Ground Motion-Based Testing of Seismic Hazard Models in New Zealand

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Abstract

We develop a methodology for testing the New Zealand national probabilistic seismic hazard (PSH) model that builds on the groundwork of previous studies. Our fundamental approach is to test the output of the model (ground motion exceedance for a given return period). Our results show that the PSH model is: (1) rejected as underpredicting the historical exceedance rates for specific peak ground acceleration (PGA) levels calculated from the 169 year historical Modified Mercalli Intensity (MMI) record, and; (2) not rejected by similar test criteria obtained directly from instrumental accelerograph data over the past two decades. Establishment of a protocol for formally testing the New Zealand PSH model within a Testing Centre will require resolution of the above results, and consideration of the fact that the tests are generally limited by the available datasets of strong earthquake shaking. The work represents one of the active areas of PSH model testing research being conducted internationally that ranges from short-term seismologically-based testing (testing models for $\leq 10^1$ year time periods) to long-term geomorphologically-based testing (testing models for $\geq 10^3$ year time periods). Arguably the most important end-result of testing and evaluation work in New Zealand will be formal evaluations of future versions of the national PSH model. Such evaluations will become mandatory prior to the PSH model being used in practical end-user applications.

1 Introduction

In the last decade there have been considerable advances in the field of probabilistic seismic hazard analysis (PSHA) and the application of PSHA methodology around the world. Arguably some of the most important applications of PSHA have been in the development of national seismic hazard models (e.g., Frankel et al., 2002; Stirling et al., 2002). The resulting probabilistic seismic hazard (PSH) maps have been the benchmark for numerous applications, most importantly for building codes (e.g., Standards New Zealand, 2005). However, efforts to validate PSH models to date have been largely limited to evaluating individual components of the models, for example, comparing observed to predicted earthquake occurrence distributions in terms of rate and location (e.g. Rhoades et al., 2002; Felzer, 2009).

We here investigate a methodology for testing an entire PSH model, rather than the individual components. The methodology explicitly tests the output of the PSH model, or in other words the hazard estimates for a given return period. The challenge in developing such a test is to constrain the strength and return period of ground motions with data that have not already been used in developing the PSH model. Efforts to develop such a methodology by Dowrick and Cousins (2003) involved using the historical record of Modified Mercalli Intensities (MMI) to generate historical rates of exceedance for ground motion levels at a suite of towns and cities. Stirling and Petersen's (2006) study also used the historical MMI record as a test criterion, and also included the conterminous United States. The historical MMI observations have only been used for assigning magnitudes to some of the older (i.e. preinstrumental) events in the historical seismicity catalogues. The MMI levels assigned to earthquakes over the one-to-two century historical record of New Zealand therefore represent a large dataset that is essentially independent of the PSH model.

Stirling and Petersen (2006) found that on average the hazard estimates from the national seismic hazard models for New Zealand and the western United States significantly exceeded the historically-observed hazard, but that the historical hazard was well in excess of the hazard model in the central and eastern United States. In this study, we substantially revise the New Zealand component of the earlier studies with new data, methods and analyses. An important addition to the research is the instrumental accelerograph record of peak ground acceleration (PGA) as a testing criterion.

2 Data preparation

Our general procedure is to utilise the historical record of MMI-based PGA and instrumental PGA levels experienced at a suite of sites around New Zealand (Fig. 1) to calculate the annual rates of exceedance for those PGA levels, and then compare these historically-based hazard curves to the hazard curves calculated for the sites from the relevant PSH models. The spatially uniform distribution of sites encompasses areas of very high to very low seismotectonic activity and seismic hazard, and also samples the demographic spectrum of sites, from small towns to cities (Fig. 1). The sites are far enough apart that the historical earthquake records for each are assumed to be independent (i.e. individual earthquakes have not shaken more than one site at the same time). Statistical analysis of our comparisons is made on the basis of the sum total of all site data. We therefore make up for the short time period of the historical record at each individual site by combining all site data, and in doing so apply the ergodic assumption (i.e. the distribution of a random variable from a space average of a point in time is the same as for the time average for a point in space) to our analysis. In this context the historical record for all 26 sites collectively represents around 4400 years of observation (169 years multiplied by 26 sites) for MMI data, and just over 400 years for the instrumental PGA data.

For the MMI-based analysis, our starting point is to use the same MMI dataset compiled by Stirling and Petersen (2006). The dataset covers the period 1840-1997 and was taken from Dowrick and Cousins (2003). MMI data for the period 1998-2008, and all PGA data are obtained from Geonet (www.geonet.org.nz). Our attention is limited to MMIs of 6 or greater, and PGA data of 0.1g or greater. The accelerographs have typically been recording for around 20 years, representing a shorter time relative to the one-to-two century duration of the MMI record.

The lack of ground motion prediction equations available to derive hazard curves for MMI in the New Zealand PSH model requires that we first convert the historical MMI levels to the equivalent estimates of PGA to allow direct comparison of historical data to PSH model. The MMI-to-PGA conversion is achieved by way of Gerstenberger et al (in press), and the hazard curves are derived from the Stirling et al. (2002) PSH model. The hazard curves are calculated according to the ground class most relevant to the site (site class definitions from Cousins et al., 1996). The hazard curve calculations incorporate aleatory uncertainty in the ground motion estimates from the attenuation models to the 3-sigma level, consistent with the methodology used to calculate the national maps (Stirling et al., 2002).

3 Comparisons

Graphical comparisons for two of the 26 New Zealand sites are shown in Figure 1, and quantitative comparison of the historical data to the PSH model are shown in Table 1. Table 1a shows for each site a comparison of the rate of exceedance for a MMI-derived PGA of 0.1g (approximately equivalent to MMI=6 using the Gerstenberger et al. relationship) to the equivalent rates predicted from the PSH model. On the right of Table 1a is the comparison of the observed 169 year historical number of exceedances to the predicted 169 year number of exceedances from the PSH model. The statistical significance of the differences between the observed versus predicted number of exceedances from the PSH model is assessed for individual sites, and collectively for all 26 sites (columns labelled P_upper and P_lower in Table 1a). We assume that the expected number of exceedances in 169 years summed across all 26 sites has a Poisson distribution (the distribution used to construct the PSH model) and evaluate whether the summed historical data are indistinguishable from that distribution. We therefore compare the observed exceedance rate with the Poisson distribution calculated using the expected exceedance rate from the PSH model as the mean. If the observation is in the tails of the expected distribution, it may be considered unlikely, and therefore inconsistent with the prediction. A comparison showing the historical exceedance to have a probability of less than 0.025 or greater than 0.975 on the Poisson distribution (P_lower or P_upper on Table 1a) can be rejected with at least 95% confidence. An observation within these bounds is indistinguishable from the PSH model and the model is not rejected. A historical exceedance with a probability of less than 0.025 indicates that the model overpredicts the observation, and an observation with a probability greater than 0.975 indicates that the model underpredicts the observation. These probabilities, and whether or not the model is rejected in each case (N=Not rejected; Y=rejected) are shown at the base of Table 1a. The exercise is repeated for the instrumental PGA data in Table 1b. For the latter comparison, the time period for which the observed and predicted number of exceedances of 0.1g are compared (T yrs in Table 1b) is equal to the number of years of accelerograph operation at each site. In other words the column labelled “Model N (T yrs)” show the predicted number of events from the PSH model for the time period T (T being the time that the accelerograph station has been in operation). These time periods logically vary from site to site given that accelerographs have been installed at different times. For both Tables 1a and 1b we make these comparisons for all cases, regardless of whether there have been any historical exceedances of 0.1g at the individual sites. Sites where no accelerograph stations are available are of course omitted from Table 1b.

We see from Table 1a (“Y” in the bottom row labelled “Total”) that the model is rejected as underpredicting the historical data with > 95% confidence. However, Table 1b shows that the model is clearly not rejected by the historical test criteria. These contrasting results require some evaluation of the methodologies used to construct the historical exceedance rates. This would be an important aspect to address in development of a protocol for formal testing of the New Zealand PSH model. Clearly the instrumentally-based comparison is the most straightforward and transparent analysis, given that no conversions from MMI to PGA are necessary. In contrast, the less certain MMI-based PGAs have the advantage of sampling a much longer time period than the instrumental PGA data. Testing could be carried out with both criteria by weighting of the methods, in which a likely procedure would be to weight the instrumentally-based test more heavily than the MMI-based test.

4 Conclusions

We have developed a testing methodology for the New Zealand national PSH model that builds on the groundwork of Stirling and Petersen (2006) and previous studies. Our fundamental approach is to test the full model, or in other words, the output of the model (ground motion exceedance for a given return period). Our results show that the PSH model is (1) rejected as underpredicting the historical exceedance rates for specific ground motion levels calculated from the 169 year historical MMI record, and (2) not rejected by test criteria obtained directly from instrumental accelerograph data over the last two decades. The results are different to those of earlier, preliminary studies which suggested the PSH model was predicting hazard significantly higher than that of the historical record. Both of our new tests have associated merits that counteract their deficiencies, in that the less certain MMI data cover the complete length of the historical period, and the shorter-duration instrumental dataset comprises actual measures of PGA rather than being inferred from MMI. Establishment of a protocol for formally testing the New Zealand PSH model within a Testing Centre will require resolution of the above results, and consideration of the fact that the tests are generally limited by the available datasets of strong earthquake shaking. Large challenges also confront short term seismologically-based ($\leq 10^1$ year) and long term geomorphologically-based (10^3 year) testing research being conducted in New Zealand and elsewhere. Arguably the most important end-result of testing and evaluation work in New Zealand will be formal evaluations of future versions of the national PSH model. Such evaluations will become mandatory prior to the PSH model being used for practical end-user applications.

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Figure 1 The 26 New Zealand sites examined in this study.

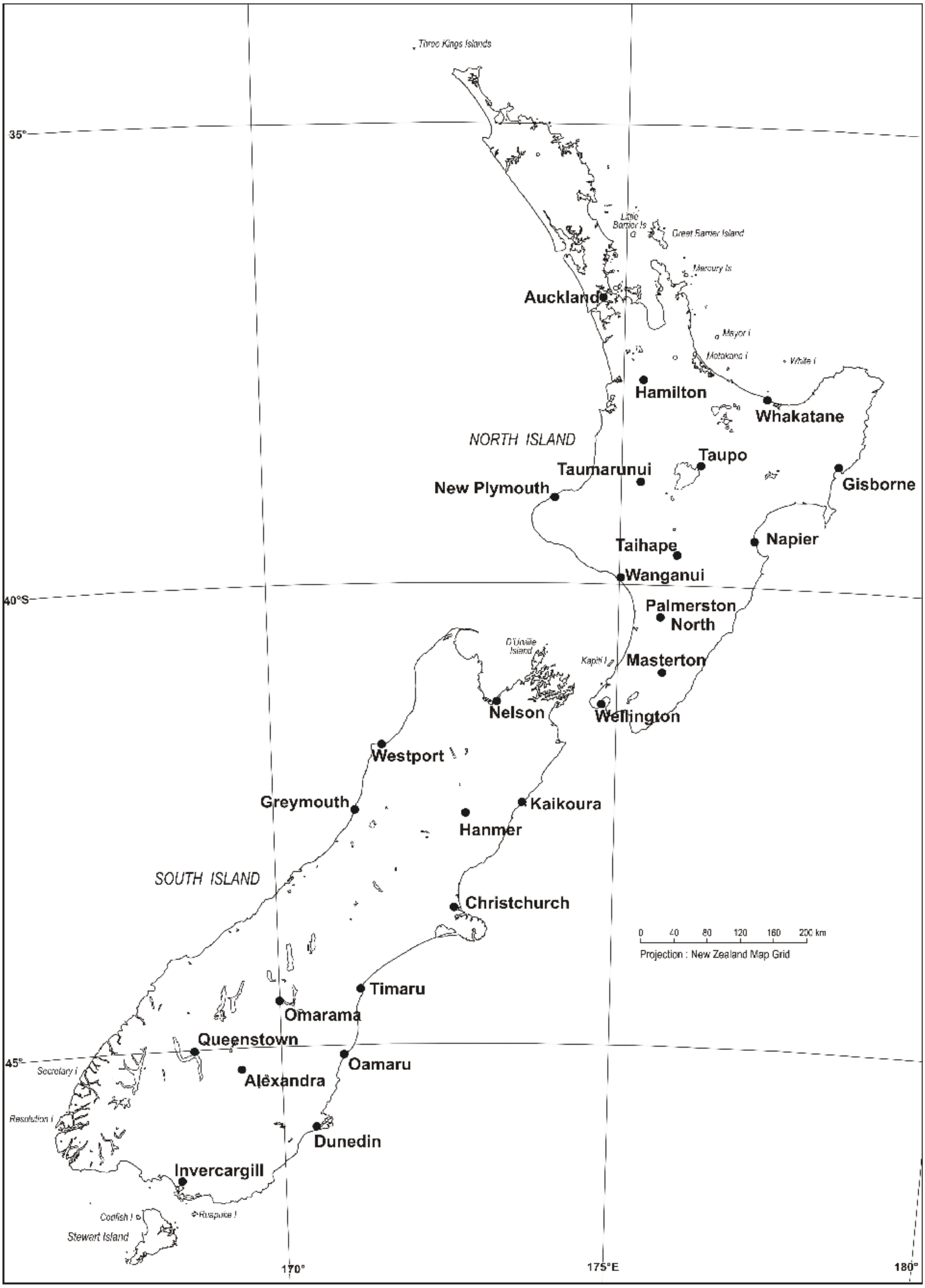
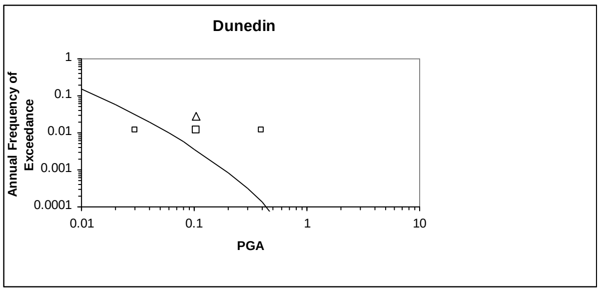


Figure 2. Hazard curve graph showing a comparison of historically-observed hazard to the predicted hazard from the New Zealand PSH model (Stirling et al. 2002) for two of the 26 New Zealand sites. The square symbols show historical rates of exceedance for peak ground acceleration (PGA) levels converted from Modified Mercalli Intensity (MMI) using the Gerstenberger et al. (in press) relationship (large squares for mean, small squares for the large 1-sigma bounds). The triangles show the historical rates of exceedance for PGA obtained directly from instrumental strong motion instruments. The PGA hazard curve derived for the site from the New Zealand PSH model is shown as a solid line, and is calculated in exactly the same way as done by Stirling et al. (2002) and utilised in Standards New Zealand (2005).



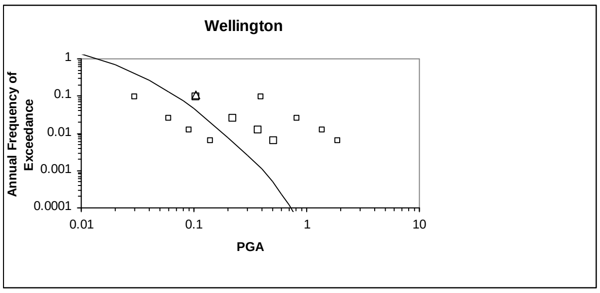


Table 1a. Comparison of the 169 year (1840-2008) historical number of exceedances for PGA ≥0.1g versus the predicted number of exceedances from the New Zealand PSH model at the 26 New Zealand sites. The historical data are PGAs converted from MMI (a). The second Table (b) is an equivalent comparison that uses the more recent instrumental record of PGA.

Site	**Hist orical (N/yr)**	**Model (N/yr)**	**Historical (169yr N)**	**Model (169yr N)**	**P_upper**	**Under Predict** Rejected@>0.975	**P_lower**	**Over Predict** Rejected@<0.025
Auckland	0.0063	0.0019	1	0.3127	0.7315	N	0.96020	N
Alexandra	0.0063	0.0156	1	2.6364	0.0716	N	0.26040	N
Christchurch	0.0372	0.0193	6	3.2617	0.8874	N	0.95150	N
Dunedin	0.0118	0.0036	2	0.6084	0.8753	N	0.97600	N
Gisborne	0.0726	0.0581	12	9.8189	0.7172	N	0.80840	N
Greymouth	0.0512	0.0512	9	8.6528	0.5022	N	0.63300	N
Hamilton	0.0179	0.0179	3	3.0251	0.4176	N	0.64160	N
Hanmer	0.1530	0.0710	26	11.9990	0.9997	Y	0.99990	N
Invercargill	0.0182	0.0054	3	0.9126	0.9351	N	0.98590	N
Kaikoura	0.0559	0.0350	9	5.9150	0.8559	N	0.92180	N
Masterton	0.0773	0.0490	13	8.2810	0.9217	N	0.95670	N
Napier	0.0720	0.0720	12	12.1680	0.4425	N	0.55680	N
Nelson	0.0556	0.0440	9	7.4360	0.6707	N	0.78370	N
Oamaru	0.0000	0.0048	0	0.8112	0.0000	N	0.44430	N
Omarama	0.0059	0.0230	1	3.8870	0.0205	N	0.10020	N
Palm Nth	0.0893	0.0580	15	9.8020	0.9264	N	0.95780	N
New Plym	0.0500	0.0166	8	2.8054	0.9918	Y	0.99750	N
Queenstown	0.0362	0.0380	6	6.4220	0.3805	N	0.53880	N
Taihape	0.0667	0.0590	11	9.9710	0.5867	N	0.70010	N
Taumarunui	0.0127	0.0170	2	2.8730	0.2189	N	0.45220	N
Taupo	0.0430	0.0250	7	4.2250	0.8646	N	0.93430	N
Timaru	0.0000	0.0026	0	0.4394	0.0000	N	0.64440	N
Wanganui	0.1111	0.0440	19	7.4360	0.9997	Y	0.99990	N
Wellington	0.0952	0.0450	16	7.6050	0.9948	Y	0.99770	N
Westport	0.1163	0.0790	20	13.3510	0.9470	N	0.96820	N
Whakatane	0.0556	0.0790	9	13.3510	0.0848	N	0.14390	N
TOTAL			**222**	**158**	**1**	**Y**	**1**	**N**

Table 1b Comparison of the strong motion accelerograph-derived number of exceedances for PGA $\geq$0.1g to the predicted number of exceedances from the New Zealand PSH model at 26 New Zealand sites. The columns labelled "Under Predict" and "Over Predict" show whether or not the model is rejected by the test criteria with >95% confidence (N=Not rejected; Y=rejected). See the text for further explanation.

Site	**Historical T(yrs)**	**Historical N (Tyrs)**	**Model (N/yr)**	**Model N (Tyrs)**	**P_upper**	**Under Predict** Rejected@>0.975	**P_lower**	**Over Predict** Rejected@<0.025
Christchurch	15	0	1.93E-02	0.28950	0	N	0.7486	N
Dunedin	36	1	0.0036	0.1296	0.8781	N	0.9922	N
Gisborne	44	5	0.0581	2.5564	0.883	N	0.9539	N
Greymouth	42	1	0.0512	2.1504	0.1165	N	0.3669	N
Hamilton	25	2	0.0179	0.4475	0.9246	N	0.9891	N
Hanmer	20	3	0.0710	1.42	0.8286	N	0.944	N
Invercargill	15	0	5.40E-03	0.08100	0	N	0.9222	N
Kaikoura	10	0	3.50E-02	0.35000	0	N	0.7047	N
Masterton	20	0	4.90E-02	0.98000	0	N	0.3753	N
Napier	37	5	0.0720	2.664	0.8688	N	0.9464	N
Nelson	15	1	0.0720	1.08	0.3396	N	0.7064	N
Oamaru	18	0	4.80E-03	0.08640	0	N	0.9172	N
Omarama	44	1	0.0225	0.99	0.3716	N	0.7394	N
Palmerston Nth	36	1	5.80E-02	2.08800	0.1239	N	0.3827	N
New Plymouth	27	2	0.0166	0.4482	0.9246	N	0.9891	N
Queenstown	22	4	0.0380	0.836	0.9893	Y	0.9983	N
Taihape	41	2	0.0590	2.419	0.3041	N	0.5645	N
Taumarunui	7	0	1.70E-02	0.11900	0	N	0.8878	N
Taupo	44	1	0.0250	1.1	0.3329	N	0.699	N
Timaru	6	0	2.60E-03	0.01560	0	N	0.9845	N
Wanganui	33	2	0.0440	1.452	0.5747	N	0.8213	N
Wellington	37	4	0.0450	1.665	0.9112	N	0.9723	N
Westport	42	9	0.0790	3.318	0.9928	Y	0.9977	N
Whakatane	15	0	7.90E-02	1.18500	0	N	0.3057	N
TOTAL		**44**		**27.87**	**0.5**	**Y**	**0.67**	**N**