Guidance on the Utilization of Earthquake-Induced Ground Motion Simulations in Engineering Practice

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This paper summarizes developed guidance on the utilization of earthquake-induced ground motion simulations for engineering practice. Attention is given to the necessary verification, validation and utilization documentation in order for confidence in the predictive capability of simulated motions to be established. The construct of a ground motion simulation validation matrix is developed for assessing the appropriateness of a particular suite of simulated ground motions from the perspective of region-to-site-specific application and for different specific engineering systems. Appropriate validation metrics and "pass" criteria, the consideration of modeling uncertainties, and limitations associated with a relative lack of validation data are also addressed. An example is utilized in order to demonstrate the application of the guidance. This document is intended to be bidirectional in the sense that it provides guidance for earthquake engineers on the appropriateness of a suite of ground motion simulations for utilization in a site-specific context, as well as ground motion simulators to understand the context in which their results will be utilized. [DOI: 10.1193/120216EQS219EP]

INTRODUCTION

Earthquake-induced ground motion simulation methods have seen rapid advances over recent years, to the point where their practical utilization is now a significant consideration in both scientific and engineering communities. Simulation-based methods—which explicitly incorporate physics associated with earthquake fault rupture, wave propagation, and surficial site response—have clear conceptual benefits over empirical ground motion models based on worldwide data from historical earthquakes. However, their practical utility is strongly dependent on the appropriateness of the earthquake rupture and three-dimensional (3-D) crustal models that are inputs in such calculations. Verification and validation are the principal means by which the predictive capability, and thus practical utility, of ground motion simulation methods and their implementation can be assessed (Oberkampf et al. 2002).

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Recognition of the utility of ground motion simulations has led to continued efforts in their development and validation (Boore 2003, Graves 1993, Graves et al. 1998, Graves and Wald 2004, Hartzell et al. 1999). More recently, larger coordinated efforts to verify and validate broadband ground motion simulation methods have occurred under the auspices of the Southern California Earthquake Center (SCEC) through the Broadband Platform (BBP) validation exercise (Dreger and Jordan 2015) and technical activity group on ground motion simulation validation (GMSV; Luco et al. 2013). Validation efforts associated with the SCEC BBP focused on the comparing median spectral acceleration predictions using one-dimensional (1-D) crustal models for four simulation methods (Anderson 2015, Atkinson and Assatourians 2015, Crempien and Archuleta 2015, Graves and Pitarka 2015, Olsen and Takedatsu 2015) against both recorded ground motions from historical earthquakes in different geographic regions, as well as against empirical ground motion models for scenarios (e.g., magnitude and source-to-site distance ranges) in which there is an abundance of recorded data. Validation efforts within SCEC GMSV have largely focused on the validation of simulated ground motions using other intensity measures (*IM*s; e.g., Burks and Baker 2014, Rezaeian et al. 2015), as well as nonlinear structural systems (e.g., Galasso et al. 2012, Galasso et al. 2013). Additionally, several other goodness-of-fit criteria have been suggested (Anderson 2004, Olsen and Mayhew 2010) by which the predictive capabilities of ground motion simulations may be measured. The number and diversity of these activities indicate the utility of validation activities, and point to the diversity of potential uses of ground motion simulations.

While the aforementioned validation efforts are necessary, they do not directly provide guidance on the practical utility of simulated motions in engineering practice. In particular, practicing engineers consider specific ground motion features, and simulations have varying predictive ability, considering geographical variations in the quality of rupture and 3-D crustal models. This paper provides explicit guidance on the utilization of ground motion simulations for engineering practice, building upon existing methods for verification and validation. The following sections provide an overview of the key ground motion simulation ingredients, the specific simulation features of relevance for engineering utilization, recommended documentation for verification and validation, and finally illustrative applications. Additional contextual material, examples, and information on the regulatory context in which ground motion simulations can be applied are available in an underlying QuakeCoRE research report (Bradley et al. 2016b).

OVERVIEW OF KEY GROUND MOTION SIMULATION INGREDIENTS

In the following subsections, the primary ground motion simulation "ingredients" are described to provide context to subsequent discussions on verification, validation, and utilization documentation.

The principal differences between the wave propagation methods revolve around the treatment of wave propagation physics. In this regard, methods can be classified along a continuum, which ranges between: (1) *comprehensive physics*: The explicit solution of the conventional 3-D wave equation; and (2) *simplified physics*: Methods that simplify the 3-D wave equation, often by considering propagation in 1-D, with various semi-empirical components which capture the essential features of the earthquake source, path and site effects. A critical factor in the numerical solution of the 3-D wave equation with comprehensive physics is that the maximum frequency that can be modeled is a function of the model spatial resolution (i.e., grid spacing). Doubling the maximum frequency of the simulation generally results in an $2^4 = 16$-fold[1] increase in computational demands. Even on high-performance computers, routine application of physics-based simulations for high frequencies is not presently practical.[2] As a result, the physics-based approach is usually adopted for the simulation of low frequency, ground motion, and then combined with high frequency simplified physics modeling—such methods are referred to as hybrid ground motion simulation methods. It is presently common for $f = 1$ Hz to represent the low/high transition frequency, but this is increasing over time with greater computational resources and scientific understanding of the earthquake source and earth's crust at shorter length scales.

The earthquake source rupture represents the initial disturbance in the wave propagation problem that leads to simulated ground motions. In general, information related to the rupture geometry (e.g., length/width, strike/dip), kinematics (e.g., spatial and temporal variation in slip amplitude), and dynamics (e.g., fault constitutive properties and initial stress conditions) are required. The specific manner by which the earthquake source is characterized is a function of the earthquake source rupture representation. In a dynamic representation of the fault rupture (Harris et al. 2009), these dynamics are obtained by solving a nonlinear rupture propagation problem requiring definition of the stress conditions on the fault and the stress-strain constitutive behavior of the fault itself. In the so-called kinematic rupture representation (Graves and Pitarka 2016, Graves and Pitarka 2010, Mai and Beroza 2002), the dynamics of the rupture are pre-defined in a parameterized fashion. Kinematic representations are the most common in present ground motion simulations, because of their lower computational burden, and because realistic dynamic rupture modeling is still a developing research topic (Anderson 2015, Atkinson and Assatourians 2015, Crempien and Archuleta 2015, Graves and Pitarka 2015, Olsen and Takedatsu 2015). Such kinematic methods are however generally pseudo-dynamic in that they are informed by on-going research into rupture dynamics.

The crustal model provides the 3-D variation of geophysical and geotechnical parameters that are required in the wave propagation calculation. The principal parameters to describe the model are the P- and S-wave velocities, density, and anelastic attenuation, $[V_p, V_S, \rho, Q_p, Q_s]$—additional parameters are needed if nonlinearities are considered (e.g., Roten et al. 2012). These properties are inherently region-dependent, and the explicit modeling of sedimentary basins (Aagaard et al. 2008, Delorey et al. 2014, Graves et al. 1998, Taborda and Bielak 2014) is critical to enable ground motion simulations at frequencies that are of engineering interest ($f = 0 - 100$ Hz).

While modeling of near-surface site response can be broadly considered part of the 3-D crustal modeling, the significant effects of nonlinear near-surface site response at high

[1] As a result of three spatial dimensions and the use of explicit time integration which requires a decreasing time-step for decreasing spatial discretization.

[2] There are also limitations in our current ability to resolve the 3-D crust and fault rupture at the short length scales required for high frequency simulations, with the use of stochastic methods providing a statistically consistent approach in the interim.

frequencies are well documented via observational data. The modeling of site response in ground motion simulation methods is generally performed as an additional module in one of two manners based on simulated ground motions at some reference site condition. The first is based on simple empirical site response amplification factors (based on the 30-m averaged shear wave velocity) that are applied to the Fourier spectral amplitudes of the reference condition simulated motion (Graves and Pitarka 2010). The second is explicit modeling of near-surface site response via numerical simulation, which may include plasticity-based soil constitutive models that consider excess pore water pressure generation, deformations in multiple translational directions (Cubrinovski and Ishihara 1998, Ziotopoulou and Boulanger 2013), and topographic modeling (Hartzell et al. 2014).

GROUND MOTION FEATURES OF RELEVANCE FOR ENGINEERING OBJECTIVES

When considering use of simulated ground motions, it is important to identify the engineering objectives of the problem under consideration (i.e., the specific structural or geotechnical system of interest), specifically, the manner in which simulations will be utilized. There are also several high-level features that the simulated motions may or may not need to possess, such as those related to the generation of multiple ground motion components at one or more spatial locations, the usable frequency range, consideration of nonlinearity, and the treatment of modeling uncertainties. This overarching objective and subsequent simulation features are addressed in the following sections.

USE OF SIMULATIONS FOR HAZARD ANALYSIS OR RESPONSE HISTORY ANALYSIS

Simulated ground motions can be utilized in two principal ways for engineering design and assessment as illustrated in Figure 1: (1) For ground motion prediction as part of seismic hazard analysis; and/or (2) As input ground motion time series for use in response history analysis. In both situations, ground motion simulation can offer benefits over conventional practice using empirical ground motion models, and recorded ground motions from global databases.

The potential benefit of using simulated ground motions in seismic hazard analysis (left-hand side of Figure 1) in place of empirical models is the site- and region-specific features that simulations can include, which are not incorporated explicitly into empirical models[3] (Rodriguez-Marek et al. 2011).

The potential benefit of using simulated ground motions in response history analysis (right side of Figure 1) in place of recorded ground motions is that simulations can be produced for earthquake conditions that are not well recorded. Specifically, large-magnitude earthquakes at close distances to the site of interest are often of primary interest in seismic active regions, but there are few such recordings of ground motions under these conditions.

[3] Even non-ergodic modifications to empirical models often cannot account for such site- and region-specific details because of insufficient observational data at intensities of primary interest.

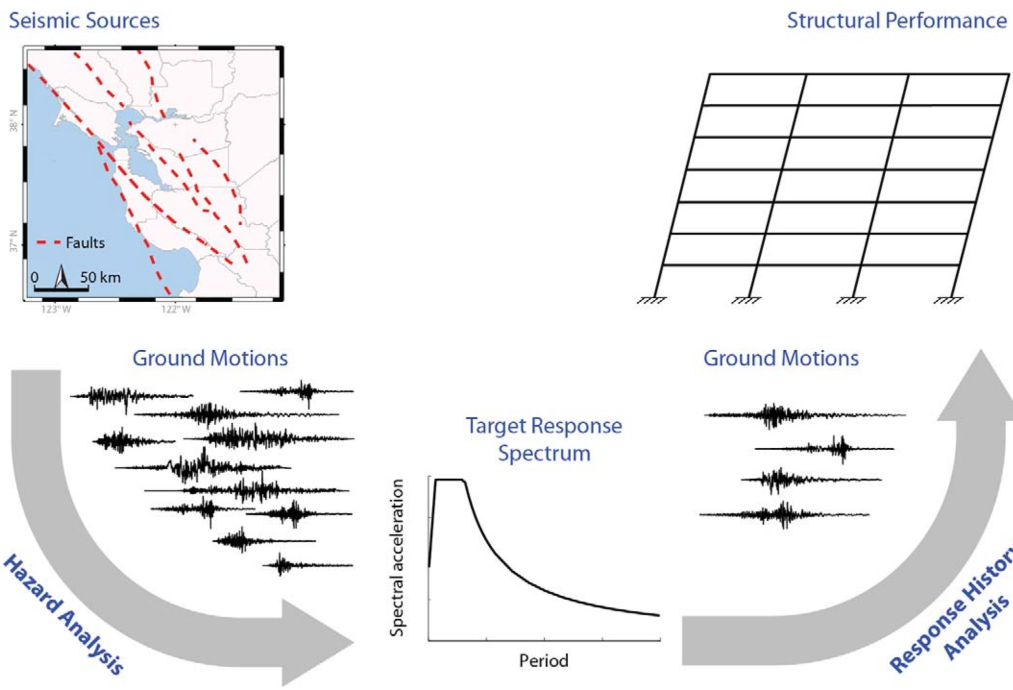

Figure 1. The two principal means for the utilization of simulated ground motions: (a) in the ground motion prediction-portion of seismic hazard analysis to determine design ground motion parameters (e.g., design response spectra); and/or (b) as input ground motion time series in dynamic response history analyses.

While it is conceptually straightforward to use the same ground motion simulations for both hazard analysis and response history analysis (Bradley et al. 2015a), in engineering practice the two steps are decoupled, and from a validation perspective a simulation algorithm may be identified as suitable for only one of the two steps. Thus, it is useful to retain the option to use differing approaches for the two steps.

The two distinct uses of simulated ground motions affect the validation needed to build predictive confidence as follows:

1. For use in hazard analysis, simulation methodologies need to demonstrate that they can provide an accurate and precise prediction of ground motion *IM*s from future earthquake events that are likely in the region of interest – thus the validation requires comparison with observed ground motions from historical earthquakes[4] (so-called historical earthquake validation).

[4] As well as potentially comparisons with empirical models for well-constrained conditions (e.g., moderate magnitude events recorded at moderate distances), which in essence is a comparison against an average of observed ground motions from historical events in lieu of comparisons on an event-by-event basis.

2. For use in response history analysis, simulation methodologies need to demonstrate that simulated motions compatible with target design *IM*s (e.g., a target spectrum) produce consistent results with those from appropriate as-recorded ground motions. In the case of a response spectrum being the target *IM*s, this approach is sometimes referred to as similar spectra validation.

MULTI-COMPONENT AND MULTI-SITE GROUND MOTIONS

Ground motion excitation is generally described in the form of translational motion in three orthogonal components. Not all simulation methodologies produce records with the correct amplitude and phasing across these multiple components. The differentiating factor in this regard is usually whether the methodology solves the 3-D wave equation directly or not. Direct solution methods will generally produce time series that contain amplitude and phase correlations across multiple components, whereas simplified methods generally do not. Some hybrid ground motion simulations methods may therefore have appropriate multi-component amplitude and phasing at low frequencies, but not at higher frequencies. Adequate consideration of multi-component amplitude and phase correlations is important for structural and geotechnical systems that have significant coupling between their vibration modes in orthogonal directions (resulting from torsional response, corner columns subject to bidirectional ground motion, etc.), and thus the predictive capability of simulation methods to capture these phenomena should be quantified using validation metrics (e.g., via orientation-dependent measures of ground motion intensity; Boore 2010, among others). Additionally, while some methods provide three coupled orthogonal translational motions, very rarely are ground motion simulations validated in terms of their vertical component predictions, and thus extra care should be exercised on the predictive capability of vertical component simulations using methods at the present time.

Issues of correlation apply to simulated ground motions across multiple sites. Such consideration is of particular importance for both spatially distributed infrastructure, as well as portfolio risk assessment problems where spatially isolated structures exist at a multitude of locations. For cases in which multi-site ground motions are of interest, validation metrics should confirm that the simulations provide predictions that are consistent with observations (e.g., via spatial correlations of ground motion *IM*s; Jayaram and Baker 2009, Loth and Baker 2013).

RELEVANT IMS AND USEABLE FREQUENCY RANGE OF SIMULATIONS

While all ground motion simulation development has the same end-goal of realistically simulating all of the salient aspects of the ground motion waveform, varied development efforts and inherent features mean that each simulation methodology has differing fidelity as a function of the ground motion *IM*s of interest. The topic of *IM*s of interest is discussed further in a later section, but one aspect which effects this discussion in a first order manner is the maximum useable frequency of a particular suite of simulations.

The maximum useable frequency in ground motion simulations is controlled directly by the spatial (and to a lesser extent the temporal) discretization in the adopted numerical methods, and is proportional to the computational resources available for a particular simulation calculation. Indirectly, the maximum frequency to which simulations will provide a realistic representation of salient ground motion characteristics is a function of the ability for the adopted crustal and earthquake source models to represent reality at the necessary small length scales. As a result of these constraints, not all simulated ground motion time series are useable over the same broadband of frequencies that are of common engineering interest ($f = 0-100$ Hz).

Users of ground motion simulations should have an explicit understanding of the maximum useable frequency of the simulations (and also the validity of the simulations as a function of frequency). For example, stiffer structures will need an accurate representation of high frequencies. More flexible structures will be sensitive to lower frequencies, however, they often have higher modes of response which will be important for some seismic response metrics (such as floor accelerations and shear forces, for example). Further, when nonlinear inelastic response is of interest (as is typically the case if one is performing dynamic response history analyses), low frequency shaking beyond the (elastic) fundamental vibration period will influence response (Akkar and Bommer 2006, Boore and Bommer 2005).

TREATMENT OF MODELLING UNCERTAINTIES

The necessity for ground motion simulations to explicitly account for modeling uncertainties is principally a function of whether they are intended to be used directly for the definition of seismic hazard (left side of Figure 1) or simply for providing a database of prospective ground motions for use in response history analyses once scaled to a target spectrum (consideration of uncertainties being much more important for the former case). While a detailed discussion of uncertainties in ground motion simulations is beyond the scope of this document (and is also method-dependent), such uncertainties exist in the representation of the seismic rupture, 3-D crustal, and near-surface site models. Such uncertainties are present in directly measured quantities, in adopted empirical correlations of constitutive model parameters, in assumed constitutive models themselves, and in the global nature of the equation of motion and assumed initial and boundary conditions. Most importantly, if explicit treatment of modeling uncertainties in ground motion simulation is of importance, then it is necessary that validation metrics are considered that directly quantify the appropriateness of the resulting uncertainty in simulated ground motion *IM*s.

RECOMMENDED DOCUMENTATION

Developing confidence in the predictive capabilities of ground motion simulation methods (and computational science methods in general) requires systematic processes of verification and validation to be undertaken and documented. In addition, the actual utilization of ground motions also requires additional utilization documentation which states both the details of the simulations that have been performed, as well as the manner in which they will be utilized.

It is important to note that the application of the guidance in this document is not restricted to the use of simulation-based ground motion models; on the contrary, it is also encouraged for empirical ground motion models. Furthermore, given the conventional use of empirical models in seismic hazard analysis, relative comparison of the predictive capabilities of physics-based ground motion models against observations as compared to that from empirical counterparts provides the necessary pass criteria that simulation methods need to demonstrate in order to gain widespread acceptance, particularly for use in hazard analysis (Figure 1).

As with any computational analyses, confidence in the results of the analysis can be developed through demonstration of the fidelity of the adopted methodology, including the validity of the various input models and parameters for the specific problem considered, and documentation of its implementation. Figure 2 provides a schematic illustration of the three general phases in computational modeling and simulation. A detailed discussion of verification and validation as a formal process for developing predictive capability in computational modeling is provided in Oberkampf et al. (2002). The following three subsections provide a high-level overview of the intended terminology of verification, validation, and utilization documentation in the context of ground motion simulation.

VERIFICATION

As noted in Figure 2, software programming and numerical methods are used to take a conceptual (i.e., mathematical) model and develop an implementation of this model for computational analysis. In its simplest form, verification is the assessment of the accuracy of the solution of the computational model. That is, verification is needed to ensure that there are no programmatic errors (i.e., bugs) in the code that implements the methodology, and also that the numerical methods are suitable (e.g., convergence) for the problem being considered. Obvious means by which to verify a computational algorithm are via comparison with known analytical solutions. This process is useful for verification of the various software components/subroutines of a ground motion simulation code, and for verification against simple wave propagation problems that have analytical solutions. However, since seismic wave propagation codes are ultimately utilized for solving problems with no analytical solutions, then the comparison of the results obtained from different computational codes (e.g., those developed and maintained by different groups) can often provide significant additional benefits. Examples of such inter-group verification exercises include Day et al. (2001, 2003, 2005), Bielak et al. (2010) and Maufroy et al. (2015).

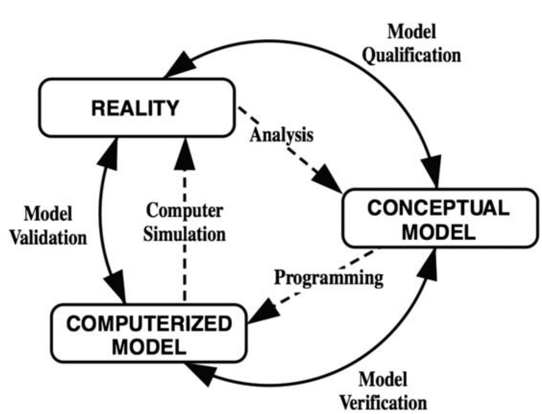

Figure 2. Phases in computational modeling and simulation and the role of verification and validation (after Oberkampf et al. 2002).

It is generally expected that a ground motion simulation code to be used in engineering practice would have undergone the following verification steps:

1. The code provides solutions to canonical problems that converge to the analytical result as the discretization increases.
2. For problems without analytical solutions, numerical solution by alternative methods and codes can be used as benchmarks.
3. Verification problems are performed on each computational resource that the code is deployed on, to ensure consistency of results across computational platforms.

Adequate verification is a critical step for implementation of existing simulation codes on new computational resources, and for the development of new methods. However, it is also important to note that for verification problems without analytical solutions, complete asymptotic convergence of numerical solutions from different methods or algorithms is unnecessary. In this regard, it is important to note that prior comparisons of independently developed computational codes have illustrated that the inter-code differences are small relative to the differences between simulations and observations, as evident via ground motion validation (Maufroy et al. 2015).

VALIDATION

As shown in Figure 2, the simulation of a (verified) computational model is used to provide a prediction of reality. Validation assesses whether a computational simulation is representative of reality as measured using experimental observations (ground motion observations being the result of natural experiments). Unlike verification, which is a computer science and mathematical modeling problem, validation is a physics problem: Does the conceptual model actually represent reality? Because complex phenomena such as earthquake-induced ground motions naturally involve a multi-faceted array of physical processes, then ground motion simulation validation should occur in a hierarchical fashion in order to ultimately build predictive confidence in the simulation to predict a situation which has not been directly observed (i.e., prediction is inherently extrapolation). Given the nature of ground motion simulation methods, validation should generally address the following aspects needed for prediction:

1. The rupture generator used to prescribe the representation of the fault rupture, specifically for the magnitude range of interest.
2. The 3-D crustal model of the region of interest, specifically for the range of source-to-site ray paths that are of significance for the rupture and site of interest.
3. The near-surface site model at the location of interest.
4. The overall ground motion simulation methodology that utilizes the rupture, crustal and near-surface site conditions as input models.
5. Quantitative metrics that, collectively, provide an adequate assessment of ground motion severity for the particular engineered system(s) that the simulations are intended for.
6. Examination of the probabilistic prediction provided by the ground motion simulation methodology as a result of modelling uncertainties.

In the context of validation, the following subsections focus on the intended usage of the simulations, a validation matrix to graphically illustrate the hierarchical validation process and its links to simulation inputs and methods; metrics to quantify predictive capability and what constitutes adequate validation; modeling uncertainties; and limitations resulting from a relative lack of validation data.

Intended Usage of Simulations

The attention to detail for each possible aspect of validation requires specific consideration of the manner in which the simulations will be utilized, which, as discussed with reference to Figure 1, can generally be considered as being either for hazard analysis or response history analysis.

To understand the required simulation validation for hazard analysis, it is useful to consider the manner in which (probabilistic) seismic hazard analysis is performed. The seismic hazard curve is generally expressed as (Bradley et al. 2015a):

$$\lambda_{IM}(im) = \sum_{k=1}^{N_{Rup}} P_{IM|Rup}(im|rup_k, Site)\lambda_{Rup}(rup_k) \quad (1)$$

where $\lambda_{IM}(im)$ is the seismic hazard curve at the site, describing the rate at which the ground motion IM, $IM \geq im$, is exceeded; $\lambda_{Rup}(rup_k)$ is the rate of rupture rup_k; $P_{IM|Rup}(im|rup_k)$ is the probability that $IM \geq im$ given rup_k; and the summation occurs over all possible earthquake ruptures affecting the site. From Equation (1) it can be seen that the utilization of ground motion simulations for hazard analysis requires that they provide an adequate description of the distribution of $IM|Rup$ – specifically, they must contain an appropriate representation of uncertainty.[5] Because we are generally also interested in more than a single measure of ground motion intensity, it is actually the distribution of a vector of IMs given an earthquake rupture, $\boldsymbol{IM}|Rup$, that is of interest.

Considering validation of ground motion simulations for response history analysis, we refer to the set of response spectral amplitudes which define the design ground motion more generally as $\boldsymbol{IM}$, and the resulting distribution of a vector of different seismic response measures as engineering demand parameters, $\boldsymbol{EDP}$. Then $\boldsymbol{EDP}|\boldsymbol{IM}$, is the principal variable by which simulated ground motions for use in response history analysis should be validated.

In this engineering analysis context, the two cases of simulation utilization ($\boldsymbol{IM}|Rup$ and $\boldsymbol{EDP}|\boldsymbol{IM}$) are largely orthogonal. That is, in the first, it is the prediction of the appropriate distribution of intensities that is of interest, whereas in the second, ground motions are utilized that already have appropriate intensities. Despite this separation, validation and subsequent simulation improvements in each are likely to have positive spill-over effects to the other. It is also noted that while the notions of $\boldsymbol{IM}$ and $\boldsymbol{EDP}$ are useful for validation and in some prospective prediction cases, they are not a necessity – the use of simulated ground

[5] It is also possible that ground motion simulation insights can be used to constrain the functional form used in empirical ground motion models, in which case the average trends in the simulations may be of principal importance, but this case is not discussed in detail here.

motion time series does allow for the direct determination of seismic response at a site for a given earthquake rupture without the need for the intermediary variable ***IM***, for example.

A Graphical Matrix for Ground Motion Simulation Validation

Simulation validation needs to evaluate the predictive capabilities of the overall simulation methodology (i.e., physical assumptions), as well as the input parameters and models. For ground motion simulation, in particular, the adequacy of input models describing the source rupture, 3-D crustal structure, and surficial site conditions are themselves complex and regionally varying. As a result, the predictive capability of ground motion simulations is region- and even site-specific. Furthermore, ground motion time series are complex transient signals, and the ability of simulations to adequately reproduce the salient features of these signals varies depending on which aspect is of particular interest. The engineering representation of ground motion severity generally refers to different ground motion *IM*s, which collectively represent ground motion severity. Some *IM*s are ubiquitous, such as elastic response spectra; some are seeing increasing awareness and utilization (e.g., parameters representing the duration and cumulative nature of the motion); and others are problem-specific (e.g., induced displacement response of a specific building typology).

Figure 3 provides a graphical validation matrix of the spatial- and *IM*-dependence of ground motion simulation validation as alluded to in the previous paragraph. The vertical axis represents the transition from generic through to site-specific locations where simulated ground motions are desired, while the horizontal axis represents the complexity of *IM* metrics used to quantify predictive capability in validation. Both of these axes are continuous in nature, however, they are discretized here for practical application.

Before discussing specific intentions of matrix elements, we consider the overall aspects of the validation matrix in the context of the previous subsection. Figure 3 identifies three principal domains of the validation matrix in the context of intended utilization. The first being that if only qualitative validation is performed by comparing the nature of simulated and observed waveforms then those simulations are not appropriate for utilization in practice – quantitative validation is essential. In the context of seismic hazard analysis, in which an accurate and precise prediction of the distribution of $\boldsymbol{IM} \mid Rup$ is needed, the specifics of the particular region and site of interest are essential components. Therefore, simulation methodologies that have been validated using only data in generic[6] (i.e., other) regions would not be considered appropriate for use in determining the seismic hazard at another region/location at which no specific validation has been performed. Ground motion simulations undertaken in generic regions that have been validated would, however, still provide simulated time series that could be utilized for response history analyses once scaled to the target design ground motion intensity, ***IM*** (this is similar to the current conventional use of as-recorded ground motions from past worldwide earthquakes for response history analysis).

The emphasis for validation in the context of the discretization of the vertical axis of the validation matrix is summarized in Table 1. There is a natural tradeoff between the volume of

[6] "Generic" is used herein to indicate a lack of development towards a specific application, as opposed to "general" which connotes broad applicability.

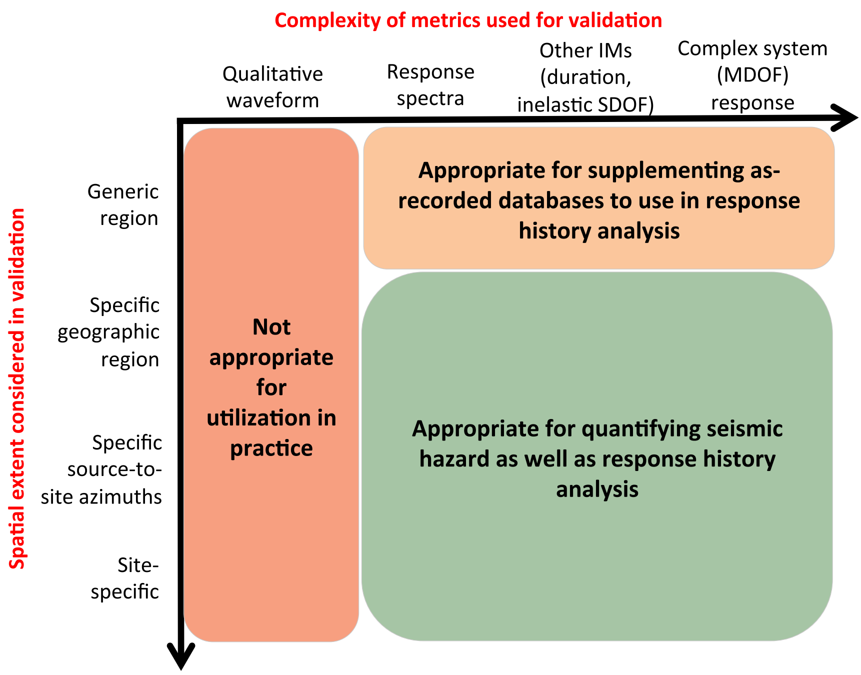

Figure 3. Ground motion validation matrix and relation to the intended usage of ground motion simulations. The vertical axis indicates the increasing spatial resolution from generic to region and site-specific validation. The horizontal axis indicates the increasing complexity of IM metrics used in quantifying simulation validation, which is a function of the specific engineered system considered.

data that is available for validation and the size of the geographical region considered in collating such data. Therefore, simulation aspects that are not specific to the particular geographical region (and specific site) of interest can draw upon significantly larger datasets. In using validation data from such generic regions (row 1 of the validation matrix), the focus naturally turns to the overall wave propagation methodology and the rupture generator. Validating the overall simulation methodology and rupture generator is critical before region- or site-specific ground motion simulations are attempted, and an appropriately high passing criteria is warranted here to ensure that these subsequent validation efforts are instructive.

When moving to the specific geographic region of interest (row 2 of the validation matrix), the total amount of validation data available can drastically reduce (particularly in regions of relatively low seismicity). Available observations should be utilized to validate, in a general sense, the crustal model for the particular region. Larger magnitude events, similar to those of interest for forward prediction, in this regional validation are obviously advantageous because of the greater number of strong motion records they will inevitably yield (which will allow examination of nonlinearities), as well as also enabling region-specific insights into the capabilities of the rupture generator beyond those obtained from its validation for generic regions.

Table 1. Emphasis in validation of ground motion simulation and its input models and parameters for each of the four discretizations in the vertical axis of the validation matrix

Spatial extent considered in validation	Focus of validation
Generic region	Overall wave propagation methodology, and the specific rupture generator and its scaling for small-to-large magnitude events
Specific geographic region	The regional 3-D crustal model and its ability to model ground motion *IM* metrics of interest
Specific source-to-site azimuths	Portions of the crustal model that are relevant for wave propagation from the rupture scenario to the site of interest
Site-specific	The shallow near-surface representation of soil deposits or weathered rock

The 3-D nature of crustal structure is known to result in significant direction-dependent wave propagation effects, and therefore beyond the regional validation of the crustal model there is a need to more explicitly examine the predictive capabilities of the crustal model for the specific source-to-site azimuths which will be relevant for the specific ruptures and sites of interest in the forward prediction problem (row 3 of the validation matrix). The increasing spatial constraints in this row of the validation matrix naturally further limit available validation data, and thus ground motion records from small-to-moderate magnitude earthquakes in the vicinity of the ruptures of interest are likely to be the most that is available. Such validation data may, as a result, be small amplitude ground motions, which are not able to assess any nonlinearity in the simulation methodology.

Finally, at the specific sites of interest there is a need to validate the representation of the local site conditions (row 4 of the validation matrix). The two key aspects in adequately modeling the site response are: (1) accurate characterization of the near surface soil conditions; and (2) an appropriate methodology by which site effects are modeled in the ground motion simulation. The direct means to do this would be via a strong motion downhole-surface pair of instruments at the site. If only a single surface instrument exists then site-specific response prediction can still be examined, although source and path effects, in addition to site response, will affect residuals between observations and simulations. If site-specific strong motion records are not available then the predictive capabilities of the site response methodology must be inferred based on the comparison of simulations and observations at other locations where such information is available (and uncertainties resulting from the application to the site of interest considered).

The emphasis of validation in the context of the discretization of the horizontal axis of the validation matrix is summarized in Table 2. Moving along this axis entails a transition from general *IM*s describing ground motion severity for all engineered systems toward measures that are specific to the subset of systems for the intended simulation utilization. Although qualitative comparison of ground motion waveforms is not sufficient for simulations to be utilized, it is mentioned in column 1 of Table 2 because there is still merit in such examinations in order to identify the appropriateness of gross assumptions regarding the rupture and

Table 2. Emphasis in validation of ground motion simulation and its input models and parameters for each of the four discretization's in the horizontal axis of the validation matrix

Complexity of metrics used for validation	Focus of validation
Qualitative waveform	Gross rupture and crustal structure representation
Response spectra	Overall (frequency-dependent) amplitudes
Other *IM*s (duration, inelastic SDOF)	Secondary aspects of the ground motions that affect many engineered systems
Complex system (MDOF) response	Tertiary aspects of the ground motions that affect specific types of systems

crustal structure representation (including as an efficient means to identify any programmatic errors in performing the validation calculations).

The use of response spectral *IM*s (column 2 of the validation matrix) is considered to be the principal means by which ground motion amplitudes can be primarily assessed because of their ubiquitous usage by engineers, and their relatively smooth variation with vibration frequency/period in relation to Fourier spectra (and thus they do not require smoothing with frequency). Because dynamic response of nonlinear inelastic multi-degree-of-freedom (MDOF) systems is dependent on factors beyond simply response spectral ordinates, then the third column of the validation matrix is focused on such secondary factors. Such secondary factors include: ground motion orientation-dependence (Bradley and Baker 2015, Shahi and Baker 2013), inelastic-to-elastic displacement ratios (Burks and Baker 2014, Tothong and Cornell 2006), correlations between response spectral amplitudes at different periods (Baker and Bradley 2016, Baker and Jayaram 2008); significant duration (Afshari and Stewart, Bommer et al. 2009), and cumulative ground motion *IM*s (Campbell and Bozorgnia 2010, Campbell and Bozorgnia 2012). While all of these secondary factors will have different degrees of importance for different specific systems, it is broadly recognized that they are important for a general characterization of ground motion severity.

Finally, the validation of simulated ground motions in the context of evaluating complex system (MDOF) response (column 4 of the validation matrix) provides an explicit means by which to assess tertiary aspects of ground motion time series for specific systems which are not completely captured via the primary and secondary *IM*s. Several past validation efforts have examined such aspects (Bijelic et al. 2014, Galasso et al. 2012), which are particularly relevant in the general usage of ground motion simulations for response history analysis (i.e., Figure 1 and Figure 3). The requirement for such MDOF validation for specific regions is onerous, and generally unnecessary for the usage of ground motion simulations for hazard analysis. Instead, it is more likely to be useful in a general academic context for evaluating simulation methodologies.[7]

[7] In general, moving from the left to right of the validation matrix corresponds to a progression from automated computation of validation metrics to a holistic interpretation of results in a general sense.

Validation Metrics and Pass Criteria

Quantitative simulation validation metrics are essential in order to compare and contrast simulation predictive capabilities relative to those in other regions, as well as to alternative empirical predictions in the same region. No specific validation metrics are endorsed in this document, because the document is intended to be agnostic to specific metrics that may evolve in the near future within the wider framework set out here. Nonetheless, several options for validation metrics are briefly described. The options principally pertain to assessment of simulated ground motions in the context of hazard analysis, but similar ideas are also transferrable to response history analyses using observed and simulated ground motions.

1. *Observed/simulated response spectra ratios:* It is common for simulation validation to focus on comparisons of the ratio of observed and simulated response spectra (at multiple vibration periods) at a set of strong motion station locations. Most such discussions focus on the mean of this ratio (Graves and Pitarka 2010), while Dreger et al. (2015) provide a slightly enhanced quantification of goodness-of-fit by quantifying the combined bias in the mean and scatter about the mean. One benefit of this simple spectral ratio approach is the ability to directly compare simulation and empirical ground motion model performance against validation data. Although not conventional, this approach should extend to *IM*s other than simply spectral accelerations that are relevant.
2. *Aggregated goodness-of-fit metrics:* Anderson (2004) and Olsen and Mayhew (2010) represent common examples of aggregated goodness-of-fit metrics which compare observed and simulated time series based on multiple criteria. One benefit of these approaches, relative to the above, is the simultaneous consideration of a multitude of *IM*s representing ground motion severity in the form of a single aggregated metric. A drawback of these two examples is that several of the measures considered do not have corresponding empirical ground motion models, and thus it is not possible to directly compare the performance of simulations as measured using these metrics with the alternative of using conventional empirical ground motion models.

Explicit Consideration of Uncertainties

Much focus in methodological development has centered on the predictive capabilities in an average sense (Dreger et al. 2015, Goulet et al. 2015) but utilization of ground motion simulations in seismic hazard analysis requires adequate representation of the complete distribution of ground motion *IM* metrics, and thus their validation should explicitly assess this distribution (e.g., Drouet and Cotton 2015, Villani and Abrahamson 2015). While comparison of simulation uncertainty with the apparent variability from empirical models can be insightful, it is not sufficient because that apparent variability is specific to the assumed empirical model functional form, and thus simulation uncertainty should be assessed directly against ground motion observations. Bradley (2011) provides a framework for validation, considering uncertainties, using data from strong motion recordings; and while initially proposed in the context of site response simulation validation, it can be generalized to ground motion simulation involving source, path and site simulation.

Consideration of uncertainties in ground motion simulation will be a critical focus of research in future years in order to develop confidence in the use of simulations directly in seismic hazard analysis (see Figure 1).

Challenges with Limited Validation Data

For specific applications not all of the above validation steps may be possible. For example, in regions of low seismicity there may be little to no observed earthquakes that have provided recorded ground motions to undertake validation. Specific instrumentation at the site of interest (i.e., a surface strong motion, or a downhole array to examine site response) will also typically not be present, meaning that the performance of simulation methods for analogue sites will be a principal form of validation. Alternative models and parameters should be used in such cases to reflect and to understand modeling uncertainty.

A lack of validation data in such cases is a hindrance for empirical ground motion models as well as simulation-based models. However, it is also recognized that the explicit consideration of physics in simulation-based models results in many more parameters and complex source and crustal models that can strongly affect the simulated ground motions. Given a lack of validation data, it is only appropriate to question the extent to which sophisticated simulations (or sophisticated velocity models) can yield improved predictions over the use of parsimonious approaches.

UTILIZATION DOCUMENTATION CHECKLIST AND SUMMARY

In addition to information on verification and validation for an adopted specific ground motion simulation methodology, there are several additional pieces of information to provide transparency (and potentially reproducibility) that should be adequately documented. The aim of such documentation is twofold: (1) explicitly list the features of a particular suite of ground motion simulations that have been performed; and (2) explicitly list the manner in which the simulations are utilized.

The utilization documentation is provided below in the form of a checklist for prescriptive use.

A. Documentation of the adopted simulations:

1. *Earthquake rupture(s) considered:* Specifics of the rupture geometry and kinematics.
2. *Computational domain:* Considered size and spatial discretization of the 3-D crustal model, including the maximum useable frequency.
3. *Temporal discretisation:* time step and any relevant parameters indicating numerical stability criteria.
4. *Model and software versions:* Version numbers for the simulation software algorithms, crustal model and rupture generator; including references to sources of archived software and data.
5. *Compute resources:* Specific computational resource(s) that the simulations are performed on, the number of compute cores utilized, and required CPU hours to perform the simulations.
6. *Information on verification:* See Section *Verification*.

7. *Information on validation:* See Sections *Validation* and *Ground Motion Simulation Validation*.

B. Documentation of the specific simulation utilization:

1. *System considered:* The type of structural or geotechnical system that is being considered, and thus the relevant ground motion *IM*s that collectively provide a representation of ground motion severity
2. *Simulation utilization:* Whether the simulations are used for hazard analysis and/or response history analysis
3. *Appropriateness of simulated motions for their intended usage:* The appropriateness and relevance of the ground motion simulation features for the specific engineered system considered:
    i. Multi-component and multi-site
    ii. Useable frequency range and IMs
    iii. Adequate treatment of nonlinear site effects
    iv. Adequacy of modelling uncertainties
4. *Adequacy of verification:* Discussion on the adequacy of verification undertaken, as described in A6. above, for the specific engineered system of interest
5. *Adequacy of validation:* Discussion of the adequacy of validation undertaken, as described in A7. above, for the specific engineered system of interest

It is noted that generally the personnel performing ground motion simulations, and personnel utilizing them for response history analysis will be different. This is the reason that the two lists have been provided separately above.

In addition to information on utilization documentation, there is also the application of ground motion simulations in a specific regulatory context for the design and assessment of civil infrastructure (Bradley et al. 2016b). The utilization guidance in this document provides essentially the high-level performance specifications by which the decision to utilize such simulations would be founded.

EXAMPLE APPLICATION: GROUND MOTION SIMULATION OF ALPINE FAULT EARTHQUAKES ON THE CANTERBURY PLAINS

To make the above discussion more concrete, an example of validation and documentation is discussed in this section. The availability of significant data and supporting research makes this a near optimal case for validation. It thus serves well to show how validation might be ideally be performed.

The Alpine Fault in New Zealand represents one of the major seismic sources for Christchurch, the South Island's largest city. Great earthquakes ($M_w \sim 8$) on the Alpine Fault are likely to result in significant ground motion shaking in Christchurch as a result of directivity-basin coupling in the Canterbury sedimentary basin (e.g., Figure 4a). This example provides a summary of the expected documentation to justify the utilization of simulated ground motions in Christchurch from Alpine Fault earthquakes in line with the guidance provided in earlier sections. Note that the specific structural system considered and other details in Part B of the utilization documentation is hypothetical.

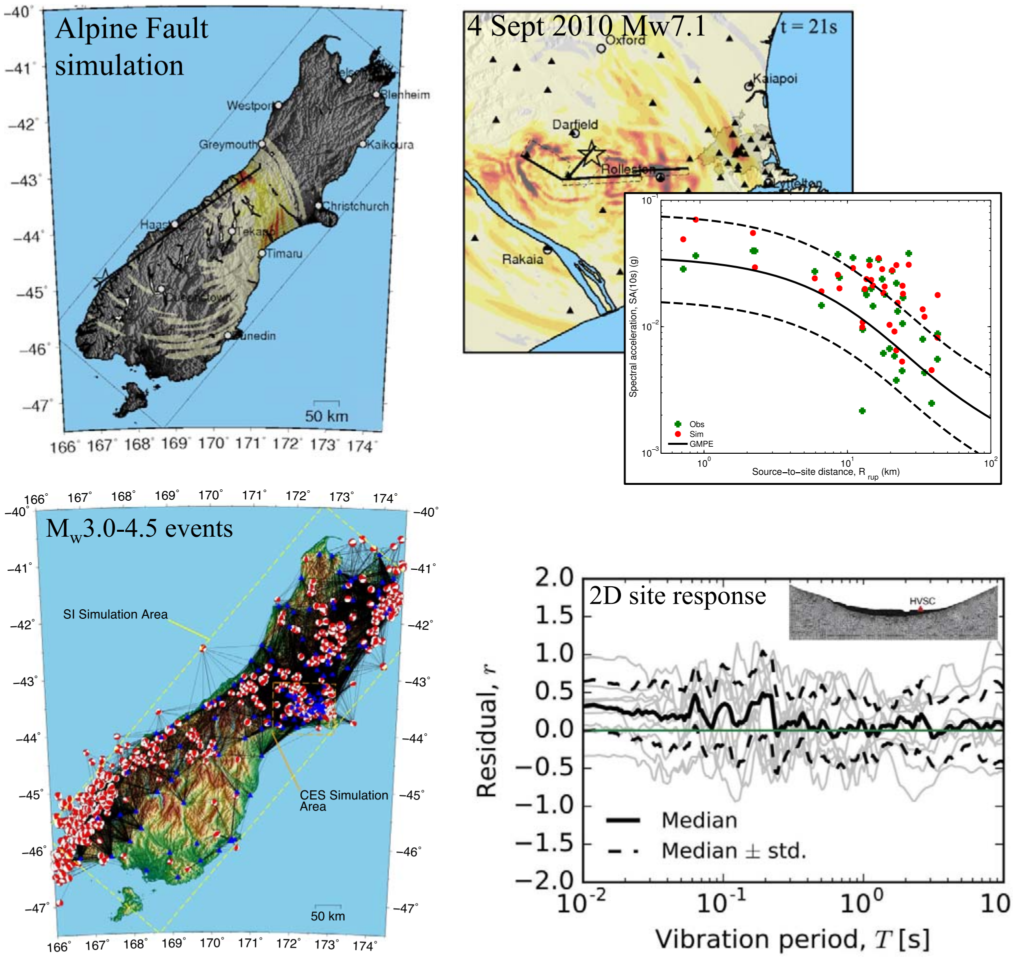

Figure 4. Visual summary of ground motion simulation validation for an Alpine Fault rupture scenario for a hypothetic structure located in the Canterbury region: (a) The prospective ground motion simulation for which validation is being undertaken for; (b) simulation validation for events in the 2010–2011 Canterbury earthquakes (e.g., 4 September 2010 M_w7.1) in terms of response spectral ordinates; (c) simulation validation using small-to-moderate magnitude events covering a range of source-to-site azimuths; and (d) validation of 2-D numerical site response analyses in terms of response spectral ordinates.

A. Documentation of the adopted simulations:

1. *Earthquake ruptures considered:* The Alpine-to-Kelly segment of the Alpine Fault as described in Stirling et al. (2012). The fault is 411 km in length, with a dip of 60 degrees and a down-dip width of 17.3 km. The average rake is 15 degrees. Using Leonard (2014), a mean M_w7.9 event was considered. Hypocentres at the southern, central, and northern ends of the fault are considered (Bradley et al. 2017).

2. *Computational domain:* The computational domain was 800 km × 350 km × 100 km in length, width, and depth, respectively, as illustrated by the rectangular box in Figure 4a. The spatial discretisation of the uniform finite difference grid was 0.1 km. The minimum shear wave velocity is 500 m/s. The transition frequency between the low and high frequency portions of the hybrid simulation method was $f = 1.0$ Hz.
3. *Temporal discretization:* A time discretization of $\Delta t = 0.005$ s was used. A total of 50,000 time steps were computed, enabling simulated ground motions for $t = 0{-}250$ s.
4. *Model and software versions:* The ground motion simulation methodology and version is that of Graves and Pitarka (2015). The rupture generator and version is that of Graves and Pitarka (2015). Source and compiled codes were provided directly from Rob Graves. The 3-D crustal model comprised the version 1.0 Canterbury Velocity Model (CantVM) of Lee et al. (2017), with the region outside the Canterbury sedimentary basin being modeled simplistically with the travel time tomography model of Eberhart-Phillips et al. (2010) to create a South Island velocity model (SIVM) as discussed by Thomson et al. (2016).
5. *Compute resources:* The ground motion simulations were performed on the BlueGeneP HPC at the University of Canterbury. The simulations utilized 8,192 compute cores, and required approximately four days of wall clock time (a total of approximately 0.8 million core hours).
6. *Verification information:* The implementation of the Graves and Pitarka simulation methodology into a computational workflow is discussed by Bae et al. (2016). The workflow is stored on GitHub (https://github.com/ucgmsim), and its components have been individually verified across two compute resources (UC BlueGeneP, and the NIWA Power6 clusters of NeSI: https://www.nesi.org.nz), as well as against original source code benchmarks provided by Rob Graves. Online documentation of such verification is available at: https://wiki.canterbury.ac.nz/pages/viewpage.action?pageId = 53381307.
7. *Validation information:* The validation activities for this ground motion simulation utilization case are summarized in Figure 4, and the validation matrix elements in Figure 5 are explained in the following sentences. The Graves and Pitarka (2015) wave propagation methodology and rupture generator have been validated extensively for multiple active shallow crustal earthquakes worldwide using regional 3-D crustal models (Graves and Pitarka 2010), as well as within the (1-D crustal model) SCEC BBP (Goulet et al. 2015) (which focused on spectral acceleration *IM*s). There have been other efforts to validate similar simulations based on significant duration (Afshari and Stewart), and nonlinear structural response history analyses (Galasso et al. 2012; the "generic region" row of the validation matrix in Figure 5). Ground motion simulations for the 10 major earthquake events in the 2010–2011 Canterbury earthquake sequence have been examined by Bradley et al. (2015b) and Razafindrakoto et al. (2017), focusing on spectral accelerations and significant duration (Figure 4b and the "specific geographic region" row of the validation matrix). Lee et al. (2016) present ongoing work toward the validation of the Canterbury velocity model (v1.64), and its extension to the South Island

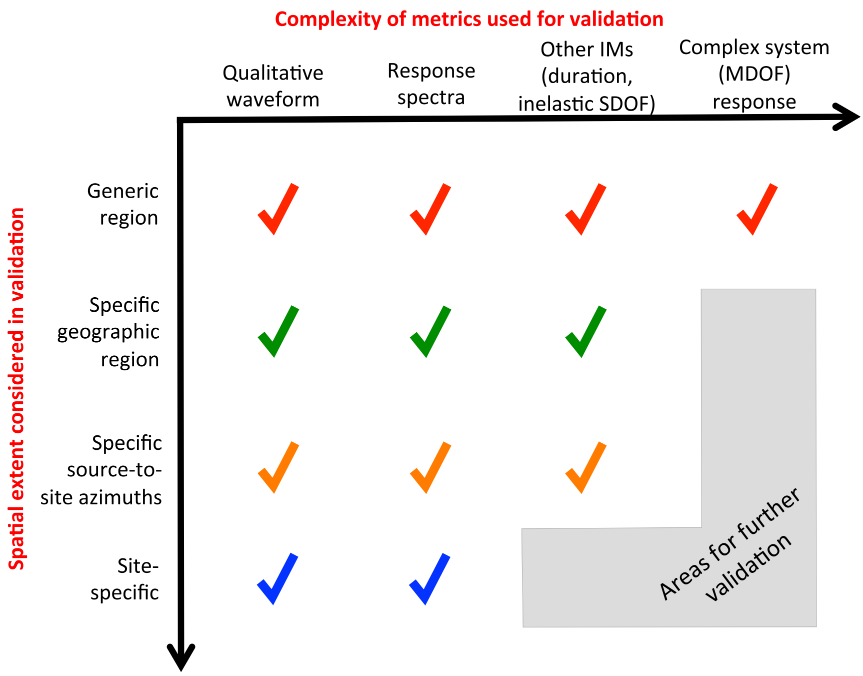

Figure 5. Validation matrix for ground motion simulation outputs for an Alpine Fault rupture scenario in the Christchurch region based on the validation activities summarized in Figure 4.

Velocity Model (SIVM v1.64) (Thomson et al. 2016), using small-to-moderate magnitude (M_w3.0–4.5) events (Figure 4c). While the work of Lee et al. (2016) is ongoing, the validation is intended to examine both spectral accelerations and other conventional engineering *IM*s. Nazer et al. (2016) also present validations for three moderate magnitude events located in the vicinity of the Porters Pass fault. Both Lee et al. (2016) and Nazer et al. (2016) thus examine validation for events located outside the Canterbury basin, and which have source-to-site azimuths similar to those of relevance for an Alpine Fault rupture (hence the "source-to-site azimuth" row of the validation matrix in Figure 5). All of the references in the paragraph to this point have utilized the empirical V_{S30}-based site effects modelling of Graves and Pitarka (2010) based on V_{S30} estimates at Canterbury stations. Significant additional site response modelling has been performed at a few discrete locations. One such location is Heathcote Valley, in which detailed geological and geophysical characterization of the basin edge and 1-D and 2-D wave propagation simulations have been performed by Jeong et al. (2015, 2016) focusing on response spectral ordinates (Figure 4d and the "site-specific" row of the validation matrix).

Note that with reference to the previous discussion of validation metrics and pass criteria, the depiction in Figure 5 is focused on the various forms of validation that are considered, and for the purposes of this example application, no explicit discussion is given here on whether the validation results are considered as a pass or otherwise.

B. Documentation of the specific simulation utilization:

1. *System considered:* The ground motion simulations are intended to be utilized for the design of a seven-story reinforced concrete building located in Heathcote Valley, Christchurch, New Zealand with a first mode vibration periods of $T = 1.5$ s. The soil conditions at the site are summarized as colluvial deposits overlying volcanic rosk, with a 30-m averaged shear wave velocity of $V_{S30} = 422\,\mathrm{m/s}$ (Wood et al. 2011).[8] The ground motion *IM*s of interest include spectral accelerations for vibration periods in the range of 0.2–2.0 s, and 5–95% significant duration.
2. *Simulation utilization:* Because the simulation validation has not addressed the appropriate uncertainties in simulation modeling then the simulations are not used for seismic hazard analysis. The simulations are intended to be used in both a scenario context (to understand the mean performance of the structure in the event of an Alpine Fault earthquake scenario), as well as for amplitude scaling to the 10% in 50 year exceedance probability design ground motion intensity (a conditional spectrum and significant duration target based on spectral acceleration at 1.0 s), which has been determined using empirical ground motion models as documented in a separate project-specific engineering seismology report.
3. *Appropriateness of the simulated motions for their intended usage:*

   i. *Multi-component and multi-site:* The system considered is located at a single site, and is not particularly sensitive to bidirectional ground motion effects, or the vertical ground motion component. Because of the use of a hybrid broadband methodology (with long period motion ($f < 1$ Hz) obtained from 3-D physics, and short period motion ($f > 1$Hz) via a simplified 1-D semi-empirical approach), it is acknowledged that the multi-component ground motion correlation is likely to be adequately captured at longer periods ($T > 1.0$ s), that affect the fundamental mode response, but not at shorter periods, which affect the higher modes.

   ii. *Useable frequency range and IMs:* The simulations are broadband (0.01–10 s) so encompass all frequencies that this system is sensitive to. The *IM*s of relevance (item B.1) have been considered in the simulation validation.

   iii. *Adequate treatment of nonlinear site effects:* The site conditions at this location are consistent with the sites at which strong ground motion instruments exist in the Canterbury region that have been used in the simulation validation.

   iv. *Adequacy of modeling uncertainties:* Modeling uncertainties have not been extensively considered in the simulations. As a result, the simulations are used in a scenario sense, and when scaled to an independently derived design ground motion target, as opposed to being directly used in defining the seismic hazard at the site.

4. *Adequacy of verification:* The verification of the computational software and its implementation is transparent, based on the use of open-source software, version control, and openly available documentation.

[8] Additional structural detailing and geotechnical conditions documented in separate structural and geotechnical assessment reports could be referred to here in practical application of this checklist.

5. *Adequacy of validation:* The intended use of the simulations is (1) scenario ground motions, and (2) amplitude-scaling of the simulations to a ground motion target spectrum, in lieu of the use of as-recorded ground motion time series from global databases. The validation testing which examined the simulation predictive capability at regional, specific source-to-site azimuths, and site-specific spatial extents for response spectra and other IMs indicates that the ground motion simulations provide time series that are appropriate for use as scenario ground motions. The validation testing which examined the simulation predictive capability for generic regions using response spectra, other IMs, and MDOF structural models indicates that the simulations provide time series that are appropriate for amplitude-scaling to a target spectrum.

DISCUSSION AND CONCLUSIONS

This document has developed guidance on the utilization of ground motion simulations in engineering practice. Specific sections focused on the overall ground motion simulation ingredients, features of relevance for engineering objectives, and specifics on the recommended documentation in the form of verification, validation, and utilization specifics. Particular attention in validation was given to variation in simulation predictive capability for different geographic regions and sites, and also for different ground motion *IM*s. A validation matrix was presented as a means for concisely depicting the hierarchical nature of this validation, and an example illustrated the application of the guidance presented.

This document provides high-level guidance for those undertaking ground motion simulations in practice, or for fundamental research, as well as those who intend to utilize ground motion simulations for response history analyses. A utilization checklist also provides a specification to support this guidance. For modelers who perform ground motion simulations, the utilization checklist provides targets for seven aspects of information needed in order for their simulations to be considered fit for use in engineering practice. The final two aspects—verification and validation—deserve special mention in this regard. For users of ground motion simulations, the utilization checklist provides five aspects that they should consider (and document) regarding the manner in which they utilize such simulations.

We anticipate some of this guidance to continue evolving, and some to remain stable. The utilization aspects to consider and documentation checklist headings themselves are likely to be stable. Because the validation matrix definition is separate from the specific validation metrics and acceptance criteria, we also expect that this guidance will provide an ongoing framework. Short-term progress is likely to result from advances in: (1) specific validation metrics; (2) the extent to which explicit uncertainties are considered in simulations; and (3) the considered acceptable levels of verification and validation to warrant adoption in practice. These changes will require application of the guidance and lessons that feed into research advancements.

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