NEW ZEALAND SOCIETY FOR EARTHQUAKE ENGINEERING
2019 Pacific Conference on Earthquake Engineering
TURNING HAZARD AWARENESS INTO RISK MITIGATION
4 – 6 April | SkyCity, Auckland | New Zealand

Footprint based PSHA: the case of Christchurch, New Zealand

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ABSTRACT

3D physics-based numerical simulations are nowadays a theoretically sound and mature methodology, capable to produce synthetic seismograms as reliable as the observed one, at least within a certain frequency range. Forward physics-based simulation is an increasingly popular tool to investigate specific effects that are rarely empirically observed, such as strong ground motion in the near field of an earthquake. Probabilistic seismic hazard analysis simply based on ground motion prediction equations tends to be insufficiently constrained at short distances and available data only partially account for the rupture process, seismic wave propagation and three-dimensional complex configurations. To overcome this issue it is possible to enrich the existing empirical dataset with synthetic records: i) conducting a probabilistic analysis on physics-based simulations and ii) implementing the results as a generalized attenuation function into the classical probabilistic seismic hazard analysis. This paper aims at shortly describing the "footprint" based probabilistic seismic hazard analysis, a streamlined and novel approach for further enhancing the probabilistic seismic hazard analysis, based on the direct integration into the probabilistic framework of a set of

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deterministic scenarios, wisely chosen and associated to a probability of occurrence. Furthermore the proposed approach is applied to the case of Christchurch, New Zealand, relying on 3D synthetic scenarios generated through the spectral element code SPEED. Finally the hazard maps obtained through classical, generalized attenuation function (GAF) and footprint based probabilistic seismic hazard analysis are compared.

1 THE CHRISTCHURCH CASE STUDY

1.1 Set-up of the 3D computational model for Christchurch area

The Physics-Based Simulation (PBS) requires the creation of a 3D numerical model for the area under investigation and therefore the Christchurch alluvial plain was numerically reconstructed, combining three set of input data: i) the topography model; ii) the seismotectonic model; and iii) the 3D velocity model.

Significant advances have been made recently in constraining the velocity model of the region of interest, extending over the Canterbury Plains and including the city of Christchurch (Lee et al., 2017; Razafindrakoto et al., 2018). However, In this work we essentially keep the model presented in Guidotti et al. (2011), for the following reasons: (i) the model qualitatively and quantitatively performs relatively well against observed ground motion data (Guidotti et al., 2011, 2018) in the range of interest of the PBS, (ii) the purpose of the present work is to conduct a sensitivity analysis of our results against a well-established approach to assess the seismic hazard in a certain area, rather than to improve the quality of our validation for the Mw 6.2 February 22, 2011 event, and (iii) this allows a direct comparison with the results previously presented.

The computational model (Figure 1) extends over an area of circa 60 x 60 km^2 and down to 20 km depth, and the numerical grid consists of 384,711 hexahedral elements, resulting in approximately 25.2 million degrees of freedom, using a fourth order polynomial approximation degree. A numerical mesh has been used with a size varying from a minimum of 150 m, on the top surface, up to 1500 m at 4 km depth and reaching 2000 m in the deep layers. The shape of the alluvial basin, as reported in Bradley (2012) has been implemented in the model through a Not-Honoring approach (Stupazzini et al., 2006, 2009). Table 1 provides the mechanical properties of the model. Considering 5 grid points per minimum wavelength for non-dispersive wave propagation in heterogeneous media by the spectral element approach, the model can propagate up to a maximum frequency of 2.0 Hz. Further details of the model are provided in Guidotti et al., (2011).

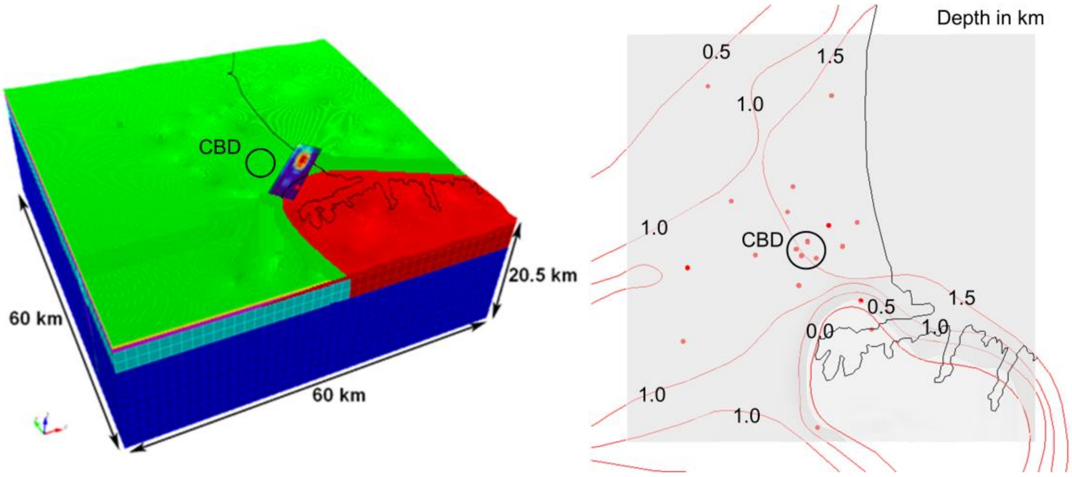

Figure 1: A) 3D geometry of the area under study, with superimposed the causative fault of the Mw 6.2, February 22, 2011 event (after Guidotti et al., 2011) B) Depth contours of the contact between the alluvial soft sediments and the bedrock (depth in km) as reported in Bradley (2012)

Table 1: Soil profile adopted in the numerical simulations. Note that the alluvial basin has a maximum thickness of 1.5 km and consists of three horizontal layers with Vs ranging from 300 m/s to 1,500 m/s.

Layer	**Depth (m)**	**Thickness (m)**	**V_P (m/s)**	**V_S (m/s)**	**ρ (kg/m^3)**	**Q**
1	0-300	300	600	300	1700	70
2	300-750	450	1870	1000	2000	100
3	750-1500	750	2800	1500	2300	100
4	0-5000	5000	5500	3175	2600	200
5	1500-5000	3500	5000	2890	2700	200
6	5000-20000	15000	6000	3465	2700	250

1.2 The simulated ground shaking scenarios

A total of 48 scenarios have been simulated along the causative fault of the Mw 6.2, February 22, 2011 event through a pre-processing toolbox that automatically generates physically constrained slip distributions for a given fault and magnitude. The toolbox takes into account the joint probability distributions of the main kinematic parameters according to the broadband rupture generator proposed by Crempien and Archuleta (2015). For each scenario, the source time function is assumed a simplified smoothed Heaviside function, while the rupture velocity follows the built-in scheme proposed in previously quoted paper. Figure 2 shows three of the 48 sources as generated with the pre-processing tool, in particular a scenario of Mw 6.2. A linear visco-elastic (LE) and a non-linear visco-elastic (NLE) constitutive model has been assumed (Stupazzini et al. 2009) to simulate the behavior of the soft soil deposits in the upper 300m, having VS,30 lower than 400 m/s. Each PBS was computed on the Blue Waters – Sustained Petascale Computing (https://bluewaters.ncsa.illinois.edu/) and took ~ 2 hours on 1024 cores, with an advancing time step of 0.0003125s and a total simulation time of 30s. Figure 3 shows the results for three of the 48 simulations.

The set of simulations presented in this work can be considered reliable up to a frequency of 2.0 Hz. In order to obtain broadband results, fundamental in several engineering applications, we adopted the methodology presented in Paolucci et al. (2018) and referred as "ANN2BB", based on the training and application of Artificial Neural Networks (ANN). The ANN-based approach, applied to the simulated results, preserves the full spatial correlation of ground motion, incorporating important physical features, such as directivity effects, radiation pattern, and 3D complex site effects, also at short periods (i.e. at T < 0.75s), and therefore beyond the frequency limit of the numerical model. This is a major improvement with respect to commonly used broadband methods, which are based on the application of independent hybrid approaches at low and high frequencies and therefore tend to neglect the spatial correlation features, as estimated by the physics-based numerical approach at long periods. To preserve the spatial correlation of ground motion at regional scale and on a wide frequency range may have a crucial role in seismic risk studies, especially within urban areas.

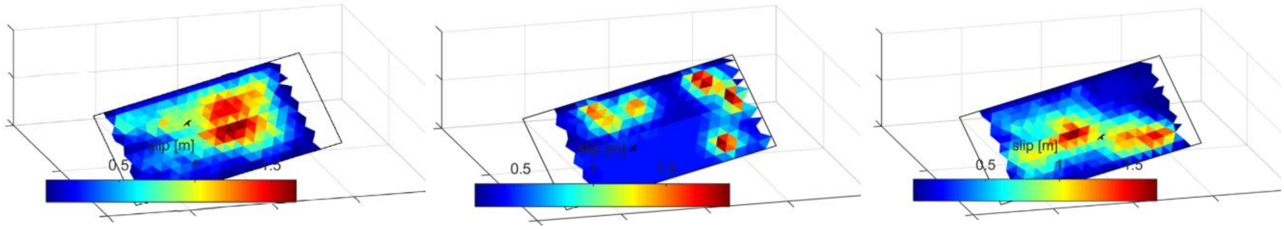

Figure 2: Example of three different slip pattern and hypocenter location for an hypothetical Mw 6.2 scenario generated on the "Christchurch" fault.

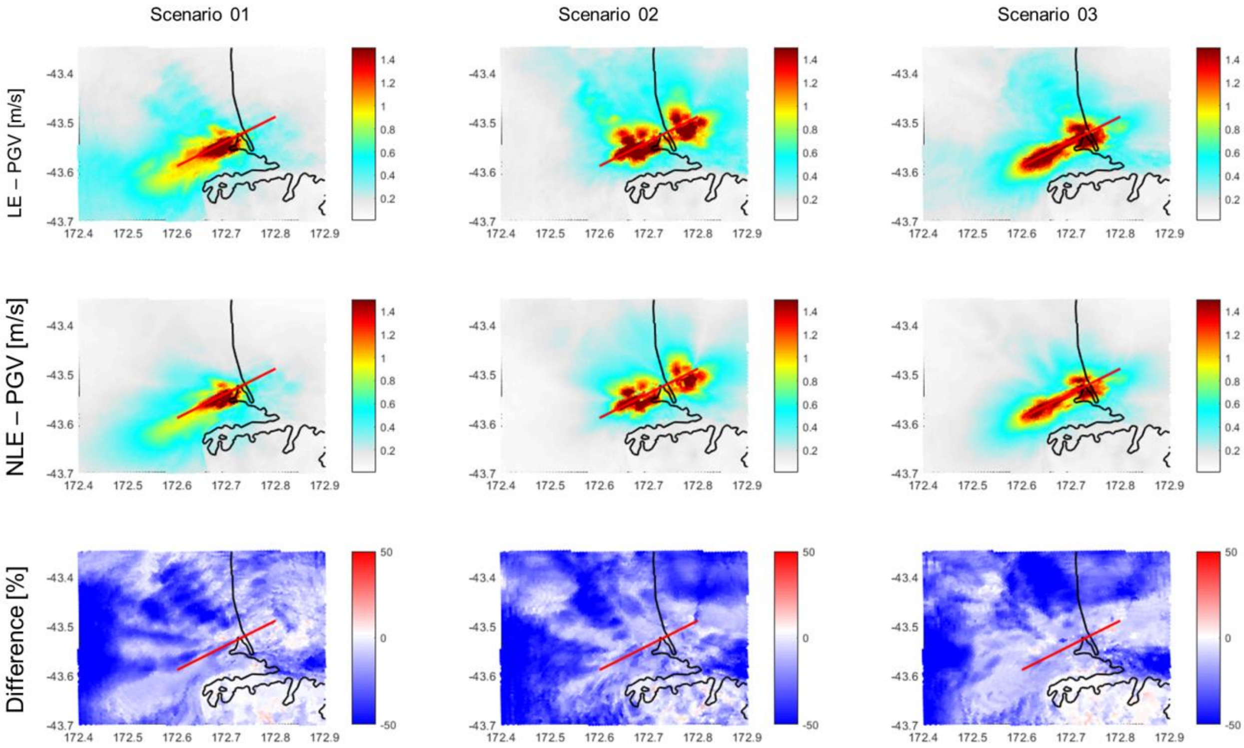

Figure 3: Magnitude 6.2 scenario occurring along the "Christchurch" fault. PGV maps obtained through the (top line) Linear visco-Elastic (LE) SPEED and ANN2BB approach, (center line) Non Linear visco-Elastic (NLE) SPEED and ANN2BB approach, and (bottom line) the percentage difference.

2 CLASSICAL VS ENHANCED PROBABILISTIC SEISMIC HAZARD ASSESSMENT

The present work uses the PBSs to assess the probabilistic seismic hazard assessment (PSHA) in the Christchurch area, achieving the twofold aim of (i) incorporating physical effects typically neglected by Ground Motion Models (GMMs), and (ii) preserving the spatial correlation of the ground motion field at different periods. To this end, we follow the approach proposed in Stupazzini et al. (2015) and Paolucci et al. (2018).

The PSHA formulation, introduced by Cornell (1968), involves essentially the following three steps: (i) identification of the potential seismic sources; (ii) estimation of the frequency-magnitude relationship able to capture the annual probability of occurrence for the different scenarios (e.g. classical Gutenberg-Richter relationship or characteristic earthquake model); and (iii) modelling of the expected ground motion at a given location (i.e.: using GMMs).

In the classical formulation, the last step is achieved adopting GMMs, therefore implying the ergodic assumption that the probability distribution of the ground motion is inferred from statistical analysis based on strong motion data, recorded from other tectonically similar regions, worldwide. The simplicity and the versatility to adapt to different site and tectonic contexts made in the past years GMMs a popular and useful tool is the seismic hazard analysis, in spite of their intrinsic limitations. GMMs are usually not adequately calibrated for several conditions that govern seismic hazard at a site, such as (i) large earthquake magnitude, (ii) near-source, (iii) soft soil sites and (iv) complex geological irregularities.

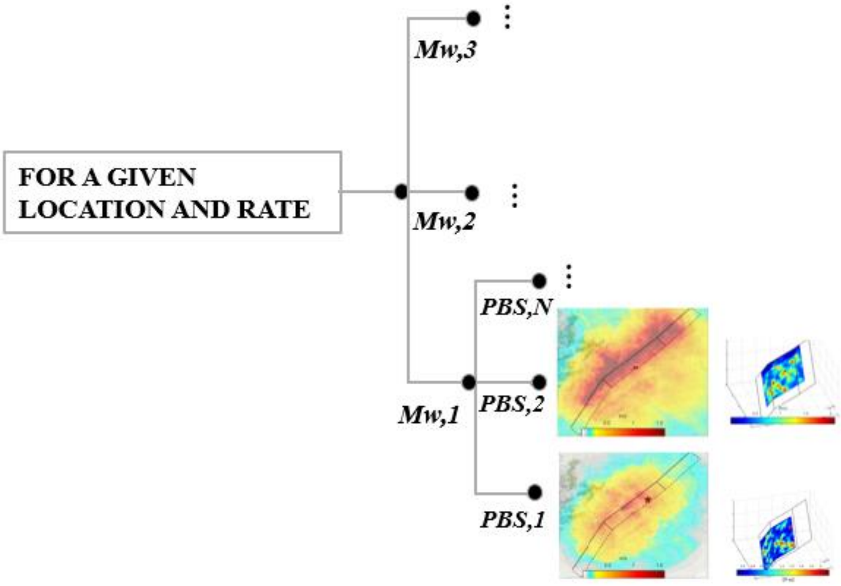

Figure 4. Integration of selected PBSs into a classical logic tree based approach.

To overcome those limitations, this paper proposes to use the PBSs directly into PSHA to achieve better results in regions characterized by a very high seismic risk, such as Christchurch and the Canterbury Plains. In the following we will use the acronym "PSHAe", where "e" stands for "enhanced" and recalls the fact that the seismic hazard assessment is based on PBSs. The PSHAe can be envisioned in two following, rather different, ways:

(i) The first way assumes that the ground motion variability at each site is described by a lognormal distribution. The moments of the distribution are calibrated directly from the PBSs, as described in Villani et al. (2014) and implemented in the CRISIS software (Ordaz et al., 2013) through generalized attenuation functions (GAF)

(ii) The second approach is referred as footprint-based PSHAe and aims at taking full advantage of the PBSs results within a logic-tree framework. Each computed scenario represents a branch of a logic tree with all the branches having the same weight (Figure 4). This allows us to not assume a specific probability distribution for the ground motion and to take into account its spatial correlation.

3 RESULTS

Herein the results of the PSHAe study conducted according to the methodologies described in the previous section are addressed and compared against the traditional GMM-based approach. Figure 5 illustrates the PGV hazard maps for the return period of 2,475 years, obtained with the footprint-based (left), GAF-based (center) and GMM-based (right) approaches, respectively. The Chiou and Young (2014) empirical model (referred as CHYO14) has been used to this end. It is worth highlighting that both the GAF and CHYO14 peak ground velocity maps have been obtained integrating over three sigma. Observing Figure 5, it is evident, as expected, that the footprint and GAF approaches produce relatively consistent results while CHYO14-based PSHA shows profound differences.

Figure 6 shows the hazard curves computed approximatively in the surrounding of the Christchurch CBD. They present a characteristic feature: the footprint and GAF based hazard curves are systematically higher than CHYO14 curve up to around 2000 years. For higher return periods the CHYO14 hazard tends to provide higher hazard values. In a nutshell, footprint and GAF are per construction PBS consistent and show a steeper trend of the hazard curve compared to classical GMM based seismic hazard analysis. It is important to notice that in this specific application we are not taking into account the uncertainty related to the location of the fault, since it was clearly identified based on the 2010-11 Christchurch seismic sequence, nevertheless, this is not always the case and it could potentially change the results. Up to now we simply considered a set of events with approximately magnitude 6.2; we are also enhancing and increasing our synthetic dataset in order to carefully test the reliability of our results.

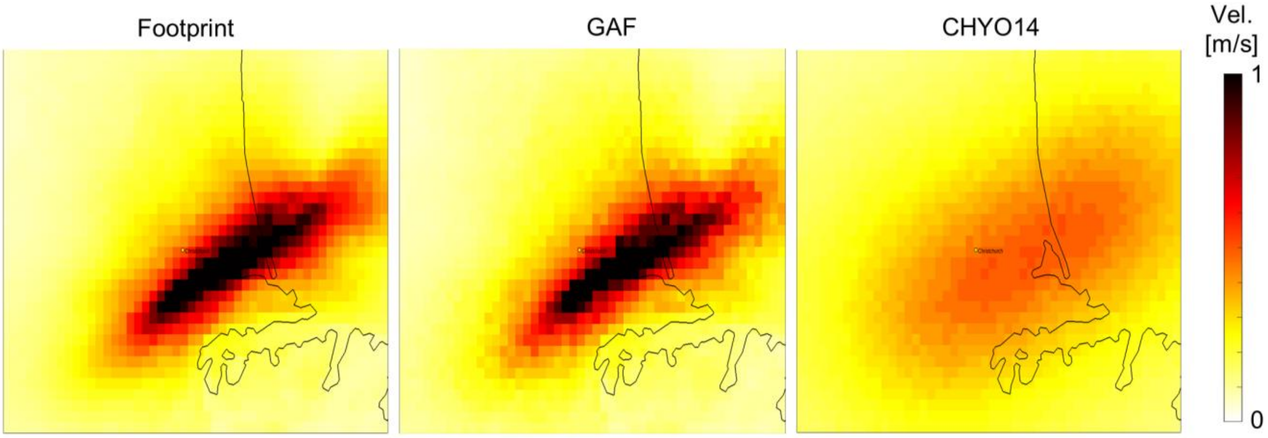

Figure 5. PGV Hazard Maps for Tr = 2475y obtained according to the Footprint (left), GAF (center) and GMM (right) method. The GMM used is the CHYO14.

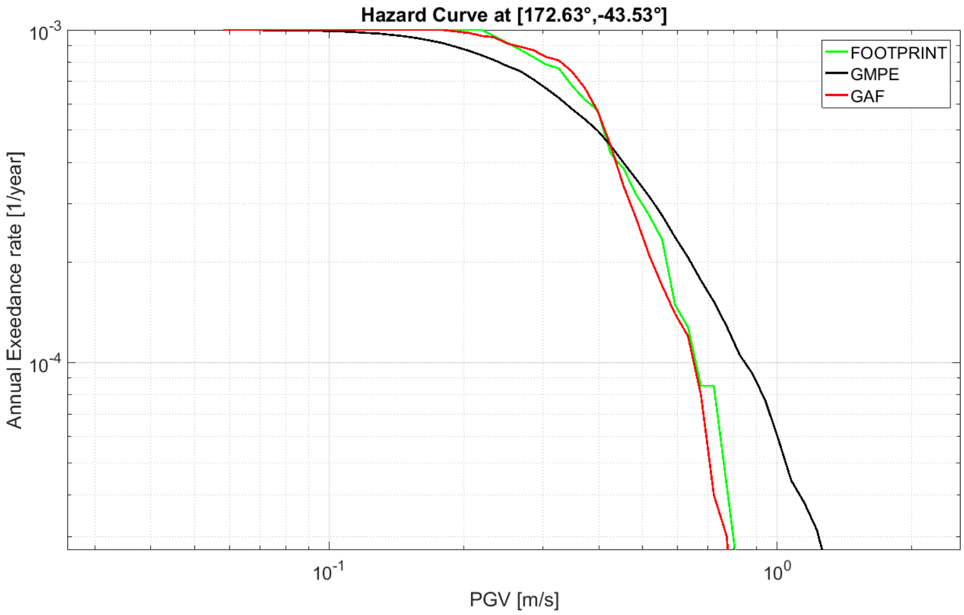

Figure 7. PGV Hazard Curve for the CBD in Christchurch (yellow point in Figure 5).

4 CONCLUSIONS

A novel approach, largely relying on a spectral element code, extensively verified (Chaljub et al., 2014 and Mazzieri et al., 2013) and validated (Smerzini & Villani 2012, Paolucci et al. 2015), was devised in order to construct deterministic low frequency seismograms in the metropolitan area of Christchurch. The low frequency seismograms have been enriched in the high frequency part, following the “ANN2BB” approach described in Paolucci et al. (2018). The dataset produced consists of about 50 Physics-Based Simulations, occurring along the causative fault of the Mw 6.2, February 22, 2011event, the most damaging of the seismic sequence that struck Christchurch and the South Island of New Zealand between 2010 and 2011.

As presented in Stupazzini et al. (2015) and Paolucci et al. (2018), the deterministic dataset has been integrated into a classical SHA, based on a logic-tree framework, through the PSHAe methodology. Three different seismic hazard assessment for the Christchurch area are compared in this work: the classical GMMs based results against the outcomes of two proposed PSHAe implementations: the Generalized Attenuation Function approach (GAF) and the footprint-based approach.

The preliminary comparisons of the seismic hazard map, in terms of PGVgmh, for the Christchurch region confirms the importance of taking into account PBS in future research, highlighting a major difference for risks located in the proximity of active faults. The described approach can be applied to other areas worldwide, targeting regions characterized by high population density and exhibiting adequate geological, geotechnical, and seismological features. The present work does not represent an isolated attempt; on the contrary, it is connected to a research area of of paramount importance in modern computational seismology (e.g.: Dreger et al. 2015 and Goulet et al. 2015). A comprehensive discussion on the alternative strategies and investigations is beyond the scope of the present work and we refer the reader to future works.

5 ACKNOWLEDGMENTS

This work has been carried out in the framework of the 2015-2017 agreement between Munich Re and Politecnico di Milano. This research is part of the Blue Waters sustained-petascale computing project, which is supported by the National Science Foundation (awards OCI-0725070 and ACI-1238993) and the state of Illinois. Blue Waters is a joint effort of the University of Illinois at Urbana-Champaign and its National Center for Supercomputing Applications.

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