysis. The Standard states in section 5.5.1 that:

“the ground motion records shall be selected from actual records that have a seismological signature (i.e. magnitude, source characteristic (including fault mechanism) and source-to-site distance) the same as (or reasonably consistent with)

the signature of the events that significantly contributed to the target design spectra of the site over the period range of interest. The ground motion is to have been recorded by an instrument located at a site, the soil conditions of which are the same as (or reasonably consistent with) the soil conditions at the site” (Standards New Zealand 2004a).

After reading this paragraph, two questions are immediately apparent: i) What is really meant by the “same seismological signature”? ii) How could the engineer know which ground motion contributed most significantly to the target design spectra?

Someone who attempts to respond to the above questions, not being a seismology expert or knowing little detail about the probabilistic seismic hazard model used to build the standard spectra, could be confronted with an impossible task, even in the case of “well-trained” professionals or designers with many years of experience. That is why currently the responsibility for record selection for time-history analysis belongs mainly to seismologists (Comartin et al. 1996). However, overseas experience has shown that seismologists tend to be prudent when asked to select records and assume that all features (magnitude, source-site distance, fault mechanism, etc.) matter to structural response. This conservatism is more related to a lack of knowledge about the influence of seismological parameters on structural response, than to scientific facts (Iervolino and Cornell 2005). That can be easy to understand, considering that this is not necessarily their expertise. Communication with several local seismologists and structural engineers has confirmed that the situation in New Zealand is similar to the experience reported elsewhere (Kelly 2007). Therefore, considering this situation, the question is: Is it possible to integrate the seismologist’s and engineer’s specialist knowledge, and recommend a suite of records to be used in time-history analysis when assessing the seismic response of existing buildings in New Zealand?

In the present study, the above question is addressed. Suites of records for different zones in New Zealand are proposed, which satisfy the requirements defined in the Standard. The results for the North Island are presented in this article. More accurate studies are required for the South Island, because of its seismological conditions. These results will be presented in a further article.

2. MOTIVATION AND SCOPE

The study reported here was motivated by the need to define a common set of earthquake records to be used in many time-history analyses to assess the seismic performance of existing URM structures, as part of the Seismic Retrofit Solutions Project being jointly conducted by the University of Auckland and the University of Canterbury (Schofield et al. 2006). Thus this research can be considered as a preliminary step of the time-history analysis study. Consequently, one of the tasks pursued here is to develop a common criterion for the selection of ground motion records for time-history analysis in New Zealand according to requirements and information available in the Standard. It is not the aim of this study to analyze the performance of the method, to validate requirements proposed by the Standard, or to examine the structural behaviour of the buildings for the selected ground motions records. A recent study (Dhakal et al. 2007) offers interesting conclusions about this last topic, but that aspect is not discussed here. Our study analyzes the seismic performance of URM buildings constructed according to typical pre-1931 New Zealand practice. There is the possibility that the results could be extended to assess the seismic response of other common types of structures (reinforced concrete, steel or timber structures), but the design of new and more sophisticated structures (for example: tall buildings, bridges and dams) is outside the scope of the present study. Probably, this last category of structures still merits the assistance of expert seismologists in the process of record selection. In particular, some of the selected records may be inappropriate for structures with natural periods greater than 1 second.

3. CHARACTERISTICS OF URM BUILDINGS

URM buildings were New Zealand’s most common type of commercial construction in the late 19th century and early 20th century, but after 1931 and because of their poor seismic performance during the Hawke’s Bay Earthquake (3 February 1931) their popularity began to decline, until 1965 when

NZS 1900 (New Zealand Standard Institute 1965) virtually banned their use (Ingham 2008; Russell et al. 2006). Despite their poor seismic resistance, many URM buildings still remain throughout New Zealand. These buildings now represent an important component of New Zealand’s architectural heritage. Considering this and the legislation related to earthquake prone structures currently in force in New Zealand (Department of Building and Housing 2004), URM buildings are prime candidates for seismic assessment and retrofit.

The characteristics of URM buildings in New Zealand are well defined. They were built mainly between 1880 and 1950 using clay bricks. Typically, they are large stand-alone or multi-storey row buildings which could rise up to 6 levels high (Figure 1a), two-storey row blocks of individual shops or residential dwellings (Figure 1b) or small single-storey isolated URM buildings (Figure 1c). A recent study (Russell and Ingham 2008b) offers an exhaustive classification and description of URM building typologies, covering most URM construction in New Zealand. In terms of their structural behaviour, URM buildings can be considered as stiff structures, with their fundamental period estimated to be between 0.1 and 0.5 seconds (Amrhein 1998), which is relatively short when compared to other kinds of structures (steel frames, timber frames, reinforced concrete frames/walls structures). Only in exceptional situations might their period exceed the 1 second limit (for example: monumental, religious and large public buildings).

URM buildings are distributed throughout New Zealand, but results from studies still under progress, based on historical population and dwelling data (Russell and Ingham 2008a; Statistics New Zealand 2007), indicate that most of these structures are located in the North Island and the Canterbury and Otago regions (Figure 2).



Figure 1: a) Multi-storey row buildings, Cuba Street, Wellington. b) Two-storey row building, Jervois Road, Auckland. c) Single-storey building, Newmarket, Auckland

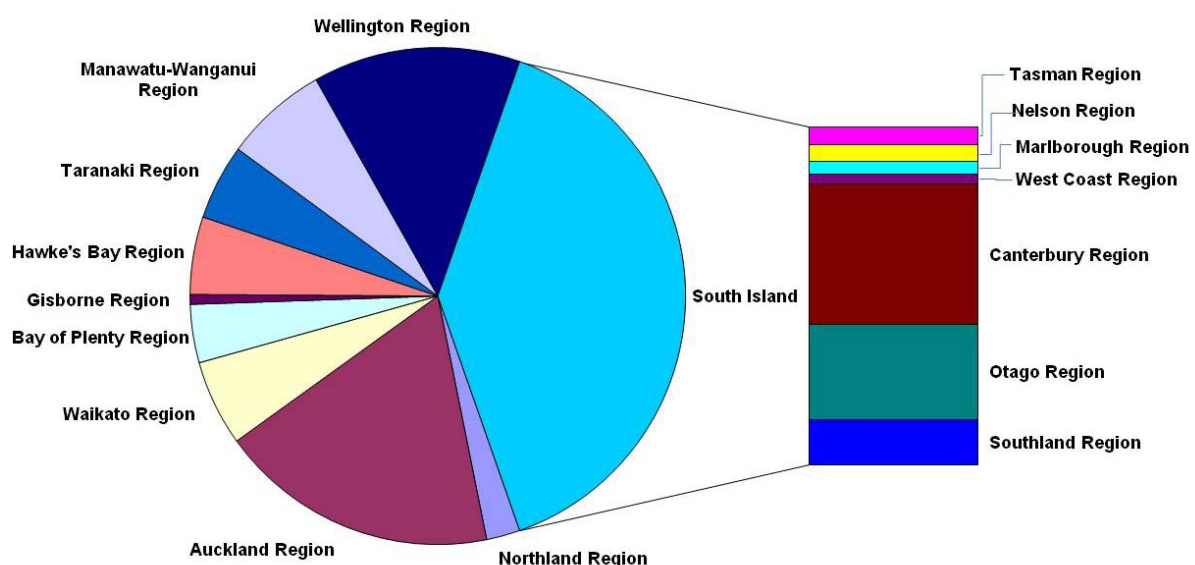


Figure 2: Estimated distribution of URM buildings in New Zealand.

4. SEISMOLOGICAL CHARACTERISTICS OF NEW ZEALAND

New Zealand is located along a highly active tectonic zone, at the confluence of the Australian and Pacific plates, which converge at a rate of 50 mm/yr in the northern zone, 40 mm/yr in the centre of the country, and 30 mm/yr at the southern edge. This relative motion of the plates is reflected by the presence of numerous active faults, a high rate of small-to-moderate ($M < 7$) seismic events, and the occurrence of several large and great earthquakes. The seismological characteristics of New Zealand are extensively described by Stirling et al. (2002) and are summarized in Figure 3. Four zones of major seismic activity may be identified in this figure:

- Fiordland subduction zone: This zone is located at the far southwestern end of the country and corresponds to a southeast-dipping subduction zone.
- Hikurangi subduction zone: This zone corresponds to a major northwest-dipping subduction zone east of the North Island.
- Axial tectonic belt: This corresponds to the 1000 km long linking region characterized by a number of dextral oblique slip faults. Essentially, all of the relative plate motion is accommodated by the faults of this area. This is dramatically illustrated by the southern section of the Alpine Fault, which accommodates virtually all of the relative plate motion in the central South Island, and geologic data provide evidence for the occurrence of large to great earthquakes with a recurrence of hundreds of years.
- The Taupo Volcanic Zone: This region corresponds to a zone of active crustal extension (10 mm/yr). An elevated number of small earthquakes is characteristic of this zone and several moderate earthquakes have also been recorded (e.g. Edgecumbe, 2 March 1987).

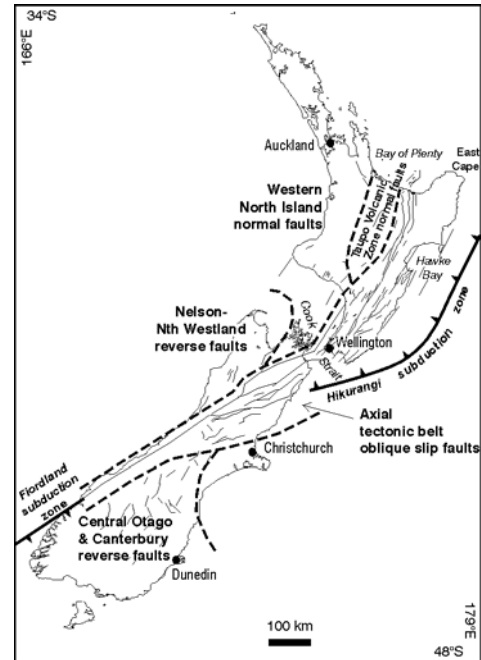


Figure 3: Plate Tectonic Setting of New Zealand (Stirling et al. 2002).

5. SEISMIC ZONATION AND CHARACTERISTICS OF THE RECORDS

Considering the situation described previously, the level of seismic hazard depends on the influence of the different faults and the characteristics of the earthquakes that could be expected for each site. This has been recognized in the New Zealand Standard by the definition of the hazard factor Z . The hazard factor corresponds to the peak ground acceleration at 0 seconds period, measured as a factor of g , for a site classified as rock and considering earthquakes with a return period of 500 years (Standards New Zealand 2004b). The values of this factor are mapped for the entire country and are shown in Figures 3.3 and 3.4 of the Standard (Standards New Zealand 2004a). This factor is used in structural seismic analysis as part of the equation that defines the earthquake spectra (Eq. 1) to be employed in the static equivalent method or the modal response spectrum method, but also defines the target spectra to be used in time-history analysis.

$$C(T) = C_h(T) \cdot Z \cdot R \cdot N(T, D) \quad (1)$$

where C_h = Spectral shape factor

Z = Hazard factor

R = Return period factor

N = Near-fault factor

T = Fundamental period of the structure

D = Shortest distance from the site to the nearest fault listed in the Standard

The current practice for time-history analysis is to define specific suites of ground motion records for each project location, considering the seismic hazard conditions, fault mechanism and the historic earthquake records that affect this location. Hence, in the case of time-history analysis, it is convenient to define zones with comparable conditions of seismic hazard, fault mechanism, and earthquake history (seismological signature) and define suites of records for each zone, instead of defining suites of records for specific sites. The specific hazard condition of each site in this zone is considered by scaling the records and matching the record response spectra with the site target spectra defined in the Standard. This topic will be addressed in a subsequent study.

A hazard zonation for New Zealand is proposed, considering the hazard mapping included in the Standard, aspects related to seismological signature (fault mechanisms, magnitude, epicentral distance, return period) and criteria that were proposed for amendment of NZS 4229:1999 (Standards New Zealand 1999) to facilitate non-specific design and maintain alignment with the Standard (Ingham 2005).

Five zones are defined for the North Island, which cover 61% of the URM building stock. A similar zonation for the South Island is still under study, considering the seismic conditions of this region. Nevertheless, it is interesting to note that URM buildings are primarily concentrated in specific areas of the South Island (Figure 2). Therefore, it is not necessary to define a complete zonation for the South Island for the analysis of URM structures, but instead it would be sufficient to develop suites of records for the specific regions of the South Island where URM buildings are concentrated.

The five zones defined for the North Island are shown in Figure 4 and have the following characteristics:

- Zone North A: This zone corresponds to a large north-western area of the North Island, where the hazard factor (Z) is less than or equal to 0.20. This zone has a low seismic hazard, and is characterized by several normal faults in the vicinity of Mayor Island, Paeroa and New Plymouth. The seismic events of this zone have an average magnitude of 6.5 (6.9-7.4 in Mayor Island; 5.5-7.1 in Paeroa and New Plymouth) and the maximal depth of the fault is between 5 km and 15 km. For this zone, it is recommended that selected records have a magnitude similar to 6.5, with an epicentral distance of approximately 20 km.
- Zone North B: This zone corresponds to the southern area of the strip limited by the 0.2 hazard factor line on the west and the 0.3 hazard factor line on the east. Its northern limit is defined by the boundaries of the Taupo Volcanic Zone (TVZ) (Wilson et al. 1995). This zone has a medium seismic hazard, and is characterized by normal faults in the south, and normal faults in the north. The seismic events of this zone have an average magnitude of 6.3 (5.4-6.9) and the maximal depth of the fault is 15 km. For this zone, it is recommended that selected records have a magnitude similar to 6.5, with a 20 km epicentral distance.
- Zone North C: This zone corresponds to the eastern coast of the North Island, where the hazard factor (Z) exceeds 0.30 and (according to the Standard) no large-magnitude ($M > 7.0$), high slip-rate ($> 5\text{mm/year}$) faults are located at a distance shorter than 20 km ($N(T,D) = 1.0$). This zone has a high seismic hazard, but it is not influenced by the near-fault effect. It is characterized by numerous normal faults and the Hikurangi subduction interface. Also, reverse and reverse-oblique faults have a significant presence in this region. The seismic events of this zone have an average magnitude of 6.7 (5.2-8.4) and the maximal fault depth is between 5 km and 30 km. For this zone, it is recommended that selected records have a magnitude of 7.0-7.5, with a 20-40 km epicentral distance, but that several reverse or reverse-oblique records with magnitude 6.5 and distance 20 km should also be included to represent the local distributed seismicity.
- Zone North NF: This zone corresponds to the south edge of the North Island, where the hazard factor (Z) exceeds 0.30 and where the main faults of the North Island are concentrated. That implies that near-fault effects (forward directivity) should be important ($N(T,D) > 1.0$). Consequently, the boundary of this zone is defined by the 20 km distance from the main faults, defined in the Standard as the region of influence for near-fault effects. This zone has a high seismic hazard, and the forward directivity effect should be considered in time-history analysis.

In this zone there are numerous strike-slip, reverse and normal faults. The largest magnitude earthquakes are generated by the Hikurangi subduction interface, but the strongest ground motions records should be generated by the surface-faulting crustal earthquakes, because the subduction interface does not come to the surface onshore. The seismic events of this zone have an average magnitude of 6.9 (5.4-8.4) and the maximal depth of the fault is between 15 km and 25 km. For this zone, it is recommended that selected records have a magnitude similar to 7.0-7.5 with an epicentral distance between 20 km and 40 km and that the suite includes records that have strong directivity characteristics.

- Zone North V: This zone corresponds to the northern area of the strip limited by the 0.2 hazard factor line on the west and the 0.3 hazard factor line on the east, and includes all the TVZ, and hence the seismic activity of this region is strongly related to the volcanic activity of the TVZ. Normal faults are typical of this zone. The seismic events of this zone have an average magnitude of 6.3 (5.7-6.8 for ground motion with volcanic origin and 6.5-7.4 for ground motion with non-volcanic origin) and the maximal depth of the fault is between 8 km and 15 km. For this zone, it is recommended to select records that come from volcanic regions or regions of crustal extension, and have a magnitude similar to 6.3 with an epicentral distance of approximately 20 km.

The previous zone description is based on the 305 fault source data presented by Stirling et al. (2002) and used for elaboration of the probabilistic seismic hazard model of New Zealand that supports the hazard factor mapping of the Standard.

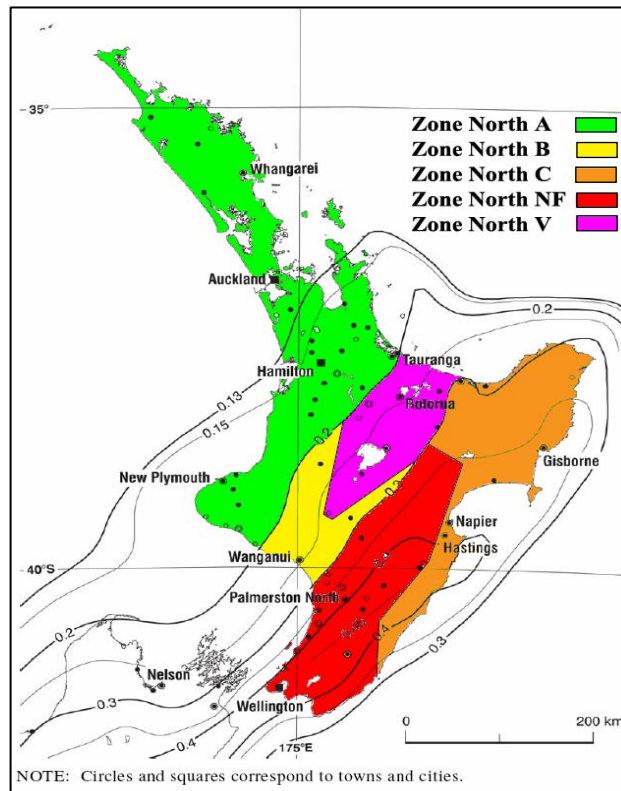


Figure 4: Seismic zones for time-history analysis in the North Island.

Suites of records have been selected for each zone, considering the general characteristics of the records recommended for each zone (in priority order: magnitude, distance, site soil, fault mechanism and depth). Special attention was given to selecting records with response spectra whose shapes match the shape of the response spectra defined for each zone by the Standard (target spectra) in the range of periods below 1 second. The selection of more than one record from a single earthquake was avoided, with the purpose of eliminating bias related to that event.

A reference record (El Centro 1940) has been included in each suite to help in the comparison of analyses in different zones if it is required. All the records have been selected from free-access databases available on the internet (Consortium of Organizations for Strong-Motions Observation

System 1999; Earthquake Commission of New Zealand and GNS Science 2004; Pacific Earthquake Engineering Research Center 2005). Currently, the Standard requires suites of at least three records for time history analysis, and the maximal response of the structure must be considered for design or assessment. Recent studies (Dhakal et al. 2007) and overseas experience indicates that when suites of seven or more records are used, it is more convenient to consider the average response of the structure for design and assessment. This fact has been considered to create the suites of records for each zone.

Because of the extension of the data, the lists of records recommended for each zone are not included here, but the complete information related to the zones, the suites of records, and the ground motion records will be available on the website of the Seismic Retrofit Solution Project, www.retrofitsolutions.org.nz/projects/seismic/masonry/mrurmb.shtml (U. of Auckland and U. of Canterbury 2004-2010).

6. COMMENTARY AND RECOMENDATIONS

Following the above definition of seismic zones and the selection of records for use in time-history analysis, some remarks are noted:

- The only North Island zone where near-fault factor effects should be considered in order to amplify the site spectra ($N(T,D) > 1$) is Zone North NF. However, this factor is not important for URM buildings, because $N(T,D)$ only assumes a value greater than unity for structures with a fundamental period greater than 1.5 sec, and URM buildings usually have shorter periods. But it is important to emphasize that this situation does not mean that strong directivity records can be omitted in this zone. In fact, the Standard requires that at least one third of the records used for time-history analysis in this zone must have strong directivity characteristics.
- In the case of stiff structures like URM buildings, soft soil conditions can strongly affect the structural behaviour of a building. It is recommended that particular care be taken in addressing this condition, and that specialized advice be sought if necessary. Further studies should be developed to consider this condition.
- Recent studies (Iervolino and Cornell 2005) have shown that there is no evidence to support the thesis that an accurate selection of records based on magnitude and distance compatibility to the site affects the results of time-history analysis, when just “normal” ground motions are considered, i.e. avoiding effects related to soft soils and forward-directivity pulse. Therefore, under far-fault conditions (Zone North A, North B, North C and North V) and in hard soils, the ground motion selection is less constrained. Despite this, it is recommended that selected records have a response spectra shape that matches the shape of the site spectra.
- The suites of records selected for each zone can be updated, by replacing or adding new records, according to the state-of-the-knowledge and the requirements or future amendments of the Standard, but it is recommended that the zones defined here be retained as a guide for seismologists and designers.
- The information related to the zones, suites of records, and records is available on the website of the Seismic Retrofit Solutions Project (U. of Auckland and U. of Canterbury 2004-2010), <http://www.retrofitsolutions.org.nz/projects/seismic/masonry/mrurmb.shtml>.

7. CONCLUSIONS

This article presents a zonation proposal for earthquake record selection associated with time-history analysis of URM buildings in the North Island of New Zealand, based on hazard mapping included in NZS 1170:2004, aspects related to seismological signature and criteria proposed for amendment of existing New Zealand material design standards associated with non-specific design. Five zones have been defined in the North Island, and it is estimated that this zonation covers most of the URM building stock in New Zealand. A description of the suitable records for each zone is presented, along with general criterion for the selection of actual records. Specific suites of records are suggested for each zone. Finally, some comments and recommendations about the use and updating of these suites of records are included.

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