Review of "The Canterbury Earthquake Sequence and Implications for Seismic Design Levels" dated July 2011

Prepared by

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Introduction

I reviewed the report entitled "The Canterbury Earthquake Sequence and Implications for Seismic Design Levels" dated July 2011 (hereafter, called the "CES report") and the companion report entitled "update of the Z-factor for Christchurch considering earthquake clustering following the Darfield earthquake" dated May 2011 (hereafter, called the "Z-factor report").

My review is intended to provide technical insights for a general audience with the objective of identifying the broad issues involved in evaluating the need for revisions to the New Zealand National Seismic Hazard Map (NSHM) in light of the Canterbury earthquake sequence and, in particular, the damaging Christchurch earthquake.

There are three main issues that addressed in this review:

(1) Was the occurrence of the Canterbury earthquakes and the resulting ground motions consistent with the earthquake and ground motion models used in the New Zealand National Seismic Hazard Map (NSHM)?

(2) Should there be a change in the models and methods used to develop the NSHM for all of New Zealand?

(3) Should there be a change in the models and methods used to develop the NSHM in the Christchurch region to account for the increased short-term hazard due to the ongoing earthquake sequence?

The review of these three main issues is focused on two aspects: (1) the earthquake science models used to conduct the seismic hazard analysis and (2) comparison of methods used for developing the Z factors for the NSHM with international practice.

1. Was the occurrence of the Canterbury earthquakes and the resulting ground motions consistent with the earthquake and ground motion models used in the New Zealand National Seismic Hazard Map (NSHM)?

Chapter 3 of the GNS (2011b) report provides a good overview of the four largest earthquakes in the Canterbury sequence: 4-Sep (M7.1), 26-Dec (M4.7), 22-Feb (M6.2), and 13-Jun (M6.0). The occurrence of these earthquakes and the resulting ground motions are discussed below.

1.1 Occurrence of the Canterbury earthquakes

The Canterbury earthquakes occurred on previously unknown faults. So a key question is if similar earthquakes could occur elsewhere in New Zealand on unknown faults.

Around the world, most large magnitude crustal earthquakes (M>7) in active regions occur on known faults, but it is common for earthquakes in the M5-M6.5 range to occur on unknown faults and some M7 earthquakes occur on unknown faults. The occurrence of large earthquakes on previously unknown faults reflects the limitations of the earthquake sciences. The short historical observation period (100s of years), compared to the rates of large magnitude earthquake occurrence in low activity areas (1000s of years), means that use of historical data will not capture infrequent earthquakes.

In probabilistic seismic hazard analysis (PSHA), earthquakes occurring on unknown faults are considered through use of areal source zones that allow earthquakes up to some maximum value (e.g. M7.2 in New Zealand) to occur anywhere in the zone. The rate of these earthquakes is based on historical seismicity which is limited to the relatively brief observation period.

To extend the observation time period, geologic studies are the used to identify faults. This has been done for the major surface rupturing faults, but faults that do not reach the surface are more difficult to identify and characterize.

Geodetic strain rates can be used to infer regional strain rates from short-term observations (10s of years). An example of geodetically inferred strain rates is shown in Figure 2-2 (CES report). The strain rate in the Canterbury Plains region is about 1-2 mm/yr (CES report, page 4). While this information can be used to provide an idea of the rates of earthquakes, it does not provide the resolution to identify individual faults in the Canterbury Plains. Based on my experience reviewing PSHA reports that use geodetic data in California, the geodetic data does a good job of identifying the fault location and estimating the slip-rates for the high activity faults, but geodetic data does not provide much of a constraint for faults with slip-rates of 1 mm/yr or less in active regions containing other high activity faults.

The CES report (page 45) notes that geodetic arrays around cities could be used to identify areas of higher strains that could then be used to target detailed geological studies. Because of the time needed to accumulate enough strain to allow for reliable estimates of the strain rates, such a program would need to run for decades before producing results. Although, such a program will not help in the short term, these programs need to get started so that there is progress in the next 10-20 years.

Lower Limit on Z factors

In addition to allowing earthquakes to rupture on unknown faults using areal zones, we can account for unknown faults with low activity rates that may not be apparent in the observed seismicity or in the geology by setting a lower limit on the Z factor. This is discussed more below in section 2.3.

Maximum Magnitude of Earthquakes on Unknown Faults

The 4-Sep earthquake had a moment magnitude of 7.1. This is a large magnitude for an earthquake on an unknown fault. The NSHM uses a maximum magnitude of 7.2 for zones (other than the Taupo Volcanic zone). This is slightly higher than then M7.0 used for the US national hazard maps. In many site-specific studies, the maximum magnitude is set at about 6.5 for zones.

While the 4-Sep, M7.1 earthquake was unexpected, the occurrence of this earthquake does not violate the model used in the NSHM. I think that using M=7.2 for the maximum magnitude in areal source zones in New Zealand is appropriate, but the sensitivity of the hazard to this parameter should be evaluated (see discussion in Section 2.1)..

Depth of earthquakes on Unknown Faults
The shallow depth of the 22-Feb earthquake (top of rupture at 1 km depth) is less than the minimum depth of 10 km used for the NSHM (Z-Factor report, page 10). The occurrence of the 22-Feb earthquake violates the model for this zone. This part of the source model that should be revised. The proposed revision is discussed in Section 2.1.

1.2. Ground Motions for Canterbury earthquakes
The evaluation of the ground motions from the Canterbury earthquakes given in Section 3 of the CES report is focused on the spectral acceleration for a spectral period of 1 sec. Because the New Zealand building code Z factor, described in Appendix 5, is based on the T=0.5 sec spectral acceleration, it would have been more useful to have seen the plots of the attenuation for T=0.5 sec rather than for T=1 sec. I understand the need to keep the report short for the general public, but it would have been easier to review of the plots were related to the building code parameters.

The CES report discusses four possible issues for ground motions during these earthquakes: high stress drop, forward directivity, basin effects, site effects, and large vertical ground motions.

Stress-Drops and Energy Magnitude
The CES report uses energy magnitude to show that the Canterbury earthquakes had above average ground motions, which is interpreted to imply above average stress-drops.

I found the use of energy magnitude to be confusing and misleading. Energy magnitude is not a standard parameter (this is the first time I have ever seen it used in ground motion evaluations) and, as discussed below, it is inconsistent with the observed ground motions. In seismic hazard analysis, it is standard practice to use moment magnitude as a measure of the energy in an earthquake and to use stress-drop as a measure of how the energy is released in space and time. (Stress-drop measures the compactness of the energy in space and/or time.). If the energy is compacted into a smaller area or shorter time (high stress drop), then the resulting short-period ground motions are larger. Conversely, if the energy is spread out over a larger area or over a longer time (low stress drop), then the resulting short-period ground motions are lower.

The CES report gives the energy magnitude for Darfield as M_e=8.0 compared to a moment magnitude of M_w=7.1, but the T=1 sec spectral accelerations from this earthquake, shown in Figure 3.5 (CES report) are not high compared to the McVerry et al. (2006) model. For this magnitude earthquake, the T=1 sec spectral accelerations should be sensitive to the stress-drop.

Other preliminary comparisons have also shown that the short-period ground motions from Darfield are not unusually high. For example, the Darfield ground motions at short periods are similar to the median prediction from the Abrahamson and Silva (2008) NGA model. This is not consistent with a high stress drop for this earthquake.

Similarly, the T=1 sec spectral accelerations for the 13 June event (M_w=6.0, M_e=6.7), shown in Figure 3-15 (CES report), are not high compared to the McVerry et al. (2006) model. This should be checked for spectral periods less than 1 second because the effect of stress-drop changes is stronger at short periods.

For the 4-Sep and 13-Jun earthquakes, the high values of the energy magnitude, as compared to the moment magnitude, are not consistent with the ground motions. The ground motions for the 26-Dec earthquake were not shown so I don't know if it had unusually large ground motions or not.

In all of these comparisons, it is important to understand that there are two random components in the ground motion models. First, there is an event term that represents the average misfit between the model predictions and the observed ground motions for a single earthquake. Second, there is a "within-event" term that represents variability from site to site about the model prediction adjusted for the event term. Even if there are many recordings from a single earthquake that are all above average, this still represents only a single sample of the event term. It does not mean that there is high confidence that the ground motions from future earthquakes will also be high. The evaluation of stress-drops of future earthquakes needs to consider the small number of earthquakes.

One of the conclusions of the report is that the stress-drops for the 4-Sep, 22-Feb, and 13-Jun Canterbury earthquakes were above average, based on the larger energy magnitudes. Given that the short-period ground motions are not unusually high for the 4-Sep and 13-Jun events, I don't think that there is compelling data to support the interpretation that future earthquakes in the Canterbury sequence will have above average stress-drops.

Finally, keeping in mind that there is large variability from earthquake to earthquake, the concept that high stress-drops occur for earthquakes in low activity regions is over-simplified. I agree there are some areas of low activity that have high stress-drops, but there are also areas of low activity that have low stress-drops. As part of the NGA project, there was an evaluation of the correlation of slip-rate and the event term. They found no correlation (Figure 1), indicating that there is no systematic trend of higher ground motions (stress-drops) with the fault activity rate.

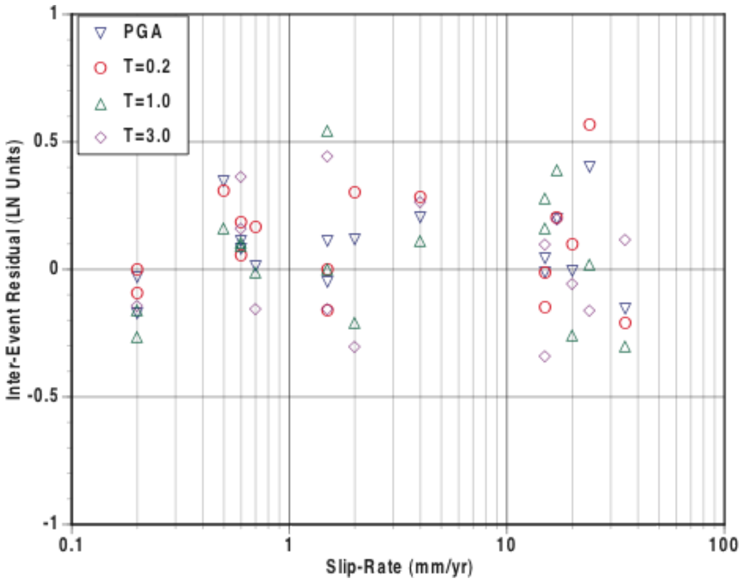

Figure 1. Correlation of event terms and fault slip-rate from the NGA data (from Abrahamson, 2008)

Forward Directivity Effects

Directivity is related to the direction of the rupture on the fault. As noted by Somerville, et al (1999), there are two parts of the directivity effect on the long period ground motion: (1) an increase in the average horizontal component spectral acceleration for ruptures coming toward a site (forward directivity) and a decrease in the average horizontal component spectral acceleration for ruptures that are away from a site, and (2) a systematic difference in the horizontal component aligned perpendicular to the strike of the fault as compared to the horizontal component aligned parallel to the strike of the fault.

The CES report identifies forward directivity as a cause for some of the high ground motions observed in the 4-Sep and 22-Feb earthquakes. I agree that it directivity effects are likely a cause of some of the higher ground motions during these earthquakes. The difficulty with directivity is that the rupture direction will vary from earthquake to earthquake and the directivity effects are dependent on the rupture/site geometry. As a result, there is a large variability in the rupture directivity effects.

While rupture directivity can help to explain the observed ground motions, for future earthquakes, it mainly contributes to the variability of the average horizontal component and a systematic increase in the strike-perpendicular component as compared to the strike parallel component.

With the increase in the size of the empirical data sets, they now contain a good sampling of the variability due to directivity for earthquakes with magnitudes less than 7. The sampling becomes worse as the magnitude increases above M7.

The need to include changes to the directivity effects for the major faults is discussed in Section 2.2.

Site Effects and Basin Effects

Site effects represent the effects of the soil (or rock) properties at a specific site. Site effects can amplify or attenuate ground motions based on the period and amplitude of the ground motion. Typically, site effects are characterized by the 1-D velocity profile at the site. Because site effects are mainly 1-D, an average site effect can be estimated from a relatively small number of earthquakes recorded at a site.

Basin effects represent effects of 3-D basins on the ground motion. Typically, basin effects are strongest in the long period range and can lead to large increases in the amplitude and duration of the long period ground motion. Because basin effects are due to the 3-D velocity structure, the basin effects can very different depending on the direction that the earthquake waves are entering the basin. Therefore, repeatable basin effects are difficult to estimate from small numbers of earthquakes.

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The CES report attributes some of the high amplitude ground motions in the central Christchruch region to site and basin effects, but for evaluations of single recordings, it is difficult to separate the site effects from the basin effects. Using multiple recordings at a site from different earthquakes, the site effects can be estimated, but if the earthquakes are all from a similar direction, then the basin effects are also present.

The CES report notes that there are some strong site/basing effects, but there is no attempts to estimate the site effects. The site effects represent systematic, repeatable effects that could be used to improve the ground motion estimates in Christchurch. Given that there are recordings from multiple earthquakes at many of the sites, I think that site effects could be estimated from this data. Appendix 4 shows examples of the spectra from three earthquakes at several sites. To estimate the site term from small data sets, the earthquake event terms should be added to the ground motion model and the average misfit between the event-term specific model prediction and the observed ground motion should be computed. This average misfit represents a site-specific adjustment to the model. This is discussed further in section 3.2.

Vertical Ground Motions

The report notes that during the 22-Feb earthquake, the vertical peak acceleration at short distances are larger than the horizontal peak accelerations. This is commonly observed for earthquakes with near-fault recordings.

Current engineering practice does not address the vertical component of ground for typical building code structures. Verticals are considered on special projects but not for standard building design. The large vertical ground motions are unlikely to be the main cause of poor performance of the buildings, but this may be a good time to revise the vertical component in the New Zealand building code. This is discussed in Section 2.2.

Ground Motions from Afterhsocks
An issue not dicussed in the CES report is the difference between the median ground motions from mainshock and aftershocks. The Abrahamson and Silva (2008) and Chiou and Youngs (2008) NGA models both found that, on average, the short-period ground motion from aftershocks is about 40% less than from mainshocks. This difference has been recognized earlier (e.g. Boore and Atkonson, 1992) and it was the reason that the Boore and Atkinson (2008) and Campbell and Bozorgnia (2008) models excluded aftershocks from their NGA models.

A recent issue has arisen on this topic is the definition of "aftershock" for ground motion models. The Pacific Earthquake Engineering Research (PEER) center is been working on the this topic. Currently, for ground motion prediction, aftershocks are being defined as earthquakes that occur along the rupture plane of the mainshock (e.g. within a Joyner Boore distance of 2 km) and during the time window given by the Gardner & Knopoff (1974) model. With this definition, earthquakes that occur off of the main shock rupture, such as triggered events, would be classified as mainshocks for the purpose of ground motion estimation.

The estimation of ground motions from aftershocks and from triggered events is important for the seismic hazard estimation in the Christchurch region. This points out the need to develop a robust model for estimating the ground motions from aftershocks. The 22-Feb earthquake is part of the Canterbury earthquake sequence and would be called an aftershock by most seismologists; however, with the definition being used by PEER, this earthquake would use the mainshock ground motion model because it was located off of the rupture plane of the 4-Sep earthquake. The 13-Jun earthquake would use the aftershock ground motion model because it is located along the rupture of the 22-Feb earthquake.

This issue of different GMPEs for mainshocks and aftershocks is an area of active research. The McVerry et al. (2006) model does not address this possible difference: the data set used by McVerry et al. includes a mixture of mainshocks and aftershocks. It would be useful to evaluate the McVerry et al. data set for the difference between median ground motions for mainshocks and aftershocks, following the PEER definitions.

2. Should there be a change in the models and methods used to develop the NSHM for all of New Zealand?

Several modifications to the source characterization and ground motion models are discussed in Section 5 of the CES report. On the top of page 51, there is a warning that care must be taken to avoid over-interpreting the relatively small data set from the Canterbury earthquakes. I fully agree with this warning. Earthquake ground motions can be considered as samples from random processes with a high degree of variability. Some of the effects observed in the Canterbury earthquake will be systematic, repeatable effects, whereas other effects will vary randomly for future earthquakes. The goal should be to capture the systematic effects in the median models and the random variability as part of the model distributions.

2.1 Need for Changes to the Source Characterization.

Depth of earthquakes in zones

As noted in section 1.1, the 1 km depth of the top of rupture of the 22-Feb earthquake is much smaller than the minimum depth of 10 km used in the NSHM. The proposed change is to use a single depth of 5 km (Z-factor report, page 10). While I agree that the 10 km depth is too large, assuming that all of the earthquakes are at 5 km depth is too restrictive and does not capture the variability. I would suggest that a depth range be used.

A minimum depth of 1 km seems appropriate as this was seen in 22-Feb earthquake. The maximum depth should be based on the thickness of the crust and the depth of historical seismicity in the broad region. Including a range of depth will lead to larger variability of the resulting ground motions. That is, it will allow for infrequent, but severe earthquakes with shallow depths.

Maximum Magnitude for Zones
The CES report suggests that a re-evaluation of the maximum magnitude for zones, M_{cutoff}, is needed. For most hazard studies that I have conducted or reviewed, a change in the M_{cutoff} value of less than 0.5 units does not lead to much difference in the computed hazard, but the use of magnitude weighting factors, discussed later in section 2.4, may make the hazard more sensitive to the M_{cutoff} value. I don't have experience with this.

I think that the use of M_{cutoff} =7.2 is reasonable but the earthquake science field is clearly moving toward allowing for larger magnitude earthquakes to occur. Before a large effort is made on this topic, I suggest that a sensitivity study be conducted to evaluate the impacts of the M_{cutoff} value on the computed hazard, both with and without magnitude weighting factors.

Faults Identified from the Canterbury Earthquake Sequence
The CES report proposes to add the faults indentified from the Canterbury sequence to the source model. Clearly, these faults should be added, but as noted in the CES report, using typical time-dependent models will cause these faults to have a very low probability of rupturing in a large earthquake in the next 50 years, so the addition of these faults will have a small impact on the NSHM.

2.2 Need for Changes to the Ground Motion Models

GMPEs used in NSHM
The NSHM is based on one ground motion prediction equation (GMPE): the McVerry et al (2006) model. Using a single GMPE is not standard practice. The ground motion model is often one of the largest sources of uncertainty in seismic hazard studies and the

standard is to use a suite of GMPE that are considered to be applicable to the region.

In my opinion, the NSHM ground motion model should be the changed to include additional GMPEs considered applicable to New Zealand. This could be achieved either by using global GMPEs from other regions or by applying epistemic uncertainty to the McVerry et al. (2006) GMPE to create alternative versions of the McVerry et al. GMPE. For example, alternative constant factors could be added to the McVerry et al. model to create a suite of models.

Adding additional epistemic uncertainty to the median GMPE leads to the question of how much uncertainty should be added. The basic concept is that the epistemic uncertainty in the ground motion models for New Zealand should be at least as large as the epistemic uncertainty for regions with larger data sets such as California. With this concept, the epistemic uncertainty found for California based on the NGA GMPEs, for example, can be used as a lower bound of the uncertainty to be applied to New Zealand. Using the NGA models, there are two parts of the uncertainty: the range in the median ground motions for a given earthquake/site pair and the uncertainty at short distances due to sparse data in this range. A model of he uncertainty of the GMPEs based on the NGA data base is described in BCHydro (2011, appendix 3). A simpler approach is to use the range of used by the U.S. Geological Survey for crustal events (Petersen et al. 2008).

Vertical Component

As seen in the ground motions from the 22-Feb earthquake, the V/H ratio of 0.7 that is current used in the New Zealand building code to scale the horizontal spectrum to estimate a vertical spectrum is not applicable for short spectral periods for sites at short distances. The model of Bozorgnia and Campbell (2004) provides V/H ratios for code-based spectra that could be adapted to the New Zealand code.

2.3 Lower limit for Z factor

One way to account for unknown faults with low activity rates that may not be apparent in the observed seismicity or in the geology is to set a lower limit on the Z factor. The lower limit Z factor used in the NSHM is 0.13 (CES report, page 54)

The report indicates that the lower limit is based on a magnitude 6.5 earthquake at a distance of 20 km with the 84th percentile ground motion. If this was the basis for the lower limit, it would be a high value compared to US practice; however, the minimum Z factor of 0.13 is not consistent with the 84th percentile motion from a magnitude 6.5 earthquake at a distance of 20 km. The median and 84th percentile spectra for a M6.5 strike-slip earthquake at a distance of 20 km for a shallow soil site (McVerry et al. site class C) are shown in Table 1.

The Z factor is one half of the spectral acceleration (in g) at T=0.5 sec. Based on Table 1, it appears that the median ground motion, and not the 84th percentile, was used to derive the lower limit on the Z factor. Furthermore, it appears that the lower limit is based on the average horizontal component, not the larger component that is the basis for the NSMP.

Table 1. Evaluation of the lower limit of Z factors for M=6.5, R=20 km, site class C (shallow soil)

	Mech	Sa (T=0.5 sec)	Z Factor
Median, Larger Horiz	SS	0.34g	0.17
84th percentile, Larger Horiz	SS	0.57g	0.28
Median, Ave Horiz	SS	0.27g	0.13
Median, Larger Horiz	RV	0.38g	0.19

The use of the median ground motion from a M6.5 earthquake at 20 km distance for the lower limit is consistent with international practice and I think that it is appropriate. There is a question about the component (average horizontal versus larger horizontal) and the mechanism (strike-slip versus reverse). To be consistent with the NSMP, I think that the larger horizontal component should be used. For the mechanism, the average of the Z factors for the SS and RV mechanisms seems reasonable. That would lead to a lower limit Z factor of 0.18.

The description of the lower limit in the CES report which refers to the use of 84th percentile should be changed to avoid confusion about the level of conservatism in the lower limit.

If there is a desire to have the building code to capture the ground motions from a greater percentage of earthquakes on unknown faults that may be close to cities, then one option would be to reduce the distance used for the lower limit. For example, the distance could be reduced from 20 km to 10 km. This would increase the lower limit on the Z factor to about 0.28. Such a high lower limit would be much more conservative than international practice and may not be economically feasible, but that is the issue that must be addressed. The design values can be increased to cover rare events, but there is a cost associated with the increased safety. This issue is discussed further in Section 2.5.

2.4 Magnitude Weighting Factors

As described in the CES report Section 4.1 (page 35) and in Appendix 5, the NSHM applies magnitude weighting factors as part of the hazard calculation. The use of magnitude weighting factors is not standard in seismic hazard analysis for buildings. I have some concerns about this approach which are described below.

The magnitude weighting factors are intended to account for the difference in the seismic demand on structures for a given response spectral acceleration from a moderate magnitude earthquake compared to the seismic demand from the same spectral acceleration from a large magnitude earthquake. For example, a ground motion with a peak acceleration of 0.7g from a magnitude 5 earthquake may not be as damaging as a ground motion from a magnitude 7 earthquake with the same peak acceleration. The

CES report suggests that this difference is due to shorter duration of shaking for the smaller magnitude earthquakes.

The magnitude weighting factors used as based on studies of the effect of duration on the liquefaction of soils. The application of factors developed for liquefaction to structural response is a major stretch as there is no reason to expect duration effects of structural response to be similar to duration effects for liquefaction of soils.

The technical basis for using the magnitude weighting factors given in the CES report is a study by Kennedy et al. (1984). The Kennedy et al. study was based on results from structural response using 11 recorded earthquake ground motions from earthquakes that ranged from Ms=4.3 to 7.7 and covering distances from 1 to 40 km. Both duration and frequency content can change due to earthquake magnitude. Kennedy et al. found if the strength of the ground motion was characterized by the peak acceleration, then using the magnitude scaling factors helped to explain the differences in the structural response for earthquakes with different magnitudes but the same peak acceleration; however, they note that the difference in frequency content (spectral shape) was more important than the duration for their small data set. In my opinion, the agreement between the magnitude factors used for liquefaction and the influence of magnitude on structural response may be fortuitous from the small (11) number of time histories used.

Ignoring the above concerns and allowing that the liquefaction based magnitude factors are applicable to structural response, I still have concerns about the application in the NSHM.

If the ground motions for the NSHM were based on peak acceleration, then application of magnitude weighting factors would be appropriate; however, the NSHM uses the spectral acceleration at a period of 0.5 seconds, not the peak acceleration. Using a longer spectral period already accounts for the differences in the strength of shaking from small and large magnitudes. For example, Figure 2 shows the spectra using the McVerry et al. model for magnitudes 5 to 7.5 for site class C (shallow soil). For this example, for each magnitude, the distance was adjusted to give a peak acceleration of 0.34g. As shown in this figure, for the same peak acceleration, there is a large range in the longer period spectral values. In Figure 3, the magnitude weighting factors used in the NSHM are compared to the scaling of the spectral acceleration for T=0.5 sec based on spectra shown in Figure 2. The scaling of the spectral content is similar to the scaling for the magnitude weighting factors.

Based on this comparison, it looks like two different methods for accounting for the difference in the damage characteristics of ground motion were used: the magnitude weighting for PGA and the spectral shape differences at T=0.5 sec. It looks to me like the magnitude effects are being double counted here. If the key feature of the ground motion for predicting structural response (other than the spectral level) is spectral shape and not duration, it appears that the use of magnitude weighting factors is double counting the magnitude dependence of the spectral shape.

I understand that the magnitude scaling is only applied to periods between 0.0 and 0.5 sec. For period longer than 0.5 sec, no magnitude scaling is applied. But what is done for T=0.5 (the dividing point between these two ranges) which is the spectral period used for the NSHM?

Finally, the use of magnitude weighting factors to reduce the impact of the moderate magnitude earthquakes does not seem to be consistent with the observed damage from the February 22 Christchurch earthquake.

I may be missing something here in terms of how the New Zealand building code works, but in my opinion, the use of magnitude weighting factors as part of the hazard analysis used to derive the Z factors should be reconsidered with a focus on the issue of the magnitude dependence of the spectral shape already included in the T=0.5 sec spectral acceleration. Because seismic building codes have many different parts that need to fit together, any changes to the hazard calculation needs to be considered taking the other parts of the building code into account.

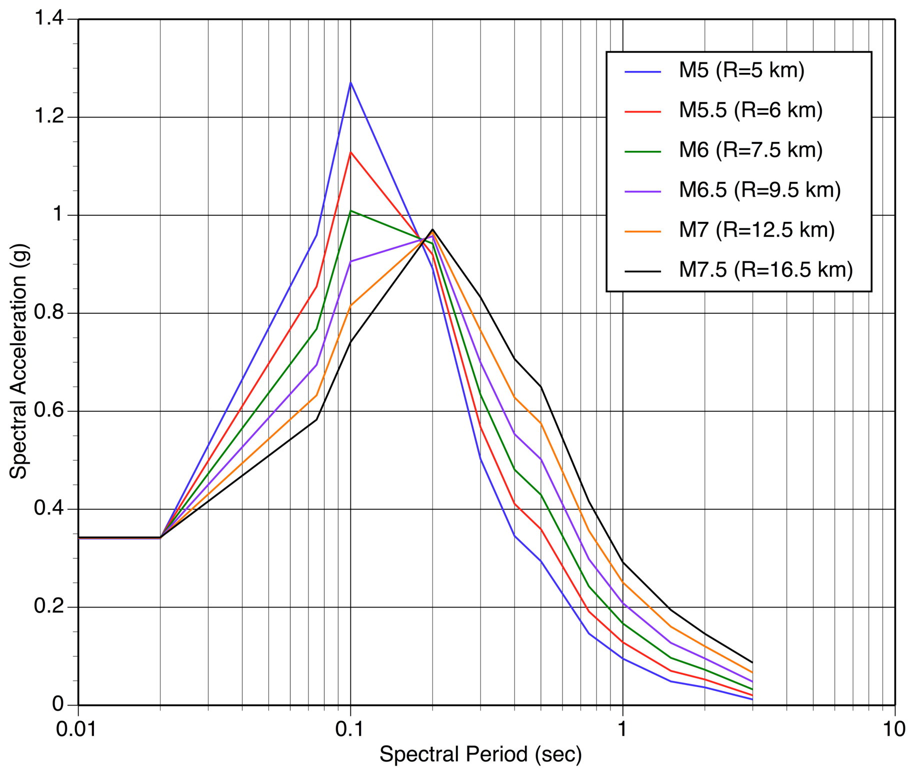

Figure 2. Comparison of the spectral shapes (from McVerry et al. class C) for M5 to 7.5 with the same peak acceleration of 0.34g.

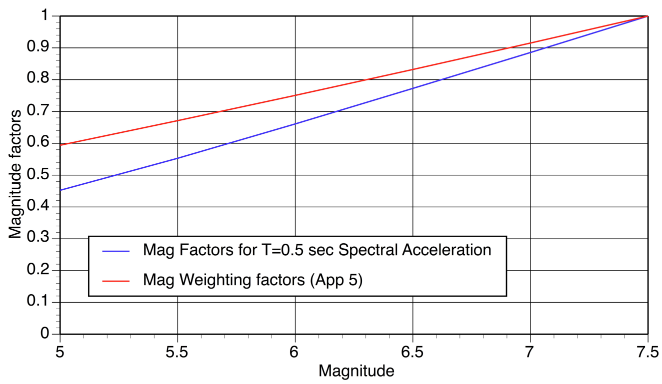

Figure 3. Comparison of the scaling based on the magnitude weighting factors and the scaling based on the spectral shape at T=0.5 sec.

2.5 Probability Levels for Z factors

In earthquake engineering, we do not design structures for the worst-case ground motion because the costs would be very high and the ground motion is too rare to justify the costs. Because we use a ground motion lower than the worst case, there is always residual risk that ground motions larger than the design basis will occur and collapse a structure.

One key issue for building codes is the selection of the acceptable risk level and the probability level of the ground motion required to achieve the acceptable risk level. The CES report provides some information on the risk goals for the New Zealand building code. The risk goals given on page 55 of the CES report show that the risk of collapse should be in the range of 1E-4/yr to 1E-6/yr. This is a very low risk level. For example, the collapse risk goal reported for the US building code is 2E-4/yr.

The report also gives the annual fatality risk goal of 1E-6/yr. I am not sure what this means (is it the probability of one fatality in a given structure?) Again, this seems like a very low value. It is not clear how this risk goal is being achieved. I am not familiar with how these values were developed for the New Zealand building code, but I am skeptical that this risk goal is being achieved.

The risk goals are an important context for the evaluation of what should be done following the Canterbury earthquakes. The central issue for a revision to the New Zealand building code in light of the damage from the Christchurch earthquakes is how safe should New Zealanders be from earthquakes and what is the cost for added safety? The 22-Feb Christchurch earthquake was a strong earthquake located very close to a city. As discussed above, the lower limit of the Z-factors could be increased to cover the ground motions from a future Christchurch type earthquake on an unknown fault close to a city, but there is probably high economic costs to achieve such a high level of safety.

One approach for dealing with public safety from earthquake risk is to compare the earthquake risks to other risks faced by the population. For example, the goal could be that the earthquake risk similar to the risks from other natural disasters or it could be that the earthquake risk is much lower than this risk from other risks faced in daily life.

In addition to the public safety issue, there is an issue of economic impacts on the county. The economic risk can be addressed by improving the strengths of structures (mitigating the risk) or by purchasing insurance for the risk. Both approaches should be considered in a evaluation of need for changes to the building code.

3. Should there be a change in the models and methods used to develop the NSHM in the Christchurch region to account for the increased short-term hazard due to the ongoing earthquake sequence?

3.1 Source Characterization

Accounting for Aftershocks & increased hazard

In the short term, the hazard in the Canterbury region is clearly increased due to potential aftershocks and triggered events from the ongoing Canterbury earthquake sequence, but the hazard will change with time as the aftershocks die down. The key issue is how to address this time varying hazard.

The proposed approach addresses the increased hazard by including the hazard from aftershocks over the next 50 years. The proposed model for the occurrence of the aftershocks is reasonable. There is some conservatism in the use of the STEP model in the first year and then averaging all three models for the remaining years.

The impact of the aftershocks on the hazard calculation is difficult to follow. It would have been a great help to have a plot of the hazard with and without aftershocks.

For the benefit of the general audience, it is worth mentioning that the average size of earthquakes during an aftershock sequence does not change. Through time, the rate of occurrence of aftershocks decreases exponentially, but the relative number of small magnitudes to large magnitudes remains the same. This is important because a large magnitude aftershock can occur late in the aftershock sequence (years after the mainshock). This affects the evaluation of how to treat the increased hazard due to the ongoing aftershock sequence.

There are a couple of approaches that could be used to address the increased hazard. The easiest to apply is the approach recommended in the CES report in which the Z-factors are developed based on the hazard in the next 50 years, including the effect of aftershocks. One issue with this approach is that in a few years, the hazard for the following 50 years will be lower. Should the Z-factors be reduced with time as the aftershock sequence decays or maintained at their increased level?

Alternatively, there could be Z-factors developed for construction in the short term (say the next 1-2 years) with lower factors developed for construction that started later. This has an advantage of allowing for reduced seismic demand for later construction, but it may be too complicated for code applications.

3.2 Ground Motion Models

Higher stress-drops

The CES report concluded that the stress-drops for the Canterbury earthquakes were about 150 bars as compared to a reference stress-drop of 100 bars. They propose to account for this difference based on stress-drop scaling from the Atkinson & Boore (2006) model. The increase in stress-drop seems to be the focus of the ground motion revisions in the Canterbury region.

As noted earlier, I am not convinced that the stress-drops for the Canterbury earthquakes are above average. Before a correction for higher stress-drops in Canterbury region is applied (150 bars / 100 bars), additional evaluations of the other earthquakes should be make to check that the average stress-drop for earthquakes in the Canterbury sequence is higher than average and not just for the Feb 22 earthquake.

Stress-drops Scaling Model

The proposed method for scaling of the ground motion due to increased stress-drop is described in the Z-factor report and is based on the ground motion scaling with stress-drop scaling given in the Atkinson and Boore (2006) model. The equation for stress-drop effects for spectral acceleration (page 10 from the Z-factor report) has a typo:

$$\ln SA(SD) = \ln SA(SD_{ref}) + 2.3 \times \left(\ln\left(\frac{SD}{SD_{ref}}\right) \div \ln(2) \right) + \min\left(0.2, 0.05 + 0.15\left(\max(M-4,0) \div 1.5\right)\right)$$

The "min" term should be multiplied by previous term, not added to it. The correct equation is

$$\ln SA(SD) = \ln SA(SD_{ref}) + 2.3 \times \left(\ln\left(\frac{SD}{SD_{ref}}\right) \div \ln(2) \right) \times \min\left(0.2, 0.05 + 0.15\left(\max(M-4,0) \div 1.5\right)\right)$$

The effect of the stress-drop scaling shown in Figure 3.11 of the CES report has the correct scaling, so it appears that this error was only in the report and not in the implementation of the model, but this should be confirmed.

Site Effects

The CES report did not include use of site-specific site effects based on the recordings from the Canterbury earthquakes. It seems to me that this is missing an opportunity to make improvements to the model. I understand that this must still fit into the building code approach. One option would be to develop Canterbury-specific site factors for the building code. If that was too complicated, the Z-factors could be adjusted such that the scaled spectral shapes capture the site-specific amplification for this regions seen in the ground motions for the Canterbury earthquakes.

The CES report does say that the amplified ground motion for site class D is similar to the spectrum based on the building code (Figure 4.4). I found this figure to be confusing. For example, if the Z-factors are based on the spectral value at T=0.5 sec, then why do the code value and the uniform hazard spectrum (UHS) not agree at T=0.5 sec? Also, the peak of the spectrum is severely truncated. Because this UHS was computed applying magnitude weighting factors at short periods and also truncating the M5.0-M5.5 earthquakes, the UHS without these reductions would be much higher at short periods.

If most of the structures in Christchurch are just a few stories, then I would expect more concern with capturing the short period part of the spectrum that may be near the natural periods of these buildings. Again, I may be missing something in how the New Zealand building code works, but I suggest that the short period part of the spectrum, without the magnitude weighting and with the M5.0-M5.5 events be evaluated to check that the short period part of the spectrum is adequate.

3.3 Lower magnitude Limit

In the revisions to the seismic source model for the Canterbury region, the lower limit of the magnitude was increased from 5.0 to 5.5. The basis for this change was "engineering advice that structures satisfying modern code requirements performed well in all but the larger events in Christchurch" and because this change also "offset the very high rate of small-to-moderate magnitude earthquakes, as it was felt that the combination of the dominance of M5 events with their relatively short duration was over-estimating the hazard in terms of its effect on structural performance" (CES report, page 36).

The issue here is not if typical M5 earthquakes would cause damage, but rather if unusually strong M5 earthquakes would cause damage. The small sample of M5 earthquakes in the Canterbury sequence is not large enough to determine that all M50-M5.5 are not damaging. Furthermore, because the Z factors are based on the T=0.5 sec spectral acceleration, the method used already screens out earthquakes that have only large high frequency spectral accelerations and don't have large T=0.5 sec spectral accelerations.

Increasing the lower limit to M5.5 causes an inconsistency with standard practice. There should be very good reasons for doing this. I suggest that the decision to increase the lower magnitude from 5.0 to 5.5 be re-evaluated. If there is no systematic difference in the stress-drop and the aftershock scaling effects on the ground motion are included, then there may not be such a large impact of the M5.0-M5.5 earthquakes in the hazard in the Christchurch region.

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