Is our true understanding of earthquake occurrence reflected in modern building codes?

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Abstract

For more than 20 years, the New Zealand National Seismic Hazard Model (NSHM) has been constructed using the standard methods of probabilistic seismic hazard assessment. In this approach a source model is first constructed by combining models developed from earthquake catalogue data and active fault data; these models are assumed to be Poissonian in nature. The combined source model is then coupled with ground-motion prediction equations (GMPEs) to estimate the potential shaking at desired locations. In recent years, there has been considerable progress and improvement in understanding of the uncertainties inherent in GMPEs. In our current work, we are revisiting some of the fundamental assumptions of the NSHM and investigating how both model and parameter uncertainties in the earthquake source and ground motion modelling propagate through to the end uses of the model. In New Zealand, a major end-use is the development of anti-seismic provision in the national building design standards. Some uncertainties are not quantified in the present model. These include uncertainties resulting from a paucity of earthquake occurrence data and from different methods that can be used to model the seismic sources. Also the stationary Poisson asumption ignores the known clustering of earthquakes in time and space. This paper will explore the impact of including these uncertainties in the NSHM on downstream risk-based applications of the model, with a view to more robust estimates of risk for use by industry and in the development of design standards.

Keywords: PSHA; Seismic Hazard; Uncertainty; NSHM, New Zealand

1. Introduction

Seismic hazard modelling in New Zealand has relied on probabilistic seismic hazard analysis (PSHA) since the 1980s. Beginning with the use of large regional zones, the modelling has become progressively more detailed and precise [1,2] with the use of active faults, gridded smoothed seismicity, and New Zealand optimised ground motion prediction equations (GMPE; e.g.,[3]). The most recent revision [4] contains approximately 530 fault sources for which time-dependent fault rupture probabities are included where available. These faults dominate the hazard estimates over much of the country. In a current revision of the National Seismic Hazard Model (NSHM) we are rethinking many of the fundamental assumptions of the model's development, while attempting to understand the inherent uncertainties and to develop a model that best meets the needs of potential users.

PSHA is an algorithmic approach to model creation, where disparate data sets and concepts are coupled to forecast the probibility of a given level of ground shaking over a specific time-frame (e.g. 50-years). The New Zealand NSHM [4] is developed using standard PSHA methods as applied in many other regions of the world. The NSHM is constructed from two classes of component models: 1) the earthquake rate 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, including its uncertainty.

In the NSHM, the rate model is developed from two independent model components. The largest contributor to the rates at high magnitudes is the fault model, where each fault source is attributed a characteristic magnitude, a slip-rate and a length. The rates 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., [5]), or from regressions between mapped fault length and earthquake magnitude [6]. The fault model contains sources of magnitude 6.5 and greater. Despite the large number of mapped faults in New Zealand, the fault model does not contain all of the potential faults in this magnitude range [7]. To account for this a rate model is created based on the GeoNet historical earthquake catalogue of earthquakes since 1840. In this component model, future earthquakes are expected to occur at similar locations and at a similar rate as in the historical catalog. 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. For most of New Zealand, this component model forecasts earthquakes from magnitude 5.0 to 7.2, with an implicit assumption that all faults capable of generating earthquakes with magnitude greater than 7.2 are identified and included in the fault model. The complete rate model is developed by coupling the two component models. Interestingly, the fault-source model represents knowledge covering many thousands of years and the catalog based model represents approximately 170 years worth of knowledge. There is no attempt to address epistemic uncertainty in the earthquake rate model of the NSHM. In contrast, a time-dependent hazard model that has been developed for Canterbury, New Zealand (CSHM) addresses epistemic uncertainty through the use of 15 plausible component models [8].

Future applications of seismic hazard analysis in New Zealand are likely to include physics-based ground motion simulations to estimate the potential ground shaking. However, most current PSHA models, including the NSHM, use empirical GMPEs derived from regressions between observed shaking and earthquake source data. The past two NSHMs have not accounted for epistemic uncertainty and have applied a single GMPE: McVerry [3]. However, for the CSHM, we have used both the McVerry [3] and the Bradley [9] GMPEs. Other recent work [10] has identified that estimating ground motions based on next generation attenuation GMPEs (NGA West2) may produce equally satisfactory results for New Zealand. Due to a paucity of data on strong ground-motions, particularly near to the sources of large earthquakes, there is substantial uncertainty involved in developing GMPEs; the residual standard deviation and standard errors of coefficients can be large, and the results of different GMPEs can vary markedly, even if they are based on the same dataset. Because of this, several different GMPEs are often used in combination to account for the epistemic (modeling) uncertainty. This important aspect of uncertainty has been a focus of the PSHA community for many years. Traditionally the combination is achieved by means of a logic tree in which each GMPE is assigned a weight to be used in a combined model (e.g., [11]); recent approaches suggest more rigorous statistical techniques (e.g., [12-14]).

As is typical for PSHA, the output of the NSHM is often expressed as the ground-motion with some probability of exceedance in the next 50 years. For example the New Zealand building design standard of NZS1170.5:2004 [15] is based on the 5% damped response spectral acceleration at 0.5 seconds that is calculated to have a annual exceedance rate of 1/500. Most commonly this is referred to as the 500-year return period map corresponding approximately to a 10% probability of exceedance in 50 years. Most commonly this is referred to as the 500-year return period map. Implicit in equating a 10%-in-50 year value to approximately a 500-year return period is an assumption that the earthquake rates are stationary in time, independent of the time since the last occurrence. This is inconsistent with the well-known clustering of earthquakes in time and space and with any model including time-dependence, such as, to a limited extent, the NSHM (it includes time-dependent rupture probabilities for a few faults) and the CSHM [4,8]. A time-dependent model applies only to the forecast period (t) for which it was developed; its hazard estimates should be reported as a probability of exceedance of p in t years, where t is the exposure time for which the model has been developed, not in terms of return periods. Similarly, it is incorrect even to scale idown its exceedance probabilities to some shorter exposure time using the Poisson probability formula. In other words, for a time-dependent model a 10%-in-50 year ground motion is not equivalent to a 475-year return period ground motion, or to a 2%-in-10 year ground motion. It is important for the end-users of hazard information to appreciate this.

1.1 End-uses of the New Zealand NSHM

Ideally, every seismic hazard model is designed for a specific end-use, or set of end-users. There are particular stakeholders who use the model and whose needs it should be designed to address. The New Zealand NSHM is designed for two target catagories of use: 1) design standards and application: including building design standards, NZS1170.5 [15] 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. In New Zealand, the foundation of the national building design standard is hazards-based and is a direct translation of the 10%-in-50 year hazard value with requiring for less likely events as the importance of structures increases.

Risk assessments are sensitive to uncertainties in lower probability events, because they involve multiplying the hazard by the consequences of the event,. For example, while the hazard estimated in the NSHM for the Auckland region of New Zealand is 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, because of the large population affected. 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.

2.0 Quantification of Uncertainty in PSHA

In recent years, the PSHA community has focused considerable effort on better quantification of the uncertainty in ground motion prediction, and methods of quantifying and modelling this uncertainty are continually improving. Far less attention has been given to understanding the true model uncertainties in the earthquake rate models. For example, once source of uncertainty comes from the assumption of a stationary Poisson process as is generally applied to rate models. Because the uncertainties related to a Poisson process are small when compared to those of GMPEs, the uncertainty in the rate is often ignored, as it is in the New Zealand NSHM [4]. However, it has long been known that earthquakes are clustered and are not adequately described by a stationary Poisson process (e.g., [16-17]); 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 our current model development research we are working on methods to better quantify both model and parameter uncertainty in the earthquake rate model and also to better understand the implications of this uncertainty on the end uses 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 Predictibility (CSEP; [18]) has developed methods for statistical evaluation of earthquake forecast models. 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. In other words, it would likely provide a reasonable approximation of the magnitude-frequency distribution of earthquakes, but without any spatial information it is of limited practical use. 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 spatial resolution is roughly the same as is used by the NSHM, NZS1170.5:2004 and by other hazard models around the world. 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, and how do we determine, the optimal resolution for applications such as NZS1170.5:2004?

2.1 Fault Model Incompleteness

As outlined above, the NSHM earthquake rate model is composed of two component models developed from independent data sets. An important decision in the model is how the forecast rates are partitioned between the fault source model and the earthquake catalogue source model. Nicol et al., [7] investigated this question by attempting to assess the completeness of the New Zealand fault model; in other words how many faults are likely to be missing from the model. To do this they asked the 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 paleo-seismologists, was roughly one-half or fewer of the events would have occurred on known faults. 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

The CSHM is a hybrid model that uses fifteen different source models (based on different paramaterisations of 8 individual models) and varients of two different GMPEs (five in total) in order to capture the epistemic 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 plausible models forecast earthquake rates that differed by several orders of magnitude [8,19]. Figure 1 shows the ratio of the forecast rates between two alternate models from the CSHM. These models represent the range of models considered plausible by the expert panel. The ratio is smallest in the immediate region of the larger aftershocks and increases moving away to the east; this is indicative of the relative similarities of the short- and medium-term models, and the large variability across the long-term models.

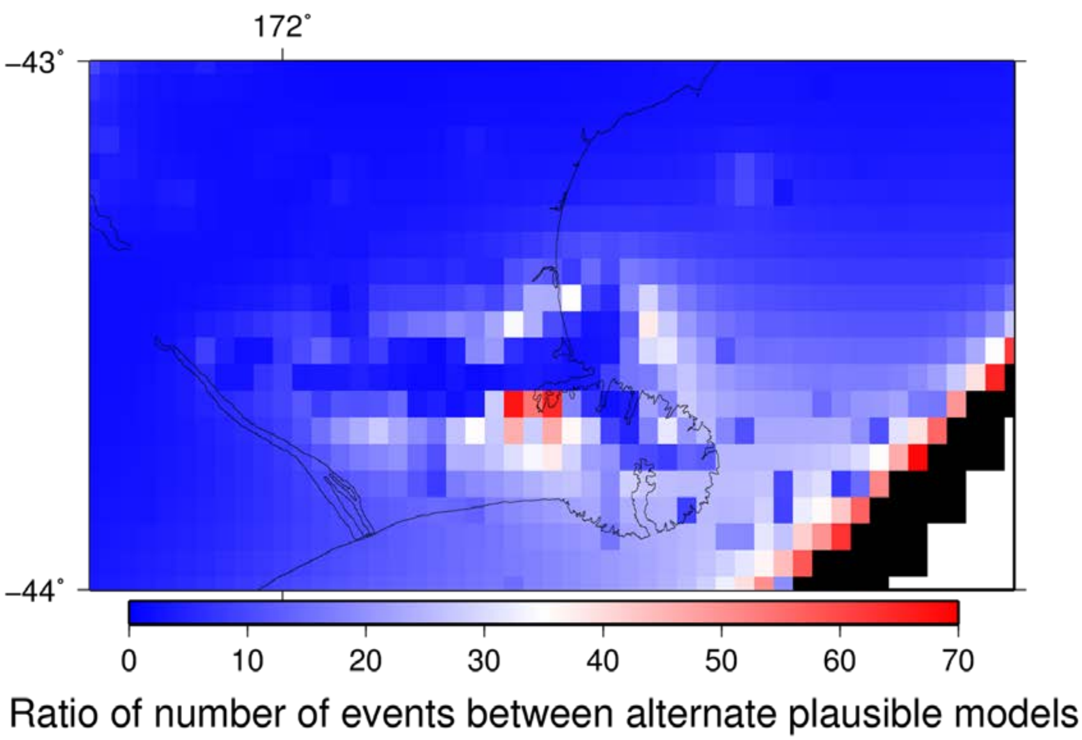

Figure 1. A map showing the ratio of forecast events from two model realisations of the CSHM considered plausible based on the weights and their uncertainties provided by the expert panel. The black region to the east has a ratio of greater than 70.

An important contribution to this uncertainty comes from the specifics of the learning catalog used. A fundamental question that we do not yet have an answer to is: what time-period of catalog gives the best forecast for the next 50 years? It is not yet clear if it is optimal to include, e.g., the last 50 years of data or the last 150 years of data. Additionally, different time-periods have different data quality issues related to magnitude and location uncertainties and also magnitude of completeness. Declustering a catalog is the process of removing aftershocks and is done to obtain a Poisson catalog for PSHA. If this is done, it also introduces its own significant uncertainty (Christophersen et al., 2011) [20]. The simplest expression of these uncertainties will be via their effect on the estimates of the a- and b-values of the Gutenberg Richter Relation [21]. Currently the uncertainties in these parameters are not exploited in most PSHAs and including the data uncertainty will only increase the variability of the parameter estimates.

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 [22] 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 [23] and for California [24] 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 Earthquake data and small sample sizes

In many parts of New Zealand, particularly in the low seismicity regions, we are limited by the amount of both catalog data and fault data that we have collected. Because seismicity is non-stationary, meaning earthquake rates and locations vary through time, it is not clear what this small sample size is representing. A key challenge is that the data sample we have is not a random sample of the entire process, it is a small, possibly biased sample from some part of the process. We are currently working on methods to incorporate the uncertainties that come from small sample sizes. Very much related to this is the idea of the "floor rate" which is often added as a minimum rate in low seismicity areas. Constraining the floor rate can be challenging and is often subjective; by getting a better estimate of the uncertainty in low seismicity regions, we may be better able to constrain this floor rate, or, alternatively, provide a better estimate of the epistemic uncertainty in the earthquake rate model..

2.4 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 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 [25].

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., [24]), 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 [21].

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., [26] 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.

2.5 Megathrust Earthquakes

In New Zealand, the Hikurangi Megathrust follows the east coast of the North Island, underlying approximately 600km of coastline. It passes approximately 25km beneath the capital city of Wellington and is a similar distance from a number of regional centres across the country. Currently we have very limited knowledge of past ruptures on the megathrust, and we do not have good undertanding of the values of parameters that control the potential for future ground shaking. Recent estimates of interseismic strain accumulation based on continuous global positioning system (cGPS) data suggest a maximum down-dip extent of strain accumulation to be about 50km, giving a total potential rupture width of about 200km, similar to the Tohoku-Oki rupture. Combined with the lateral extent of the zone of current strain accumulation and analysis of aseismic creep and tectonic tremor, the best estimate of maximum megathrust event is M>8. However, estimates of strain accumulation are limited to data sampling little more than a decade of crustal strain and it is uncertain if the interseismic accumulation of stress is static. Another possibility is that aseismic creep does not yield total stress drop and patches of the megathrust that are currently estimated as being weakly coupled can facilitate rupture, much like the great Tohoku-Oki earthquake ruptured patches of the megathrust with documented recent aseismic slip. In a recent comparison with the 2011 Tohoku-Oki earthquake [27] demonstrated that a similar event in New Zealand could cause sustained PGA of approximately 0.25g for the city of Auckland and sustained shaking for Wellington of >1.0g. Furthermore, much of the lateral extent of the shallow interface (~<15km depth or ~100km Cartesian distance) is offshore making estimates of current interseismic strain accumulation difficult. Future earthquakes on the megathrust represent a significant source of hazard for the North Island and parts of the South Island that remain poorly quantified.

2.6 Moment Calculations and Balancing the Total Number of Forecast Events

The most common way to constrain the total earthquake rates produced by a seismic hazard model is to calculate the total moment released in the earthquakes forecast by the model and to compare this to some long-term estimate of what the cumulative moment budget. The moment of the forecast events is calculated based on estimated basic parameters of fault characteristics and fault dimensions. Small changes in these parameters may have a significant impact on the estimated moment for the particular forecast earthquake. The long-term moment rate can be estimated using different methods, but it is often derived using geodetic observations. Plate convergence rates represent long-term geological processes and geodetic data represent short-term processes; for example, in New Zealand we have directly-measured geodetic data representing the last 10-20 years of plate movement. To calculate moment rates from geodetic observations, a model must be assumed that describes how geodetically observed strain is accommodated by earthquakes. A critical assumption of such models is how much of the strain is partitioned into earthquakes and how much is released aseismically. Additionally, implicit in the comparison of forecast moment rates and those modelled from geodetic observations is that geodetic observations from the last 10 to 20 years are assumed to be representative of what we should expect in the next 50 years. Finally, large uncertainties exist in both the forward calculations of moment (i.e., how much is forecast) and quantification of past moment release (both short-term as seen in contemporary geodetic data and long-term, from the geologic record). These large uncertainties make it challenging to constrain the earthquake rates in a seismic hazard model.

3.0 Discussion

A comparison of the earthquake hazard in Auckland and Wellington serves to illustrate the impact of source model uncertainties. In the most recent version of the NSHM [4], the hazard estimated for Auckland is very low and the hazard estimated for Wellington is high. The PGA for shallow soil sites with a 10%-in-50-year probability of exceedance is estimated to be less than 0.1g in Auckland and 0.6g in Wellington. The low estimate for Auckland is a result mainly of the background model, and is controlled by the rates for earthquake sources with magnitudes from 5.0 to 6.8 at distances of up to 70km. The high estimate for Wellington is a result mainly of the fault model and is controlled by the estimated recurrence times for rupture of several major faults that pass through or nearby to Wellington city (e.g., the Wellington, Ohariu South and Wairarapa faults), all of which are deemed to generate magnitudes of 7.5 or greater [4].

A relatively large amount of data supports the estimates for the Wellington region. The background source model can rely on more than 2300 earthquakes of magnitude greater than 4 in the GeoNet Catalogue (http://quakesearch.geonet.org.nz) for the region since 1840 and numerous well-studied active faults in the region contribute to the fault model. In contrast, there is little data in support of the estimates for the Auckland region. Only about 100 earthquakes in the Auckland and Northland region have been recorded in the GeoNet catalogue since 1840. These include two earthquakes with estimated magnitude greater than 6.0, but with high uncertainty because both were in the 19th century. There is only one active fault in the fault model for the Auckland region, and none in the Northland region. The future discovery of a few more faults near to Auckland or a future moderate increase in the regional earthquake rate could have a large impact on the perceived seismic hazard in the Auckland region.

There is no doubt that the earthquake hazard in Auckland is much lower than in Wellington based on the available data and our present knowledge of seismology and tectonics. There is reasonable doubt, however, about how the uncertainty on that hazard estimate should be assessed. Given the small amount of data for the Auckland region and the modelling uncertainties outlined in the previous section, the uncertainty in the Auckland hazard estimate seems larger than that in Wellington, where the future discovery of a new fault or an increase in the regional earthquake rate would have only a minor impact on the existing estimate. This uncertainty is particularly important for risk applications of the NSHM outputs, because of the high concentration of vulnerable assets in Auckland. To produce robust estimates of risk, this uncertainty needs to be taken into account somehow. 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 here and our current inability to model them precisely, it may be that the needs of risk modellers and building design standards are not best served by using the present result that is expressed on a spatial grid with spacing as small as 5km. It may be that a more regionalized application of the model outputs, or a smoothed approach which relies on a greater quantity of data over a larger area, may give results that are more robust for uses such as the building design standard. The current standard NZS1170.5:2004 [15] partially acknowledges 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? A regionalized interpretation of the PSHA outputs will likely better reflect the uncertainties in the risk-based results and provide a more trustworthy estimate of the risk for Auckland and other regions.

An additional potential impact of better quantification of the uncertainty in the earthquake rates and hazard is to the process of moving from the use of one version of the NSHM to the next. The fundamental science around how to best estimate seismic hazard changes at a rapid pace. This rapid change is often considered to be unacceptable for end-uses which have a long term impact, such as the building design standards. We are currently working on methods that will allow for more smooth transitions between subsequent models, for applications that are dependent on the model.

4.0 Conclusions

A key consideration in our current work to revise the NSHM is to understand the influence of uncertainties and how they propagate through to policy and other end uses of the model. 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. Through accounting for additional epistemic uncertainty, including how models might be affected by a paucity of data, we aim to improve the utility of the NSHM for stakeholders in the building design and risk management sectors.

Finally, we are working towards increasing the end-user input into the development of our model. The goal of this is to ensure that the model that we are developing not only meets the needs of scientific advancement and rigor, but that it also provides the most useful output to the end users. This includes considerations for how we can more smoothly transition from one version of the NSHM to the next. Ultimately this should be aided by moving towards a risk-based building standard rather than one that is hazards based.

Acknowledgements

We thank Bill Fry and Mark Stirling for their many helpful discussions in developing this manuscript.

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