RMS' new model for ruptures on known crustal faults in New Zealand and its implications for risk

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ABSTRACT: The hazard component in RMS' new NZEQ risk model is largely based on the GNS 2010 NZEQ hazard map products. Departures from GNS' model include a different treatment of time-dependence and the introduction of cascading events involving faults or sets of faults previously assumed to only rupture independently. Those developments were necessary because unlike hazard models, risk models include 1) the set-up of financial models which require the modeling of realizations of the order in which events may occur (i.e., the probability density functions are needed, not just the mean hazard rates) and the non-linearity of the exceedance probability (EP) curve for losses relative to the conditional probability density function (PDF) of event occurrence, and 2) the fact that longer (than 475 year) return period losses need to be defined to compute risk metrics for capital requirement calculation.

To address the first point, the methodology by Fitzenz et al 2012 was adapted and used for the Wairarapa 1855-type events, the Wellington-Lower Hutt Valley fault, and the Ohariu fault. It provides the probability density functions for inter-event times resulting from a Bayesian combination of models computed by integrating long-term slip rates, slip per event, and historical and trench data. To address the second point, we adapted the tool developed by UCERF3 within OpenSHA to generate a rupture set using an unsegmented fault model. We selected complex ruptures affecting high exposure areas and will propose a set of frequencies compatible with known slip rates and trench data.

1 CONTEXT

1.1 RMS's context

The last update to our NZEQ risk model was released in 2007. Since then exposure, vulnerability, and the earthquake catalogue have evolved and the community at large learned a lot of lessons from worldwide and New Zealand earthquakes and earthquake sequences. RMS is also moving to a new platform that uses realizations of time series of events, more flexible and modular, in the cloud, faster: this transition prompted us to explore new methods and requires the characterization of timing information instead of frequency of events. Finally, the insurance regulatory environment is becoming more stringent and pushes for better uncertainty quantification and propagation (and traceable consistency between model updates), and the use of the tail of the exceedance probability curve to set capital requirements (as opposed to using a given return period loss). It is thefore crucial to incorporate rare (but physically possible) large loss causing events into the risk model.

1.2 New Zealand context

Stirling et al. (2012) published the 2010 National Seismic Hazard Map (NSHM) for New Zealand. It incorporates new region-specific magnitude-length scaling relationships, updated magnitude-frequency functions resulting from an updated analysis of the earthquake catalog, new maximum magnitude assumptions and a M9 event on the Hikurangi interface (in reaction to the occurrence in 2011 of the (unmodeled) Tohoku event). In addition, for crustal faults with paleoseismological information time-dependent hazard is defined differently from the previous model, and also differently from the standard way the USGS (NSHM) models time-dependent fault behavior. The method uses a combination of hazard rates from 3 time-dependent models derived using Bayesian methods from slip per event, slip rate, and trench data that includes both epistemic and aleatory uncertainties (Van Dissen et al. 2013). The 2010 NSHM includes long return period events only far from exposure (mostly in the South Island, e.g., Hump Ridge, 63240 yr or Old Man, 362150 yr). Berryman et al. (2012) provided 23 dates for large events on the southern Alpine fault, showing that larger datasets are possible to obtain, but raising questions about the lateral extent of the ruptures captured in the trenches (Howarth et al. 2013). Recent and on-going GPS surveys perform detailed monitoring of slow-slip events on the subduction interface, and those raised new questions about the ability of those areas to participate in a large interface earthquake (conditionally unstable). Finally, New Zealand has been through two earthquake sequences: the Canterbury sequence which started in 2011 with the Darfield event (involving previously unmapped faults and severe liquefaction) and the Cook Strait sequence which started in July 2013 (involving previously unmapped faults in known high deformation area with dense fault network).

1.3 Recent advances in the Probabilistic Seismic Hazard Assessment (PSHA) community

UCERF3 (Field et al., 2013) led the way towards an unsegmented view of fault systems, to go beyond what we know happened in the past to a set of those ruptures that do not violate empirical observations and mechanical constraints, and therefore are potential scenarios for the future.

In this manuscript, we are going to focus on the modeling of renewal models for mature faults (in particular around Wellington) and on our experience adapting a UCERF3 tool to identify potential cascading events beyond those already included in the NSHM, especially in high exposure areas. Note that RMS is working on many other features (e.g., see Apel and Nyst, this conference, Ancheta et al., 2013, Muir-Wood and Fitzenz, 2013).

2 MATURE FAULTS WITH WELL-DOCUMENTED FAULTING BEHAVIOR AND TIME-DEPENDENT MODELS

2.1 What is the impact on risk of choices on the treatment of parameter uncertainty

Whereas PSHA helps define the building code required to prevent buildings from killing people, risk models help insurers and re-insurers remain solvent and guarantee that those insured will be able to move on, adapt and rebuild when and where the earthquakes strike.

Let's summarize those aspects of risk management that are both very demanding and specific :

1. An average annual loss (AAL) has to be provided along with a loss Exceedance Probability (EP) curve for up to very long return periods, and both have an impact on society. The AAL is the expected loss per year averaged over the return period and is used in the establishment of insurance premiums. It is more sensitive to the shortest return period events, so that premiums are computed on the basis of the losses due to the most frequent events (typically not the largest events). In the event of a large unfrequent earthquake, the collected premiums would not be enough to cover the claims. This is why insurers need to assess their longer-term risk, and manage their solvency issues (e.g., possibilities to get reinsurance, quantification of the reserves needed, etc.).

2. Exceedance probabilities for losses (i.e, the probability of exceeding xx losses at some given return period) are not a linear function of event conditional probability density function (PDF). If the chosen framework to incorporate uncertainties is a logic-tree, its structure regarding recurrence models needs to be thought-out very carefully;

3. Loss per event needs to be known for even very unfrequent events, together with their geometrical extent, to assess earthquake risk correlated between locations within one portfolio for the purpose of risk diversification ;

4. Financial models can be complex and may require knowing in which sequence events may happen, and not just the frequency of each individual event (e.g., due to hours clauses, renewal

seasons, apportionment). In such cases, simulations of time series of events become an essential part of the model. In order to produce those simulations, the inter-event time PDFs are needed;

5. Recent stringent regulatory requirements further stress the need to incorporate the best available science into the loss models but also to grasp the sources and the extent of model uncertainties.

One of the largest loss causing events in the current New Zealand model is a M7.5 on the Wellington-Lower Hutt fault, and the occurrence of that event is modeled in a time-dependent fashion with two parameters: mean recurrence time, and aperiodicity (or coefficient of variation, 0 for periodic behavior, between 0 and 1 for quasiperiodic, 1 for memory-less, >1 for clustered behavior). We therefore chose it to investigate how the Tail Value at Risk beyond the 1 in 250 yr loss event evolves through time since the last event depending on the assumptions taken in the modeling of parameter uncertainty. Figure 1 shows the posterior computed as described in 2.3 for parameters of the Brownian Passage Time model (BPT). Fig. 1 c stresses how much more capital is required for low to average aperiodicities (purple and green curves) than for larger ones as the elapsed time approaches the mean recurrence time. Such decisions should be made once the uncertainties are accounted for only.

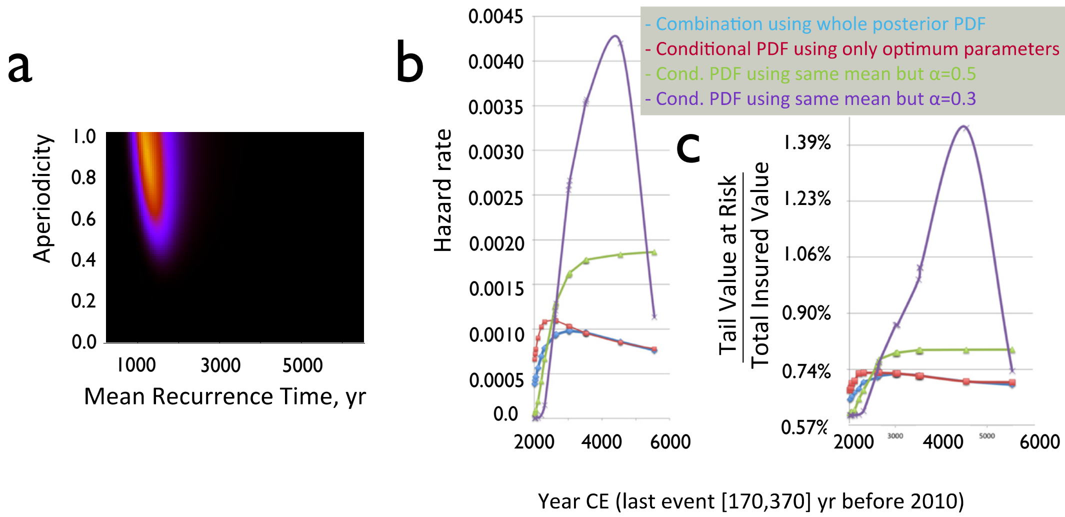

Figure 1. a. Posterior PDF, b Hazard rate vs time, and c normalized Tail Value at Risk vs time for the BPT model applied to the Wellington-Lower Hutt fault with 4 ways of dealing with the uncertainties.

2.2 **Following GNS' lead**

Rhoades et al. (1994) pioneered the use of Bayesian inference and the use of geologically-based priors on mean recurrence time into the characterization of renewal models for hazard computation. Following that methodology, Rhoades et al. (2011) and Van Dissen et al. (2013) incorporated slip rate and slip per event distributions fitted to field measurements and used a Bayesian method to incorporate and propagate uncertainties on earthquake dates from trenches and prior information, and combine the PDFs of the chosen renewal according to the posterior of the model parameters. Van Dissen et al., (2013) proposed to use a mixture of several renewal models to account for epistemic uncertainties. Stirling et al (2012) used average hazard rates over 50 and 100 years in the time-dependent national seismic hazard map (NSHM).

2.3 **Deviations from the Rhoades et al. (1994) approach and Stirling 2012 implementation**

We followed the general methodology used by Van Dissen et al. (2013). Deviations from this method include 1) the likelihood is computed for both the mean recurrence time and the aperiodicity and not just the aperiodicity; 2) the method remains Bayesian all the way through to the final hazard rates (i.e., includes the weight computation for the mixture of renewal models and the use of PDFs to do the mixture and not hazard rate functions, see Fitzenz et al, 2012 and Figure 2 for details); 3) we enlarged slip per event uncertainty to account for a short sample and also because the resulting prior on mean recurrence time is barely compatible with the likelihood from trench data, pointing to the need for more work on good priors (Fig.3); 4) we use no sampling but analytical or numerical integration methods instead. Finally, the time scale of interest is different between our needs and those of a NSHM study: earthquake insured loss risk management requires models that capture the current (1 to 6 years ahead, depending on the duration of contracts) characteristics of the natural phenomenon. On the other hand, hazard models have the mission of informing the building codes, so that the time scale most relevant to a PSHA study has to do with the optimal lifespan of the building or facility of interest, the shorter being for residential dwellings and the longer being for nuclear power plants or waste disposals.

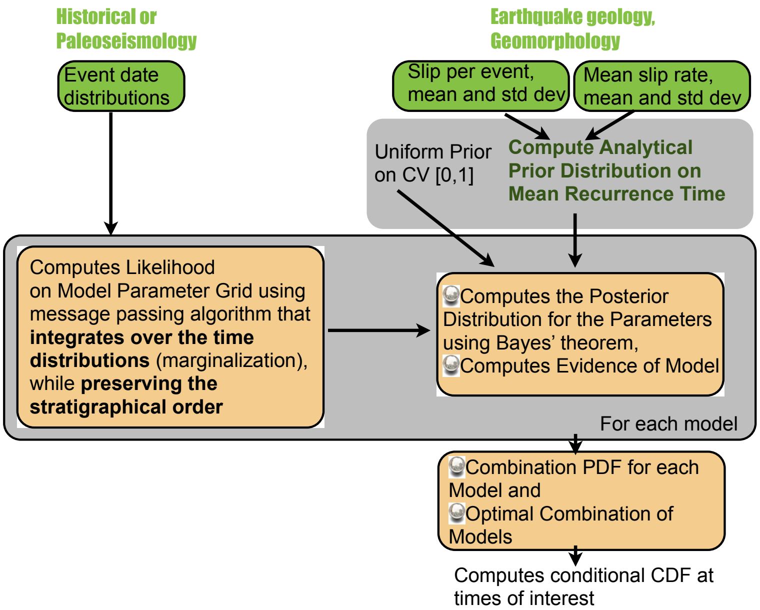

Figure 2. Framework of our Bayesian method: from earthquake geology a priori PDFs (priors) for mean recurrence time, through trench data likelihood for each renewal model parameters, to Bayes factors for each model, and corresponding mixture of PDFs and average hazard rates.

2.4 Table of results

For faults studied during GNS' It's Our Fault project, we apply the framework from Fig.2 and get the conditional PDF for interevent time for the Bayesian mixture of models for the Wellington-Hutt fault, the Wairarapa-1855 event, and the Ohariu fault. We can use those conditional PDFs to draw simulated time series, and we can use them to compute an equivalent return period over 1 yr, starting in 2010 or over 100 yr, see Table 1.

The introduction of trench data (5 events) for Wellington-Hutt, associated with a large likelihood of large mean recurrence time (Fig.3) increases the equivalent return period compared to the previous model (based on mean slip rate and slip per event only). The non-negligible weight of the Weibull distribution in the combination for Wairarapa on the contrary reduces the apparent return period (very large in the previous RMS, NZEQ07, which was based only on BPT model, and the elapsed time was about 1/10 of the estimated mean recurrence time). The same effect can be seen for the Ohariu fault (the elapsed time was about 1/3 of the estimated mean recurrence time).

Table 1. Summary of equivalent return periods (computed using the integral of the conditional probabilities given in (), using the computed model weights).

Model	Wellington-Hutt	Wairarapa 1855	Ohariu
Mixture of models, 1 yr average 2010	2366.5 yr (4.225 10^{-4})	15,736 yr (6.35 10^{-5})	2438 yr (4.1 10^{-4})
Mixture of models, 100 yr average, starting 2010	2054 yr (0.0475)	10,904 yr (0.0090)	2,334 yr (0.0419)
Model Weights	39.7% BPT 22.9% Weibull 37.4% lognormal	31.1% BPT 36.5% Weibull 32.4% lognormal	33.2% BPT 33.1% Weibull 33.7% lognormal
NZEQ07 (BPT only, aperiodicity 0.5), yr 2010	411.5 yr	99,814 yr	15,278 yr

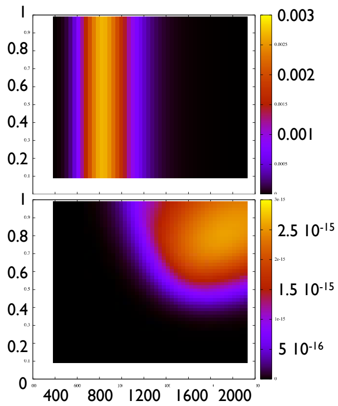

Figure 3. Wellington fault. The prior built from slip per event and slip rate information (top) is almost incompatible with the likelihood built with the trench data (bottom), restraining the posterior to a very small subset of the parameter space. The prior on the aperiodicity is uniform between 0 and 1 (y-axis).

2.5 The other faults for which past earthquake dates have been compiled

Paleoseismological records exist for several other crustal faults in New Zealand in or around the Cook Strait (such as Wairau and Awatere, see Fig.4 after Pondard et al. 2010) as well as for the southern Alpine fault (Berryman et al., 2012). Recent or ongoing lidar survey interpretations are also yielding new information on cumulative fault offsets and slip per event to supplement field and aerial photography studies (Hope fault, Langridge and Berryman, 2005). When put together, the trench dates seem to be records of participation in a large event and the slip per event seem to indicate larger slip than would be expected for individual segments. More work needs to be done to infer the rupture length and tips. Earthquake geology and geomorphology, as well as the study of lake sediments (Howarth et al., 2013) will play a big part in defining how those records are used in the future.

3 POPULATING THE TAIL OF THE EP CURVE OR HOW TO PREPARE FOR THE UNEXPECTED

3.1 Review of large RP events vs location of high exposure areas

Former risk and hazard models for New Zealand were based on two asumptions 1) Wellington south and Wairarapa and Ohariu on their own define the risk in Wellington; 2) ruptures can not cross the

Western part of the Cook Strait. However, Pondard et al, 2010 compile paleoseismicity records for on shore south and north of the Cook Strait and off-shore faults in-between, with many earthquake date PDFs that overlap (Fig.4). Those overlap could be interpreted as either coseismic propagation or rapid succession of events. We need to check whether such events would be mechanically consistent with observations of multi-segment ruptures throughout the world, build such events into our models, and check how the resulting loss distribution differs from that produced from ruptures of shorter length as considered in GNS' model.

3.2 UCERF3 methodology to define candidate ruptures in an un-segmented fault system

UCERF3 compiled field observations and earthquake simulator results to come up with a set of rules to link up fault sections into potential ruptures. First they discretized all faults in short fault elements (called subsections) of about 7 km in length (i.e., about half the average down-dip width in California).

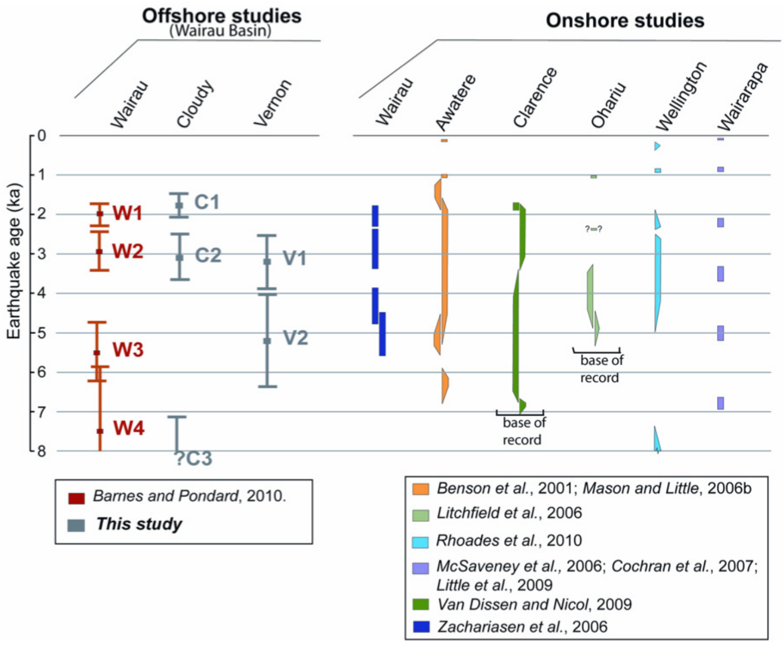

Figure 4. Compilation of regional Holocene paleoearthquakes in the Cook Strait region, Fig 13 in Pondard et al 2010. Error bars in submarine ages show 95 % confidence intervals.

To these subsections, they apply the following tests (Milner et al., 2013) :

1. The shortest distance between 2 fault sections is 5 km or less
2. Strikes cannot vary by more than some amount between neighboring subsections (e.g., 60º)
3. Strikes cannot change by more than some total amount along the rupture length (e.g., 560º)
4. Rakes cannot change by more than some amount between subsections (e.g., 180º=maxCum)
5. Ruptures cannot include a given subsection more than once (e.g., preventing ruptures from looping back on themselves)
6. Rupture on previous subsection results in increase in Coulomb Failure Stress (CFS, no threshold value, just >0)

We opted to use criteria 1 to 4, although Pondard et al. (2010) computed CFS for most faults around and in the Cook Strait area and this work could be used as a basis to build the table needed in OpenSHA. To get the magnitude of the events, the proper length-magnitude or area-magnitude scaling has to be selected (see compilation in Stirling et al. 2012).

3.3 Results: candidate scenarios

Once we modified the Wairarapa 1855 geometry to account for the uplift and subsidence patterns observed in relation to the event (Townend et al. 2005), we obtained over 400,000 potential ruptures (vs 536 in GNS' NSHM). Those ruptures have a minimum magnitude of about 6 whereas only characteristic (full-segment or full succession of segments) events are modeled on known faults in the NSHM : smaller events are modeled in the background only. By construction there are also a lot of partially overlapping ruptures, and many largely overlapping ruptures (i.e., only the tips of the ruptures vary from one scenario to the next). Finally, some scenarios involve crustal faults rupturing at the same time as the subduction interface. The Wairarapa 1855 is likely to have been such an event (Fig.5), but this method identifies more possibilities, based on the current segmentation of the subduction implemented by GNS (currently undergoing re-assessment within RMS).

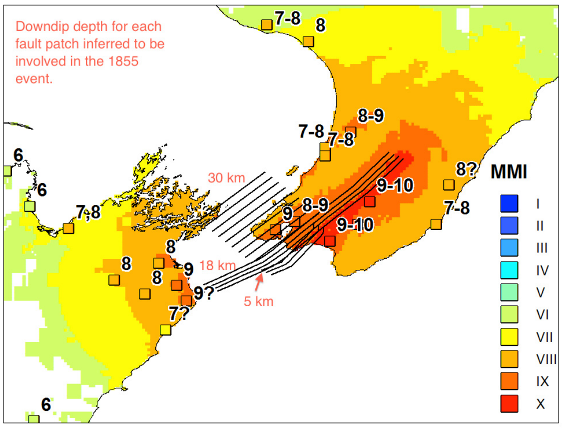

Figure 5. Contour lines of the new geometrical representation of the 1855 Wairarapa earthquake, validated against macroseismic intensities computed using McVerry's attenuation law (color scale) and from macroseismic surveys (colored squares) (Figure courtesy of E.V. Apel). The rupture involves the Wairarapa fault, a shallow Wharekauhau thrust and part of the subduction interface.

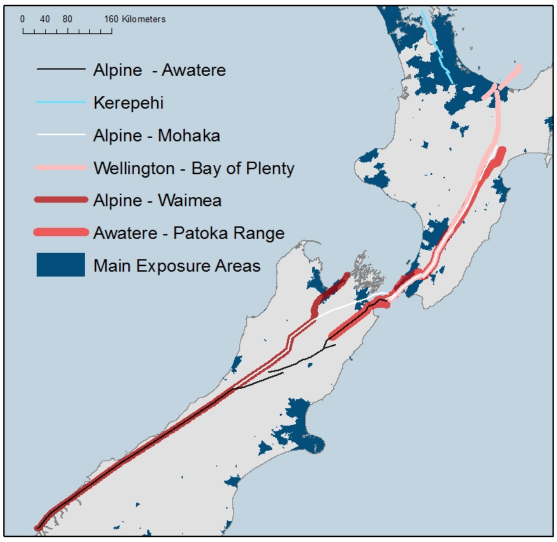

Figure 6. Candidate complex events overlain on main exposure areas.

3.4 How to assess the frequency of those events

The first step when pondering the addition of potential complex ruptures is to view them as scenarios and assess their loss per event. Once identified, the most impactfull will be given a small rate of occurrence that preserves the moment rate previously accomodated by individual segments or shorter combination of segments.

4 CONCLUSION AND PERSPECTIVES

The new RMS NZEQ risk model is largely based on GNS' 2010 (and onward) update of the NZEQ hazard model. In the translation from hazard to risk RMS is bringing a lot of innovations to the NZEQ model that will be one of the first High Definition earthquake model on RMS(one). The high-performance and modularity of the new platform deployed on the cloud allows to better account for uncertainties through the simulation of thousands of realizations of time series. One needs PDFs of inter-event times and conditional PDFs for time-dependent sources, that reflect the uncertainties. When models or parameters are uncertain, PDFs tend to be wider and hazard rate functions tend to be flatter, this is how uncertainties are reflected, not as an error-bar on a hazard rate at a given time. The way to account for the lack of precise knowledge of recurrence model parameters in particular for large loss causing events has a large impact on risk metrics that inform capital requirements.

More collaboration is needed with geologists and geomorphologists to build better priors or new likelihoods for model parameters and also to start developing models for joint probability between faults, or slip rate constraints that should be used when simulating time series.

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