ABSTRACT: A team of earthquake geologists, seismologists and engineering seismologists from GNS Science, NIWA, University of Canterbury, and Victoria University of Wellington have collectively produced an update of the 2002 national probabilistic seismic hazard (PSH) model for New Zealand. The new model incorporates over 200 new onshore and offshore fault sources, and utilises newly developed New Zealand-based scaling relationships and methods for the parameterisation of the fault and subduction interface sources. The background seismicity model has also been updated to include new seismicity data, a new seismicity regionalisation, and improved methodology for calculation of the seismicity parameters. Future efforts to improve the model will focus on time-dependent hazard estimation, testing and evaluation of the model, and greater use of GPS data to model potential earthquakes unaccounted for by the fault and background seismicity models.

1 INTRODUCTION

We present a précis of a major update of the national probabilistic seismic hazard (PSH) model for New Zealand (National Seismic Hazard Model, or NSHM). The new NSHM supersedes the earlier NSHM (Stirling et al. 2002), used as the hazard basis for the New Zealand Loadings Standard (Standard New Zealand, 2004) and numerous other end-user applications. The update of the NSHM is largely focussed on the source models, while the choice of ground motion prediction equations and overall PSH methodology used in the earlier NSHM have been preserved. The new NSHM is the product of a large team of earthquake geologists, seismologists and engineering seismologists, reflecting the large team-orientated approach to seismic hazard modelling that has evolved in New Zealand over the last decade.
2 GENERAL APPROACH

The probabilistic seismic hazard analysis (PSHA) methodology of Cornell (1968) forms the generic basis for the NSHM. The methodology includes two steps: (1) using geologic data and the historical earthquake record to define the locations of earthquake sources and the likely magnitudes and frequencies of earthquakes that may be produced by each source; and (2) estimating the ground motions that the sources will produce at a grid of sites that covers the entire country. The computation of ground motions in (2) is achieved with a seismic hazard code that is an improved version of the code developed by Stirling et al. (1998, 2002). Specifically, improvements to the code are in the treatment of distributed seismicity for input to the PSHA, and ground motion prediction equations (GMPEs) for New Zealand (McVerry et al. 2006) are incorporated into the code.

3 SOURCE MODEL

3.1 Fault sources

The fault source model has been substantially updated from that of the earlier NSHM. New onshore geological mapping and interpretation, combined with a substantial contribution of offshore fault sources, and major revamp of the Hikurangi (Wallace et al. 2009) and Fiordland subduction zones has resulted in the addition of over 200 new sources, and the revision of many of the existing sources. For simplicity of modelling the large number of fault sources we use a characteristic or maximum magnitude model (e.g. Wesnousky, 1994; Stirling et al. 1996) to estimate the likely magnitude (M\text{max}) and recurrence interval of M\text{max} for each fault source. We therefore assume that earthquakes of smaller magnitudes than the M\text{max} are modelled from the distributed seismicity model, as was the case in the earlier NSHM (Stirling et al. 2002). However, our methods of developing these earthquake parameters have been substantially updated from the earlier approach developed by Stirling et al., (1998) and again applied in Stirling et al. (2002). M\text{max} is calculated from three regressions of moment magnitude (M\text{w}) on fault geometry for plate boundary strike-slip faults (Eqn. 1), and newly developed regression equations for New Zealand earthquakes (Eqns. 2 and 3). The equation of Hanks and Bakun (2002):

\[ M\text{w} = 3.07 + 4/3\log A \]  
(1)

is used for the Alpine Fault, and the equation given in Berryman and Villamor (2004):

\[ M\text{w} = 3.39 + 1.33\log A \]  
(2)

is used for normal faults in volcanic and rift environments (faults in and west of the Havre Trough - Taupo Rift) or inferred shallow normal faults. Lastly, the equation given in Stirling et al. (2008):

\[ M\text{w} = 4.18 + 2/3 \log W + 4/3\log L \]  
(3)

is used for all remaining faults. Eqns. (2) and (3) were developed in unpublished, peer reviewed studies, but were first published in the associated references shown above. Recurrence interval is calculated from:

\[ T = D/SR \]  
(4)

in which T is recurrence interval in years, D is single event displacement (mm), and SR is slip rate (mm/yr). Displacement is calculated from seismic moment M\text{e} by way of the equation of Aki and Richards (1980):

\[ M\text{e} = uLWD \]  
(5)
\( u \) is rigidity modulus (assumed to be \( 3 \times 10^{11} \text{ dyne/cm}^2 \)), \( L \) is fault length in cm, \( W \) is fault width in cm, and \( D \) is single event displacement in cm. \( M_o \) is calculated from \( M_w \) by way of the equation of Hanks and Kanamori (1979):

\[
\log M_o = 16.05 + 1.5 M_w
\]  

(6)

The calculated values of \( D \) and \( T \) were compared to those derived from paleoearthquake studies. If they differed significantly, the fault length (\( L \)) was adjusted by shortening at segment boundaries, or lengthening by combining contiguous surface traces, until the mean calculated values overlapped the paleoearthquake values. We use the mean or preferred parameters as our input to the NSHM. This is a similar approach to that used in previous versions of the NSHM (Stirling et al. 1998; 2002)

A total of 14 fault domains are recognised in New Zealand, and these are used to divide the large fault source model according to regions of similar characteristics (tectonic class and fault slip type).

3.2 Distributed seismicity sources

In addition to estimating the locations, magnitudes and frequencies of large (\( M_w \geq 8 \)) to great (\( M_w > 8 \)) earthquakes on the crustal faults and subduction zones, we also allow for the occurrence of moderate-to-large earthquakes (\( M_w \geq 5 \)) up to the maximum magnitude assumed for the region) to occur on unmapped or unknown faults. We refer to this as the distributed seismicity source model. While our overall approach is similar to that used in the earlier NSHM, the input data and several important steps in the methodology have been altered. The regionalization (zonation) scheme used in the earlier NSHM has been substantially updated to represent the current understanding of the distribution of seismicity and tectonics in the country. The \( b \)-value of the Gutenberg-Richter distribution is calculated on a regional basis (as for the earlier NSHM), but using the maximum-likelihood method of Aki (1965) and earthquake data from 1964 to June 2009 (the earlier NSHM used data to the end of 1997). The method used in the older model was that of Weichert (1980), which allows for combining multiple time periods with varying completeness levels. To ensure that estimates of the \( b \)-value are based on a sufficient number of earthquakes, 16 initial zones are combined into five zones of similar slip type. This allows for larger data samples than if the zones are used individually as was done in the earlier NSHM. Subcrustal zones are also defined to encompass the dipping slabs of the Hikurangi and Fiordland subduction zones, and normal-slip mechanisms are assigned to these zones (consistent with the dominant slip-type in intraslab seismicity). The \( a \)-values are calculated on a \( 0.1^\circ \times 0.1^\circ \) grid, at five depth levels (10, 30, 50, 70, and 90 km), and \( b \)-values are assigned to the grid cells according to the \( b \)-value of the zone.

In the earlier NSHM, the gridded \( a \)-value was smoothed using a 50km Gaussian smoothing kernel. To optimize the smoothing in the updated model, we compare smoothed seismicity models with three different smoothing kernels: (1) a 50km Gaussian kernel; (2) a Stock and Smith (2002) adaptive Gaussian kernel; and (3) a density based adaptive kernel based on Werner et al (submitted, 2010). The models are retrospectively tested using the information gain per earthquake (Harte and Vere-Jones, 2005) to evaluate the model forecasts. The 50km Gaussian kernel model is found to perform significantly better for the period tested. We therefore use a 50km Gaussian to smooth the \( a \)-value in the updated model. Additionally, we smooth the \( b \)-value across zone borders using the same kernel, as achieved in the earlier NSHM.

The maximum magnitude, \( M_{cutoff} \), assigned to the Gutenberg-Richter magnitude-frequency distribution of each zone and hence each grid cell within each zone is revised by expert panel discussion.
HAZARD ANALYSIS

For a given site, we: (1) calculate the annual frequencies of exceedance for a suite of ground motion levels (i.e. develop a "hazard curve") from the magnitude, recurrence rate, earthquake type, and source-to-site distance of earthquakes predicted from the source model; and (2) estimate the maximum acceleration level that is expected to be exceeded for a range of return periods. For each site, step (1) is repeated for all sources in the source model, and (2) is calculated by summing the results of (1) to give the annual frequencies of exceedance for a suite of acceleration levels and spectral periods at the site due to all sources.

We generally assume a Poisson model of earthquake occurrence for the earthquake sources, in that earthquake probabilities are based on the average time-independent rate of earthquake occurrence on each fault. The three exceptions to Poissonian modelling are the time-dependent probabilities assigned to the Wellington (Wellington-Hutt Valley), Wairarapa and Southern Ohariu Fault sources as a result of the “Its Our Fault” research (Rhoades et al. 2010; Van Dissen et al. 2010). New paleoseismic information on the activity of these faults accumulated over the last several years has resulted in revised estimates for some, or all, of the following: (1) the timing of the most recent rupture, and several previous ruptures; (2) the size of single-event displacements, and; (3) the Holocene dextral slip rate. The conditional probability of rupture of these faults has been evaluated in light of this new information, using a renewal process framework and four recurrence-time distributions (exponential, lognormal, Weibull and inverse Gaussian).

Our calculation of ground motions follows the standard practice of modern PSHA and accounts for the uncertainty in estimates of ground motion from the McVerry et al. (2006) GMPE in the calculation of PSH (up to 3 standard deviations below and above the median). Only magnitudes 5.25 and greater are included in the hazard analysis, consistent with the recommended usage of the McVerry et al. (2006) GMPE.

Because the McVerry et al. (2006) GMPE has separate expressions for crustal earthquakes of different slip type (i.e. strike slip, normal and reverse, and slip types intermediate between these extremes), and those expressions for subduction interface, shallow subduction slab and deep slab earthquakes, we estimate accelerations applicable to the slip type and tectonic environment of each earthquake source. Each fault source is assigned a particular slip type, and the attenuation expression for that slip type is used for the fault in the hazard calculations. In the case of the dipping subduction interface sources we use the interface attenuation expression. For the distributed seismicity (point) sources, the slip type assigned to the point source is the slip type of the enclosing seismotectonic zone. For the deep zones we simply use the shallow and deep slab expressions of the model, based on the observation that essentially all of the deep seismicity in the country is attributed to the dipping Hikurangi and Fiordland slabs. Application of the “volcanic path” attenuation expression for the TVZ, which strongly reduces accelerations with distance, is approximately limited to faults and point sources located in the TVZ.

MAPS AND SPECTRA

Example hazard estimates are shown for the new NSHM in map form, as well as a comparison to an equivalent map from the earlier NSHM, for the case of 475 year PGA hazard (Fig. 1). Response spectra for the new NSHM and earlier NSHM are also shown for the main centres of Auckland, Wellington, Christchurch and Dunedin (Fig. 2). All hazard maps and spectra are based on Class C (Stiff soil) site conditions.

The new PGA map shows a pattern of hazard that is highest from the southwestern South Island to the eastern North Island (the northeast-trending zone of PGA>0.5g). Hazard in this northeast-trending zone reflects the greatest concentration of active fault sources and seismicity in the model. In particular, the Fiordland (southwestern-most South Island), Alpine Fault (western-central South Island) and Hope Fault (northern-central South Island) sources are most responsible for this zone of high hazard in the South Island. The crustal and Hikurangi subduction zone sources show a strong influence on hazard in the eastern North Island. Comparison of the two maps in Figure 1 shows that
the biggest change in hazard is in the southeast of the North Island. The new Hikurangi subduction interface model has obvious impact on the hazard in this area, and highlights the importance of the new subduction interface modelling (Wallace et al. 2009). Otherwise, the pattern of hazard is similar at a national scale, with hazard decreasing away from the axis of the country towards the far northwest and southeast.

Site specific response spectra for Class C (stiff soil) sites are presented for Auckland, Wellington, Christchurch and Dunedin (Fig. 2). On each graph, spectra are shown for 150, 475, 1,000 and 2,500 years, and the spectra are compared to the corresponding spectra from the earlier NSHM. For Auckland, the spectra have reduced significantly from the earlier NSHM, reflecting the influence of the new distributed seismicity model on the hazard estimates. The increased b-value in the new model (about 1.1 for the new model versus less than 1 for the earlier NSHM) is the primary reason for the reduced spectral accelerations in Auckland. For Wellington, the only significant change to the spectra from the earlier NSHM is a slight increase in hazard at spectral periods of 0.4 seconds and greater. This increase in longer period hazard is due to the changes to the Hikurangi subduction interface sources. For Christchurch, hazard has increased for periods less than about 0.6 seconds, reflecting the decreased b-value in the new NSHM (less than 1 in the new NSHM, and close to 1.2 in the older NSHM). Lastly, spectra for the city of Dunedin generally show a slight increase in hazard for the new NSHM. This reflects a slightly decreased b-value in the new NSHM (less than 1 in the new NSHM and greater than 1 in the earlier NSHM).

Figure 1. Maps showing peak ground acceleration expected with a 10% probability of exceedance in 50 years on Class C (stiff soil) sites from the new national seismic hazard model (NSHM; left), and the equivalent map from the earlier NSHM (right).
Figure 2. Spectra from the new NSHM (solid lines) and earlier NSHM (dots), for the cities of Auckland, Wellington, Christchurch and Dunedin.

6 SUMMARY AND CONCLUSIONS

We have produced an update of the NSHM for New Zealand, the first national-scale update since the earlier NSHM of Stirling et al. (2002). The model incorporates a fault source model that has been updated with over 200 new onshore and offshore fault sources, and utilises new New Zealand-based and international scaling relationships for the parameterisation of the faults. The distributed seismicity model has also been updated to include post 1997 seismicity data, a new seismicity regionalisation, and improved methodology for calculation of the seismicity parameters. PSH maps produced from the new model show a similar pattern of hazard to the older maps at the national scale, but some significant reductions and increases in hazard at the regional scale. The national-scale differences between the new NSHM and earlier NSHM appear less than those seen between earlier NSHMs, showing that some degree of stability in the national-scale pattern of hazard estimates has been achieved, at least for return periods of 475 years and greater. While the new NSHM is by no means the final word on seismic hazard in New Zealand, it represents a considerable advance in terms of data quality, quantity, methodology, and evolution of a large multidisciplinary, multi-institutional team-based approach to PSH modelling in this country.

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