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The New Zealand National Seismic Hazard Model: Rethinking PSHA

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ABSTRACT: We are currently revising the New Zealand National Seismic Hazard Model. In this revision we are exploring some of the fundamental assumptions of the model and investigating how uncertainties in earthquake source and ground motion estimation propagate through to the end uses of the model. Uncertainties related to the source modelling that come from a paucity of data and from different methods that can be used to model the seismic sources are currently not fully quantified in the way we model seismic hazard. Additionally, seismic sources are generally assumed to be a stationary Poisson process and earthquake clustering is ignored. Including these uncertainties in the way risk is modelled based on the outputs of the National Seismic Hazard Model will likely lead to more robust estimates of risk for use by industry and in the development of design standards.

1 INTRODUCTION

1.1 Probabilistic Seismic Hazard Analysis in New Zealand

New Zealand seismic hazard modelling has relied on probabilistic seismic hazard analysis (PSHA) since the 1980s. Beginning with the use of crude regional zones, the modelling has become progressively more detailed and precise (Stirling et. al.,1998, 2002) with the use of active faults, gridded smoothed seismicity, and ground motion prediction equations (GMPE; e.g., McVerry, et. al., 2006) developed for New Zealand. The most recent revision (Stirling, et. al., 2012) contains approximately 550 faults (with time-dependence included in some cases) which control the hazard over much of the country. We are currently revising the National Seismic Hazard Model (NSHM) and are in the process of exploring many of the fundamental assumptions that have gone into the model development, while placing an emphasis on understanding the inherent uncertainties and developing a model that best meets the needs of potential users.

The original ideas of PSHA were introduced by Cornell (1968). In this algorithmic approach to model creation, disparate data sets and concepts were coupled to estimate the level of ground shaking that could be expected in a region over some time frame, such as 50-years. In New Zealand the NSHM (Stirling et al, 2012) is developed from the same building blocks as are used in many other countries. The model consists of two fundamental components: 1) the earthquake source model, which describes the rate of occurrence of earthquakes at a comprehensive set of earthquake sources defined by magnitude and location; and 2) the ground-motion prediction model, which predicts the level of ground-shaking expected for any given earthquake source.

To break things down further, the earthquake source model consists of two independent model-components. The dominant component is the Fault Model. This consists of approximately 550 faults, with associated expected magnitudes, that have been identified and mapped around New Zealand. The data that control the expected earthquakes on the faults come either from paleoseismic data, where past ruptures of the fault have been identified in such things as the stratigraphic record or lacustrine deposits (e.g., Clark et al, 2013), or from regressions between mapped fault length and earthquake magnitude (Stirling, et al, 2013). The fault model contains earthquakes of magnitude 6.5 and greater, and the contributions from these faults dominate the estimated hazard for many locations. However, we know that geologists have not been able to identify every hazardous fault around the country. Therefore, the fault model is not complete (Nicol, et al, 2014) and for this reason a background seismicity model is also developed. The background seismicity model is developed from the GeoNet earthquake catalogue, which contains the magnitudes and locations of all recorded earthquakes in New Zealand since 1840. To create the background model, the locations of past earthquakes are smoothed in space. Future background earthquakes are expected to occur at a similar rate to these past smoothed earthquakes. In other words, the future is expected to be like the past, with some smoothing to account for uncertainty in the data and variability in the process. Finally, the fault model and background model are coupled together to produce a complete distribution of earthquakes greater than magnitude 5.0.

In New Zealand, as with most current PSHA around the world, the ground-motion is estimated using empirical ground-motion prediction equations. These are derived from regressions between observed levels of shaking and earthquake source data. The New Zealand NSHM has been traditionally based on the McVerry (2006) GMPE. However, in recent work for the development of a time-dependent hazard model for the Canterbury region, we have used both the McVerry (2006) and the Bradley (2010) GMPEs. Due to a paucity of observed shaking data, particularly for strong shaking near to sources of large earthquakes, there is substantial uncertainty involved in developing GMPEs; this applies both to the result of a single GMPE, where the residual standard deviation and the standard errors of coefficients can be large, and across different GMPEs, where the results can be very different. In other words, different modellers using the same dataset may produce very different, but equally plausible, GMPEs. For this reason, multiple GMPEs are often used to account for the epistemic (modeling) uncertainty. It is important to capture this uncertainty; this topic has been a focus of the PSHA community for many years. Traditionally this uncertainty is incorporated through the use of a logic tree in which each GMPE is assigned a weight to be used in a combined model (e.g., Marzocchi, et al, 2015), with recent approaches suggesting more rigorous statistical techniques (e.g., Atkinson et al, 2014; Chiou, 2015; Kuehn & Abrahamson, 2015).

The final result of the NSHM is typically expressed as the ground-motion with some probability of exceedance in the next 50 years. For example, the Z-factor map of NZS1170.5:2004 (Standards New Zealand, 2004) is derived from the Peak Ground Acceleration (PGA) with a 10% probability of exceedance in 50-years. This value is often expressed as being the 475 year return period PGA; such a statement implicitly assumes that earthquake rates are stationary in time. This assumption is incompatible with any model including time-dependence, such as the New Zealand and Canterbury specific models (Stirling et al, 2012; Gerstenberger et al, 2014). A time-dependent model applies only to the next 50-years (or whatever time period it is developed for); it is incorrect to extrapolate it to some statement about return period. In other words, a 10%-in-50-years result in a model that contains non-stationarity (e.g., some form of time-dependence) expresses the probability for some level of ground motion to occur in the next 50-years and does not imply anything about longer time intervals.

1.1 *Uncertainty in PSHA*

Because of the large identified uncertainties in predicting ground-motions, the seismic hazard community has focused on understanding the uncertainties related to GMPE. As a result, the techniques to quantify these uncertainties have been steadily improving. In contrast, there has not been much focus on understanding the uncertainties related to earthquake source models, such as we use in New Zealand, for which a stationary Poisson process is generally assumed. Because the uncertainties related to a Poisson process are small when compared to the known uncertainties of GMPEs, this Poisson uncertainty is typically ignored, as it is in the New Zealand NSHM (Stirling et al, 2012). However, it has long been known that earthquakes are clustered and are not adequately described by a stationary Poisson process (e.g., Kagan, 2010, 2014); yet, in the framework of PSHA, such clustering is not easy to incorporate and therefore the uncertainty resulting from this assumption has not been quantified.

In Section 2 we outline several sources of uncertainty and discuss the implications for the use of the NSHM.

1.2 *Why does the source uncertainty matter?*

Before we discuss the uncertainty, it is important to understand what the intended use of the NSHM is. Each country with a NSHM has particular stakeholders who use the model and whose needs it should be designed to address. In New Zealand there are two broad categories of use for the NSHM: 1) design standards and application: including building design standards, NZS1170.5 (Standards New Zealand, 2004) and related design work; and 2) risk assessment: within both the government and the private sector, e.g., civil defence, the insurance and reinsurance industries. In both categories, risk-based application of the outputs of the NSHM is required.

Because risk assessments involve multiplying the hazard by the consequences of the event, risk assessment results are sensitive to lower probability events. For example, while the hazard estimated in the NSHM for the Auckland region of New Zealand may be very low when compared to more seismically active parts of the country, the consequences of a large event in the region may be significant when compared to an event elsewhere. It follows that, if the uncertainties in the hazard information in Auckland are higher than in other parts of the country, the risk may be sensitive to those uncertainties and therefore it may be important for this to be reflected in the hazard and its application.

2 SOURCE MODEL UNCERTAINTIES

In the development of a revised version of the New Zealand NSHM we are attempting to improve the quantification of uncertainty in the source model and better understand the downstream implications of the uses of the output of the model. As a demonstration of the uncertainty in the source model a simple example is illustrative. The Collaboratory for the Study of Earthquake Predictability (CSEP; Zechar et al., 2010) has developed a computational framework to do rigorous statistical evaluation of earthquake forecasts. If we were to use such a framework to evaluate a model that creates an earthquake rate forecast for all of New Zealand, but does not attempt to forecast the locations of the events, the model is likely to demonstrate reasonable consistency with future earthquake occurrences, but would not be very useful. If we attempt to forecast at a spatial resolution of approximately 5km, as CSEP is doing, the models will be more easily shown to be inconsistent with future earthquake occurrences; this is roughly the same spatial resolution as is used by NZS1170.5:2004. This raises three questions: 1) what are the primary sources of uncertainty that contribute to reduction in performance as spatial resolution increases; 2) can we quantify or reduce these uncertainties; and 3) what is the optimal resolution for applications such as NZS1170.5:2004?

In the following sections we discuss three of the main contributing uncertainties that we have identified.

2.1 *Fault Model Incompleteness*

A recent investigation by Nicol et al (2014) examined the completeness of the fault model used in the New Zealand NSHM by asking a simple hypothetical question. If, when modern seismological records began in 1840, geologists had today's methods and understanding: how many of the large earthquakes since 1840 would have occurred on faults that would have been known about ahead of time? The answer, as judged by the paleoseismologists, was roughly one-half or fewer of the events would have occurred on known faults (Nicol et al., 2014). If we then examine the NSHM for comparison, it forecasts approximately 80-90% of the large events to occur on faults we currently have mapped. As indicated, the background model is designed to account for earthquakes on faults that we do not yet know about; however, this result indicates that there is potentially a greater probability for large earthquakes to occur away from known faults than we have so far been able to model and there is larger uncertainty in the location of the largest earthquakes than we have so far been able to quantify.

2.2 *Non-stationarity of Seismicity and Time-dependence*

In response to the Canterbury earthquake sequence, Gerstenberger et al (2014) developed a hybrid time-dependent seismic hazard model for the Canterbury region. This hybrid model uses eight different source models and two different GMPEs in order to capture the uncertainty in the expected earthquake and ground-motion rates in the Canterbury region in the next 50 years. It captures uncertainty in the temporal process across three different time-periods: short-term, medium-term and long-term. It also captures uncertainty in the spatial process by using models that distribute the forecast earthquake rates in space using different methods. The largest identified uncertainty was in the long-term rates, where alternative and equally plausible models forecast earthquake rates that differed by several orders of magnitude (Gerstenberger, et al, 2014; Rhoades, et al, 2013)

These same uncertainties apply for the purposes of the NSHM, where similar long-term models are used for the background model-component. Currently only a single model is used and we are exploring the use of hybrid models (Rhoades, et al, 2014) that will allow us to use geodetic information and other geological information to better constrain the uncertainties in the background rate. Internationally, typically only a single model is used for the background, and the uncertainties are ignored. Recent models for the US (Petersen et al, 2014) and for California (Field, et al, 2014) have incorporated two background models through the use of logic trees. However, the total epistemic uncertainty for the long-term rate remains poorly constrained both in time and in space.

2.3 *Fault source characterization*

In New Zealand, as is also common elsewhere, the majority of the large earthquakes are accounted for by the fault model. This is generally done by allowing only earthquakes of a single magnitude, or a narrow range of magnitudes, to occur on each of the approximately 550 faults in the fault model. All additional, and mostly smaller, earthquakes are assumed to occur away from the major faults and are included in the background model. Modelling earthquakes in this way is a form of the so-called Characteristic Earthquake Model (Schwartz and Coppersmith, 1984).

There is a long-standing debate in the seismological and seismic hazard communities about the range of earthquake magnitudes that a single fault can produce. With a few notable exceptions (e.g., Field et al 2014), the seismic hazard community has generally assumed that faults behave as in the characteristic earthquake model. The alternative end-member model of the debate is a power-law distribution which allows for each fault to rupture in earthquakes of all magnitudes up to some maximum magnitude; this model is commonly referred to as the Gutenberg-Richter model (Gutenberg and Richter, 1954).

The characteristic earthquake assumption has a significant impact on where modelled earthquakes occur in space and time. For example, in the current NSHM, the Alpine Fault is assumed to rupture in a Magnitude 8.1 earthquake and any earthquake of smaller size must occur at some distance from the fault and be accounted for by the background model. While the true magnitude distribution of individual faults is unknown, and is likely to be some combination of characteristic and power-law distributions, we cannot currently model anything other than purely characteristic earthquake distributions on faults in the NSHM without creating too many earthquakes in the model. In a recent study, Stirling et al (2014) assessed the impact of using several non-characteristic magnitude distributions for several major New Zealand fault sources (Wellington Fault, Ohariu Fault, Hope Fault and southern Alpine Fault). In that study, they found that by using a characteristic magnitude with an uncertainty described by a truncated Gaussian distribution, results could be obtained that were not statistically inconsistent with our understanding of long-term behaviour of seismicity patterns and paleoseismic records in New Zealand. In contrast, use of a truncated Gutenberg-Richter distribution required that the slope of the distribution be nearly flat, (i.e. a uniform distribution) in order for it to be consistent with historical seismicity and paleoseismic records.

How best to quantify the uncertainty in fault source characterization and account for it in the NSHM, therefore, remains unclear.

3 DISCUSSION

To better understand the impact of the source model uncertainties, it is instructive to again consider the Auckland example. In the most recent version of the NSHM (Stirling, et al, 2012), the hazard estimated for Auckland is very low. The PGA for shallow soil sites with a 10%-in-50-year probability of exceedance is estimated to be less than 0.1g. The comparative estimate for Wellington is approximately 0.6g. In Auckland this estimate is controlled by the background model and specifically by the rates for earthquake sources with magnitudes from 5.0 to 6.8 at distances of up to 70km. The Wellington estimate is primarily controlled by the fault model and comes from several faults (e.g., Wellington Fault, Ohariu Fault and the Wairarapa Fault), all of which have estimated magnitudes of 7.5 or greater (Stirling et al, 2012).

For the Wellington region the source model is supported by a relatively large amount of data, with more than 2300 earthquakes of magnitude greater than 4 in the GeoNet Catalogue (http://quakesearch.geonet.org.nz) for the region since 1800 and numerous active faults mapped. In contrast, in the Auckland and Northland region only about 100 earthquakes of magnitude greater than 4.0 have been recorded since 1800, including two of magnitude greater than 6.0; both of these were in the 19th century. Only one active fault has been identified and mapped in the Auckland region, and none in the Northland region.

Based on the available data and our knowledge of seismology and tectonics, any reasonable estimate would have the hazard in Auckland much lower than in Wellington. What becomes challenging, however, is to assess the uncertainty on that hazard estimate. With minimal data for the Auckland region, and given the modelling uncertainties outlined in the previous section, the true Auckland hazard, in a PSHA context, is likely to fall within a larger range, albeit much lower than in Wellington. This uncertainty becomes particularly important in risk applications of the NSHM outputs. In order to produce the most robust estimates of risk, this uncertainty needs to be taken into account. While the best estimate of the hazard is produced by using the best models, for risk applications it may be that the most useful results would come from optimizing the spatial resolution of the model and results in risk-space.

Given the uncertainties outlined above, which are by no means exhaustive, and our current ability to model them, are the needs of risk modellers and building design standards best served by using a result that is as precise as a 5km spacing? It may be that a more regionalized application of the model outputs, or a smoothed zone approach, may produce results that are more robust for uses such as the building design standard. NZS1170.5:2004 (Standards New Zealand, 2004) partially accounts for this by using a deterministic earthquake as a minimum bound (i.e., a M6.5 earthquake at a distance of 20km from the site). Is this sufficient? By using a regionalized interpretation of the PSHA outputs, the uncertainties will likely be better reflected in the risk-based results and could produce a more accurate estimate of the risk for Auckland and other regions. Figure 1 shows one possible approach to allowing for source model uncertainties in the interpretation of the hazard. An alternative could be a smoothed zone based approach which models regional zone-based hazard including uncertainties across zones, but does not include sharp boundaries between zones.

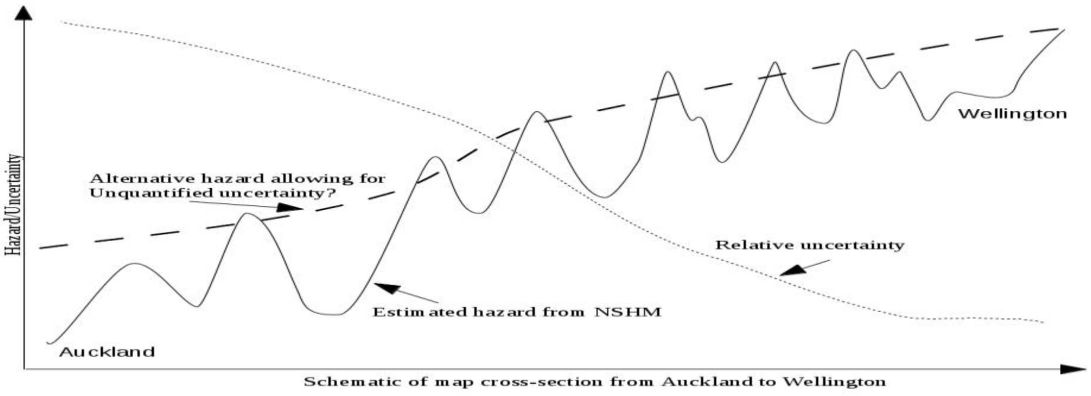

Figure 1: A schematic cross-section of the hazard from Auckland to Wellington. The hazard is not intended to accurately represent the estimate from the NSHM. Also, a schematic of the source model uncertainty over the cross-section is shown with a general increase in uncertainty where we have fewer data. One possible representation of how the uncertainty in the source models could be incorporated for risk modelling is shown.

4 CONCLUSIONS

Our current work in seismic hazard analysis and the NSHM is focused on rethinking some of the fundamental inputs to PSHA. A primary driver is to understand the influence of uncertainties and how they may propagate through to policy. We are investigating what defines a source model, what information should be included, how best to capture epistemic uncertainty, and how we can verify if a new model is indeed an improved model. By better accounting for the uncertainties in the source modelling when the outputs of the NSHM are interpreted, it may be that the needs of stakeholders in the building design and risk management sectors will be better served.

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