ARTICLE IN PRESS

Soil Dynamics and Earthquake Engineering xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

On-going challenges in physics-based ground motion prediction and insights from the 2010–2011 Canterbury and 2016 Kaikoura, New Zealand earthquakes

Brendon A. Bradley[a,b,*]

[a] University of Canterbury, Christchurch, New Zealand
[b] Stanford University, CA, USA

ABSTRACT

This paper presents on-going challenges in the present paradigm shift of earthquake-induced ground motion prediction from empirical to physics-based simulation methods. The 2010–2011 Canterbury and 2016 Kaikoura, New Zealand earthquakes are used to illustrate the predictive potential of the different methods. On-going efforts in simulation validation and theoretical developments are then presented, as well as the demands associated with the need for explicit consideration of modelling uncertainties. Finally, discussion is also given to the tools and databases needed for the efficient utilisation of simulated ground motions both in specific engineering projects as well as for near-real-time impact assessment.

1. Introduction

Earthquake-induced ground motion prediction is presently undergoing a paradigm shift from the empirical prediction of ground motion intensity measures (IMs, e.g. *PGA*, *SA*), based on regression analysis of observed IMs from past earthquakes, toward the use of physics-based simulation methods that directly predict the ground motion time series (i.e. multi-component acceleration as a function of time).

This paradigm shift is presently occurring as a result of three key factors. Firstly, the diminishing returns offered from the continual efforts in empirical ground motion modelling, most evident in terms of the lack of any appreciable reduction in the standard deviation of IM prediction over four decades [13,44]. Secondly, recent well-recorded earthquakes (such as those discussed herein, among others) illustrate that, even now, physics-based simulation methods provide predictions that are comparable to, or even superior than, those from empirically-based predictions [4,10,15,18,22]. Thirdly, the physics-based nature of such simulations provides a natural framework within which a substantially greater volume of data from seismological observations can be synthesised, enabling the incorporation of region and site-specific features, thus promising appreciable improvements in the ability to reduce prediction uncertainties in the coming years, and realising the flow-on benefits in the seismic design and assessment of built infrastructure [49].

It is important to appreciate that this empirical to physics-based modelling paradigm shift is akin to that which occurred in weather forecasting in the 1950's - although the seismic problem is complicated relative to the weather problem because the salient phenomena occur beneath the earth's surface, making direct observation challenging as compared to direct atmospheric observations. Furthermore, small length scale seismic phenomena are difficult to model, yet are of upmost practical importance; and localised effects near the earth's surface strongly affect seismic ground motion intensity measures of interest. In contrast, while these same factors are present in weather forecasting (i.e. turbulence and microclimates), they are generally not of principal importance in providing generalised information for public weather forecasts (although they remain challenges for the aeronautical industry, for example).

This paper provides a discussion of the on-going challenges to accelerating this paradigm shift in earthquake-induced ground motion prediction. An overview of physics-based and empirical prediction of the 2010 Darfield, 2011 Christchurch and 2016 Kaikoura, New Zealand (NZ) earthquakes is first presented to directly compare and contrast these two methods of prediction and examine their strengths and weaknesses. The on-going challenges in physics-based ground motion prediction are examined, namely: continued validation against recorded earthquakes to demonstrate the predictive capability of such methods and most efficiently identify avenues for improvement; theoretical developments in source, path, and site modelling within ground motion simulation; the explicit consideration of modelling uncertainties

* Corresponding author at: University of Canterbury, Christchurch, New Zealand.
E-mail address: brendon.bradley@canterbury.ac.nz.

https://doi.org/10.1016/j.soildyn.2018.04.042
Received 28 August 2017; Received in revised form 2 April 2018; Accepted 25 April 2018

Please cite this article as: Bradley, B., Soil Dynamics and Earthquake Engineering (2018), https://doi.org/10.1016/j.soildyn.2018.04.042

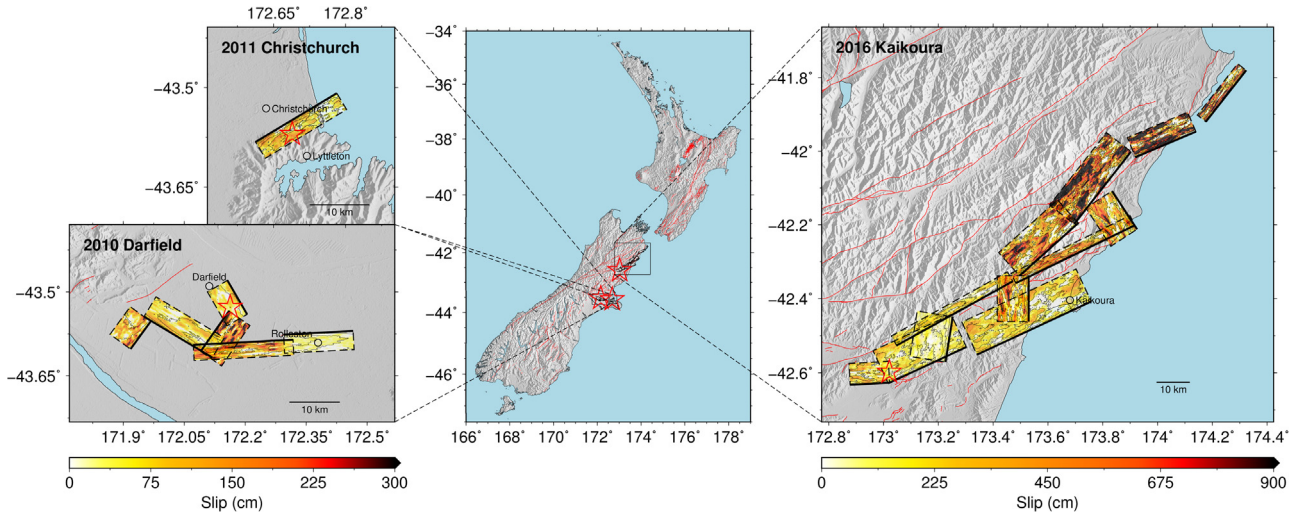


Fig. 1. Location of the 2010 Mw7.1 Darfield, 2011 Mw6.2 Christchurch, and 2016 Mw7.8 Kaikoura Earthquakes in the context of New Zealand. Slip amplitudes for the 2010 and 2011 events have the same colour scale, but a different scale is used for the (larger) Kaikoura event. Mapped active faults are shown in red.

in simulations; accessible databases by which simulations can be utilised by non-experts in engineering application; and finally the use of simulations in near-real-time impact assessment.

2. Ground motion prediction of the 2010 Darfield, 2011 Christchurch, and 2016 Kaikoura earthquakes

2.1. Overview and tectonic setting

NZ strides the boundary between the Pacific and Australian plates, with numerous large magnitude earthquakes occurring during the instrumental period. The 2010 Darfield and 2011 Christchurch earthquakes (as part of the Canterbury earthquake sequence) and the 2016 Kaikoura earthquake, whose locations are noted in Fig. 1, are the most significant events to occur over the past decade, and arguably the most impact events since the 1931 Napier earthquake. Because of their geographical proximity, rupture complexity, and the dense network of strong motion stations in the region, these events provide a significant opportunity for the examination of ground motion features and validation of ground motion prediction methods.

Ground motion prediction using empirical and physics-based methods have been previously presented for these three events [4,10,37], and therefore in this paper attention is given to a summary of the insights from such validation in order to contextualise the subsequent discussion of the on-going challenges in this field.

2.2. Details of physics-based ground motion prediction

Physics-based ground motion predictions for these three earthquakes [4,10,37] utilised the Graves and Pitarka [19] methodology, a 'hybrid' approach in which the low frequency (LF) waveforms are comprehensively computed by solving the elastodynamic equation in a 3D crustal model domain (using finite differences), while the high frequency (HF) waveforms utilise a phenomenological simplified physics approach. In the simulations of the 2010 Darfield and 2011 Christchurch earthquakes a transition frequency between the LF and HF approaches of $f = 1\ Hz$ was utilised (based on a spatial grid of 100 m and a minimum shear wave velocity of 500 m/s), while for the 2016 Kaikoura earthquake a transition frequency of $f = 0.5\ Hz$ was adopted (i.e. a 200 m spatial grid) because of the larger spatial domain.

In the adopted methodology, the seismic source is prescribed in the form of a kinematic rupture description. The specific kinematic rupture generator utilised in the simulations is described by Graves and Pitarka [22], based on the default parameters of that model, and extended to consider multi-segments ruptures for the 2010 Darfield and 2016 Kaikoura earthquakes, as described in the aforementioned references for each event simulation. For each event, the fault geometry and hypocentre are prescribed, but the slip distribution over the rupture area is stochastically prescribed, in order to ensure consistency between retrospective validation and prospective utilisation.

Fig. 2 illustrates the spatial distribution of simulated peak ground velocity for the three events which highlights, in particular, the importance of source directivity and sedimentary basin effects on amplifying surface ground motions. The role of source directivity is least pronounced in the 2011 Christchurch earthquake because of its moderate magnitude and the general misalignment of the direction of rupture propagation and slip vectors [8]. Directivity in the 2010 Darfield earthquake was most pronounced in central and northern Christchurch as a result of the west-to-east rupture of the Greendale fault [6]. Finally, while the 2016 Kaikoura earthquake was the result of an exceptionally complex multi-segment rupture, strong directivity effects were present in the north eastern part of the South Island and the Wellington region as a result of the general south-to-north rupture propagation direction [10].

2.3. Comparison of observed and predicted ground motion IMs for the 2016 Kaikoura earthquake

Fig. 3 illustrates the ground motion spectral amplitudes for four vibration periods (T = 0.0, 0.2, 3.0, and 10.0 s) as a function of source-to-site distance for the 2016 Kaikoura event. The observed and simulated ground motion amplitudes for the 162 stations within the simulation domain are shown. In addition to the simulation predictions, for reference, the NZ-specific empirical ground motion model (GMM) of Bradley [7] is also shown based on a single representative $V_{s30} = 250\ m/s$ value. Only a single empirical GMM is presented, as no attempt is made to exhaustively quantify empirical GMM epistemic uncertainty.

Fig. 3 illustrates that the simulations provide a good comparison with the observed amplitudes. In particular, the observed distance attenuation of short period amplitudes (i.e. T = 0.0 and 0.2 s) is consistently predicted by the simulations, while the empirical model predicts a slower attenuation; conversely at long periods, the empirical model predicts a faster attenuation than exhibited by both the observed and simulated amplitudes.

Fig. 3 also separately annotates the simulated and observed amplitudes based on their location in either the North or South Island, for which both observation and simulation consistently illustrate higher-

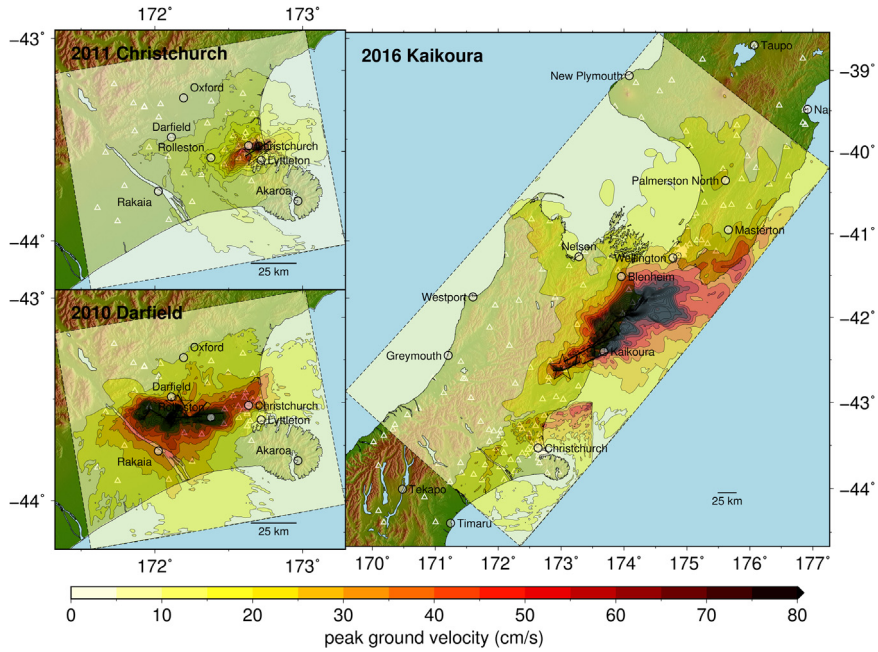


Fig. 2. Simulated peak ground velocities for the 2010 Darfield, 2011 Christchurch, and 2016 Kaikoura events. Strong motion station locations, which recorded the consequent ground motions, are shown in white triangles.

than-average amplitudes of North Island ground motions relative to those in the South Island for the same source-to-site distance - because of the aforementioned effect of rupture directivity.

2.4. Overall spectral acceleration bias with period for all three earthquake events

Fig. 4 illustrates the mean and ± one standard deviation range of the prediction residuals for each of the three earthquake events. The residual is defined as the logarithm of the observations defined by the ground motion model (either physics-based or empirical). For the 2011 Christchurch and 2010 Darfield events, the physics-based and empirical model residuals have a similar mean at short vibration periods ($T < 1\,s$), for which the physics-based prediction is dominated by the HF 'simplified physics' portion of the simulation. At long periods ($T > 1\,s$) in these two events, the physics-based prediction generally tends to outperform the empirical prediction (an exception being $1 < T < 3\,s$ for the 2010 Darfield event), illustrating the benefit of the 'comprehensive physics' in the LF portion of the simulation. Finally, in the 2016 Kaikoura event, the physics-based simulation performs better than the empirical prediction at short periods ($T < 2\,s$), principally because of its ability to consider the amount of slip on each of the multiple fault segments, whereas the empirical model simply uses the source-to-site distance based on the nearest fault segment [10]. At long periods ($T > 2\,s$) both physics-based and empirical predictions exhibit bias, in opposite directions, principally due to the uncertainty in the source characterisation of this recent and complex event, which further research is expected to shed light on.

3. On-going challenges in ground motion simulation

This section examines on-going challenges in physics-based ground motion simulation in order to accelerate the transition toward their utilisation in engineering practice. While attention is focused on simulation methods, this does not imply that an analyst must make an exclusive choice between physics-based or empirical methods. Because it is convention to consider ground motion prediction via multiple models in a logic tree framework, then both empirical and physics-based methods can be used in tandem via multiple models. As logic tree weights should be assigned based on predictive capability (i.e. inversely proportional to the uncertainty in the prediction), then the sentiments in the introduction imply that over time simulation methods will progressively receive greater logic tree weighting relative to empirical methods, until the point where the sensitivity to the empirical model weights becomes insignificant.

3.1. Ground motion simulation validation

3.1.1. Prediction validation for simulation utilisation in engineering practice

As the previous section illustrated via example for several NZ events, validation of ground motion simulation methods is imperative to understand predictive capability in terms of prediction uncertainty and also the particular parameter space (i.e. specific source, path and/or site conditions) for which prediction can be most easily improved. A detailed discussion of verification and validation as a formal process for developing predictive capability in computational modelling is provided in Oberkampf et al. [34].

In addition to individual validation studies (e.g. [35,36,17,46], among others), more recently larger coordinated efforts to verify and validate a multitude of 'broadband' ground motion simulation methods have occurred under the auspices of the Southern California Earthquake Center (SCEC) through the Broadband Platform (BBP) validation exercise [14] and technical activity group on ground motion simulation validation (GMSV) [31].

Simulation validation needs to evaluate the predictive capabilities of the overall simulation methodology (i.e. physical assumptions), as well as the input models and their parameters. For ground motion simulation, in particular, the adequacy of input models describing the source rupture, 3D 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 a collection of different ground motion IMs. Some IMs are ubiquitous, such as elastic response spectra; some are seeing increasing awareness and utilisation (e.g. parameters

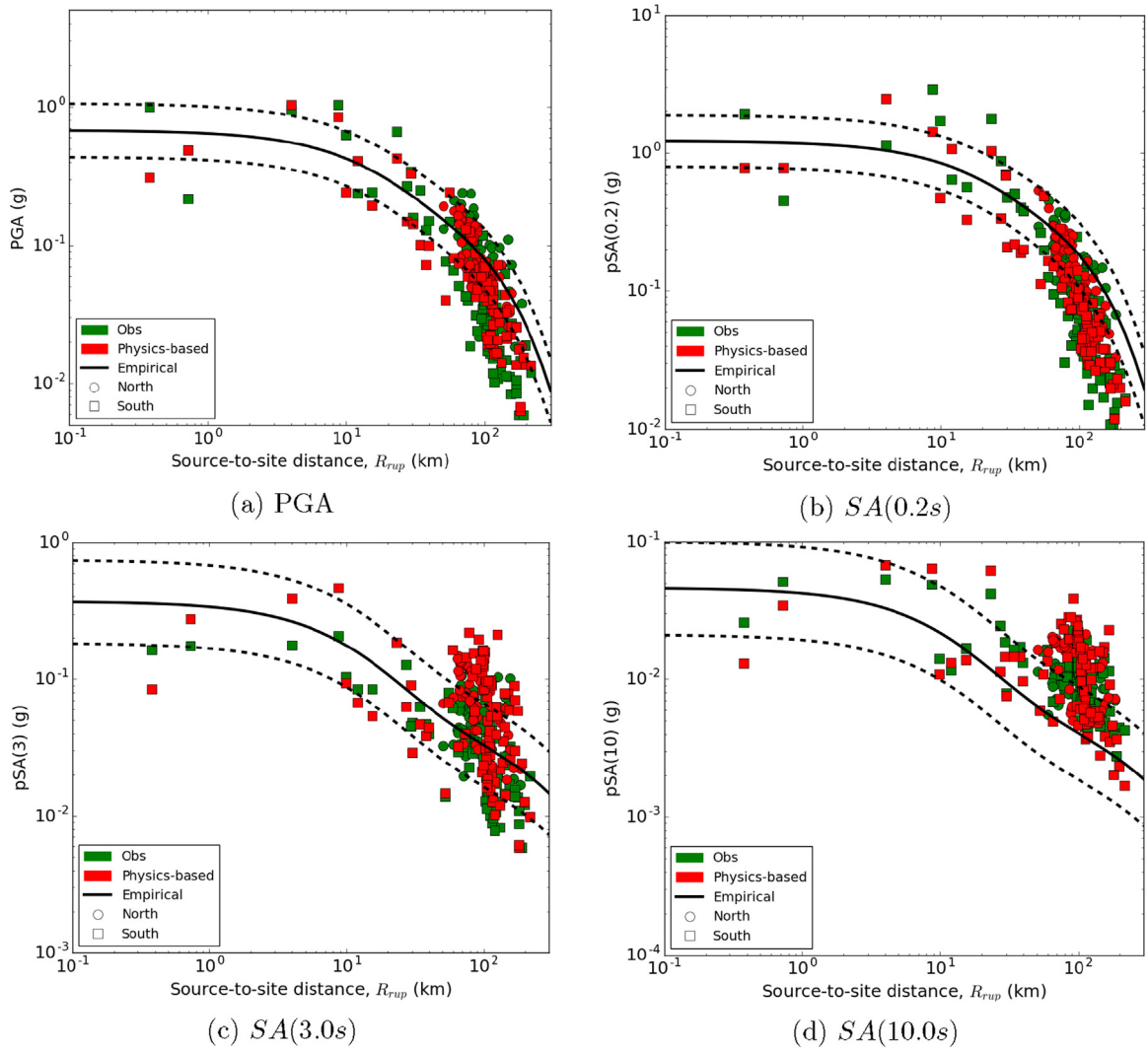


Fig. 3. Observed, physics-based and empirically-predicted geometric mean ground motion intensities as a function of source-to-site distance (R_{rup}) for the 2016 Kaikoura Earthquake. Symbol shape indicates location of the station in the North or South Island. The median, and 16th/84th percentiles of the empirical prediction Bradley are represented by solid and dashed lines, respectively.

representing the duration and cumulative nature of the motion); and others are problem-specific (e.g. induced displacement response of a specific building typology).

Fig. 5 provides a graphical validation matrix of the spatial- and IM-dependence of ground motion simulation validation, as presented by Bradley et al. [9]. 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 discretised here for practical application.

Fig. 5 identifies three principal domains of the validation matrix in the context of intended utilisation. 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 utilisation in practice, i.e. quantitative validation is essential. In the context of seismic hazard analysis, in which an accurate and precise prediction of the distribution of IM 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 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 utilised for response history analyses once scaled to the target design ground motion intensity (this is similar to the current conventional use of as-recorded ground motions from past worldwide earthquakes for response history analysis).

As would be expected, a framework for validation, and accompanying documentation [9], is critical for a bi-directional understanding between earthquake engineers on the appropriateness of a suite of ground motion simulations for utilisation in a site-specific context, as well as ground motion simulators to understand the context in which their results will be utilised. The increased realisation of the benefits of utilising simulated ground motions is likely to provide a demand-side increase in the adoption of simulated motions, hence ongoing simulation validation is essential.

3.1.2. Simulation validation for small-to-moderate magnitude events

As noted with reference to Fig. 5, the ability to explicitly model region- and site-specific phenomena is a key potential strength of physics-based simulation methods. Use of the word 'potential' is important because simulations should be validated to ensure that such effects can in fact be predicted by the adopted model(s). The consideration of region- and site-specific effects naturally requires the

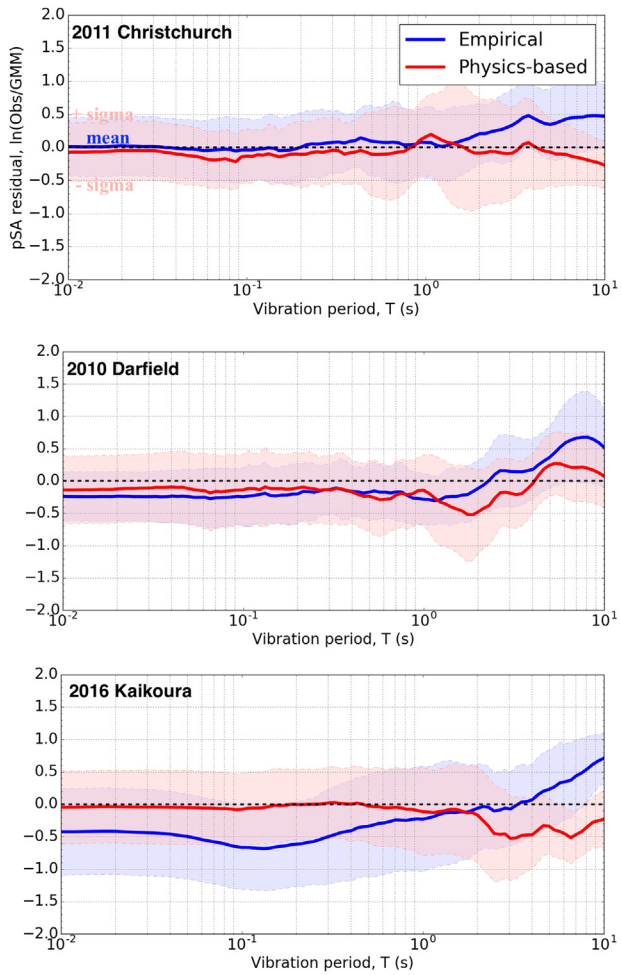


Fig. 4. Comparison of spectral acceleration residual distribution as a function of vibration period for the three considered events based on physics-based and empirical ground motion predictions. The solid line represents the mean of the residual distribution and the shaded region the one standard deviation range.

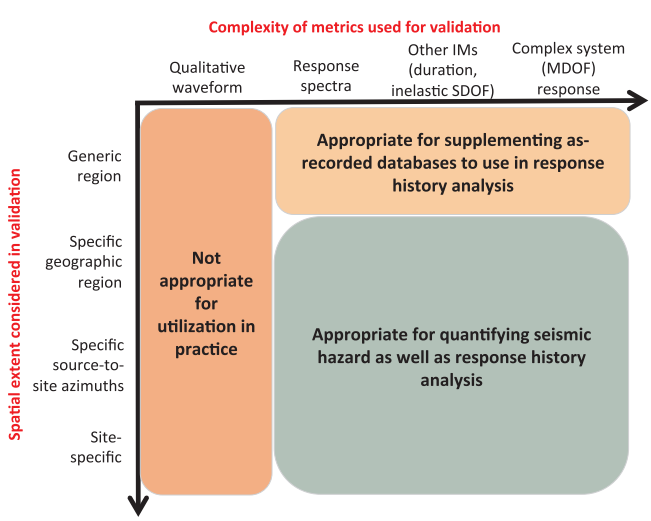


Fig. 5. Ground motion validation matrix and relation to the intended usage of ground motion simulations. The vertical axis indicates the increasing spatial resolution from generic to region and site-specific validation. The horizontal axis indicates the increasing complexity of IM metrics used in quantifying simulation validation, which is a function of the specific engineered system considered. Figure after Bradley et al. .

evaluation of simulation predictions over a smaller geographical region than possible to evaluate predictive performance for generic regions, which entails a reduction in validation data for all other things equal, making statistically-significant statements sometimes challenging.

The consideration of ground motions from smaller magnitude events naturally enables a significant increase in the number of data which can be utilised for simulation validation. The appropriateness of using ground motion records from small magnitude earthquakes for 'testing' the applicability of empirical ground motion models for larger magnitude events (which are of primary concern for seismic design) has long being a topic of debate (see [2], and references therein). However, the physics-based nature of ground motion simulation methods provide a rational framework in which to evaluate the predictive capability of various model 'components'. Of course, the use of small magnitude earthquakes for validation offers limited (if any) ability to examine finite-fault kinematic source rupture or nonlinear near-surface site response modelling, but the observations can obviously be used for validation of the considered crustal (velocity) model, such as demonstrated by Lee et al. [28].

Despite the obvious need, extensive region- and site-specific simulation validation has not yet become commonplace. Fig. 6a provides one example from Lee, R.L. [30] in which 144 $M_w = 3.5 - 5.0$ earthquakes in the Canterbury, NZ, region were used to validate the commonly-adopted Graves and Pitarka [19] simulation methods. This dataset provided 1819 ground motions for validation and enabled Lee, R.L. [30] to systematically identify several features of the Graves and Pitarka [19] method that can be refined in order to provide improved predictions in this region, as well as likely biases in the adopted crustal model. Such improvements are also likely to result in improved validation outcomes for the larger magnitude event simulations that were presented in Section 2. In this regard it should be recognised that the 144 events in Lee, R.L. [30] represent only about 8% of the 1731 $M_w = 3.5 - 5.0$ earthquakes recorded in NZ under the GeoNet programme to date (since 2003), as shown in Fig. 6b, with another 129 events for $M_w > 5.0$. Hence, validation over the full spectrum of ground motion intensity levels is likely to accelerate the improvement of simulation methods themselves, as well as provide further statistical evidence of their fidelity relative to empirical prediction models.

3.2. Theoretical improvements in ground motion simulation 'ingredients'

The inherent physics basis of ground motion simulation methods provides an underlying framework for the assimilation of seismological observations to develop conceptual models, implement these conceptual models using computational methods, use simulation for prediction, and validate simulations using observations. Identified limitations from model validation allow for further iterations of this process in conjunction with better theories and better data – what Jordan [25] describes as the 'inference spiral' of system science.

3.2.1. Seismic source models

Quantitative understanding of the earthquake sources is the most difficult piece of the ground motion prediction problem, and is likely to remain so (with advances in crustal and site response modelling occurring much more readily). Two notable problems hindering ground motion simulation are: (a) source generation for simulation at high frequencies ($f < 1\ Hz$); and (b) source generation for multi-segment earthquake ruptures (a third problem of uncertainties in seismic source modelling is discussed separately in a later section). Both of these problems gain significant insight from the use of dynamic rupture simulations, however, present computational demands require that regional ground motion simulations generally utilise kinematic representations of earthquake rupture (referred to as pseudo-dynamic models if they are parametrised based on dynamic considerations).

In relation to high frequency source generation, for example, Graves and Pitarka [20] present a further iteration of a prior kinematic rupture

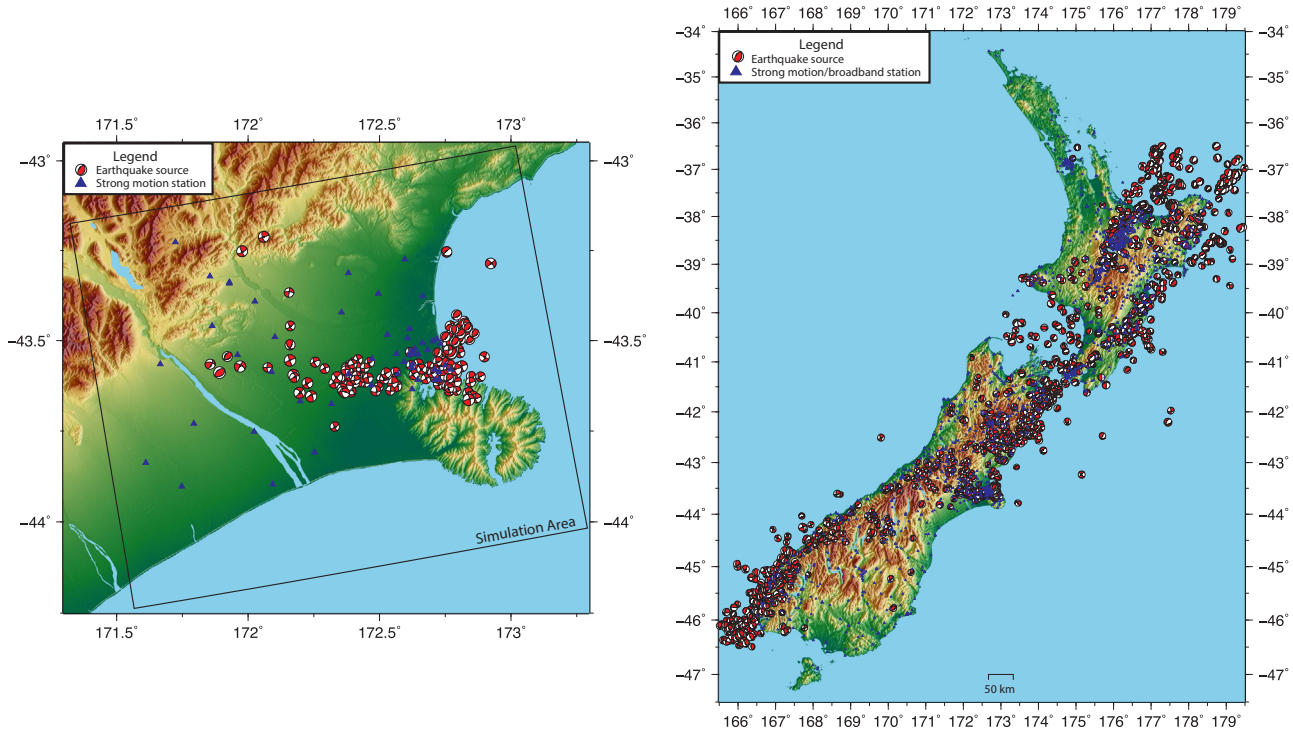


Fig. 6. (a) 144 $M_w = 3.5 - 5.0$ earthquakes, providing 1819 ground motions at 53 strong motion stations, considered by Lee, R.L. [30] in simulation validation of the Graves and Pitarka [19] method for the Canterbury, NZ region; and (b) 1731 $M_w = 3.5 - 5.0$ earthquakes recorded in NZ under the GeoNet programme (since 2003) that could be used for simulation validation.

generator that emulates the effect of geometric fault complexity (i.e. non-planar faults), fault damage zone (a lower velocity region in the vicinity of the fault), and also random perturbations to the underlying crustal velocity model. The principal need for these factors relates to the observed homogenisation of the ground motion radiation pattern (i.e. general orientation-independence of ground motion amplitudes) at frequencies $f > 1\ Hz$, which was not present in prior simulated ground motions. Figure 17 of Graves and Pitarka [20] illustrates the polarisation of ground motion amplitudes at forward directivity sites, for a synthetic earthquake that is modelled closely after the 1979 Imperial Valley event, based on different source modelling assumptions. While prior source modelling methods produce ground motion amplitudes with appreciable polarisation at high frequencies, the consideration of fault roughness, velocity perturbations and a fault damage zone can all be seen to result in a reduction in the fault normal-to-parallel ratio, to the point that the ground motions are essentially unpolarised for $f > 1\ Hz$ - consistent with observations. The ability to accurately model source rupture at high frequencies, combined with a similar capacity for crustal modelling (which, most notably, requires a significant increase in computational demand) allows for an increase in the transition frequency between the so-called comprehensive and simplified approaches in hybrid simulation methods (and eventually the redundancy of the simplified approach).

The increased resolution of imaging earthquake rupture also reveals their inherently complexity, and that the assumption of a single planar fault segment is often not realistic for ground motion simulation, particularly for larger magnitude earthquakes. The inferred source geometries of the 2011 Christchurch, 2010 Darfield, and 2016 Kaikoura earthquakes shown in Fig. 1 are an apt illustration of this increasing complexity as the length scale of rupture increases. While ground motion simulations with a single fault segment provide comparable results to observations for the 2011 Christchurch earthquake, as shown in Fig. 4, the consideration of multiple segments is clearly necessary to describe the ground motions resulting from the 2010 Darfield and 2016 Kaikoura earthquakes. In the kinematic rupture modelling of multi-segment events, additional parameters are the location and time at which rupture occurs on each fault segment (i.e. 'hypocentre' initiation on each segment). Ground motion simulations of the 2016 Kaikoura earthquake, Bradley et al. [10] made several heuristic assumptions regarding the location and timing of 'hypocentre' nucleation on each segment (some well constrained, others poorly).

The consideration of multi-segment ruptures in earthquake rupture forecasting also involves the additional problem of specifying whether multi-segment rupture is actually possible (i.e. at what segment separation distance; change in segment strike/dip orientation, among other factors, would multi-segment rupture not occur). The modelling challenges in the consideration of multi-segment ruptures are significant, but are clearly a priority as evident from these recent earthquake events.

3.2.2. Crustal (velocity) models

3D crustal models (often referred to as 'velocity models') provide the 3D domain over which the wave equation is solved. Models of crustal velocity exist in the majority of the world's seismic regions for the purpose of earthquake location determination. It is important to recognise however that the spatial resolution of those models is generally insufficient for their direct use in ground motion simulation. This is because the latter involve both higher frequencies of interest (thus requiring a finer spatial resolution), and also full ground motion waveforms rather than just arrival times, for which crustal impedance contrasts, particularly in the presence of sedimentary basins, have more significance.

The explicit modelling of sedimentary basins in crustal models is generally achieved via the use of geological surfaces which are 'embedded' into regional 3D crustal models (from earthquake location tomography), with the sediments between each layer having their constitutive properties assigned in a number of approaches [29,32,33,36]. However, arguably the most promising approach involves the direct use of recorded seismological data (either earthquake-induced ground motions, 'passive' ambient vibrations, or 'active' vibrations from

geophysical experiments) to iteratively improve the crustal model using the full seismological waveform, so-called 'full waveform tomography' [11,27,47]. The principal benefit of full waveform tomography is that full ground motion waveforms are used to invert the crustal model, which is the same features of the ground motion that are of interest in the forward problem. In contrast, the construction of crustal models through the use of geological surfaces and parameterised constitutive relations does not directly validate the resulting model against seismic waveforms [27,28].

Lee and Chen [27] provide a detailed illustration of the ability of full waveform tomography to reproduce the inherent features of crustal structure through a comparison of the tomographically-improved model with independent topographic and isostatic gravity anomaly data. The ability for such methods to directly capture crustal structure complexity and, moreover, to identify basins that are completely absent in an initial model is particularly significant. The only limitation to bear in mind is that present computational demands often limit the maximum frequency considered in tomographic inversions, and thus the ability to adequately invert for shallower crustal properties (i.e. approximately depths shallower than 3 km). Future computational capabilities are however expected to overcome this issue.

The transition frequency between the comprehensive and simplified portions of physics-based ground motion simulations has recently been on the order of f = 1 Hz. However, increasing computing capacities have allowed for the exploration of the adequacy of the comprehensive approach at higher frequencies. Taborda and Bielak [46] illustrated via simulation validation of the 2008 Chino Hills earthquake that the conventional assumptions in the comprehensive physics-based simulation approach tend to result in relatively poorer prediction of high frequency ground motions. The push toward using comprehensive physics at higher frequencies in ground motion simulations requires several important considerations in crustal modelling: (i) spatial heterogeneity to stochastically represent small-scale variability that is beyond the wavelengths resolvable in the development of crustal models [20,23]; (ii) frequency-dependent anelastic attenuation [50]; (iii) surface topography [24,38,39]; and (iv) nonlinear inelastic constitutive response [42,43] both in the immediate vicinity of the fault (on-fault) and in the near-surface (off-fault).

The above references provide initial research efforts on each of these aspects, and validation against historical earthquake up to these high frequencies is now required in order to understand the adequacy and relative importance of each of these various factors, and hence whether the use of comprehensive physics to these high frequencies is able to provide better predictions than the parsimonious simplified physics approach.

3.2.3. Surficial site response

Physics-based ground motion simulations commonly have neglected surificial site effects (including soil nonlinearity) as a result of using viscoelastic soil models, coarse spatial grids, and minimum shear wave velocities corresponding to stiff soils. Four different methods have been used or proposed to incorporate soil nonlinearity into simulations: (i) fully-coupled 3D simulation models that directly allow soil nonlinearity in surficial soils [45,51]; (ii) the domain reduction method for decomposing the physical domain into multiple subdomains for separate simulation [3,52]; (iii) conventional 1D wave propagation site response analysis uncoupled from the simulations [41]; and (iv) the use of simple empirically-based site amplification factors dependent on Vs30 [22].

While the explicit consideration of site response using approaches (i)-(iii) above would be considered preferable over the use of empirically-based site amplification factors, there has previously been no systematic examination of the benefits of explicitly modelling site response based on validations against historical earthquakes. de la Torre et al. [12] recently used the 10 most significant earthquake events in the 2010–2011 Canterbury earthquake sequence to examine site response modelling effects in ground motion simulations. Fig. 7 illustrates

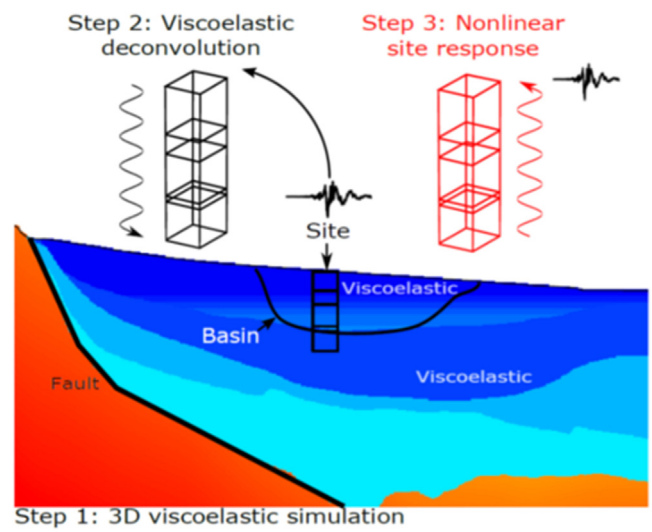


Fig. 7. Schematic of incorporating soil nonlinear behaviour into physics-based simulations through deconvolution of simulated ground motion followed by 1D wave propagation nonlinear site response analysis. (after de la Torre et al. [12]).

the multi-step process for the explicit consideration of site effects by de la Torre et al., in which the surface ground motion obtained from the (regional) 3D viscoelastic simulation (step 1) is deconvolved using 1D viscoelastic site response (step 2) and then nonlinear 1D site response analysis (step 3) is used to obtain surface ground motions accounting for nonlinear inelastic site response. This uncoupled approach has the benefit of inter-operability between computational tools that are tailored for the different spatial resolutions and material modelling of regional ground motion simulation and site response. The use of deconvoluted surface motions, rather than directly obtaining simulated motions at depth is also necessary in order to retain long period surface waves which are present at the surface (and 1D deconvolved motions), but not in the directly simulated motions at depth.

The empirical results of de la Torre et al. illustrate that the explicit consideration of site response in ground motion simulation is important (as expected), however, the use of 1D site response analysis methods still leave substantial room for improvement, with comprehensive statistics from site response analyses at downhole array sites indicating that appreciable biases with 1D site response analysis do exist [1,26].

3.3. Explicit consideration of modelling uncertainties

Much focus in ground motion simulation development and validation against historical events has centred on their predictive capabilities in an average sense [15,18]. However, utilisation of ground motion simulations in seismic hazard analysis requires adequate representation of the complete probability distribution of ground motion IM metrics, and thus their validation should explicitly assess this distribution ([16,48], e.g.). While comparisons 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.

Confidence of ground motion simulations for prediction in the average sense, and recognition of the need for appropriate uncertainty, has led to recent research into ground motion simulation modelling uncertainties. As an example, Razafindrakoto et al. [37] examined the impact of uncertainties in various seismic source parameters of the Graves and Pitarka [19] rupture generator for simulations of the 2011 Christchurch earthquake. They found that parameter uncertainties can result in a standard deviation in the between-event residual of up to 0.3

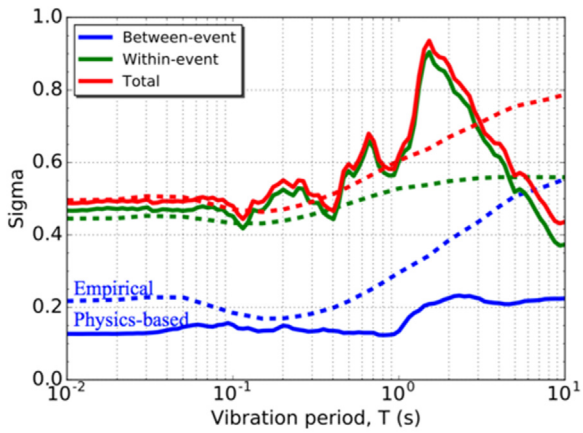


Fig. 8. Within-, between- and total standard deviations for ground motion simulations (with modelling uncertainty in the source representation) for the 2011 Christchurch earthquake and comparison with empirical modelling standard deviations (after Razafindrakoto and Bradley (2017)).

at long periods (principally as a result of uncertainty in the event magnitude), where as the Brune stress parameter, $\Delta\sigma$, results in the largest variability in high-frequency ground motion amplitudes.

Fig. 8 provides a comparison of the between-, within- and total standard deviations resulting from the simulation validation against observations for the 2011 Christchurch earthquake from Razafindrakoto et al. [37]. Because seismic source uncertainties have a correlated effect on most simulated ground motions then the majority of the parameter uncertainty is mapped onto the between-event residual, with little contribution to the within-event residuals. Thus, the majority of the within-event standard deviation of the simulations results from the inaccuracies in the simulation methodology and specifically the modelling of the seismic source and crustal structure.

Comparison with the standard deviations in conventional empirical models (for the New Zealand-specific model of Bradley [7] in this instance) in Fig. 8 illustrates that the total standard deviations of simulated and empirical models are similar at short periods (as a result of the use of a simplified physics approach which is semi-empirical in nature), the simulated standard deviations are larger than those from the empirical models for T = 1–3 s, and then decrease significantly for $T > 3\ s$ to be half as much for T = 10 s. The significant reduction at long periods (T = 10 s) is illustrative of the long-term benefits that physics-based simulation methods can provide, and results from the adequacy

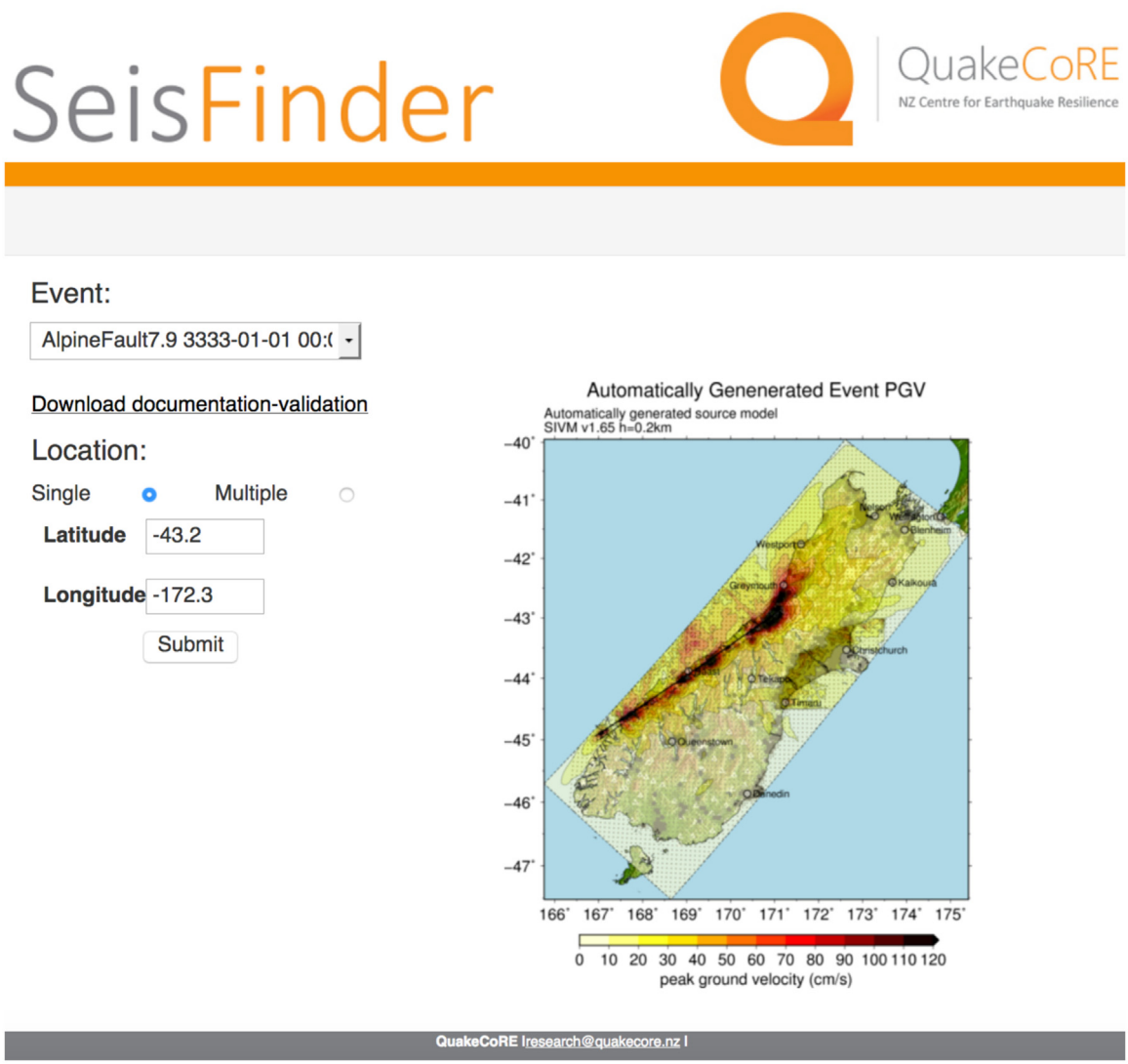


Fig. 9. Illustration of the 'SeisFinder' web application (http://quakecoresoft.canterbury.ac.nz/seisfinder/) for the retrieval of simulated ground motions for use in site-specific applications.

of the source and crustal models at the length-scales which affect such long period ground motion. Improvements in source, path, and site effects discussed in the previous sections are expected to result in this lower relative standard deviation at T = 10 s shifting to shorter vibration periods in the near future.

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 probabilistic seismic hazard analysis. In this regard it is worth mentioning that current uses of ground motion simulation in probabilistic seismic hazard analysis, such as SCEC's Cybershake project [21,49], focus on hypocenter and slip distribution variability, but not explicitly on uncertainties in other rupture parameters, crustal or site parameters; or the adopted rupture, crustal structure, and site effects model methodologies themselves.

A greater focus on uncertainties also requires the explicit inclusion of simulation uncertainties within validation itself. Bradley [5] provides a framework for simulation validation with uncertainties using data from strong motion recordings; and while initially proposed in the context of site response simulation validation, it can be generalised to ground motion simulation involving source, path and site simulation.

3.4. Accessibility of simulated ground motions for utilisation in site-specific engineering applications

In addition to guidelines and documentation for the utilisation of ground motion simulations as noted in Section 2.1, the accessibility to utilise simulated ground motions is essential for their for site-specific engineering applications. While it is conceptually feasible that ground motion simulations are performed on a problem-specific basis for the most important safety-critical facilities, the overwhelming usage of simulated ground motions will occur in the situation in which ground motion simulations have been performed by a disciplinary expert, stored in a database, and then accessed by an earthquake engineer for use in a specific structural and/or geotechnical problem. The use of off-the-shelf simulations is equivalent to the use of as-published empirical ground motion models, which represent the majority of usage in seismic hazard analysis project. Therefore it is essential that databases exist to enable simulated ground motions to be stored and easily queried.

Because the direct utilisation of simulated ground motions in engineering practice (as opposed to utilisation by earthquake engineers in an research context) is only now emerging, then databases of simulated ground motions are not readily available. 'SeisFinder' (Fig. 9) is one such database that has recently been developed by QuakeCoRE in which simulated ground motions from various NZ historical or future earthquake ruptures. Users select the specific earthquake event (historical or future), the particular model (if there is more than a single simulation), and geographic location(s) of interest for which they wish to extract the simulated ground motions. Documentation is provided by those who undertook the simulation (based on that proposed by Bradley et al. [9]) to provide users with an understanding of the predictive capability of the simulations in different regions, as are scripts (Python, Matlab, Visual Basic/Excel) necessary to manipulate the extracted ground motion time series. Finally, simulated ground motions are available either with empirical Vs30-based site amplification, or for a deconvoluted condition, following the discussion in Section 3.2.3.

3.5. Use of simulated ground motions in near-real-time impact assessment

The potential improvements offered by ground motion simulations (over empirical models) also have relevance to near-real-time impact assessments, such as USGSâs Prompt Assessment of Global Earthquakes for Response (PAGER). The use of simulated motions in near-real-time applications requires several additional considerations that are trivial for empirical models because of their simplicity and low computational requirements. The first of these is that (semi-) automated software workflows are needed to take near-real-time earthquake source information (location, moment tensor, and finite fault) provided by a relevant agency and compute ground motions. This entails the development of a seismic source model from limited source information that evolves with time, the generation of a velocity model whose reference location and domain size is relevant for the event location and magnitude, performing the ground motion simulation and post-processing the results to obtain the necessary ground motion 'outputs' that are then passed onto impact computations. The second consideration is that since current physics-based ground motion simulations typically make use of significant high-performance computing (HPC) resources then prioritised access to such resources is necessary in order to be useful in near-real-time impact assessments.

Under the umbrella of QuakeCoRE, a NZ capability for real-time ground motion simulation has been pursued since November 2016, where such a capability was clearly needed following the 2016 Kaikoura earthquake. This capability is tested monthly via real-time drills. The drills make use of historical earthquakes (the specific earthquake for each drill is obviously unknown ahead of time), which also serves the purpose of continual validation of simulations against ground motion observations. The use of real-time drills also serves to highlight areas of weakness in computational workflows and theoretical models which are less evident when researchers undertake tasks in the absence of a high-pressure environment. Over the source of six months, such drills have reduced the human time required to perform a ground motion simulation (of an event provided in real time) from a full day, down to several minutes. Ironically, at present, New Zealand does not have an automated centroid moment tensor (CMT) solution in operation, so the sole task that requires manual intervention is taking a manually-derived CMT solution [40] and inputting it into the automated ground motion simulation workflow.

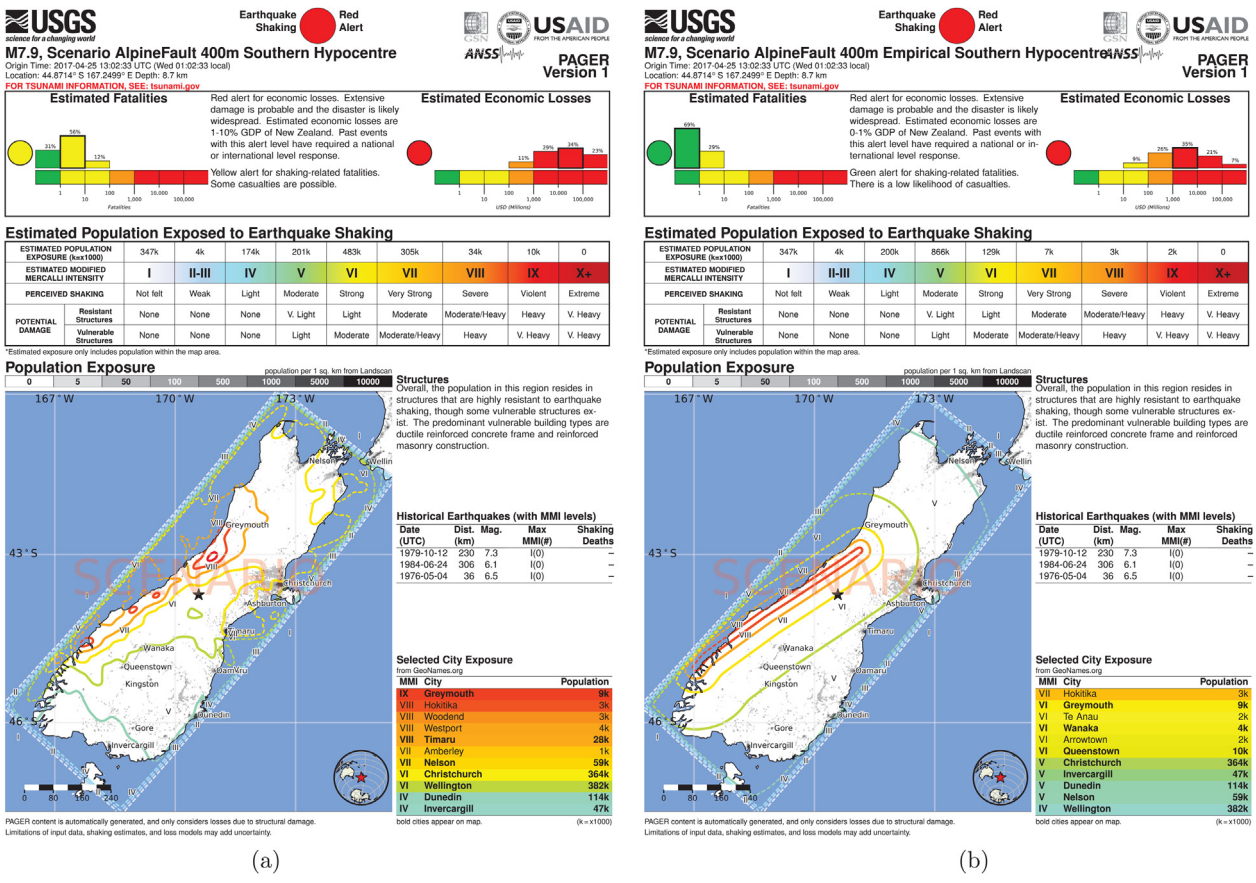
The current computational resources available in New Zealand through the National eScience Infrastructure (NeSI) enable ground motion simulations of moderate magnitude events to be performed within approximately one hour, while large magnitude events (which require a larger spatial grid) require several hours, and QuakeCoRE prioritised access means that wait time in the queue is generally very small.

As an illustration of the role of simulated ground motions for real-time or future scenario events, Fig. 10 illustrates USGS PAGER impact assessments for a potential future large earthquake on the Alpine Fault, and its dependence on the use of (a) physics-based ground motion simulations, or (b) empirical ground motion modelling. As discussed further in Bradley et al. [10], the principal differences between the physics-based and empirical ground motion models is that the physics based model results in appreciably greater ground motion amplitudes in the upper half of the South Island of New Zealand as a result of forward directivity, which is not modelled in the empirical prediction. As a result, the PAGER estimates of fatalities and economic losses are appreciably larger for the simulation-based estimate.

While not explicitly shown here, the capability of simulation-based methods to directly provide ground motion time series also means that real-time seismic response estimates of built infrastructure can be obtained from dynamic analysis models which have been constructed ahead of time (as opposed to empirical vulnerability functions that depend on IMs such as PGA, PGV etc.). Such capabilities will enable insights into seismic response to assist in direct visual inspections to assessment potential damage, as well as enabling truly prospective seismic response prediction, which will have spin-off benefits in the assessment and validation of numerical models and constitutive relations for geotechnical and structural systems.

4. Discussion and conclusions

This paper presented on-going challenges in the present paradigm shift of earthquake-induced ground motion prediction from empirical to physics-based simulation methods. An overview of recent ground



(a) (b)

Fig. 10. Comparison of USGS PAGER (Prompt Assessment of Global Earthquakes for Response) impact assessments for a potential large magnitude earthquake on the Alpine Fault based on (a) ground motion simulations; and (b) empirical ground motion prediction.

motion simulation validation efforts based on observed ground motions from the 2010 Darfield, 2011 Christchurch and 2016 Kaikoura earthquakes was presented as an illustration of the current prediction capabilities. On average, across the three events and a vibration period range of T = 0.01–10 s, the physics-based simulations were seen to generally provide a superior prediction to the contemporary use of empirical ground motion models.

These comparisons illustrate that, in certain circumstances, physics-based simulation methods already offer a superior prediction over empirical models. Of course, continual validation against ground motion observations from historical earthquake events, and the use of hierarchical validation is necessary to understand the specific predictive capability of simulated ground motions for site-specific applications.

The inherent physics basis of ground motion simulation methods provides an underlying framework for the assimilation of seismological observations, conceptual model development, computational implementation, and simulation prediction and validation. This process around a 'spiral of inference' continues to identify better theories and data for improving simulation models, and several source, path, and site aspects of simulation methods that are currently being pursued were examined.

The use of physics-based methods to obtain simulated ground motions entails a more complex process by which uncertainty in the simulation results is obtained, via the need to propagate uncertainty in the model parameters, and models themselves that are components of the overall simulation. In contrast, the development of empirical ground motion models based on statistical regression which directly provides estimates of model uncertainty. This additional complexity for uncertainty quantification using physics-based methods can also be partly attributed as the reason why uncertainty analysis of dynamic geotechnical and structural analysis models is still not commonplace. Given the due emphasis placed on ground motion uncertainty within probabilistic seismic hazard analysis, clearly an increased research emphasis on ground motion simulation uncertainty is needed to acceleration the adoption of simulated ground motions in practice.

Finally, discussion was also given to the tools and databases needed for the efficient utilisation of simulated ground motions both in specific engineering projects as well as for near-real-time impact assessment. Because of the high-performance computing (HPC) demands associated with performing such simulations, storage and easy retrieval of terabytes of simulations, streamlined software workflows, and access to HPC resources for near-real-time simulation are also necessary in order to realise the full benefits.

Acknowledgements

Hoby Razafindrakoto, Robin Lee, Viktor Polak, and Chris de la Torre helped prepare several figures in this paper. Collaboration with Mike Hearne and David Wald on USGSs PAGER software is greatly appreciated. The high performance computing used in this research was provided through NZ's National eScience Infrastructure merit allocation scheme. This work was also supported by the Royal Society of New Zealand Marsden Fund and Rutherford Discovery Fellowship, and QuakeCoRE: The Centre for Earthquake Resilience. This is QuakeCoRE publication number 0205.

References

[1] Afshari Kioumars, Stewart JP. Implications of california vertical array data for modelling of non-ergodic site response; 2015. p. 11.
[2] Beauval Caroline, Tasan Hilal. Aurore Laurendeau, Elise Delavaud, Fabrice Cotton, Philippe Gueguen, and Nicolas Kuehn. On the testing of ground motion prediction

equations against small magnitude data. Bull Seismol Soc Am 2012;102(5):1994–2007. http://dx.doi.org/10.1785/0120110271. [URL›.].

[3] Bielak Jacobo, Loukakis Kostas, Hisada Yoshiaki, Yoshimura Chiaki. Domain reduction method for three-dimensional earthquake modeling in localized regions, part i: theory. Bull Seismol Soc Am 2003;93(2):817–24. http://dx.doi.org/10.1785/0120010251. [URL›.].

[4] Bradley BA, Jeong S, Razafindrakoto Hoby NT. Strong ground motions from the 2010–2011 canterbury earthquakes and the predictive capability of empirical and physics-based simulation models; 2015. p. 16.

[5] Bradley Brendon A. A framework for validation of seismic response analyses using seismometer array recordings. Soil Dyn Earthq Eng 2011;31(3):512–20. http://dx.doi.org/10.1016/j.soildyn.2010.11.008. [ISSN 0267-7261. ›.].

[6] Bradley Brendon A. Strong ground motion characteristics observed in the 4 September 2010 Darfield, New Zealand earthquake. Soil Dyn Earthq Eng 2012(42):32–46. http://dx.doi.org/10.1016/j.soildyn.2012.06.004. [ISSN 0267-7261. ›.].

[7] Bradley Brendon A. A New Zealand-specific pseudospectral acceleration ground-motion prediction equation for active shallow crustal earthquakes based on foreign models. Bull Seismol Soc Am 2013;103(3):1801–22. http://dx.doi.org/10.1785/0120120021. [URL›.].

[8] Bradley Brendon A, Cubrinovski Misko. Near-source strong ground motions observed in the 22 February 2011 Christchurch earthquake. Seismol Res Lett 2011;82(6):853. http://dx.doi.org/10.1785/gssrl.82.6.853. [URL›.].

[9] Bradley Brendon A, Pettinga Didier, Baker Jack W, Fraser Jeff. Guidance on the utilization of earthquake-induced ground motion simulations in engineering practice. Earthq Spectra 2017. http://dx.doi.org/10.1193/120216EQS219EP. [ISSN 8755-2930›.].

[10] Bradley Brendon A, Razafindrakoto Hoby NT, Polak Viktor. Groundâ motion observations from the 14 November 2016 Mw7.8 Kaikoura, New Zealand, earthquake and insights from broadband simulations. Seismol Res Lett 2017;88(3):740–56. http://dx.doi.org/10.1785/0220160225.

[11] Chen Po, Zhao Li, Jordan Thomas H. Full 3D tomography for the crustal structure of the los angeles region. Bull Seismol Soc Am 2007;97(4):1094–120. http://dx.doi.org/10.1785/0120060222. [URL›.].

[12] de la Torre CA, Bradley BA, Jeong S, McGann C. Incorporating soil nonlinearity into physics- based ground motion simulation through site- specific ground response analysis; 2017. p 8.

[13] Douglas J. Earthquake ground motion estimation using strong motion records: a review of equations for the estimation of peak ground acceleration and response spectral ordinates. Earth Sci Rev 2003;61:43–104.

[14] Dreger Douglas S, Jordan Thomas H. Introduction to the focus section on validation of the SCEC Broadband Platform v14.3 simulation methods. Seismol Res Lett 2015;86(1):15–6. http://dx.doi.org/10.1785/0220140233. [URL›.].

[15] Dreger Douglas S, Beroza Gregory C, Day Steven M, Goulet Christine A, Jordan Thomas H, Spudich Paul A, et al. Validation of the SCEC Broadband Platform v14.3 simulation methods using pseudospectral acceleration data. Seismol Res Lett 2015;86(1):39–47. http://dx.doi.org/10.1785/0220140118. [URL›.].

[16] Drouet Stephane, Cotton Fabrice. Regional stochastic GMPEs in low-seismicity areas: scaling and aleatory variability analysis application to the French alps. Bull Seismol Soc Am 2015. http://dx.doi.org/10.1785/0120140240. [URL ‹http://www.bssaonline.org/content/early/2015/07/02/0120140240.abstract›.].

[17] Frankel Arthur. Modeling Strong Motion Recordings of the 2010 Mw 8.8 Maule, Chile, Earthquake with High Stressâ Drop Subevents and Background Slip. Bull Seismol Soc Am 2017;107(1):372–86. http://dx.doi.org/10.1785/0120160127.

[18] Goulet Christine A, Abrahamson Norman A, Somerville Paul G, Wooddell Katie E. The SCEC broadband platform validation exercise: methodology for code validation in the context of seismicâ hazard analyses. Seismol Res Lett 2015;86(1):17–26. http://dx.doi.org/10.1785/0220140104. [URL›.].

[19] Graves Robert, Pitarka Arben. Refinements to the Graves and Pitarka (2010) broadband groundâ motion simulation method. Seismol Res Lett 2015;86(1):75–80. http://dx.doi.org/10.1785/0220140101. [URL›.].

[20] Graves Robert, Pitarka Arben. Kinematic groundâ motion simulations on rough faults including effects of 3D stochastic velocity perturbations. Bull Seismol Soc Am 2016;106(5):2136–53. http://dx.doi.org/10.1785/0120160088.

[21] Graves Robert, Jordan Thomas, Callaghan Scott, Deelman Ewa, Field Edward, Juve Gideon, et al. CyberShake: a physics-based seismic hazard model for Southern California. Pure Appl Geophys 2011;168(3):367–81. http://dx.doi.org/10.1007/s00024-010-0161-6. [ISSN 0033-4553,›.].

[22] Graves Robert W, Pitarka Arben. Broadband ground-motion simulation using a hybrid approach. Bull Seismol Soc Am 2010;100(5):2095–123. http://dx.doi.org/10.1785/0120100057. [URL›.].

[23] Hartzell Stephen, Harmsen Stephen, Frankel Arthur. Effects of 3D random correlated velocity perturbations on predicted ground motions. Bull Seismol Soc Am 2010;100(4):1415–26. http://dx.doi.org/10.1785/0120090060.

[24] Hartzell Stephen, Guzman Leonardo Ramerez-, Meremonte Mark, Leeds Alena. Ground motion in the presence of complex topography II: earthquake sources and 3d simulations. Bull Seismol Soc Am 2017;107(1):344–58. http://dx.doi.org/10.1785/0120160159.

[25] Jordan TH. The inference spiral of earthquake system science; 2015.

[26] Kaklamanos James, Bradley Brendon A, Thompson Eric M, Baise Laurie G. Critical parameters affecting bias and variability in siteâ response analyses using KiK-net downhole array data. Bull Seismol Soc Am 2013;103(3):1733–49. http://dx.doi.org/10.1785/0120120166. [URL›.].

[27] Lee En-Jui, Chen Po. Improved basin structures in southern california obtained through full-3D seismic waveform tomography (F3DT). Seismol Res Lett 2016;87(4):874–81. http://dx.doi.org/10.1785/0220160013. [URL ›.].

[28] Lee En-Jui, Chen Po, Jordan Thomas H. Testing waveform predictions of 3d velocity models against two recent los angeles earthquakes. Seismol Res Lett 2014;85(6):1275–84. http://dx.doi.org/10.1785/0220140093. [URL›.].

[29] Lee RL, Bradley BA, Ghisetti F, Thomson EM. Development of a 3D velocity model for the canterbury, new zealand region for broadband ground motion simulation. Bull Seismol Soc Am (Submitt) 2017.

[30] Lee RL. Development of a 3D Canterbury seismic velocity model and investigation of systematic effects through hybrid broadband ground motion simulation of small to moderate magnitude earthquakes [Ph.D. Thesis]. University of Canterbury; 2017.

[31] Luco N, Jordan TH, Rezaeian S. Progress of the southern california earthquake center technical activity group on ground motion simulation validation. Seismol Res Lett 2013;84(2). [URL ‹https://collaborate.scec.org/gmsv/Main_Page›.].

[32] Magistrale Harold, Day Steven, Clayton Robert W, Graves Robert. The SCEC southern california reference three-dimensional seismic velocity model version 2. Bull Seismol Soc Am 2000;90(6):S65–76. http://dx.doi.org/10.1785/0120000510. [URL›.].

[33] Maufroy E, Chaljub E, Hollender F, Kristek J, Moczo P, Klin P, et al. Earthquake ground motion in the mygdonian basin, greece: the E2VP verification and validation of 3D numerical simulation up to 4Hz. Bull Seismol Soc Am 2015;105(3):1398–418. http://dx.doi.org/10.1785/0120140228. [URL›.].

[34] Oberkampf WL, Trucano TG, Hirsch C. Verification, validation, and predictive capability in computational engineering and physics; 2002. p. 74.

[35] Paolucci R, Mazzieri I, Smerzini C. Anatomy of strong ground motion: near-source records and three-dimensional physics-based numerical simulations of the Mw 6.0 2012 May 29 Po Plain earthquake, Italy. Geophys J Int 2015;203(December (3)):2001–20. http://dx.doi.org/10.1093/gji/ggv405. [ISSN 0956-540X.›.].

[36] Ramrez-Guzman Leonardo, Boyd Oliver S, Hartzell Stephen, Williams Robert A. Seismic velocity model of the central united states (version 1): description and simulation of the 18 April 2008 Mt. Carmel, Illinois, earthquake. Bull Seismol Soc Am 2012;102(6):2622–45. http://dx.doi.org/10.1785/0120110303. [URL ‹http://www.bssaonline.org/content/102/6/2622.abstract›.].

[37] Razafindrakoto Hoby NT, Bradley BA, Graves RW. Broadband ground motion simulation of the 2011 Mw6.2 Christchurch earthquake, New Zealand. Bull Seismol Soc Am (Submitt) 2017.

[38] Restrepo Doriam, Bielak Jacobo. Virtual topography: a fictitious domain approach for analyzing free-surface irregularities in large-scale earthquake ground motion simulation. Int J Numer Methods Eng 2014;100(7):504–33. http://dx.doi.org/10.1002/nme.4756. [ISSN 1097-0207. ›.].

[39] Restrepo Doriam, Bielak Jacobo, Serrano Ricardo. Juan GÃ^{3}mez, and Juan Jaramillo. Effects of realistic topography on the ground motion of the colombian andes â a case study at the aburrÃ¡ valley, antioquia. Geophys J Int 2016;204(3):1801–16. http://dx.doi.org/10.1093/gji/ggv556. [ISSN 0956-540X. URL ‹http://dx.doi.org/10.1093/gji/ggv556›.].

[40] Ristau John. Update of regional moment tensor analysis for earthquakes in new zealand and adjacent offshore regions. Bull Seismol Soc Am 2013;103(4):2520–33. http://dx.doi.org/10.1785/0120120339. [URL ‹http://www.bssaonline.org/content/103/4/2520.abstract›.].

[41] Roten D, Olsen KB, Pechmann JC. 3D simulations of M7 earthquakes on the Wasatch fault, utah, part II: broadband (0-10 Hz) ground motions and nonlinear soil behavior. Bull Seismol Soc Am 2012;102(5):2008–30. http://dx.doi.org/10.1785/0120110286. [URL ‹http://www.bssaonline.org/content/102/5/2008.abstract›.].

[42] Roten D, Olsen KB, Day SM, Cui Y, Fah D. Expected seismic shaking in Los Angeles reduced by San Andreas fault zone plasticity. Geophys Res Lett 2014;41:2769–77. http://dx.doi.org/10.1002/2014GL059411.

[43] Roten D, Cui Y, Olsen KB, Day SM, Withers K, Savran WH, Wang P, Mu D. High-frequency nonlinear earthquake simulations on petascale heterogeneous supercomputers; 2016.

[44] Strasser FO, Abrahamson NA, Bommer JJ. Sigma: issues, insights, and challenges. Seismol Res Lett 2009;80(1):40–56.

[45] Taborda R, Bielak J, Restrepo D. Earthquake ground-motion simulation including nonlinear soil effects under idealized conditions with application to two case studies. Seismol Res Lett 2012;83(6):1047–60. http://dx.doi.org/10.1785/0220120079. [URL ›.].

[46] Taborda Ricardo, Bielak Jacobo. Groundâ motion simulation and validation of the 2008 chino hills, california, earthquake. Bull Seismol Soc Am 2013;103(1):131–56. http://dx.doi.org/10.1785/0120110325. [URL›.].

[47] Tape C, Liu Q, Maggi A, Tromp J. Seismic tomography of the Southern California crust based on spectral-element and adjoint methods. Geophys J Int 2010;180:433–62.

[48] Villani Manuela, Abrahamson Norman A. Repeatable site and path effects on the ground-motion sigma based on empirical data from southern california and simulated waveforms from the CyberShake platform. Bull Seismol Soc Am 2015;105(5):2681–95. http://dx.doi.org/10.1785/0120140359. [URL›.].

[49] Wang Feng, Jordan Thomas H. Comparison of probabilistic seismicâ hazard models using averaging-based factorization. Bull Seismol Soc Am 2014;104(3):1230–57. http://dx.doi.org/10.1785/0120130263. [URL›.].

[50] Withers Kyle B, Olsen Kim B, Day Steven M. Memory-efficient simulation of frequency-dependent q. Bull Seismol Soc Am 2015;105(6):3129–42. http://dx.doi.org/10.1785/0120150020. [URL›.].

[51] Xu Jifeng, Bielak Jacobo, Ghattas Omar, Wang Jianlin. Three-dimensional nonlinear seismic ground motion modeling in basins. Phys Earth Planet Inter 2003;137(1):81–95. http://dx.doi.org/10.1016/s0031-9201(03)00009-8. [ISSN 0031-9201›.].

[52] Yoshimura Chiaki, Bielak Jacobo, Hisada Yoshiaki, Fernandez Antonio. Domain reduction method for three-dimensional earthquake modeling in localized regions, part II: verification and applications. Bull Seismol Soc Am 2003;93(2):825–41. http://dx.doi.org/10.1785/0120010252.