RECOMMENDATIONS ON BEST AVAILABLE SCIENCE FOR THE UNITED STATES NATIONAL SEISMIC HAZARD MODEL

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Abstract: *The 50 state update to the 2023 United States National Seismic Hazard Model (NSHM) is the latest in a sequence published by the U. S. Geological Survey (USGS). The 2023 NSHM is intended for use in building codes and similar applications at return periods of 475 years (corresponding to exceedance probabilities of 10% in 50 years) or longer. In reviewing the model, the NSHM Program Steering Committee, consisting of the authors of this paper, considered the characteristics of "best available science" that are applicable to the NSHM. Best available science must perform better than the previous NSHM, and there should be no available alternatives that could improve the models. The following are suggested characteristics of "best available science":*

A) Clear objectives
B) Rigorous conceptual model
C) Timely, relevant and inclusive
D) Verified and reproducible
E) Validated intermediate and final models
F) Replicable within uncertainties
G) Peer reviewed
H) Permanent documentation

This article focuses on the justification for, and intent of, the above criteria for best available science.

1. Introduction

The 2023 U.S. National Seismic Hazard Model (NSHM) presents a significant update to a long sequence of past seismic hazard models published by the United States Geological Survey (USGS). These include Algermissen and Perkins (1976), Frankel et al. (1996, 2002), Klein et al. (2001), Wesson et al. (2007), and Petersen et al. (2008, 2014, 2020, 2022). The NSHM synthesizes data and models produced by hundreds of earthquake professionals throughout the United States and the international community.

The NSHM is presented generally as maps that contour expected ground-motion levels from earthquakes at various return periods, V_{S30} values, response spectral periods and damping ratios. Among other products, the NSHM identifies possible earthquakes that contribute most to the hazard at any location. The NSHM is developed from observations of past earthquake locations, magnitudes, and mechanisms, geological observations of surface faulting and other surficial effects of past earthquakes, geodetic observations of active deformation of the earth, observations of shaking in past earthquakes, and geophysical measurements of subsurface geometry and properties of the crust (e.g. subsurface layer thicknesses and basin shapes, wave speeds and crustal attenuation; borehole measurements of seismic velocities, $V_{S30,}$ and site attenuation). These observations are used to create a hierarchy of components that contribute to the two main components. The first main component, the earthquake rupture forecast (ERF), gives long-term forecasts for the locations, magnitudes, and rates of earthquakes. The second main component, the ground motion characterization (GMC), estimates ground motions that could ensue from each possible earthquake. These two models, considering uncertainties, are combined, thereby generating the NSHM. The NSHM products are designed for a range of audiences, including the engineering community, risk and insurance industries, emergency management, local and regional planners and decision-makers, as well as the general public. The development of this earthquake ground-motion hazard model benefits the entire population of the United States by providing up-to-date scientific information (i.e., the “best available science”) for these users to reduce and/or mitigate seismic risk across the Nation.

The National Seismic Hazard Model Program Steering Committee (SC) reviews and provides advice on development of the NSHM. The committee consists of nine members, the authors of this paper, who have been selected by the US Geological Survey, based on their expertise and experience.

The 2023 model is described by Petersen et al. (2023). The two main components, the ERF and the GMC, are described by Field et al. (2023) and Moschetti et al. (2023), respectively. The ERF and GMC were reviewed by Jordan et al. (2023) and Stewart et al. (2023), respectively, and the resulting NSHM was reviewed by Anderson et al. (2023). It represents a substantial improvement over the previous NSHM as it includes a significantly expanded database of active faults, incorporates new geodetic deformation observations and models that associate those deformations with active faults, better methods to estimate earthquake occurrence rates on faults, new ground motion models based on a large increase of strong ground motion data, basin models, and use of ground-motion simulation data to complement the recorded ground-motion data.

Beyond review of the 2023 NSHM, the NSHMP also requested advice on long-term, broader issues for the next cycle including the committee thoughts on the meaning of “best available science”. The Committee thoughts on this question are presented in the remainder of this paper.

2. Overview of Best Available Science Characteristics

2.1 Criterion for Scientific Progress

A primary criterion for scientific progress is articulated by Karl Popper (e.g. Popper, 1992, Chapter 2):

> We regard one hypothesis, a new hypothesis for example, as better than another if it fulfils the following three requirements. First, the new hypothesis must explain all the things that the old hypothesis successfully explained. That is the first and most important point. Second, it must avoid at least some of the errors of the old hypothesis: that is, it should, where possible, withstand some of the critical tests that the old hypothesis could not withstand. Third, it should, where possible, explain things that could not be explained or predicted by the old hypothesis.

The National Seismic Hazard Model is a hypothesis, in the sense of this quotation. We will refer to this as the “Popper criterion”. As the NSHM is synthesized from a hierarchy of component models, the Popper criterion must be applied to all components as well as to the final synthesis. Jordan et al. (2023) ask a similar question, “Does the 2023 NSHM perform better than the 2018 NSHM?”

2.2 Literature on Best Available Science

Several publications specifically address the characteristics of “best available science” in a regulatory setting. The publications identify many shared characteristics, but there are differences that depend on the application. National Research Council (NRC 2004) focused on the meaning of best available science for fisheries management. That study identified six criteria that define best available science: relevance, inclusiveness, objectivity, transparency and openness, timeliness, and peer review.

Sullivan et al. (2006) expanded the NRC (2004) audience to include environmental regulation in general. Their list of characteristics is somewhat different: *a clear statement of objectives; a conceptual model, which is a framework for characterizing systems, making predictions, and testing hypotheses; a good experimental design and a standardized method for collecting data; statistical rigor and sound logic for analysis and interpretation; clear documentation of methods, results, and conclusions; and peer review.* Delta Stewardship Council (2015) largely follows the recommendations of Sullivan et al. (2006) in the application to management of the Sacramento River Delta.

The Organization for Economic Development and Cooperation (OECD, 2014) focused on the mechanics of advisory committees, motivated by the issues raised by the tragedy of the L’Aquila, Italy, earthquake. The report emphasizes that scientific advice should be based on the best available scientific evidence, and that scientific uncertainties need to be clearly communicated.

The National Academies of Sciences, Engineering, and Medicine (NASEM, 2017) focused on integrity of science. Their focus is on individual and collective adherence to core values of objectivity, honesty, openness, fairness, accountability, and stewardship. The National Academies of Sciences, Engineering, and Medicine (NASEM, 2019) focused on assuring the integrity of research that has a potential major impact on the public, emphasizing reproducibility and replicability of research. The NSHM is clearly in the category of research requiring the utmost integrity, as it influences the life safety and resilience of new buildings throughout the nation.

Finally, as a part of the ERF review Jordan et al. (2023) offered a list of criteria characterizing best available science: relevance, inclusiveness, verification, validation, transparency and openness, timeliness, and peer review. In this summary, objectivity from National Research Council (2004) is replaced by verification and validation.

Characteristics of best available science must be adapted to the application. Considering the above studies and the characteristics of the NSHM, we propose a set of characteristics that incorporate all of the relevant suggestions of these previous studies.

Our modified set of characteristics are:

A) Clear objectives

B) Rigorous conceptual model

C) Timely, relevant and inclusive

D) Verified and reproducible

E) Validated components and final models

F) Replicability within uncertainties

G) Peer reviewed

H) Permanent documentation

The next section defines and discusses each of these characteristics.

3. Discussion of Characteristics

3.1 (A) Clear objectives

Clear objectives are essential to prevent haphazard procedures and to ensure unambiguous results (Sullivan et al., 2006; Delta Stewardship Council, 2015). The objectives must identify the intended applications and assure users that the model is relevant for those applications. This implies that the National Seismic Hazard Model Program (NSHMP) should continuously interact with users, identify their needs, and provide clear guidance on the range of validity and limitations on its use. The SC believes that the NSHMP does this well.

The goal of the 2023 NSHM is to determine the time-independent seismic hazard of the United States for applications to seismic provisions in building codes and related products. It is also expected to help identify and mitigate earthquake losses and enable effective planning and response for earthquake emergencies.

Clear guidance on the range of validity and limitations on the use of the current and all future versions of the NSHM is necessary. As a time-independent model, Jordan et al. (2023) and Anderson et al. (2023) recommend that the 2023 NSHM is appropriate for low exceedance rates (e.g. 1/475 per year or less, corresponding to an exceedance probability of 10% in 50 years or smaller). This is the range of exceedance rates that is recommended for most buildings in the United States (Building Seismic Safety Council (BSSC), 2020).

Time-dependent PSHA is scientifically justified and recommended (Jordan et al., 2023). Considering the elastic rebound model, a fault that has not ruptured in the most recent decades or centuries may have a higher probability of rupturing than its long-term average would predict. The 2023 NSHM model does not include those considerations. Such long-term adjustments have, however, been developed for the San Francisco Bay region, for southern California, and for California on a statewide basis (e.g. Working Group on California Earthquake Probabilities, 1999; Field et al. 2015. Time dependence is used for building code applications in the seismic hazard models of Japan (Earthquake Research Committee, 2005) and New Zealand (Gerstenberger et al., 2022a,b).

On the shortest time scales, as could be important for building national resilience to earthquake disasters, the National Research Council (2011) recommended that USGS set the objective of operational earthquake forecasting. This involves updating earthquake probabilities on time scales as short as days in response to recent earthquake activity. The scientific basis for this is the statistical behaviour of aftershock sequences (e.g. Reasenberg and Jones, 1989).

3.2 (B) Rigorous Conceptual Model

This characteristic is also recommended by Sullivan et al. (2006). A fully documented and statistically rigorous conceptual model provides an essential framework for characterizing the physical processes that cause the hazard and for making hazard estimates. Documenting the model is a component of assuring that the NSHM is transparent in its approach, and that it can be independently verified and validated. The conceptual, mathematical model for probabilistic seismic hazard analysis (PSHA) at small exceedance rates is well established, clearly documented in numerous publications, and statistically rigorous (e.g. Baker et al, 2021).

However, the model needs to consider alternative “scenarios”, within which possible consequences and risks can be explored (e.g. SSHAC, 1997; Sullivan et al., 2006). The “alternative hypotheses” are the epistemic uncertainties in PSHA. These are currently handled with the use of logic trees, where each limb of the logic tree yields its own unique hazard curve. Ideally, the distribution of consequent hazard curves define the center, body and range of the hazard (SSHAC, 1997). The weight of each limb is treated as a probability to find fractiles of the hazard curves. When the weights are assigned by expert judgment, the probability distribution can be called the “expert distribution” (e.g. Marzocchi and Jordan, 2018). As much as possible, the weights of logic tree branches should be assigned using clearly defined and scientifically justified criteria, i.e. the assignment should be transparent and reproducible. Assigning equal weights because the science cannot be judged is not a defensible approach.

3.3 (C) Timely, Relevant and Inclusive

In the NSHM context, timeliness, relevance, and inclusiveness are very closely related. As applied to the NSHM, the timeliness criterion of National Research Council (2004) requires that all available, relevant, finished and reviewed data contributions and component models that might contribute to the hazard estimates should be considered. This maximizes the quality, objectivity, inclusivity, and integrity of the NSHM. The NSHM depends on the input of the entire community of earthquake hazard professionals, and inclusiveness requires that “all available” data and models from this large community should be considered. Because the NSHM is a community effort, to promote inclusiveness, it is very helpful for NSHMP scientists to attend national and regional scientific meetings. Interaction in this setting helps others in the community of earthquake professionals to understand needs of the NSHM and by helps NSHMP personnel to be acquainted with new results and the response of other scientists to these new results.

Balancing the goals of timeliness, and incorporating “best available science”, and updating data sets and models is more likely to provide a solid, reviewable and timely product to review with a well-defined review plan. The Steering Committee recommends setting and enforcing deadlines for all new models (both USGS and external researchers), with exceptions only for *critical incomplete or interim studies*. The review plan should include explicit goals and deadlines for each component of the NSHM for initial review, revision, and secondary review. Data collections and component models that are still in preparation or under review in time for thorough consideration by USGS should not be considered “available”.

Recommendation to Define Desired Models Characteristics

Model developers should be informed about the characteristics and acceptance criteria that new components should meet to be useful for the NSHM. For example, Rezaeian et al. (2015, 2021) describe properties that ground motion models should meet. Developers should be informed about the issues associated with correlations of uncertainty so that this issue will be recognized, at least, in model preparation. The Steering Committee recommends that hazard map developers specify essential criteria for all types of component models, including ground motion simulations, deformation models, earthquake rupture forecasts, basin velocity and amplification models.

Orderly procedure for model updates

Echoing the recommendation of the ERF panel (Jordan et al., 2023), a good procedure is to create a “research model”, which could also be referred to as a “development model”, in which new data, methods, or component models are continuously being implemented, evaluated, and tested in uniquely identified versions. This is in contrast to the “policy model” that is the formally reviewed model for use by stakeholders. The research and policy models should be clearly distinguished. Ideally, all new models/data/research should be implemented first in the research model for testing and review. A research model that meets all the characteristics of best available science and that meets the Popper criteria is a candidate for being implemented into the policy model in the next revision.

A common theme of all reviewers was that more time was needed for review of the models. Future review panels should be formed and should begin interaction with component developers at least several months to a year in advance of initial deadlines. The complete NSHMP timeline should thus include explicit goals and deadlines for conceiving, implementing, and testing all contributing components of the ERF and the GMC models in research models. The timeline should explicitly allow adequate time for initial review, revision, documentation, and secondary review. Additionally, the update process should include a well-specified review schedule for the content of hazard estimates produced by a policy model. This may include initial results such as ground motion hazard curves for specified locations, and regional and national hazard maps for varying exceedance rates and various ground motion intensity metrics. Maps should ideally include results with uncertainties. USGS currently provides ratios and differences of results relative to alternate models (e.g., prior NSHM releases, or with and without a particular model component update), which is good practice. Development of this plan would help with scheduling of model development and would aid in systematically review by the review committees and users.

Recognition of knowledge gaps and uncertainty sources, and prioritization of future research to reduce those gaps

Subsequent recommendations include determining the total uncertainties and also component contributions to those uncertainties in the final hazard estimates. A consequence of that process should be the ability to recognize the knowledge gaps and the relatively important sources of uncertainty in the model. This information should be used to prioritize future research, both internal and by external scientists, to reduce the uncertainties.

3.4 (D) Verified and Reproducible

The NSHM and all of the contributing component models should be fully verified and reproducible. These properties should be supported by openly available data and computer codes. This critical characteristic is essential to achieving transparency and openness (NRC 2004), and is explicitly recognized as essential to the integrity of scientific research by NASEM (2017, 2019). Following the NASEM report, verification and reproducibility are closely related. According to NASEM (2019), verification "*confirms the correctness of the model by checking that the numerical code correctly solves the mathematical equations*" while reproducibility "*means computational reproducibility—obtaining consistent computational results using the same input data, computational steps, methods, code, and conditions of analysis*". The intent of this criterion is to assure that the NSHM is uniquely defined, and completely reproducible.

3.5 (E) Validated Component and Final Models

A hierarchy of component models are developed and implemented to generate the hazard curves in the NSHM. For example, geological observations on individual faults include field mapping, trenching, measuring offsets of prehistoric earthquakes, and dating of geological materials. Correlation models use these observations to estimate magnitudes of the past events while dated stratigraphy is used to estimate their frequency of occurrence. Geodetic observations measure the slow, continuous movements of the surface. Deformation models based on these observations estimate slip rates on mapped faults, and in the future may also be used to constrain the rates of more diffuse deformation between mapped faults. Seismicity-based earthquake location and occurrence rate models are estimated from seismicity catalogs. Earthquake rupture forecasts, the main component at the top of the seismicity model hierarchy, combine these studies to model the future locations, magnitudes, and rates of earthquakes. Ground motion models depend on an equally complex hierarchy of observations and components.

All component models must be carefully validated. Component results are propagated, through the robust mathematical model, to the final NSHM hazard curves. Uncertainties need to be carefully recognized, quantified, and propagated to the extent possible. After they are combined into hazard curves in the NSHM, the hazard curves are in general difficult to compare with data, as they are estimating ground motions that are very rare compared to the observational interval. There should also be efforts to validate the final hazard curves to the extent possible (e.g. Stirling and Petersen, 2006, Daxer et al., 2022; Petersen et al., 2023).

Complexity in component validation

Sometimes, when a new model is compared with an old model, the results are not uniformly better. It can happen that the new model is better in some aspects, but not as good in other aspects. For instance, a new ground motion model might do a better job of matching the available data in one region, but perform poorly in another. In other words, the Popper criterion is not completely met. Dealing with this type of issue requires the professional judgement of relevant experts. USGS decisions on how to handle these situations should be reviewed by the model developers and independent experts. Time should be allocated in the model development and review process for these evaluations, and early experimentation with the model in a research version should provide initial insights to guide validation.

Retiring old components

A model component (e.g. a ground motion model) that was used in a previous version of the NSHM may need to be retired. On the other hand, retaining older models within the logic tree can provide some stability in the estimates of the mean hazard – a feature that is desired by many users of the NSHM.

The Steering Committee suggests that older models be retired when they are superceded by a newer study meeting the Popper and best available science acceptance criteria and developed by the same modeling team. In other cases, the basis should be the quality of fit to data, not age of the model. Another criterion is whether the model makes a unique contribution to defining the body and range of the uncertainty in the hazard estimates, in which case a demonstration that some data are better fit by that model is needed. Stability in mean hazard estimates is not by itself a scientifically defensible criterion.

3.6 (F) Replicable Within Uncertainties

NASEM (2019) recognizes replicability, a characteristic closely related to validation, as a second essential characteristic of scientific studies that have a significant impact on public policy. NASEM (2019) defines validation as "*the process of deciding whether a model replicates the data-generating process accurately enough to warrant some specific application, such as the forecasting of natural hazards*," and defines replicability *"to mean obtaining consistent results across studies aimed at answering the same scientific question, each of which has obtained its own data*". Quantification of uncertainty in the data is essential for developing and validating components. In contrast, quantification of uncertainty in the model prediction is essential for replicability, as it is not possible to decide if independent studies are consistent without knowing the uncertainties in the results.

The essential role of reporting uncertainties is recognized by several of the sources addressing the characteristics of best available science. NRC (2004) states "*Scientific reports should explicitly identify the level of uncertainty in results, provide explanations of the sources of uncertainty, and assess the relative risks associated with a range of management options.*" OECD (2014) states "*As a general rule, scientific advice should include assessment and clear communication of uncertainties (or probabilities).*" NASEM (2019) includes the following: "*RECOMMENDATION 5-1: Researchers should, as applicable to the specific study, provide an accurate and appropriate characterization of relevant uncertainties when they report or publish their research. Researchers should thoughtfully communicate all recognized uncertainties and estimate or acknowledge other potential sources of uncertainty that bear on their results, including stochastic uncertainties and uncertainties in measurement, computation, knowledge, modeling, and methods of analysis.*"

Thus representation of the uncertainty is an essential component of PSHA. The mean hazard is the best estimate of the seismic hazard, but it does not represent the complete hazard analysis. Without epistemic uncertainty, the NSHM is incomplete. Determining the uncertainty is a non-trivial problem. One source of difficulty is the complexity of the logic tree, in which different regions are modeled differently. Another is the question of how uncertainties are correlated. These issues are discussed in greater detail by Jordan et al. (2023).

There are multiple ways of reporting uncertainty. A national perspective can be presented by mapping the standard error, as is done in Italy (Meletti et al., 2021) and New Zealand (Gerstenberger et al., 2022b), or selected fractiles from the set of hazard curves (e.g. Mezcua et al., 2011). For representative locations, it is informative to show the full set of hazard curves as obtained from the logic tree, and/or develop tornado plots, so that the important sources of uncertainty are identified (e.g. Molkenthin et al., 2017). No matter the style of uncertainty reporting, it should be done in a manner such that the contributions of the components to total uncertainty can be identified.

Uses of Uncertainty

Most uses of the NSHM focus on the mean hazard, in part because that is all that has been available in the past. Users should nonetheless be reminded that the uncertainty is an important component of the model.

The following are some possible uses of uncertainty.

1. Comparison with other seismic hazard studies, and thus enabling testing the replicability of the results.

2. Comparison with data from ground motion recordings, felt intensities, and fragile geologic features, enabling validation of the results (e.g., Baker et al., 2013).

3. Checking whether the new estimate of the hazard is significantly different from the prior estimate. Differences of only a small fractile in mean hazard might be considered too small to be a basis for changing a building code, for instance.

4. Uncertainty can be considered in the design of important and critical facilities.

5. Communication of the potential for hazard estimates to change in the future, depending on the size of the uncertainties and the outcome of future studies.

6. Targeting research to focus on model components identified as important contributors to uncertainty, with the goal of improving future maps.

3.7 (G) Peer Review

All of the recommendations for best available science require thorough, rigorous, unbiased peer review.

The NRC (2004) proposed guidelines for peer review. They recommended an "explicit and standardized peer review process". They recognize the need for flexibility to adapt for individual circumstances. They identify four key elements that should be included. One is specific to fishery applications. The general three are:

- *the review should be conducted by experts who were not involved in the preparation of the documents or the analysis contained in them;*
- *the reviewers should not have conflicts of interest that would constrain their ability to provide honest, objective advice;*
- *all relevant information and supporting materials should be made available for review;*

The specific element is this:

> *a peer review should not be used to delay implementation of measures when a fishery has been determined to be overfished.*

This latter specific recommendation recognizes, and allows, that there are some circumstances when the peer review process may be justifiably and appropriately abbreviated in order to achieve other important objectives. Peer review is necessary for all elements of the NSHM, but an abbreviated process can be allowed to accommodate significant late-breaking science. This should, however, be the exception rather than the rule.

In practice, the USGS encourages reviewers, including the review panels and the SC, to interact with the USGS, potentially closely, for the good of the hazard model. The USGS recognizes that there may be some degree of conflict of interest for such a participatory peer review, but since these committees are advisory rather than decisional, such conflicts are manageable.

A key aspect of the peer review process, as indicated previously, is that it should start early and that adequate review time should be built into the project timeline. Reviews for updated components should be organized when that update is nearing completion, and ideally coordinated with its testing in a research model.

3.8 (H) Permanent Documentation

Thorough, permanent documentation of all results and uncertainties, and public access to this documentation, is essential to transparency and openness. The discussion of verification and reproducibility (Criterion D) has already noted that all data and methods should be readily accessible to the public. The NRC (2004) notes that transparency extends to results to all findings. The report states that "All *scientific findings and the analysis underlying management decisions should be readily accessible to the public. The limitations of research used in support of decision making should be identified and explained fully.*"

The NSHM is a large and complicated model, and it is not possible for all of the results to be compressed into peer-reviewed journal articles. Publication of main results in peer-reviewed journals should of course be continued, as a critical method of informing the larger community of earthquake professionals about the new models. In addition, the more detailed results should be available in permanent digital archives, and version numbers should be utilized to enable clear association of model versions with results and publications. Comprehensive results such as these need to be preserved in permanent archives under the control of the USGS.

4.0 CONCLUSIONS

The goal of these recommended characteristics of best available science is to assure the public and all users of the NSHM that the model has been developed using the best available science. Implementing all of these recommendations will require significant resources. The contribution of NSHM to the safety and resilience of the people of the U.S.A. justifies that effort.

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