Seismic Zonation and Default Suite of Ground-Motion Records for Time-History Analysis in the North Island of New Zealand

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ABSTRACT

A seismic zonation to be used in the selection of ground-motion records for time-history analysis of buildings in the North Island of New Zealand is presented. Both deaggregations of the probabilistic seismic hazard model and the seismological characteristics of the expected ground motions at different locations were considered in order to define the zonation. A profile of the records expected to apply within each zone according to the identified hazard scenarios is presented and suites of records are proposed for each zone based on region-wide criteria, to be used in time-history analysis in the absence of site specific studies. A solution for structures with fundamental periods of between 0.4 and 2.0 seconds is proposed, considering a 500-year return period and two common site classes (C and D according to the New Zealand Loadings Standard).

INTRODUCTION

Improvement in the processing, memory, and storage capacities of computers, the development of design philosophies based on performance and displacement, and the increasing number of earthquake ground-motion records available in internet-based depositories have triggered a significant growth in the use of the time-history analysis method in structural engineering. More recently, this technique has migrated from academia to professional practice, becoming a widely employed tool used by many consulting engineering firms for both seismic design of new structures and for seismic assessment of existing buildings (Kelly, 2004).

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In response to emerging practice, the New Zealand Standard for Structural Design Actions, NZS 1170.5:2004 (SNZ, 2004a), henceforth referred to as “the Standard”, dedicates extended sections to criteria defining the selection and the scaling of ground-motion records for time-history 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*” (SNZ, 2004a).

A structural designer who attempts to select records based on this statement, not being a seismology expert and knowing little detail about the probabilistic seismic hazard (PSH) model used to assemble the Standard spectra and which ground motions contributed most significantly to these spectra, is 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 is primarily assigned to seismologists (ATC, 1996).

Presently, the extensive number of ground-motion records available in internet-based depositories contributes to make more accessible records that may satisfy the requirements of the Standard. However, this large number of available records makes it difficult to objectively select an appropriate suite of records for use in seismic assessment and/or design for a specific site (Iervolino et al., 2008; Iervolino et al., 2009). Elsewhere, the problem of which records should be selected from a batch of candidates was solved by establishing an explicit suite of records in the seismic design regulations (ATC, 1996). In other cases, the question has been answered by software-aided record selection procedures (Iervolino et al., 2010). Explicit sets of design accelerograms or automatic software procedures for obtaining appropriate records that satisfy the requirements of the Standard currently have not been implemented in New Zealand. Each project that considers time-history analysis requires specific seismic hazard deaggregations studies to define the most appropriate set of records for the particular project location. The aim of the study reported here was to identify the main characteristics of records that match the seismological signature of different zones in the North Island of New Zealand when considering different hazard scenarios.

A specific task pursued in this study was to define a seismic hazard zonation to be used in the selection of ground motion records for time-history analysis of buildings in New Zealand. This zonation was established by identifying regions that have earthquakes contributing to their seismic hazard that have similar magnitude, source-to-site distance and tectonic types. The most important hazard scenarios for each zone were identified and suite profiles that characterize the expected records associated with the identified scenarios are proposed. Finally, specific suites of records were recommended for different zones and site classes, based on the profiles and the requirements established by the Standard. It was not the aim of this study to validate requirements proposed by the Standard, or to examine the structural behaviour of buildings for the selected ground-motion records. Also, it is not intended that the recommended suites of records should constrain those who undertake specific studies to select alternative suites appropriate to a particular location and structure.

Only results for the North Island of New Zealand are presented. This area incorporates 75% of the national population, the largest urban centers, and New Zealand's capital city (Wellington).

SEISMIC ZONES AND EXPECTED GROUND MOTION CHARACTERISTICS

New Zealand is located along a highly active tectonic zone, at the junction of the Australian and Pacific plates. The relative motion of these 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 Stirling et al. (2008) and are summarized in Figure 1. Four zones of major seismic activity may be identified in this figure. The northwest-dipping Hikurangi subduction zone is located to the east of the North Island. Opposite this zone, at the far south-western end of the South Island, is the southeast-dipping

Fiordland subduction zone. The link region between these two subduction zones is known as the axial tectonic belt, and corresponds to a 1000 km long area characterized by a number of dextral oblique slip faults. In addition, it is possible to identify a zone of active crustal extension (10 mm/yr) referred to as the Taupo Volcanic Zone or TVZ (Wilson et al., 1995).

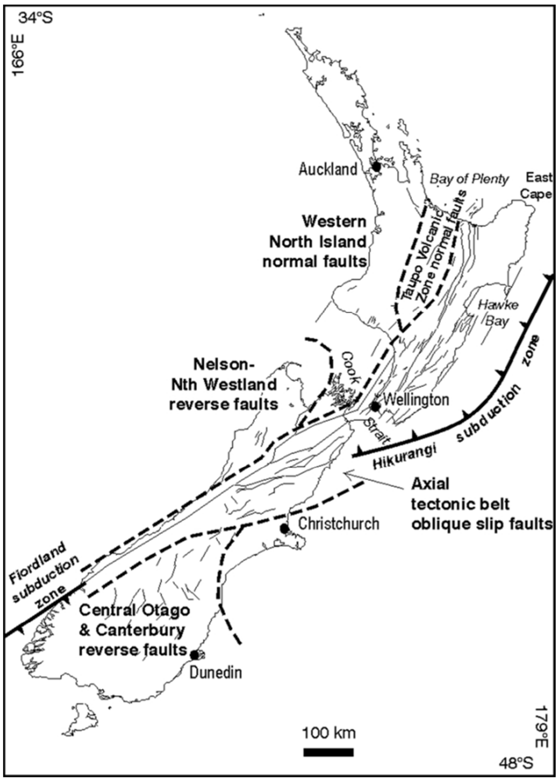

Figure 1. Plate Tectonic Setting of New Zealand (Stirling et al., 2002)

Considering the situation described above, 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 dependency has been recognized in the Standard by definition of the hazard factor Z which is part of the equation that defines the design spectra and, consequently, the target spectra used to select and scale records employed in time-history analysis. This factor corresponds to 0.5 times the 500-year return period value of the 5% damped response spectrum acceleration (measured as a factor of g) at a period of 0.5 seconds for the shallow soil class defined in the Standard. In the Standard, this value is also assigned to the spectral ordinate associated with a response period of zero seconds (i.e. peak ground acceleration) for a site classified as rock (SNZ, 2004b). Figure 2 presents the mapping of this factor included in the Standard for the case of the North Island of New Zealand.

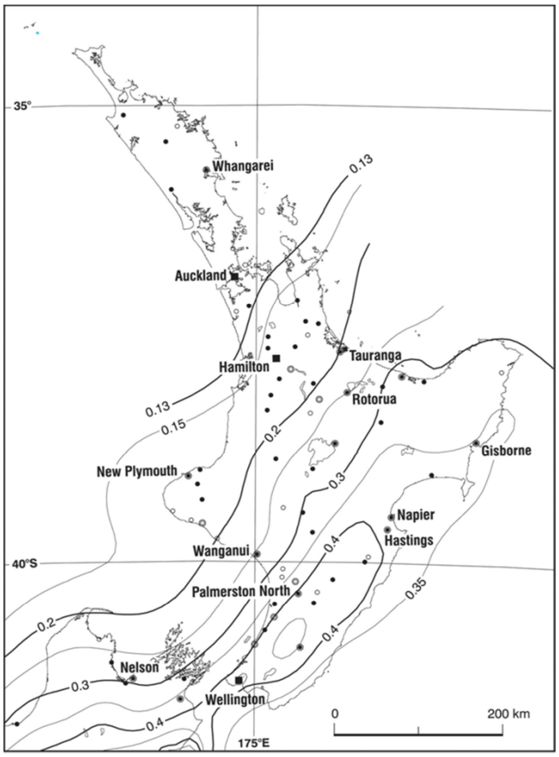

Figure 2. Hazard factor (Z) mapping for the North Island of New Zealand (SNZ, 2004a)

The current practice for time-history analysis is to determine specific suites of ground-motion records for each project location, considering the seismic hazard conditions, fault mechanism and the historic earthquake records (seismological signature) that affect this location. In contrast, our study defines a set of zones having relatively uniform seismological characteristics within each zone. For this purpose, historical information about earthquakes recorded at different locations in the North Island of New Zealand and the PSH model (Stirling et al., 2002; Stirling et al., 2008; Stirling et al., in prep.) employed to define the seismic hazard maps for the country were considered. The particular characteristics of each zone were determined in terms of seismological signature features, such as dominant tectonic types, fault mechanism, magnitude and site-to-source distance.

To determine the different possible hazard scenarios and to identify those faults that more strongly contribute to the zone's seismic hazard, deaggregations of the contribution of individual sources to the seismic hazard curves computed by the PSH analysis were conducted at different locations within each specific zone. These deaggregation analyses were also used to determine the characteristics of the expected earthquake within each zone and to assist the definition of the zone boundaries. In this procedure a return period of 500 years was considered, corresponding to the return period for the Ultimate Limit State for normal-use structures in the Standard (SNZ, 2004a). Seismic hazard deaggregation plots at different locations in the North Island for PGA and the fundamental periods of 0.5, 1.0, 1.5 and 2.0 seconds were obtained. The results of this analysis demonstrate that often the PGA hazard deaggregations significantly differ from those with spectral periods equal to or longer than 0.4 seconds, as illustrated in Figure 5 where the specific case of Wanganui is presented. In the analysis, an upper limit of 2.0 seconds has been intentionally selected to indirectly restrict the use of this method to "common buildings", rather than special structures such as high-rise or base-isolated buildings that have periods greater than 2 seconds. Therefore, the findings of this study are applicable to the seismic assessment or design of buildings with fundamental periods of between 0.4 and 2.0 seconds. These limits were chosen to allow one single set of records per Zone/Site class that was valid for the entire period range. It was possible to verify that the results for spectral periods equal to 0.5 seconds are representative of the entire range of periods under study. Those results are displayed in Figures 4 to 8.

As the zones used for the sets of ground-motion records are intended to encompass locations for which the hazard is contributed by similar types of earthquakes, they are based loosely on subdivisions of the tectonic zones shown in Figure 1, with the subdivisions guided by the deaggregation results. For the convenience of engineering users, Z-factor contours were used to specify the zone limits, as they are known by the New Zealand structural engineering community and are readily available in the Standard (SNZ, 2004a).

Five zones have been defined in the North Island (Figure 3). The main characteristics of each zone are described in the following paragraphs. Also, deaggregation results for the contributions to the exceedance rates of the 500-year return period motions at 0.5 second period are discussed as illustrative examples. In these discussions, several specific faults are mentioned. The precise location of these faults can be determined by referring to Stirling et al. (2002), and specifically to Figure 2 and Appendix A1. These descriptions also include recommendations of the magnitude and distance ranges and earthquake types that should ideally be associated with the suitable records for these zones.

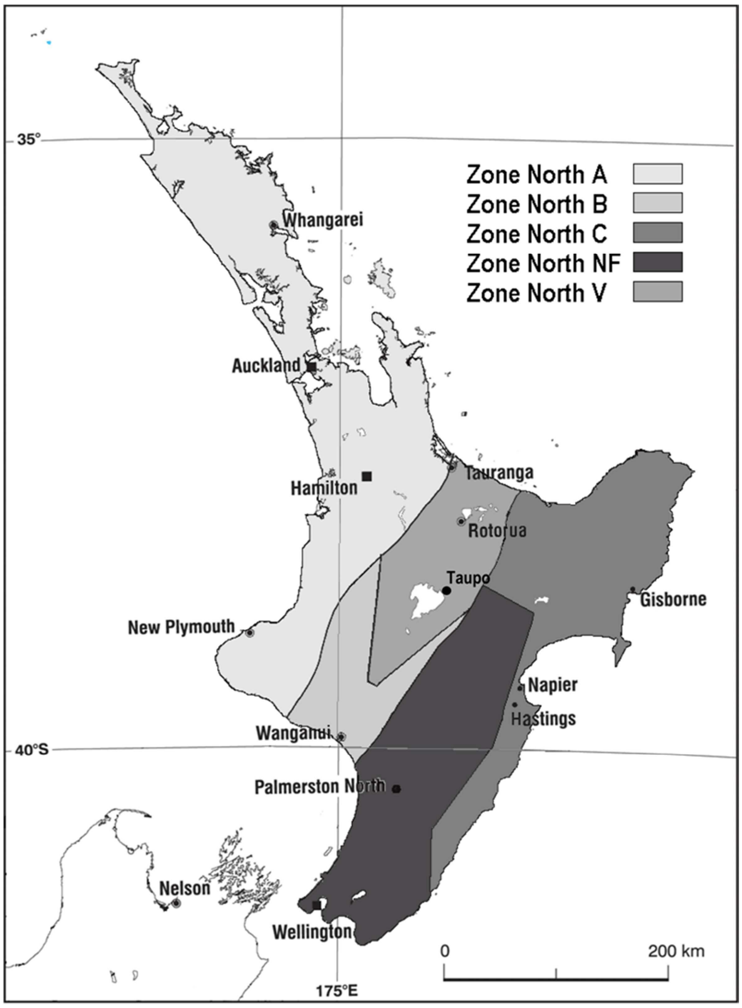

Figure 3. Seismic hazard zonation for the North Island of New Zealand proposed for the selection of suites of ground-motion records

- **Zone North A:** This zone corresponds to a large north-western area of the North Island, where the hazard factor (Z-factor) is less than or equal to 0.20. This zone has a low seismic hazard, with the 500-year hazard governed by distributed seismicity rather than specific faults, and is characterized by normal-mechanism earthquakes. According to Stirling et al. (2002), the few modelled faults of this zone have an average magnitude of 6.5 (M5.5-M7.4) and have shallow crustal characteristics. Most faults have long recurrence intervals well in excess of 1000 years, so contribute little to the 500-year hazard even for near-fault locations. A single suite of earthquake records can be used for this large region because the 500-year hazard is largely controlled by the distributed seismicity, with different scaling factors according to the value of the Standard hazard factor Z.

An extended area of this zone is assigned a Z-factor equal to 0.13 (Figure 2). This value is the minimum allowed by the Standard and corresponds to a minimum requirement for structures to survive without collapse in 84-percentile ground motions associated with a normal-mechanism magnitude 6.5 earthquake at a 20 km distance (SNZ, 2004b). The minimum Z value includes a factor of 2/3 introduced to account for the nominal margin between Ultimate Limit State (ULS) motions that are specifically designed for and the motions that are expected to be survived without collapse. As the ULS design motions in the Z = 0.13 region are governed by this minimum hazard scenario, deaggregations of the actual estimated 500-year hazard are not required to characterize the target design events for this part of zone North A extending from south of Auckland to North Cape. For the portion of this zone where the Z-factor exceeds 0.13, deaggregation analyses were considered at Hamilton and New Plymouth.

In the case of Hamilton (Figure 4a), the earthquakes that contribute to the exceedance rates of the 500-year hazard values for spectral periods from 0.25 to 1.0 second have an average magnitude of 6.3. Approximately 50% of the contribution originates from events having magnitudes of less than 6.2, 16% is generated by earthquakes having magnitudes of less than 5.5 and another 16% comes from events with magnitude greater than 6.8. About half the contributions come from earthquakes located within 30 km and about 5% of the contribution derives from segments of a specific fault (Kerepehi fault) with magnitudes ranging between 6.5-6.8 at distances of between 40 and 55 km.

In the case of New Plymouth, for periods of 0.2 to 2.0 seconds the 50-percentile and average magnitudes for the 500-year hazard contributions are 6.1 and 6.9, and about 30-50% of the contributions come from earthquakes located within 20 km. In the deaggregation plots (Figure 4b), the specific contribution of the magnitude 6.8 southern segment of the Turi fault at 11 km is prominent (10-13% of the contributions), but has a localized effect according to the PSH model (Stirling et al., 2002).

For zone North A, it is recommended that selected records come from regions of extensional tectonics and have a magnitude of between 5.5 and 7.0, with a shortest distance (measured from the surface projection of the source) of approximately 10-30 km. There should be a bias towards records from earthquakes of about magnitude 6.5 located at 20 km distance, bearing in mind this scenario for the minimum allowable ULS spectrum.

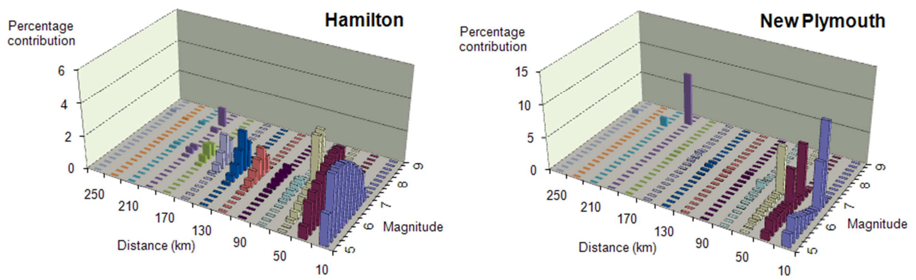

Figure 4. Deaggregation for 500-year return period at 0.5 seconds spectral period. Zone North A: a) Hamilton, and b) New Plymouth.

- **Zone North B:** This zone corresponds to the southern area of the strip limited by the 0.2 Z-factor line on the west and the 0.3 Z-factor line on the east, and has a northern limit defined by the boundaries of the TVZ (Wilson et al., 1995). This zone has a medium seismic hazard, characterized by numerous normal faults and strongly influenced by distant seismic sources. The seismic hazard for short-period structures is dominated by shallow crustal distributed seismicity. The subduction interface sources affect structures that have fundamental periods greater than 1.0 second. The modelled faults of this zone have an average magnitude of 6.3 (M5.4-M6.9) (Stirling et al., 2002).

From deaggregation analysis performed for Wanganui it was determined that the average magnitude of the earthquakes contributing to the exceedance rates of the 500-year hazard values for spectral periods from 0.2 to 1.0 second is 7.1, with a median value of 6.8. The average magnitude increases with period to 7.5-7.6 for periods of 1.5 to 2.0 seconds. For the 500-year hazard values at 0.5 seconds spectral period (Figure 5b), 33% of the contribution comes from crustal earthquakes having magnitudes less than 7.0 and distances less than 60 km. Another 30% of the contributions originate from subduction slab earthquakes having a magnitude of less than 7.0 at distances of 60-140 km. These events make less contribution at longer periods, being replaced by the large magnitude subduction interface events. Magnitude 8.1-8.4 subduction interface events, split between distance ranges of 60-80 km and 105-120 km, contribute about 25%, increasing at longer periods. Finally, approximately 14% of the hazard contribution comes from magnitude 7.5 Wellington fault events at about 80 km and magnitude 7.3 Wairau fault events at about 50 km.

For zone North B, it is recommended that selected records represent three different hazard scenarios. Therefore, it is suggested that the suite includes crustal records that have a magnitude of between 6.5 and 7.5, with a shortest distance of about 40 to 70 km and several long distance subduction records, considering two magnitude-distance combinations: magnitude 6.5-7.0 subduction slab earthquakes at 60 to 100 km and magnitude 7.5-8.3 subduction interface earthquakes at 70 to 120 km.

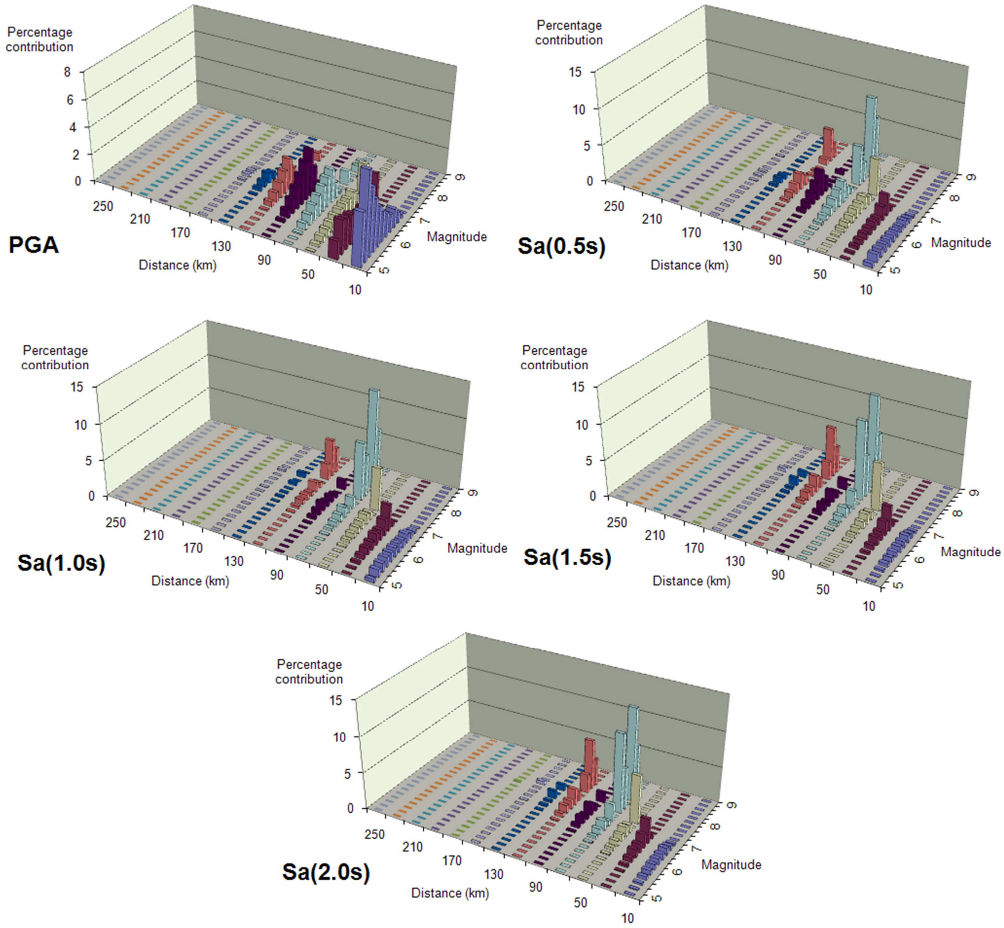

Figure 5. Deaggregation for 500-year return period.
Zone North B, Wanganui: a) PGA, b) Sa(0.5s), c) Sa(1.0s), d) Sa(1.5s) and e) Sa(2.0s).

- **Zone North C:** This zone corresponds to the south-eastern coast of the North Island where the Z-factor exceeds 0.30, but the Standard does not require the use of near-fault factors to account for near-source directivity effects[†]. Much of the high seismic hazard of this zone is contributed by the Hikurangi subduction interface. Reverse and reverse-oblique faults have a significant presence in the southern part of this region and the part of the region

[†] The Standard refers to a "near-fault effect", in relation to those near-fault records with forward-directivity characteristic. The term "near-fault effect" is used here instead of the more specific expression "forward-directivity characteristics" to be consistent with the terminology used in the Standard.

between Hawke's Bay and East Cape is characterized by numerous normal faults, generally too short to be shown in Figure 1. These faults have relatively minor influence on the hazard because they are either associated with moderate magnitudes (generally magnitudes smaller than 7, and sometimes smaller than 6) or long recurrence intervals (10,000 years or longer). The modelled fault sources of this zone have an average magnitude of 6.7 (M5.2-M8.4) (Stirling et al., 2002).

Deaggregation analysis conducted for Gisborne (Figure 6a) shows that at 0.5 seconds period the contribution of magnitude 7.5 to 8.1 events at about 15 to 25 km distance related to the Hikurangi subduction interface corresponds to 60%. A magnitude 7.5 offshore reverse fault at 23 km is another significant contributor and a local normal fault modeled as producing magnitude 5.5 earthquakes within 5 km is important at short spectral periods.

For Napier (Figure 6b) the contribution due to subduction events is only 38%, with another 24% originating from faults whose updip end is at least partially offshore in Hawke's Bay, including the 1931 Napier earthquake source.

For zone North C it is recommended that about half of the selected records should represent subduction interface events of magnitudes 7.5 to 8.3 at distances of 15 to 25 km. Other selected records should represent reverse-faulting events with a magnitude of 7.0-7.5, with a 20-40 km shortest distance. Several reverse (or reverse-oblique) records with a magnitude of 6.5 and distances of 20 to 60 km (representing the local distributed seismicity) should also be included.

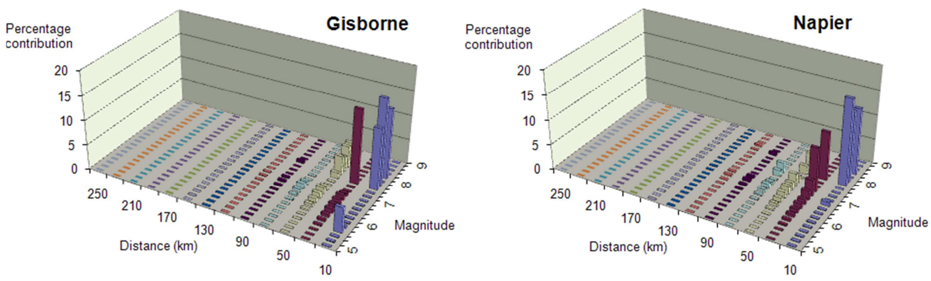

Figure 6. Deaggregation for 500-year return period at 0.5 seconds spectral period.
Zone North C: a) Gisborne, and b) Napier.

- **Zone North NF:** This zone coincides with the region referred to in the Standard as 'the zone of influence of near-fault effects', where provision is made for strong forward-directivity effects (SNZ, 2004a). This zone is located at the southern end of the North Island, where the main faults of the North Island are concentrated (M > 7.0 and slip rate > 5 mm/year). Specifically, this zone corresponds to a region where the distance is less than 20 km to a series of main faults explicitly listed in the Standard. The selected faults are limited to New Zealand's most active major strike-slip faults. The Standard specifies Near-Fault factors to modify the spectrum beyond 1.5 seconds. The Near-Fault factors depend on spectral period and distance from the closest of these faults, falling to 1.0 for distances of 20 km and greater. This zone has a high seismic hazard, with the Z-factor exceeding 0.30, with numerous strike-slip, reverse and normal faults. The largest magnitude earthquakes are generated by the Hikurangi subduction interface, but the strongest ground-motion records should be generated by shallow crustal earthquakes because the subduction interface does not come to the surface onshore. The modelled fault and subduction interface sources of this zone have an average magnitude of 6.9 (M5.4-M8.4) (Stirling et al., 2002).

Deaggregation analysis performed for Palmerston North (Figure 7a) demonstrates that the average and median magnitudes are approximately 7.6 for contributions to the exceedance rate of the 500-year spectral accelerations at 0.5 seconds. It has also been determined that the main contributions to the exceedance rate are from the Wellington North fault (36%) and less significant are the contributions from the Wairarapa, North Ohariu and Ruahine South faults and several Hikurangi subduction interface sources.

In the case of Wellington, nearly 60% of the contribution to the exceedance rate is from the Wellington-Hutt Valley fault (M7.3 at 1 km) and the Ohariu fault (M7.4 at 5 km). Another 30% of the contribution originates from large magnitude earthquakes on the Wairarapa fault and the subduction interface sources (Figure 7b). However, more recent hazard models (Stirling et al., in prep.) have decreased the Wellington-Hutt Valley fault contributions and increased the subduction interface contribution. Although, this recent information has been considered in our analysis, it is not necessarily reflected in the deaggregation plots, which were constructed based on the 2002 PSH model (Stirling et al., 2002).

For zone North NF it is recommended that most of the selected records have a magnitude similar to 7.0-7.5 with a shortest distance of up to about 10 km from the rupture surface, and that the suite includes subduction interface records (magnitude 7.5-8.3 at about 15 to 25 km of shortest distance) and records that have strong forward-directivity characteristics.

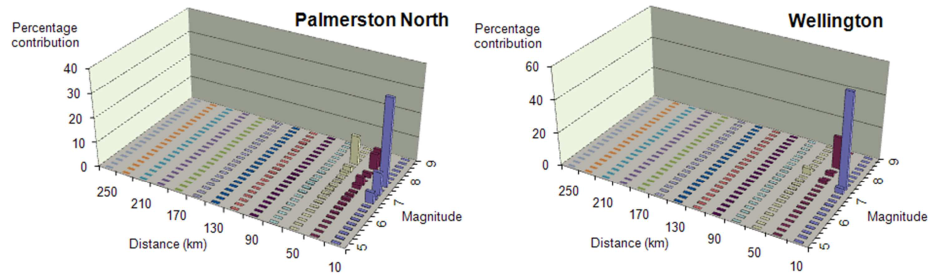

Figure 7. Deaggregation for 500-year return period at 0.5 seconds spectral period. Zone North NF: a) Palmerston North, and b) Wellington.

- **Zone North V:** This zone corresponds to the northern area of the strip limited by the 0.2 Z-factor line on the west and the 0.3 Z-factor line on the east, and includes all the TVZ (Wilson et al., 1995) as well as most of the Central Volcanic Region that encompasses it. Hence the seismic activity of this region is strongly related to the extensional tectonics of this volcanic region. Normal faults are typical of this zone. The TVZ part of the region has been demonstrated to have high attenuation rates at periods less than about 1 second (Cousins et al. 1999; McVerry et al., 2006). The modeled faults of this zone have an average magnitude of 6.3 (M5.7-M6.8 for TVZ faults and M6.5-M7.4 for faults outside the TVZ) (Stirling et al., 2002).

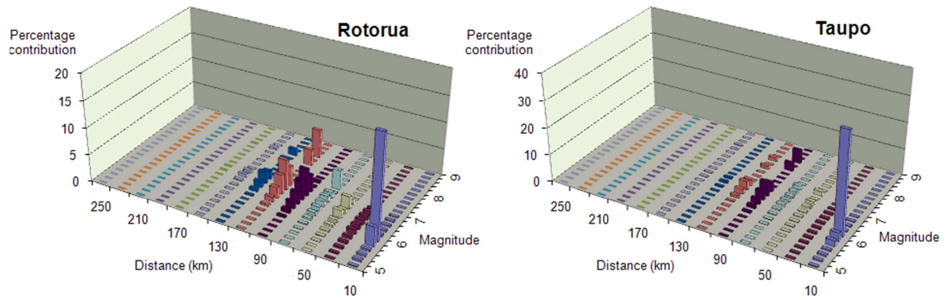

Figure 8. Deaggregation for 500-year return period at 0.5 seconds spectral period. Zone North V: a) Rotorua, and b) New Taupo.

Taupo and Rotorua deaggregations (Figure 8a and 8b) show that most of the contributions to the exceedance rate come from local faults located at distances of less than 20 km, in the magnitude range of between 5.9 and 6.3. Inspection of deaggregation listings show that the peaks correspond to the combined effects of several TVZ faults. The contributions of distant sources outside the TVZ are over-represented in the deaggregation plots for Rotorua because TVZ attenuation was not included for sections of the travel-paths inside the TVZ. The median magnitude for Taupo, which is less affected by distant sources, is about 6.2 across all spectral periods.

For zone North V, it is recommended to select records that come from volcanic regions or regions of extensional tectonic regimes and that have a magnitude of between 6.0 and 7.0 with a shortest distance of 20 km or less.

DEFAULT SUITE OF RECORDS

The current Standard requires that suites of at least three records must be considered for time-history analysis, and that the most disadvantageous response must be considered for design (for example, the largest value of the maximum strength demands). However, when following this criterion the design can be strongly influenced by the response of a specific ground motion with particularly strong peaks. In contrast, other standards and recommendations (CEN, 2004; ASCE, 2007) propose to design considering the average response of seven or more records. Recent studies (Dhakal et al. 2007; Oyarzo-Vera and Chouw, 2008) have demonstrated that the seismic demand estimated from the average of the time-history analyses using seven different ground motions has less variability than that estimated from the maximum response using only three ground motions and, at the same time, the use of seven records reduces the influence of specific ground motions. In addition, in the North Island of New Zealand there are few locations where the hazard is totally dominated by one earthquake source. Even for sites adjacent to one of the major strike-slip faults, there are usually other nearby faults or the underlying subduction zone influencing the hazard, especially for spectral periods of about 1.0 second and longer, as described above. Thus seven accelerograms for a zone generally cover a wider range of earthquake types or magnitude-distance combinations. Taking into account the international trend, the studies mentioned previously and the particular seismic characteristics of the North Island, suites of seven records were recommended in order to perform time- history analysis for each zone and site class.

The method proposed for selecting the most adequate suites of records for each zone is based on the characteristic earthquakes identified in the previous section. Suite profiles were defined for each zone, taking into account the hazard scenarios identified as contributing significantly to the 500-year hazard for each zone in the range of spectral periods between 0.4

and 2.0 seconds. It is unusual for a single source to contribute almost all the hazard, so often several scenarios with different magnitudes, distances and even tectonic types (e.g., crustal and subduction interface) are covered by the selected ground motions.

These suite profiles always include a reference record (El Centro 1940) because of its long history of use in New Zealand. The reference record has a spectral shape that matches well with the shape of the Standard's target spectra for both classes C and D, and it makes strong demands on structural performance across a broad period band. This is important because the matching of spectral shape is one of the primary criteria in this study for selecting accelerograms.

In the selection of records for zones North A and North V, the record data set for regions of extensional tectonic regimes used to develop SEA99 (Spudich et al., 1999) was used as one data source. For zone North B, North C and North NF, the selection of subduction records (interface and slab) was assisted by the database proposed in Atkinson and Boore (2003). For zone North NF, it was necessary to include two or three strong forward-directivity records to satisfy the Standard requirement that one record in three should possess this characteristic for time-history analysis in near-fault zones.

Table 1. Recommended suite profile for each seismic zone

Zone	Hazard scenario	Magnitude	Distance (km)	Tectonic class/Fault mechanism
North A	A1	5.5 – 6.5	10-50	Records from regions of extensional tectonic regimes (Spudich et al., 1999).
	A2	6.5 – 7.0	~20	
North B	B1	6.5 - 7.5	40-70	Shallow crustal earthquakes
	B2	6.5 - 7.0	60-100	Subduction slab records (Atkinson and Boore, 2003).
	B3	7.5-8.3	70-120	Subduction interface records (Atkinson and Boore, 2003).
North C	C1	7.5 - 8.3	15-25	Subduction interface records (Atkinson and Boore, 2003).
	C2	7.0 - 7.5	20-40	Reverse-faulting records
	C3	6.5 – 7.0	20-60	Reverse (or reverse-oblique) faulting records
North NF	NF1	7.0 - 7.5	<~10	Shallow crustal earthquakes without pronounced forward-directivity features
	NF2	6.5 - 7.5	<~10	Records with strong forward directivity characteristics (2 or 3 records in the suite of seven records)
	NF3	7.5 – 8.3	15-25	Subduction interface records (Atkinson and Boore, 2003).
North V	V1	6.0 – 7.0	<20	Records from regions of extensional tectonic regimes (Spudich et al., 1999).

The suite profiles are summarized in Table 1. In this table, the columns indicate the criteria (magnitude, distance and tectonic type/fault mechanism) for selecting appropriate records for each zone, considering the different hazard scenarios identified for the range of periods of interest (0.4 to 2.0 seconds). The suite profiles are valid for any of the five site classes (soils) listed in the standard, but accelerograms are recommended only for site classes C and D (which are most common for NZ building projects). The suite profiles are in some cases very different for peak ground accelerations, and may not be appropriate for guiding the selection of records for design studies that are based on PGAs, such as liquefaction assessments and other geotechnical studies.

The selection of the specific records to be part of each suite was conducted using a two stage process:

i) Pre-selection of candidate records:

Records available on free-access internet databases (COSMOS, 1999; EQC-GNS, 2004; PEER, 2005; K-NET, 2010) were pre-selected as candidates for each seismic zone. This pre-selection was based on matching record characteristics (magnitude, distance, tectonic class, fault mechanism for crustal earthquakes, site class) with the selection criteria presented in suite profiles (Table 1). Several hierarchical combinations for the record characteristics were tested, with some combinations found to be excessively restrictive. It was identified that the optimal combination, presented in descending hierarchical order, is: magnitude, tectonic class, site class, shortest distance and fault mechanism. However, it is important to recognize that strict compliance with all selection criteria simultaneously was not always possible, and that some flexibility associated with the lower hierarchy parameters (site class, distance and fault mechanism) was necessary.

ii) Definitive selection of records for each zone:

Once the set of candidate-records that satisfied the pre-selection criteria was identified, suites of records were defined. The definitive record selection for the suite for each zone gave special attention to obtain a close match between the spectral shapes of the record and the target spectrum defined for each site by the Standard in the range of fundamental periods of the structures under study (0.4 to 2.0 seconds).

The Standard's commentary (SNZ, 2004b) recommends that the selected records shall fit reasonably well to the target spectra, based on a criterion related to the root mean square difference between the logarithms of the scaled principal component of the selected records and the target spectra over the period range of interest (0.4 *T* to 1.3 *T*), as follows:

$$D_1 = \sqrt{\frac{1}{(1.3-0.4)\cdot T}\cdot\int_{0.4T}^{1.3T}\left[log\left(\frac{k1\cdot Record\ Spectrum}{Target\ Spectrum}\right)\right]^2 d\tau} \leq log(1.5) \qquad (1)$$

where the principal component shall be determined according to the Standard definition (SNZ, 2004a), *T* is the fundamental period of the structure under analysis and k_1 is the record scale factor that minimizes Equation 1. Taking into consideration this requirement, a comparative scoring system was implemented to assist the final selection of the records for each suite. Scores ranging from 0 to 4 were assigned to the records under assessment, according to the D_1 value of the record's principal component as established in Table 2, with a higher score representing a better matching of the record spectra to the target spectra.

As an example, Tables 3 displays the D_1 values computed for each component of the records selected for Wellington-Shallow soil and Table 4 shows the corresponding scores (principal component score) for this suite of records. From these tables it becomes evident that the record spectra match the target spectra remarkably well, including the reference record (El Centro 1940).

Tables of the specific suites of records recommended for each zone for site classes C and D are presented in Appendix A.

Plots of the scaled ground-motion spectra and the corresponding target spectra for locations in each zone and site class are presented in Appendix B. The matches shown in Figures B1 and B2 use the record scaling factors relevant for a matching period T_1 of 1.0 second. The criterion in the Standard require the matches to be performed over the period range of 0.4 T_1 to 1.3 T_1 (i.e., 0.4s to 1.3s for T_1=1.0s), so the matches may be poor outside that period range. In those figures, the matching period (T_1) is denoted by a vertical dot-segment line, while the boundaries of the matching period range ($0.4T_1$ and $1.3T_1$) are represented by vertical segmented lines.

Table 2. Matching scores assigned to the records according to D_1 value

10^D_1	Score
< 1.2	4
1.2 - 1.3	3
1.3 - 1.4	2
1.4 - 1.5	1
1.5 - 1.6	0
> 1.6	Reject

Table 3. D_1 values for the records spectra selected for Wellington - Shallow soil (Zone North NF) compared to the Standard target spectra. In **bold font** has been denoted the principal component determined according to the Standard.

	El Centro		**Tabas**		**La Union**		**Lucerne**		**Arcelik**		**Duzce**		**HKD085**	
T	**10^D1**		**10^D1**		**10^D1**		**10^D1**		**10^D1**		**10^D1**		**10^D1**	
[sec]	**H1**	**H2**	**H1**	**H2**	**H1**	**H2**	**H1**	**H2**	**H1**	**H2**	**H1**	**H2**	**H1**	**H2**
0.4	1.34	**1.27**	1.25	**1.29**	**1.18**	1.14	**1.25**	1.34	**1.43**	1.17	1.59	**1.22**	1.15	**1.31**
0.5	1.35	**1.34**	1.20	**1.26**	**1.19**	1.16	**1.26**	1.22	1.26	**1.14**	**1.39**	1.24	1.18	**1.36**
1.0	1.14	**1.24**	1.25	**1.37**	**1.14**	1.36	**1.31**	1.08	1.16	**1.17**	1.39	**1.30**	1.36	**1.20**
1.5	1.22	**1.36**	**1.20**	1.33	**1.24**	1.33	**1.18**	1.28	1.36	**1.15**	1.36	**1.20**	1.24	**1.18**
2.0	1.19	**1.26**	**1.19**	1.21	**1.17**	1.19	**1.15**	1.22	1.36	**1.17**	1.25	**1.19**	**1.25**	1.39
Mean	1.25	1.29	1.22	1.29	1.18	1.24	1.23	1.23	1.32	1.16	1.40	1.23	1.24	1.29

Table 4. Matching score for the records selected for Wellington - Shallow soil (Zone North NF).

	El Centro	**Tabas**	**La Union**	**Lucerne**	**Arcelik**	**Duzce**	**HKD085**
T [sec]	**Score**	**Score**	**Score**	**Score**	**Score**	**Score**	**Score**
0.4	3	3	4	3	1	3	2
0.5	2	3	4	3	4	2	2
1.0	3	2	4	2	4	3	4
1.5	2	4	3	4	4	4	4
2.0	3	4	4	4	4	4	3
max. score %	65%	80%	95%	80%	85%	80%	75%

SUMMARY AND RECOMMENDATIONS

A zonation for earthquake record selection associated with time-history analysis of buildings located in the North Island of New Zealand was presented, based on aspects related to seismological signature (i.e. the magnitudes, distances and types of earthquakes that contribute significantly to the estimated 500-year hazard exceedance rates). Five zones were defined. For ease of use by engineers, these zones were defined in terms of contours of the hazard factor maps that are included in the Standard (SNZ, 2004a). A description of the suitable records for each zone was presented, along with general criteria for the selection of actual records. Specific suites of records were suggested for each zone.

Aspects of this study that are important to comment on before closing include:

- The proposed record selection method takes into account the different hazard scenarios for each location, although not always in a way that is completely proportional to their contribution to the final estimated seismic hazard. In most cases, the selected records represent the different scenarios in an approximately proportional way.

- The findings of this study are applicable to the seismic assessment or design of buildings with fundamental periods of between 0.4 and 2.0 seconds. For building projects of a more specialized nature (e.g.: high-rise or base-isolated buildings) that have periods longer than 2 seconds, it is recommended to utilize records specifically selected for the site and project conditions, instead of adopting the list of default records suggested here. In general, these kinds of projects have a dedicated budget for specialized studies. In the case of structures with periods of below 0.4 seconds, because the hazard scenarios often differ from those identified for $0.4s < T < 2.0s$, different suites of records may be required. The zone characterization and record selection for this period range has yet to be performed.

- The entire analysis has been conducted considering a return period of 500 years. Therefore the suite profiles and proposed suites of records are valid for analyses that require this return period. In general, the deaggregations and record selections are likely to be similar for a return period of 1000 years, but with greater differences for a return period of 2500 years.

- The suite profiles are valid for any of the five site classes (soils) listed in the standard, but the accelerograms presented in Appendix A are recommended only for site classes C and D (which are most common for NZ building projects).

- The zone boundaries, suite profiles and specific suites of records recommended for each zone should be periodically updated, according to the state-of-the-knowledge (PSH model actualization) and the requirements or amendments of the Standard (for example, revision of the Z-factor maps). However, because the zones are based on underlying tectonic characteristics, the changes are likely to be minor.

- The Standard requires that at least one in three records used for time-history analysis in the near-fault zones (North NF) must have strong directivity characteristics.

Finally, it is suggested that the findings of this study form the basis of a default suite of records that will be nationally recognized and endorsed by the New Zealand structural engineering and seismology community. However, it is not intended that the recommended suites of records should constrain those who undertake specific studies to select alternative suites appropriate to a particular location and structure.

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APPENDIX A: SUITES OF RECORDS FOR TIME-HISTORY ANALYSIS IN THE NORTH ISLAND OF NEW ZEALAND

Table A1. Shallow soil (Site Class C according to NZS 1170.5:2004)

Zone	Record name	Date	M[†]	D[*]	FM[⌘]	FD[♠]	HS[★]
North A	El Centro, Imperial Valley, USA	19-May-40	7.0	6	ss	No	Ref-A2
	Delta, Imperial Valley, USA	15-Oct-79	6.5	22	ss	No	A1
	Convict Creek, Mammoth Lakes, USA	25-May-80	5.9	6	ss	No	(A1)
	Bovino, Campano Lucano, Italy	23-Nov-80	6.9	45	n	No	(A2)
	Kalamata, Greece	13-Sep-86	6.2	10	n	No	A1
	Matahina Dam D, Edgecumbe, NZ	2-Mar-87	6.6	16	n	No	A1
	KAU001, Chi-Chi-IV, Taiwan	20-Sep-99	6.2	45	ss	No	A1
North B*	El Centro, Imperial Valley, USA	19-May-40	7.0	6	ss	No	Ref
	Gormon Oso Pump Plant, Sn Fdo, USA	09-Feb-71	6.6	44	r	No	B1
	Llolleo, Chile	03-Mar-85	7.8	23	sdi	No	(B3)
	Freemont M. S. Jose, Loma Prieta, USA	18-Oct-89	6.9	39	ro	No	B1
	Duarte, MelCanyon, Northridge-1, USA	17-Jan-94	6.7	48	r	No	B1
	HRS016, Japan	24-Mar-01	6.8	64	sds	No	B2
	HKD085, Hokkaido, Japan	26-Sep-03	8.3	43[♣]	sdi	No	(B3)
North C	El Centro, Imperial Valley, USA	19-May-40	7.0	6	ss	No	Ref
	Boshroyeh, Tabas, Iran	16-Sep-78	7.4	24	r	No	C2
	La Union, Mexico	19-Sep-85	8.1	16	sdi	No	C1
	Bear Valley #5, Loma Prieta, USA	18-Oct-89	6.9	53	r	No	C3
	Freemont M. S. Jose, Loma Prieta, USA	18-Oct-89	6.9	39	ro	No	(C2)
	HKD085, Hokkaido, Japan	26-Sep-03	8.3	43[♣]	sdi	No	(C1)
	Gisborne, New Zealand	20-Dec-07	6.8	31	n	No	C3
North NF	El Centro, Imperial Valley, USA	19-May-40	7.0	6	ss	No	Ref-(NF1)
	Tabas, Iran	16-Sep-78	7.4	2	r	Yes	NF2
	La Union, Mexico	19-Sep-85	8.1	16	sdi	No	NF3
	Lucerne, Landers, USA	28-Jun-92	7.3	1	ss	Yes	NF2
	Arcelik, Kocaeli, Turkey	17-Aug-99	7.5	14	ss	Yes	NF2
	Duzce, Duzce, Turkey	12-Nov-99	7.1	8	o	No	NF1
	HKD085, Hokkaido, Japan	26-Sep-03	8.3	43[♣]	sdi	No	(NF3)
North V	El Centro, Imperial Valley, USA	19-May-40	7.0	6	ss	No	Ref-V1
	Managua, Nicaragua	23-Dec-72	6.2	4	ss	No	V1
	Delta, Imperial Valley, USA	15-Oct-79	6.5	22	ss	No	V1
	Convict Creek, Mammoth Lakes, USA	25-May-80	5.9	6	ss	No	V1
	Calitri, Campano Lucano, Italy	23-Nov-80	6.9	13	n	No	V1
	Kalamata, Greece	13-Sep-86	6.2	10	n	No	V1
	Matahina Dam D, Edgecumbe, NZ	2-Mar-87	6.6	16	n	No	V1

[†] M = magnitude in Mw.
[*] D = shortest distance in km from the surface projection of the source.
[⌘] FM = fault mechanism or tectonic class. n = normal; o = oblique; r = reverse; ro = reverse-oblique; ss = strike-slip; sdi = subduction interface; sds = subduction slab
[♠] FD = Forward directivity. NZS 1170.5:2004 states that when the site is near a major fault (Zone North NF), one in three records of the suite shall consider near-fault effects (forward directivity records).
[★] HS = Hazard scenario from Table 1. The labels in brackets indicate that the Hazard Scenario requirements are only partially accomplish.
[♣] Closest distance for Hokkaido record provided by John Zhao of GNS Science.

Table A2. Deep soil (Site Class D according to NZS 1170.5:2004)

Zone	Record name	Date	M⁺	D*	FM⌘	FD♠	HS★
North A	El Centro, Imperial Valley, USA	19-May-40	7.0	6	ss	No	Ref-A2
	Delta, Imperial Valley, USA	15-Oct-79	6.5	22	ss	No	A1
	Chihuahua, Victoria, Mexico	9-Jun-80	6.3	19	ss	No	A1
	Corinthos, Greece	24-Feb-81	6.6	10	n	No	A2
	Kalamata, Greece	13-Sep-86	6.2	10	n	No	A1
	Westmorland, Superstition Hill, USA	24-Nov-87	6.5	13	ss	No	A1-A2
	CHY101, Chi-Chi, Taiwan	20-Sep-99	6.2	22	ss	No	A1
North B*	El Centro, Imperial Valley, USA	19-May-40	7.0	6	ss	No	Ref
	Taft Lincoln Sch., Kern County, USA	21-Jul-52	7.4	43	r	No	B1
	Llolleo, Chile	03-Mar-85	7.8	23	sdi	No	(B3)
	LA-R. Los Cerritos, Northridge1, USA	17-Jan-94	6.7	48	r	No	B1
	Compton Castelgate, Northridge1, USA	17-Jan-94	6.7	43	r	No	B1
	KOC017, Japan	24-Mar-01	6.8	95	sds	No	B2
	HKD085, Hokkaido, Japan	26-Sep-03	8.3	43♣	sdi	No	(B3)
North C	El Centro, Imperial Valley, USA	19-May-40	7.0	6	ss	No	Ref
	Taft Lincoln Sch., Kern County, USA	21-Jul-52	7.4	43	r	No	C2
	Boshroyeh, Tabas, Iran	16-Sep-78	7.4	24	r	No	C2
	Caleta de Campos, Mexico	19-Sep-85	8.1	16	sdi	No	C1
	Fortuna, Cape Mendocino, USA	25-Apr-92	7.0	29	r	No	C2
	HKD085, Hokkaido, Japan	26-Sep-03	8.3	43♣	sdi	No	(C1)
	Gisborne, New Zealand	20-Dec-07	6.8	31	n	No	C3
North NF	El Centro, Imperial Valley, USA	19-May-40	7.0	6	ss	No	Ref-(NF1)
	El Centro #6, Imperial Valley	15-Oct-79	6.5	0	r	Yes	NF2
	Caleta de Campos, Mexico	19-Sep-85	8.1	16	sdi	No	NF3
	Yarimka YPT, Kocaeli, Turkey	17-Aug-99	7.5	3	ss	Yes	NF2
	TCU 051, Chi-Chi, Taiwan	20-Sep-99	7.5	7	r	Yes	NF2
	Duzce, Duzce, Turkey	12-Nov-99	7.1	8	o	No	NF1
	HKD085, Hokkaido, Japan	26-Sep-03	8.3	43♣	sdi	No	(NF3)
North V	El Centro, Imperial Valley, USA	19-May-40	7.0	6	ss	No	Ref-V1
	Delta, Imperial Valley, USA	15-Oct-79	6.5	22	ss	No	V1
	Calitri, Campano Lucano, Italy	23-Nov-80	6.9	13	n	No	V1
	Corinthos, Greece	24-Feb-81	6.6	10	n	No	V1
	Kalamata, Greece	13-Sep-86	6.2	10	n	No	V1
	Matahina Dam D, Edgecumbe, NZ	2-Mar-87	6.6	16	n	No	V1
	Erzincan, Turkey	13-Mar-92	6.7	0	ss	No	V1

⁺ M = magnitude in Mw.

* D = shortest distance in km from the surface projection of the source.

⌘ FM = fault mechanism or tectonic class. n = normal; o = oblique; r = reverse; ro = reverse-oblique; ss = strike-slip; sdi = subduction interface; sds = subduction slab

♠ FD = Forward directivity. NZS 1170.5:2004 states that when the site is near a major fault (Zone North NF), one in three records of the suite shall consider near-fault effects (forward directivity records).

★HS = Hazard scenario from Table 1. The labels in brackets indicate that the Hazard Scenario requirements are only partially accomplish.

♣Closest distance for Hokkaido record provided by John Zhao of GNS Science.

APPENDIX B: GROUND MOTION SPECTRA OF THE RECORDS RECOMMENDED FOR EACH ZONE

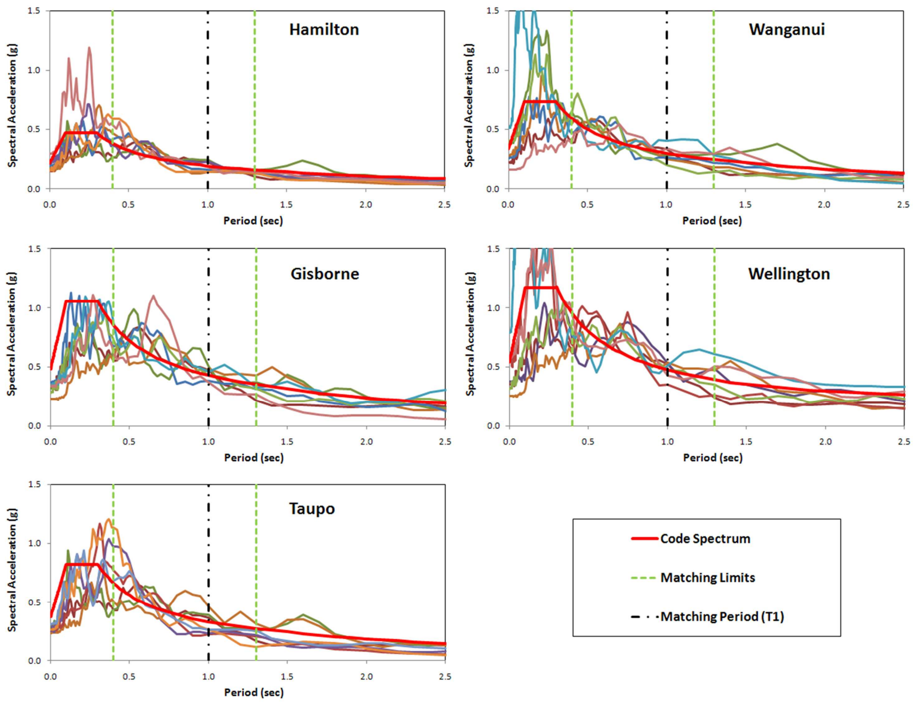

Figure B1. Ground-motion spectra and standard spectra for site class C scaled at Sa(1.0s) according to NZS 1170.5:2004.

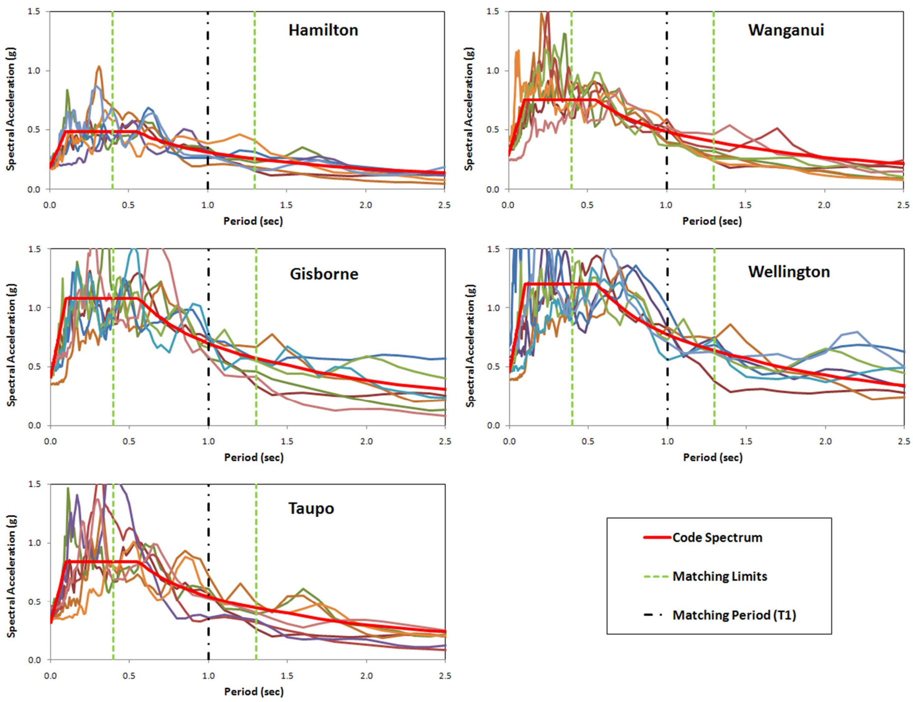

Figure B2. Ground-motion spectra and standard spectra for site class D scaled at Sa(1.0s) according to NZS 1170.5:2004.