# Design Spectra for the Reconstruction of Christchurch

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**SUMMARY:**
There have been many challenges in developing new design motions for the rebuilding of Christchurch following the destructive magnitude 6.2 earthquake on 22 February 2011. It has been necessary to account for both a productive on-going earthquake sequence and systematic effects giving rise to stronger than expected motions. The earthquake produced the strongest peak ground accelerations that have been recorded in any New Zealand earthquake, and recorded spectral motions around the Christchurch Central Business District that were generally about double the 500-year design motions. Different specifications of expected future ground motions are required for the design of multi-storey structures, for assessing liquefaction on soft soils and for assessment of rock-fall hazard. Particularly challenging has been the derivation of constant design values appropriate for the nominal design life of the next 50 years given the considerably enhanced but time-varying seismicity rates that are likely to prevail over this duration.

*Keywords: Design spectra, time-varying seismicity, Canterbury earthquakes*

## 1. INTRODUCTION

The Christchurch region in Canterbury, New Zealand, previously regarded as having only moderate seismicity, has suffered a series of destructive earthquakes since September 2010 (Fig. 1). The series initiated with the moment magnitude $M_w$ 7.1 Darfield earthquake, the largest of the sequence, on 4 September 2010, with an epicentre 37 km west of the Christchurch Central Business District (CBD). The complex rupture zone on previously unknown faults, including spectacular surface faulting along the strike-slip Greendale Fault, reached within about 20 km of the CBD. Significant damage but no deaths occurred in this event. The most damaging event of the Canterbury sequence was the $M_w$ 6.2 Christchurch earthquake at 12:51 local time on 22 February 2011, at a hypocentral distance of about 11 km but with the blind-fault rupture extending to within about 4 km of the CBD. The strength of the shaking in the CBD at such a short distance from the earthquake source resulted in numerous building collapses. Many of the collapses were of old unreinforced masonry buildings, but two-thirds of the 182 fatalities were caused by the collapse of two multi-storey reinforced concrete buildings. A notable feature of the earthquake sequence has been extensive liquefaction and lateral spreading, affecting commercial structures and many homes in the eastern residential suburbs. There have been extensive rock-falls in the hill suburbs to the south of the CBD, above the source zone of the 22 February earthquake. Both the liquefaction and rock-fall has resulted in the abandonment of thousands of houses, with large sections of some suburbs “red-zoned”. Liquefaction and spreading has also significantly affected services such as sewage, water supply, roading and electricity.

The sequence of events has continued through 2011 and 2012, with some of the more notable post-February earthquakes being the $M_w$ 6.0 event on 13 June 2011 and a pair of magnitude 5.8 and 5.9 events within just over an hour of each other on 23 December 2012, as the people of Christchurch were beginning to believe that the damaging earthquakes were over. Current studies of the ongoing sequence suggest that it is likely to persist for decades, although at a decreasing rate, rather than for months or one or two years. The increased seismic hazard over the next fifty years, corresponding to the default design life for most building structures in New Zealand, needs to be taken into account when repairing or strengthening existing structures or constructing new ones.

The peak accelerations in the Christchurch earthquake were the strongest recorded in New Zealand, with maximum values of 2.2g vertically and 1.7g horizontally, with over 0.7g horizontally around the CBD. The recorded motions at sites close to the CBD were generally about double the 500-year design motions for Christchurch that apply to normal-use buildings in terms of the New Zealand structural design standard NZS1170.5:2004 (Standards New Zealand, 2004), referred to as NZS1170.

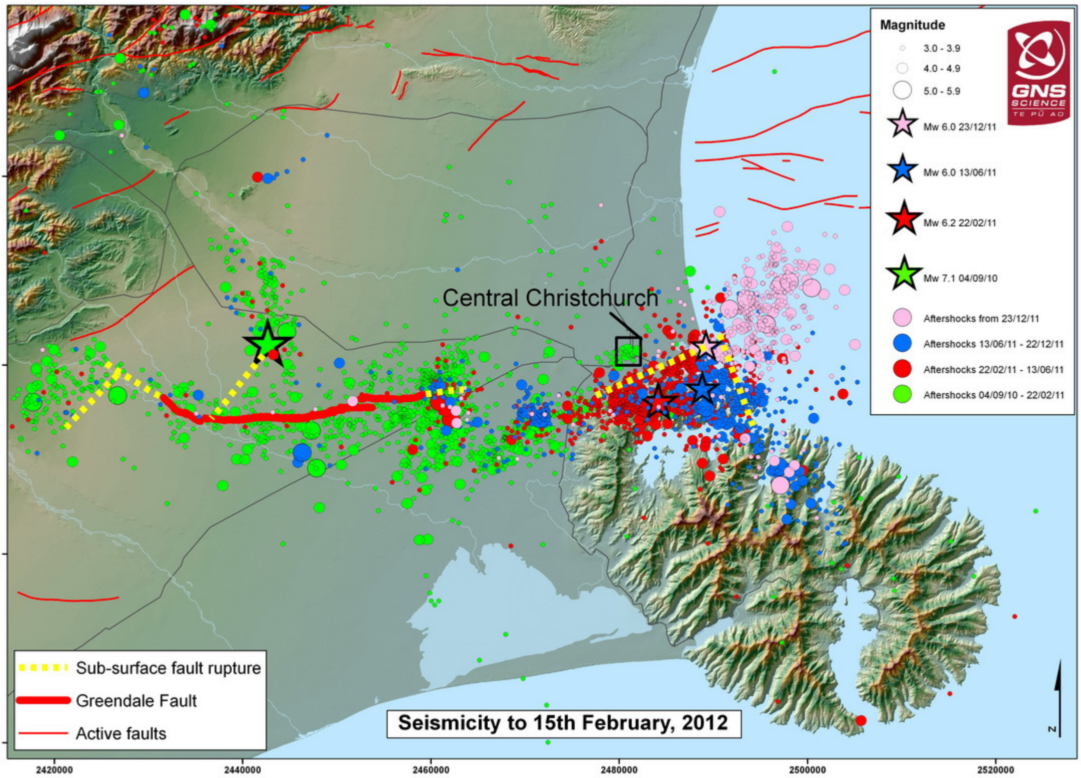

**Figure 1.** The Canterbury earthquake sequence, initiating with the Mw 7.1 Darfield earthquake of 4 September 2010 (epicenter marked by the green star, 37 km west of central Christchurch). An eastwards progression of events with time is shown by the colour coding green, red, blue and pink.

The strength of the motions and the productive on-going earthquake sequence led to a rapid reassessment of the earthquake design levels for Christchurch and the surrounding region. Spectra in the New Zealand structural design standard are defined in terms of the product of four parameters: the spectral shape factor $C_h(T)$ for horizontal motions, depending on site class; the location-dependent hazard factor Z, which scales the spectral shape to produce design spectra with an annual exceedance rate of 1/500 for the location and relevant site class; the return period factor R, which scales to other return periods required depending on the limit state (Serviceability or Ultimate) and Importance Level of the structure; and a spectral-period dependent near-fault factor N(T,D), accounting for near-source directivity effects for periods T greater than 1.5s within a distance D of less than 20 km from the closest of eleven major faults (all considerably distant from Christchurch). The NZS1170 Z-factor is scaled off the 500-year shallow soil spectral acceleration at 0.5s, but is numerically equal to the rock peak ground acceleration (pga) in terms of the NZS1170 spectral shapes.

Interim adjustments of the hazard factor Z and return period factors R for the Christchurch region were promulgated in May 2011 (Department of Building and Housing, 2011), based on probabilistic seismic hazard calculations using time-varying seismic source models to represent the ongoing earthquake sequence (Gerstenberger et al., 2011a, b). The interim Z-factor was increased to 0.3 from the previous value of 0.22 for Christchurch, while the 25-year R-factor that applies for the serviceability limit state was increased from 0.25 to 0.33.

This paper describes the derivation of the interim parameters of May 2011, and subsequent refinement of the hazard modelling working towards another revision due in June 2012. Design motions have been derived in terms of spectra and three sets of peak ground acceleration estimates - for structural applications, for liquefaction assessments and for evaluating rock fall probabilities. Some issues raised by using time-varying models to derive time-independent design parameters are also discussed.

## 2. GROUND MOTIONS IN THE 22 FEBRUARY 2011 CHRISTCHURCH EARTHQUAKE

Seismological studies indicate that many of the events in the Canterbury earthquake sequence exhibited high apparent stresses (Fry and Gerstenberger, 2011), although the recorded motions in the largest events show enhancements over expected values only for distances up to about 10 km from the rupture surfaces. The geometry of the rupture suggests that there would have been directivity enhancement in the 22 February earthquake from the propagation of the rupture up the fault plane and north-westwards towards the Christchurch CBD. There were local site amplifications, and basin effects, probably including constructive interference between waves travelling nearly vertically upwards from the underlying rock in the deep basin underlying Christchurch and those taking near-horizontal paths from the base of the Port Hills. There were strong vertical motions, which exceeded the horizontal motions in the short-period band up to about 0.1s period at many near-source sites.

Recorded motions in the Christchurch CBD in the 22 February 2011 earthquake considerably exceeded the design levels for Christchurch specified in the New Zealand earthquake design standard NZS1170.5:2004. Figure 2 compares the NZS1170 Class D deep soil spectra for Christchurch (hazard factor Z=0.22) with the larger value of the 5% damped acceleration response spectra for the two horizontal components of the recorded motions at four sites within about 1.5 km of the CBD. Design spectra in NZS1170 are based on the larger horizontal component. The solid red line is the geometric mean of these four larger horizontal component spectra. The NZS1170 elastic spectra are shown for return periods of 500 years and 2500 years. A return period of 500 years corresponds to the design-level spectra for normal-use structures, while 2500 years is used for essential facilities with special post-disaster functions. The CBD spectra (coloured lines) are higher than the design ground motions for even a 2500-year return period, especially at long periods, although they are generally somewhat less than these motions at short periods (< 0.3 – 0.4 s). The maximum spectral displacement demands in the February spectra are associated with the peaks at 3.0-3.5s, which appear relatively modest in the acceleration spectra plots.

The peaks around 1.5s are associated with the response of the soft soils in the top 20 to 30 metres of the site profiles. The longer period peaks are around the site periods of about 3 seconds associated with sediments greater than 500 m thick overlying volcanic rock underneath Christchurch. Peaks around 3s were also a feature also of the motions in the 4 September 2010 earthquake, where this period range also appeared to be associated with forward-directivity rupture-propagation effects.

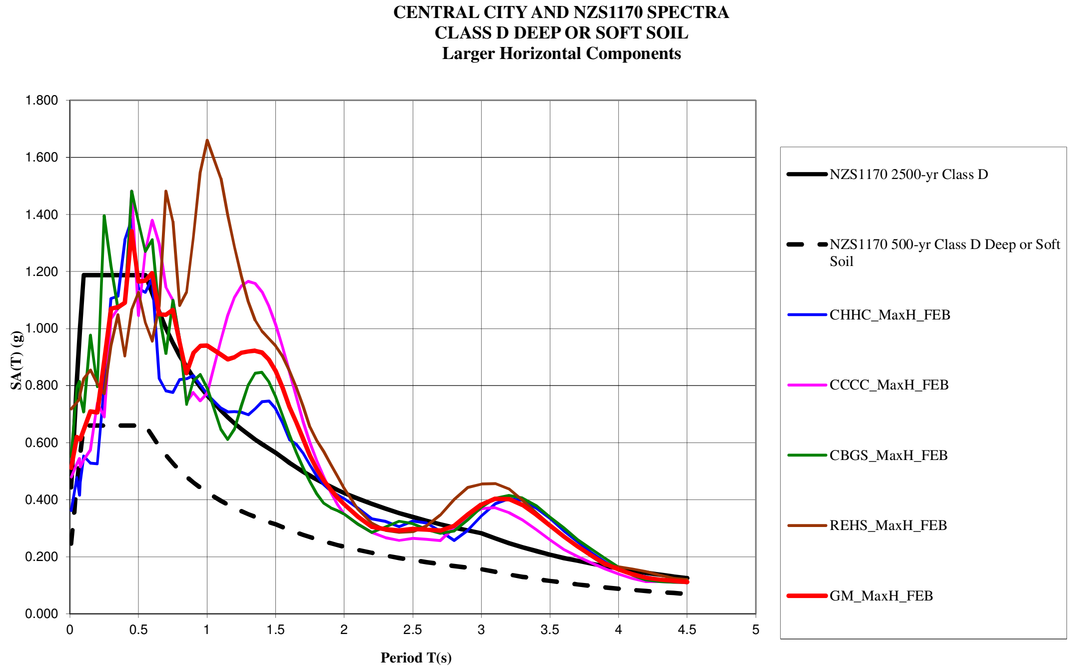

**Figure 2.** Comparison of recorded 5% damped acceleration response spectra in the 22 February earthquake for four sites within ~1.5 km of the Christchurch CBD (coloured lines) and corresponding spectra from the New Zealand design standard NZS1170 for Class D deep or soft soil sites (black lines). The solid red line is the geometric mean of the four sites. The dashed and solid black lines are the 500- and 2500-year NZS1170 spectra.

As well as exceeding the design spectra for Christchurch, the spectra of the motions recorded at the four CBD sites generally exceed the 84-percentile spectra estimated using the McVerry et al. (2006) ground-motion prediction model (GMPE) for periods longer than about 0.35s. The McVerry et al. model is used in GNS Science's National Seismic Hazard Model (Stirling et al., 2002) which was used for performing the hazard calculations that underlie the design spectra in NZS1170. Some of the enhancement of motions over modelled values may be random variability, but much of it is likely to result from specific characteristics of the causative fault, basin effects and near-surface site effects. Some of these characteristics are likely to occur in future earthquakes in the region, increasing the ground-motions from those given by the GMPE used in the development of the NZS1170 spectra.

## 3. INCREASED SEISMICITY RATES

Particularly challenging has been the need to account for the time-varying nature of the on-going earthquake sequence around Christchurch. Seismicity in the region is presently very high relative to previous activity, but is likely to reduce with time, over a period of decades. This has been handled through combining time-independent and time-varying seismicity models (Figure 3), with earthquake forecasting models used for perhaps the first time to obtain hazard estimates for engineering design.

For the May 2011 model (see Section 1), the time-varying seismicity was accounted for by combining four different types of earthquake models as explained in Gerstenberger et al. (2011a, b): a Short-Term Earthquake Probabilities (STEP) model (Gerstenberger et al., 2005) representing short-term clustering of aftershocks; the EEPAS (Every Earthquake a Precursor According to Scale) model to represent medium-term clustering of moderate-to-large earthquakes (Rhoades and Evison, 2004); the time-invariant PPE (Proximity to Past Earthquakes) model (Rhoades and Evison, 2004) to represent a constant seismicity rate that is expected to prevail from about 15-20 years after the initiation of the current sequence in September 2010; and surface fault sources that represent most of the seismicity at distances beyond about 30 km from Christchurch to the Alpine Fault at a closest distance of about 130 km. The combination of the seismicity models is discussed in the next section.

Figure 3 shows the yearly forecasts for the three seismicity-based models for years 2011-2041. The sharp decay of the aftershock sequence from the STEP model is apparent as well as the slower temporal response of the EEPAS model and the static forecast of the PPE model. It can be seen that the STEP model is dominant initially in all magnitude ranges. The EEPAS model then dominates the forecasts until roughly 2025 when the PPE model begins to produce the highest forecast rates. All these rates are considerably larger than those estimated before the start of the sequence.

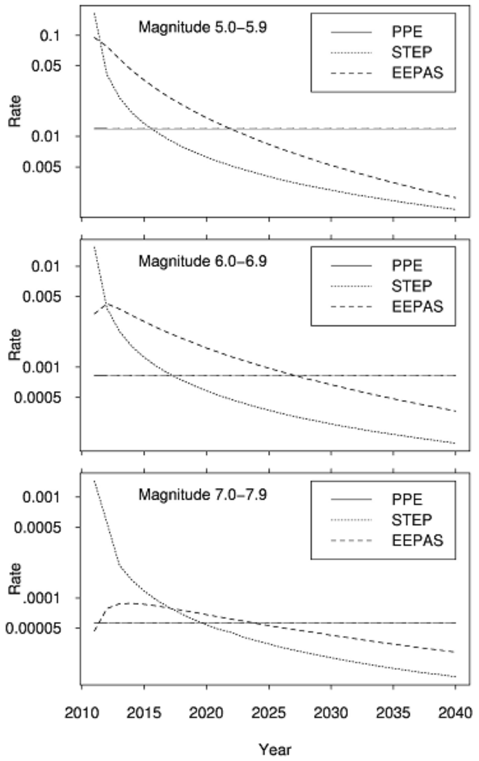

**Figure 3.** Forecast annual earthquake rates for a representative Christchurch location from the three seismicity-based models for M5.0–5.9 (top), M6.0–M6.9 (middle) and M7.0–M7.9 (bottom). The dominance of the higher rates of the STEP model initially can be seen before the EEPAS model takes over at slightly longer time scales. After 15 to 20 years, the time-invariant PPE smoothed seismicity model produces the highest rate, and defines the combined rate according to the avmax procedure (see text).

## 4. HAZARD ESTIMATES

Revised earthquake ground-motion hazard estimates were obtained for the Christchurch region by implementing the seismicity model that combined time-varying and time-independent components. Several other modifications were made to the usual modelling procedure, mainly in recognition of the very high seismicity rates that the model produced in the magnitude 5.0 to 5.5 range. The McVerry et al. (2006) model is known to increasingly over-estimate motions as the magnitude reduces below 5.5.

In recognition of this spurious behaviour, and advice from the Engineering Advisory Group that earthquakes of magnitude less than 5.5 were unlikely to produce significant damage to code-designed structures, the minimum magnitude was increased from 5.0 to 5.5.

The modelling performed to produce the May 2011 hazard estimates for Christchurch accounted for the enhanced motions by applying the Atkinson & Boore (2006) multiplicative factors for stress-drop effects to the standard hazard estimates, and reducing the source depth to 5 km rather than the minimum of 10 km in the standard New Zealand National Seismic Hazard Model. In more recent work, the seismicity has been distributed across six focal depth layers between 1 km and 30 km deep. The stress-drop term was a conveniently available tool to produce enhanced motions, rather than representing a belief that high stress-drops were the only or major contributor to the strong motions.

### 4.1 Combination of seismicity models

The estimates for revised NZS1170 spectra for Christchurch were obtained for the required annual exceedance probabilities (AEPs) averaged over the next 50 years, corresponding to the default design life. For the time-independent hazard models that are usually used for deriving engineering design spectra, the seismicity rates are the same for every year, but for time-varying seismicity models they change from year-to-year, so the duration chosen was the next 50 years. The distributed seismicity was handled by calculating the expected number of earthquakes in magnitude bands of 0.2 width on a 0.1° by 0.1° grid (now revised to a 0.05° spacing) for each year, and adding these over the 50-year duration of interest. Dividing the totals by 50 gave the effective seismicity rate over the 50-year design life for each grid cell and magnitude band. The resulting AEPs for various acceleration values were calculated using these effective seismicity rates. Calculations were also performed on a year-by-year basis, to track the change in ground-motion level associated with a given annual exceedance rate.

The seismicity rates in each year for each grid cell and magnitude band were found by a procedure that took account of the contributions from the various models, building on concepts considered by Rhoades & Gerstenberger (2009). In the first year, the distributed seismicity was represented purely by the STEP model, recognizing that the seismicity in this period was dominated by the productive aftershock sequence. For later years, an “avmax” approach was developed for combining the three distributed seismicity models (Gerstenberger et al., 2011a, b). This involved taking the average seismicity rate of the two time-varying models (STEP and EEPAS) for each grid point and magnitude band, and then taking the larger of this average or the contribution from the time-invariant PPE model. The ground-motion exceedance rates from the avmax combination were added to those from the modelled fault sources of the NSHM. The combined seismicity rate varies with time until the average rate from the two time-varying models falls to the constant rate from the PPE model.

### 4.2 Response spectra and Z-factors

Figure 4 shows the 5% damped elastic hazard spectrum for NZS1170 Class D Deep or Soft Soil that was estimated to have a 10% probability of exceedance in the next fifty years in the Christchurch CBD from the model used for the May 2011 results. This spectrum is compared with the NZS1170 Z=0.3 spectrum for this soil class, which was the basis for the recommendation to increase *Z* from 0.22 to 0.3. The hazard spectrum is more sharply peaked than the NZS1170 spectrum, partly because the Christchurch hazard estimates are now dominated by low-to-moderate magnitude events from the distributed seismicity, with little influence from the NSHM fault sources. However, the Engineering

Advisory Group that guided the selection of the new spectra wished to retain the standard spectral shape factors for Christchurch. Beyond its short-period plateau, the Z=0.3 spectrum envelopes the 10% in 50 years spectrum. The zero-period ordinate (i.e., peak ground acceleration) of the hazard spectrum is 0.6g, considerably increased from the value of 0.34g corresponding to the NZS1170 Class D spectrum for a Z-factor of 0.3, consistent with the high-frequency character of the hazard spectrum.

It was also found that the rate of change of the spectra with AEP was different from that of NZS1170. In NZS1170, the return period factor for Serviceability Limit State 1 (SLS1) with an AEP of 1/25 is 0.25. For the new time-varying model, the SLS1 return period factor for Christchurch is 0.33.

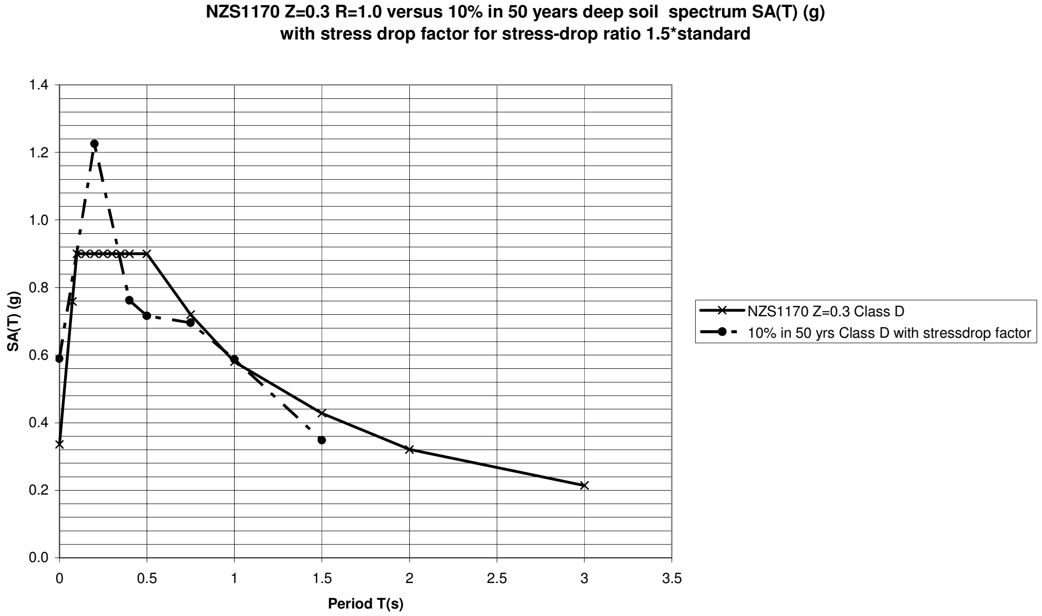

**Figure 4.** The Z=0.3 Class D deep soil spectrum approximately envelopes the hazard spectrum estimated with a 10% probability of exceedance in the next 50 years, apart from truncation of the peak of the spectrum.

## 4.3 Peak ground accelerations for structural and geotechnical applications

Geotechnical design is often based on peak ground acceleration values. As mentioned above, the peak ground accelerations calculated directly from the revised hazard model for Christchurch depart markedly from the values corresponding to a Z-factor of 0.3. Consequently, it was recommended that specific estimates of peak ground accelerations be used when they are required, rather than taking the values derived from the revised NZS1170 $C_h(0)ZR$ product.

Magnitude-weighting is an important issue for geotechnical design. Liquefaction and lateral spreading are strongly affected by duration, and its assessment frequently involves the use of magnitude-weighting factors (MWFs) in terms of magnitude M. The magnitude-weighting factors used for estimating the Z-factors were $(M/7.5)^{1.285}$, as originally proposed by Idriss (1985) and used in the development of NZS1170. However, the MWFs used for liquefaction assessment have been re-evaluated in recent years (Youd & Idriss, 2001), and alternative MWFs of $(M/7.5)^{2.5}$ have been used for estimating pgas for liquefaction assessment in Christchurch (Gerstenberger et al., 2011a). For the assessment of rock fall, MWFs are not incorporated, because it is the exceedance of a critical acceleration for a single rather than multiple cycles that is important (Massey et al., 2011).

To satisfy these requirements, three sets of peak ground acceleration values have been derived directly from the hazard analyses, using the magnitude-weighting factors appropriate for their specific uses.

### 4.4 Motions for periods of 1.5s and longer

The evaluations to date do not consider the period range longer than 1.5s, for which the recorded motions in the September, February and June earthquakes show that the spectral shapes are enhanced from the NZS1170 Deep Soil shape between about 2s and 4s. The evaluation of the peaks in this period range, which provide the strongest spectral displacements in the recorded motions, is being undertaken in other studies using methods such as SHAKE and 2- and 3-dimensional basin modeling.

## 5. VARIATION OF HAZARD ESTIMATES WITH TIME

A key issue in the use of time-varying seismicity models to obtain hazard estimates that are representative of the next fifty years is how to determine the “representative” value. In this study, the representative hazard values were found by taking the seismicity rates for each grid point and magnitude interval as the average over the next fifty years of the avmax rates, as described above, before performing the hazard calculations. The effects of this procedure were assessed by comparing the overall hazard values over the next fifty years against the year-by-year values. Figure 5 compares the representative 50-year value of the hazard factor Z with some of the values for individual years, using the most recent seismicity model derived from an Expert Elicitation (EE) process (see Discussion section). The peak ground acceleration estimates showed similar trends.

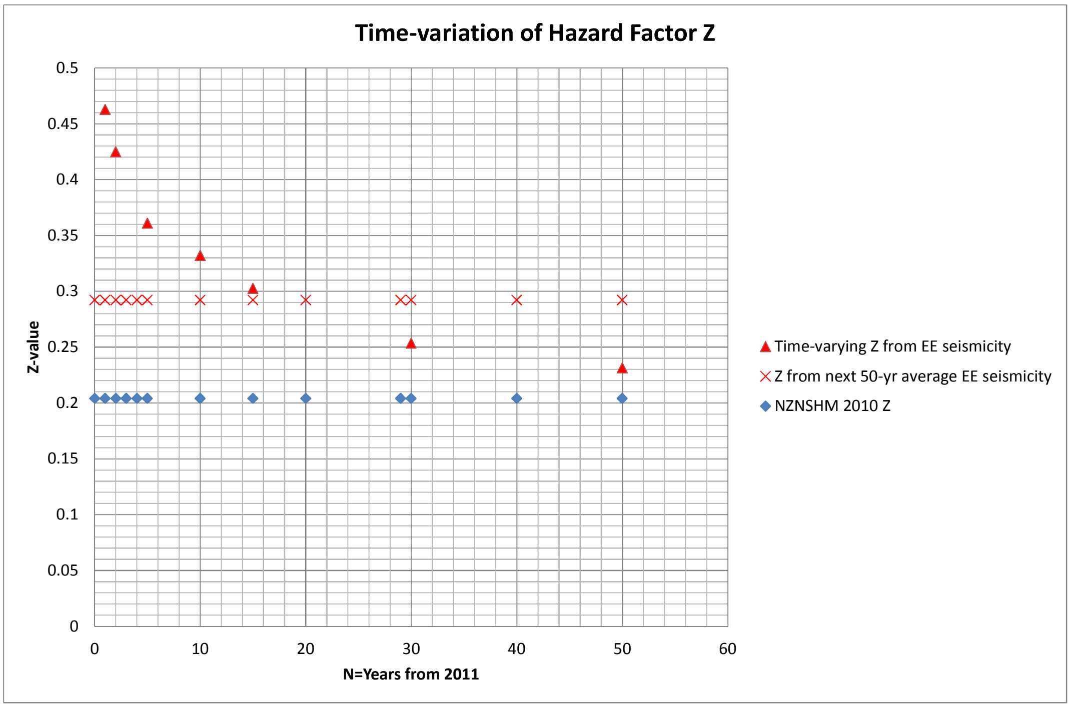

**Figure 5:** Comparison of Z-factor from the 50-year average seismicity rates (red crosses) from the recent Expert Elicitation (EE) seismicity model for one of the component hazard models, the time-varying values for individual years of the same model (red triangles), and the constant value from the 2010 pre-Darfield earthquake National Seismic Hazard Model (blue diamonds).

The Z-factors estimated for the first few years are up to 50 percent higher than the value of about 0.3 found from the average seismicity rates for the next 50 years, falling to the average value after about 15 years. These enhanced hazard rates in the first decade or more are providing policy makers with difficult decisions – should they accept higher than usual risk levels over this time interval? In the EE model, unlike the May 2011 model, the Z-factors continue to fall towards the long-term value given by the 2010 National Seismic Hazard Model (Stirling et al., in press) derived from pre-Darfield seismicity, for which the Z-factor was slightly lower than the NZS1170 value of Z=0.22 derived from the 2002 version of the NSHM.

Calculations such as these provide the information for the different time-scales that have been of interest for various purposes: months for decisions about re-occupation of properties threatened by rock-fall, one or a few years for insurance purposes and for evaluating hazard during reconstruction, and 50 years for the nominal design lives of most structures.

## 6. DISCUSSION

In November 2011, GNS undertook an Expert Elicitation (EE) procedure involving an international expert panel to update the seismic hazard model for the region affected by the Canterbury earthquake sequence. This led to recommendations for weighted combinations of multiple seismicity models for each of the aftershock, mid-term and long-term components of the model, as well as similar logic-tree approaches for other aspects of the hazard modelling (e.g. source depth, minimum magnitude, stress-drop modification and inclusion of epistemic variability in the GMPE). Also, Bradley & Cubrinovski (2011) have shown that a New Zealand–specific GMPE developed before the Canterbury earthquakes (Bradley, 2010) provided a good match to the Darfield and Christchurch earthquake data.

Revised seismicity rates from the EE model have recently been released, incorporating seismicity up to early January 2012. These were incorporated along with the other changes to the hazard modelling, including addition of the Bradley GMPE, in late March 2012. Spectra for structural design and pgas for assessment of liquefaction and rock-fall from this model will be available in the near future.

## 7. CONCLUSIONS

This paper summarises the background to the May 2011 interim modification of the seismic hazard spectra for Christchurch in the New Zealand Standard NZS1170 *Structural Design Actions*, completed over a short time-frame following the damaging Christchurch earthquake of 22 February 2011. More recent work towards a second modification due for release in May 2012 is described. With the importance of liquefaction and rock-fall in Christchurch, specific estimates of peak ground accelerations have been produced for assessment of these hazards. Fundamental to the derivation of the new design parameters has been the modelling of a productive ongoing earthquake sequence, requiring the application of time-varying seismicity models, perhaps for the first time in developing engineering design standards.

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