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PHYSICS-BASED PROBABILISTIC SEISMIC HAZARD AND PROBABILSITIC RISK ASSESSMENT IN LARGE URBAN AREAS

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Abstract

The broad goal of earthquake engineering is the mitigation of the risk induced by earthquakes and in order to accomplish this difficult task it is of paramount importance producing a reliable predictions of the consequences of strong earthquakes on urban areas and civil infrastructures. The spatially extended nature of an urban environment makes a proper description of the spatial correlation of the ground motion crucial for any reliable damage/loss estimation, especially in the so-called "near-source" region. In fact, an empirical ground motion models (GMMs), as normally used, can only roughly take into account the peculiar tectonic and geotechnical conditions, and it remains unfortunately still nowadays, poorly calibrated in the region located in immediate proximity to the causative fault.

In the last decades, boosted by the increasing availability of computational resources, significant progress have been made worldwide in predicting the strong motion shaking thanks to the 3D physics-based numerical simulations (PBSs). Earthquake ground motion, including a full 3D seismic wave propagation model from the source to the site, have gained increasing consensus thanks to different verification/validation exercises, and they are becoming a valuable complementary tool at GMMs to provide realistic ground motion estimations.

Physics-Based Probabilistic Seismic Hazard Assessment is getting more popular and showing remarkable differences if compared against classical GMMs based one; in spite of that, it remains quite rarely applied and essentially because of two important reasons: (i) the accurate level of description from a geological/geotechnical and geotectonic perspective and (ii) the large computational efforts required to carry out numerical simulations.

The present work focuses on the recipe that was developed and recently presented to take advantage of physics-based approaches, on the one hand, within a classical Probabilistic Seismic Hazard Assessment (PSHA) framework and, on the other, in order to accomplish reliable Probabilistic Risk Assessment (PRA), especially suited for large urban areas.

Two approaches are here considered and compared: "GAF" (Generalized Attenuation Function) and "*footprint"* based approach. The former consists of extrapolating the lognormal distribution fitting the frequency histogram of the PBSs and replacing the statistical moments of such distribution into the PSHA in place of the statistical moments of the GMMs. The *footprint*-based PSHA adopts directly the PBSs, without postulating any specific probability distribution by simply taking all the realizations of the scenario earthquake within a logic-tree framework, as multiple branches, each equally weighted.

The scope of this work is to (i) accomplish PSHA and PRA at urban scale according to the two above mentioned Physics-Based approaches and to (ii) compare the results obtained against the more classical approach based on GMMs. To this end the cities of Istanbul, Beijing and Christchurch have been selected as pilot case studies since they share: (i) the proximity to well-known mapped faults capable to trigger a severe earthquake and (ii) a good description of the geotechnical characterization of the soil.

Keywords: 3D Physics-Based Numerical Simulations, Probabilistic Seismic Hazard Assessment Probabilistic Risk Assessment, Urban Area, Istanbul, Beijing, Christchurch.

1. Introduction

An accurate evaluation of seismic hazard, based on suitable approaches for earthquake ground motion prediction, is the key for the reliable assessment of seismic risk in large urban areas. However, the classical approaches relying on GMMs), that are most often used for this purpose, roughly take into account the specific tectonic and geotechnical conditions in which the urban area lies and tend to be poorly calibrated in the near-source region of large earth-quakes, thus producing in many cases significant underestimations of the earthquake ground motion intensity.

In the recent years, boosted by the increasing availability of computational resources, PBSs of earthquake ground motion including a full 3D seismic wave propagation model from the source to the site, have gained increasing interest so that they are expected to become, in near future, the most promising tool to generate ground shaking scenarios from future realistic earthquakes. In this work, the code SPEED - Spectral Elements in Elastodynamics with Discontinuous Galerkin (http://speed.mox.polimi.it/, [1]), a certified high-performance open source code, developed by Politecnico di Milano, was used to provide massive 3D broadband (i.e., usable in the whole frequency range of interest for engineering applications) shaking scenarios in large urban areas.

The application of this state-of-art approach to several strategic urban areas worldwide (see review in [2]) is, therefore, of paramount importance to make this approach feasible and closer to the needs of seismic engineering applications. In this context, Munich RE funded a research activity with Politecnico di Milano between 2015 to 2017, having the objective of developing an advanced integrated probabilistic/deterministic procedure for seismic hazard assessment in large strategic urban areas, making use of 3D numerical physics-based ground shaking scenarios. In conjunction with this objective, the scope of the work presented in this paper was the generation of a wide set of 3D broadband physics-based ground shaking scenarios for the three cities of Istanbul (Turkey), Beijing (China) and Christchurch (New Zealand) and its use for the assessment of seismic hazard and seismic risk at urban scale.

In fact, all selected cities are situated on a sedimentary basin, and have been chosen because they are highly exposed to the seismic threat, as many other cities all around the world. The aforementioned physics-based fault rupture, coupled with ANNs, trained on a set of strong-motion records, to predict the response spectral ordinates also at short periods, was adopted in order to start a critical revision of the seismic hazard and risk in the three urban areas previoulsy mentioned.

2. Istanbul, Beijing and Christchurch case studies

In order to perform a PBS, the SPEED code requires the discretization of the computational domain. This step was conveniently accomplished using the Trelis® software, which incorporates a set of powerful and advanced meshing schemes specifically developed to handle hexahedral unstructured meshes. The different meshes have been designed according to a conservative rule of thumb of 5 grid points per minimum wavelength for non-dispersive wave propagation in heterogeneous media by the SE approach [3,4]; frequencies are propagated accurately up to about 1.0, 1.5 and 2.0 Hz, respectively for the case studies of Istanbul, Beijing and Christchurch. The number of elements spans from around 380,000 up to more than 2,2 million elements in the three models. In all the cases it has been used a fourth order polynomial approximation degree. Finally the mesh elements have a size largely varying, from a minimum of 150 m, at the top surface, up to more than 1000 m in the bottom layers. The simulations were performed on the Marconi-A1 cluster installed at CINECA, Italy. Table 1 summarizes the main features of the three computational domains. It is worth reminding the reader that PBSs database will be soon freely available within the SPEED code web site.

In Figure 1 and 2 show some details about the mechanical properties and the numerical mesh created for the the Beijing area.

Table 1 – Summary of the models created for the different regions under investigation.

Area investigated	Model size (LxWxD) [km]	hexahedral elements	# DoF $[10^6]$	Min/Max el. size [m]	Fmax [Hz]	Faults, studied*	Mw range	# Events
Istanbul (TUR)	165x100x30	2,257,482	≈ 475	180/600	≈ 1.0	NAF-MS	7.0-7.4	66
Beijing (CHN)	70x70x30	859,677	≈ 160	150/600	≈ 1.5	SQL, TN	6.5-7.3 6.5-6.9	31 17
Chirstchurch (NZL)	60x60x20	384,711	≈ 25.2	150/1500	≈ 2.0	CHCH	6.1-6.3	47

Acronyms of the faults studied: North Anatolyan Fault, Marmara Segment (NAF, MS), Shunyi-Qianmen-Liangxiang (SQL) and Tongxian-Nanyuan (TN) faults; Christchurch Fault (CHCH).

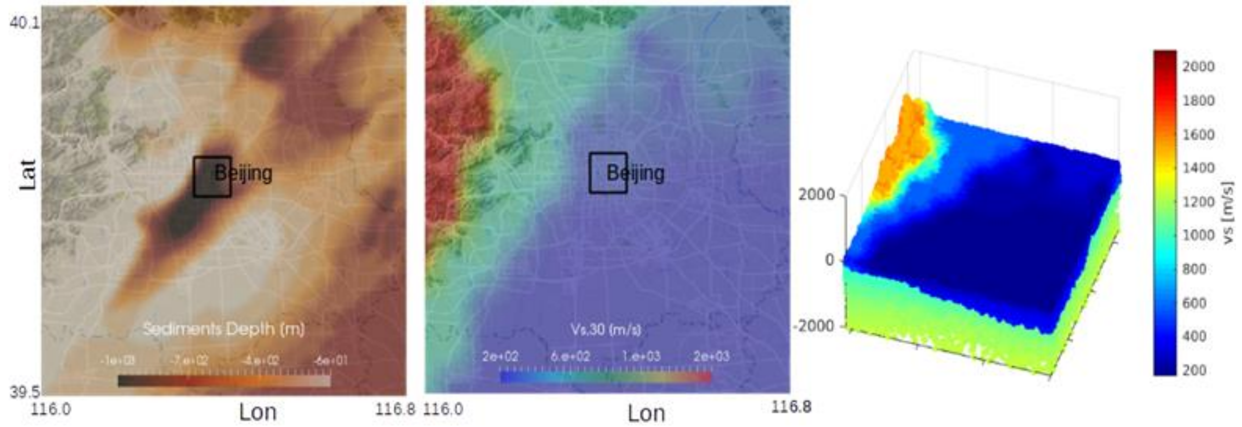
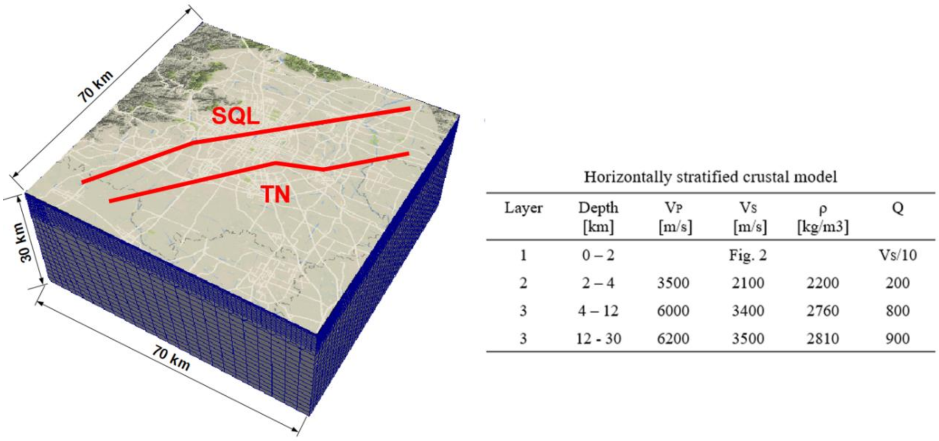


Fig. 1 - Sediment thickness (left), VS30 map (center) and VS(z) model (right) for the first layer 0-2 km.



Horizontally stratified crustal model

Layer	Depth [km]	VP [m/s]	Vs [m/s]	ρ [kg/m3]	Q
1	0 – 2		Fig. 2		Vs/10
2	2 – 4	3500	2100	2200	200
3	4 – 12	6000	3400	2760	800
3	12 - 30	6200	3500	2810	900

Fig. 2 - 3D computational model for the Beijing area (left) and 3D crustal model (right)

3. Classical versus enhanced seismic hazard and risk assessment

The main goal of the present work is to use the PBSs to assess PSHA and PRA in Istanbul, Beijing and Christchurch area, achieving the twofold aim of (i) incorporating physical effects that are normally neglected by GMMs, and (ii) preserving the spatial correlation of the ground motion field at different periods. To this end, the approach addressed in [5] and [6] is followed.

As it is well-known, the PSHA formulation introduced by [7] involves the following steps: (i) identification of the potential seismic sources, (ii) estimation of the frequency-magnitude relationship capable to describe the annual probability of occurrence for the different scenarios (e.g. classical Gutenberg-Richter relationship or characteristic earthquake model) and finally (iii) modelling of the expected ground motion at a given location (i.e.: by means of GMMs).

In the classical formulation, the last step is achieved adopting GMMs (see Figure 3 as an example), 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 tectonically similar regions, worldwide. The ease of use of GMMs combined with their adaptability to different site and tectonic contexts made GMMs a popular and useful tool, in spite of their intrinsic limitations: GMMs are usually not adequately calibrated for all those 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.

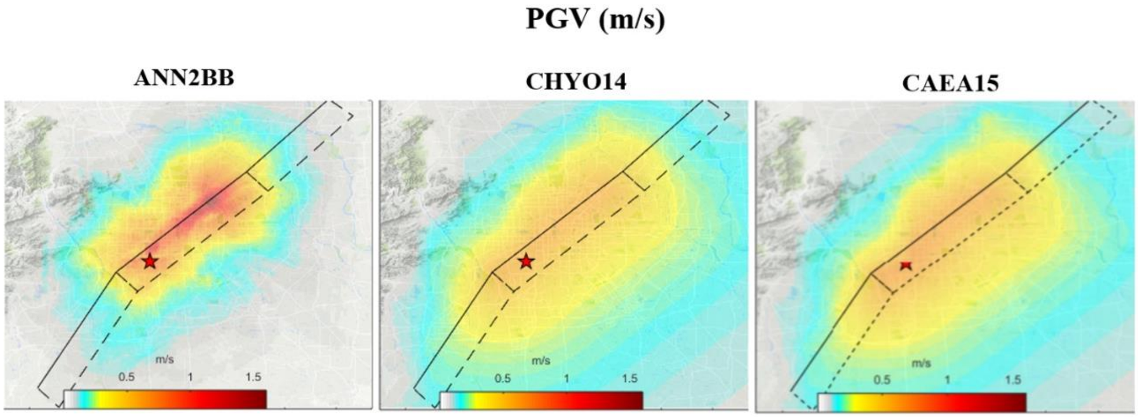


Fig. 3 - Magnitude 6.5 scenario occurring along the SQL fault. PGV maps obtained through the ANN2BB approach (right), with Chiou & Youngs, 2014 [8] (center) and with Cauzzi et al., 2015 [9] (left).

In order to overcome those limitations, the idea herein proposed is to make use of the PBSs directly into PSHA in order to better constrain the results for those areas characterized by a very high seismic risk, such as Beijing. In previous publications we referred to “PSHAe”, where “e” stand for enhanced and recall the fact that the seismic hazard assessment is based on PBSs. The method can be envisioned in two rather different ways: (1) assuming that the ground motion variability at each site is described by a lognormal distribution and therefore calibrating the moments of the distribution directly out of the PBSs, as already proposed by Villani et al. (2014) and implemented in the CRISIS software [10] through the so-called generalized attenuation functions (GAF) or by means of an alternative approach, (2) called footprint-based PSHAe, aiming at taking full advantage of the PBSs results within a logic-tree framework. Each computed scenario represents a branch of the logic tree and all the branches are characterized by the same weight (Figure 4). This basically avoids postulating a specific probability distribution for the ground motion and furthermore it allows to take into account the full spatial correlation as physically constrained.

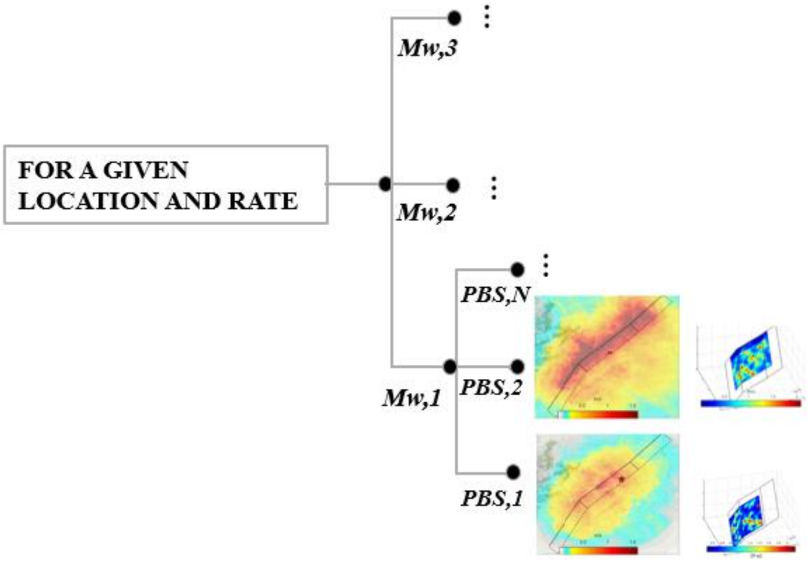


Fig. 4 - Integration of selected PBSs into a classical logic tree based approach

4. PSHA results

Herein the results of PSHA studies conducted according to the methodologies shortly described in the previous section, are addressed and compared against the traditional GMM-based approach. Figure 6 illustrates the PGV hazard maps for the return period of 2475 years, obtained by means of the GMM-based (upper), GAF-based (middle) and footprint-based (lower) approaches. The Chiou & Young 2014 empirical model, referred hereinafter 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 the Figure, it is evident, as expected, that in all the three cases the footprint and GAF approaches produce relatively consistent results while CHYO14-based PSHA shows profound differences.

Concerning the Istanbul case study the hazard maps computed by means of CHYO14, on the one hand, and GAF/footprint on the other, are relatively similar on the western side of Bosporus while a large discrepancy is observed on the eastern side. We refer to Infantino et al., [11] for an exhaustive and critical analysis of these findings. Here we want simply to remark that the geometrical shape of the NAF-MS and the location of the Istanbul metropolitan region can be properly taken into account only if PBSs are adopted.

Referring to the Christchurch and Beijing cases, two regions can be easily identified and compared: (1) in the area located in the immediate proximity of the fault segment (i.e. SQL and TN faults) the hazard estimated through PSHA (i.e. footprint and GAF) tends to be much higher than that one estimated through GMM-based PSHA; (2) further we get from the fault the hazard level predicted using PBSs is similar to the GMM estimation, even if the results of PSHA against the GMM-based one, show a much faster decay with distance. These observations are confirmed by the PGV hazard curves computed for different sites along a section orthogonal to the faults investigated, as already shown in [12].

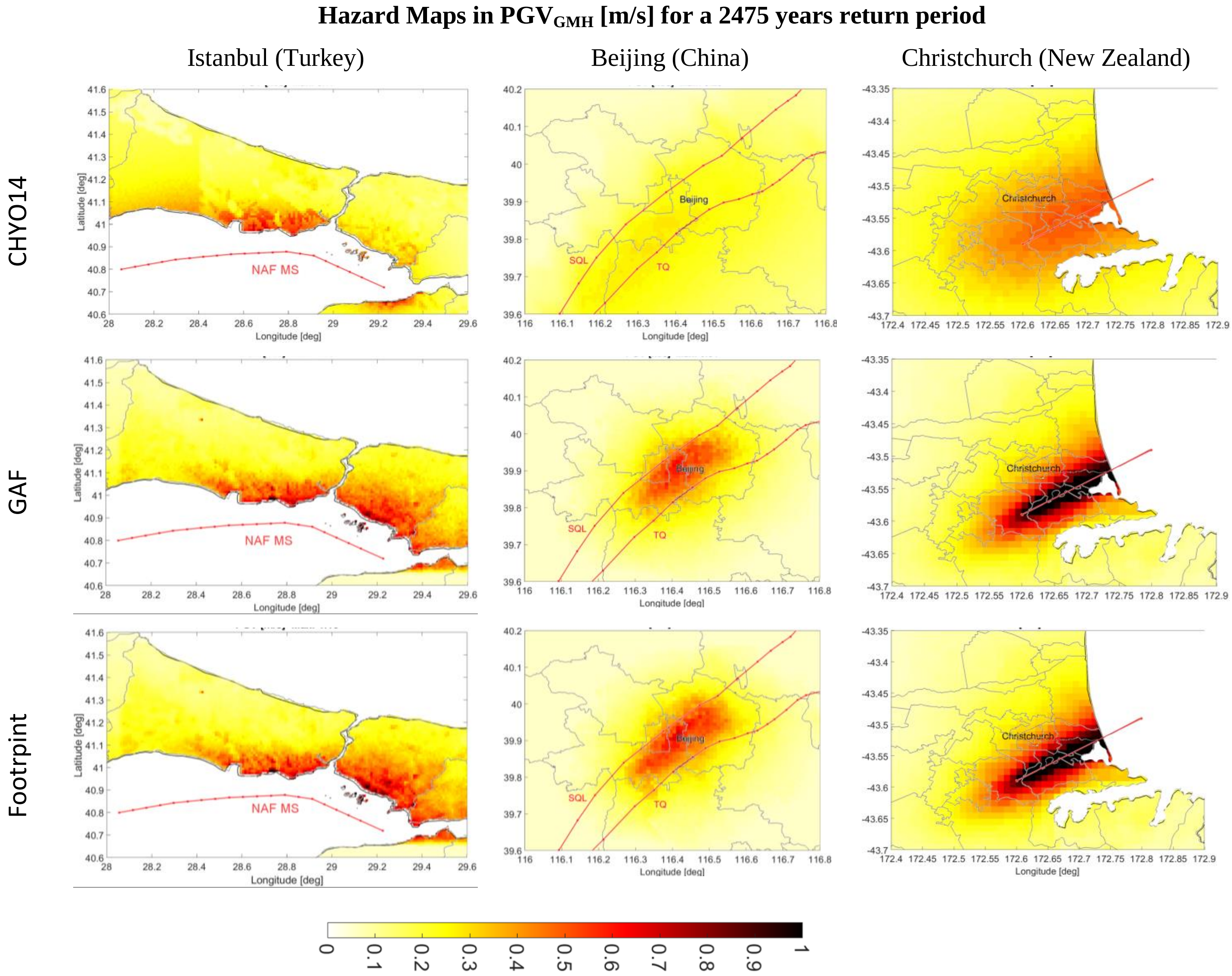


Fig. 5 – PGV [m/s] hazard maps computed for the three different metropolitan regions of Istanbul (left), Beijing (center) and Christchurch (right). First, second and third row show the maps obtained respectively by means of CHYO14, GAF and Footprint based PSHA.

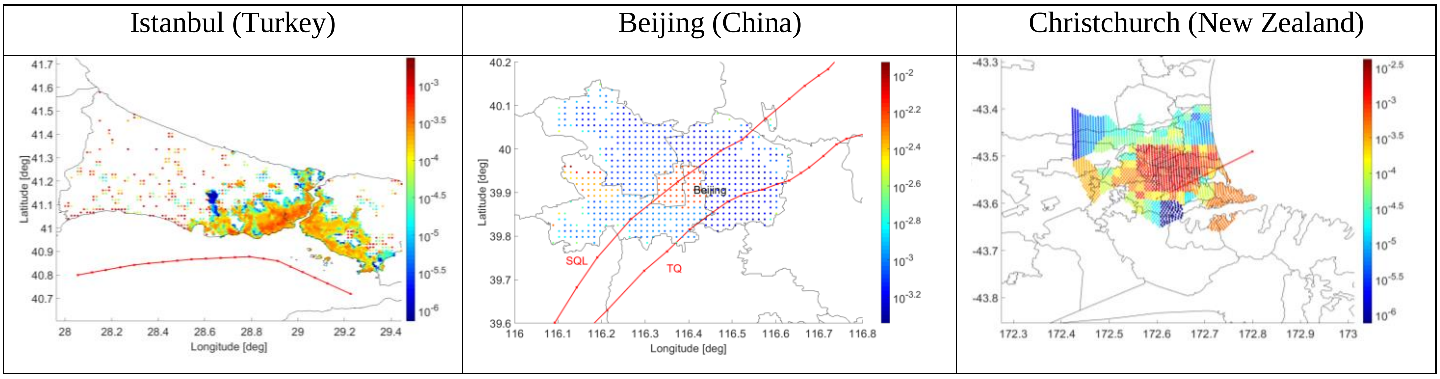
5. PRA results

As already mentioned the hazard maps obtained by means of GAF or through the footprint based approach are almost indistinguishable; the only difference is related to the fact that former approach implies a certain analytical expression for the ground motion distribution, while the latter does not. The situation is completely different once that we are interested in the Probabilistic Risk Assessment (PRA) for a given portfolio (e.g.: a large number of different risks/assets) distributed all over a certain region. In this case the spatial distribution of the portfolio, on the one hand, and the spatial correlation of the ground motion, on the other, are clearly playing a crucial role on the final results. Results will be presented in terms of Probable Maximum Loss (PML), representing the loss amount for a given annual exceedance frequency, or its inverse, the return period [13].

In order to emphasize the novelty of the method it was decided to create a relatively simple artificial portfolio: all over the area considered (i) only one building typology is adopted and (ii) the value is distributed according to a specific density distribution (see Figure 6). In this way is possible to adopt always the same vulnerability and therefore we can easily isolate and examine the effect only related to the spatial correlation. For Istanbul and Beijing we adopted respectively the vulnerability provided by Özcebe et al., 2014 for the Reinforced Concrete Low Rise and High Rise buildings. In the case of Christchurch we opted to choose the empirical vulnerability of timber frame buildings as proposed by [14].

Herein the results of PRA studies conducted according to the methodologies previously described are presented. The results are presented in Figure 7 and can be commented as follows:

- PML based on classical GMMs (in this case CHYO14) is systematically lower compared to the other curves;
- adopting the spatial correlation of Jayaram and Baker 2009 [15] in order to improve the classical results (GMMs based) does not change significantly the results;
- PML obtained through the Bray Rodriguez-Marek 2004 [16], GMM, are generally higher than the other curves. In fact this is expected given the dataset adopted by the authors;
- GAF based PML is unsuitable to describe properly the spatial correlation at portfolio level. It performs poorly and present a curve with a “stepwise” shape;
- Footprint based PML is generally well constrained between the two GMMs PMLs (CHYO14 and BRRM04).



Istanbul (Turkey) | Beijing (China) | Christchurch (New Zealand)

Fig. 6 – Artificial portfolios considered characterized by (i) only one building typology and (i) a distribution of the value customized for each city.

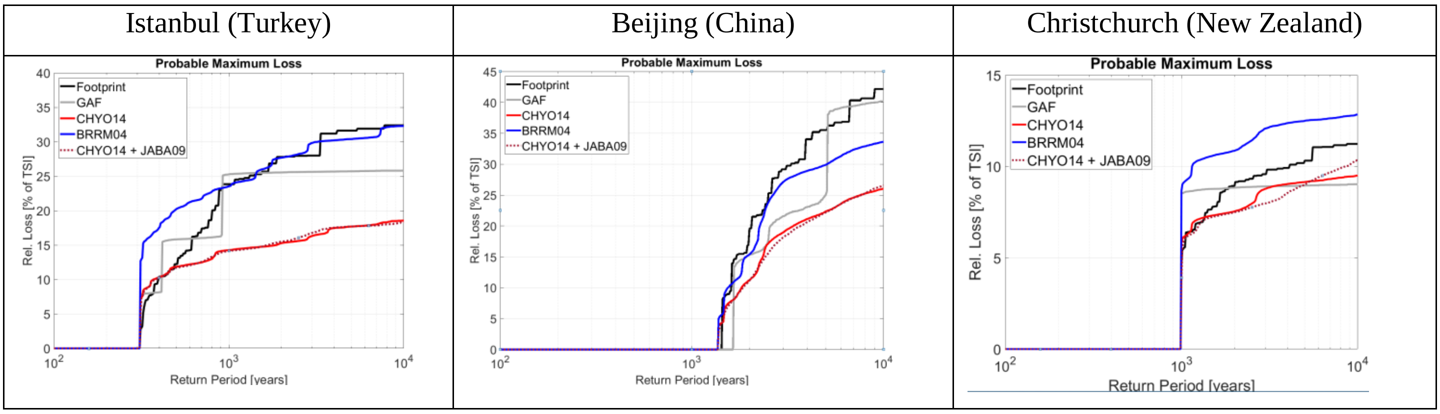


Fig. 7 – Different PMLs obtained by means of classical approaches (based on GMMs, e.g.: CHYO14, CHYO14+JABA09 and BRRM04) and with the GAF and Footprint approach.

6. Conclusions

A novel approach, largely relying on a spectral element code, extensively verified ([17] and [1]) and validated ([18] and [19]), 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 [6]. The entire dataset produced consists of about 160 Physics-Based Simulations, occurring in different regions of the world and along different causative faults: in Istanbul it was considered the Marmara segment of the NAF, where of a well-known seismic gap is located. In Beijing two seismic faults have been considered, namely the Shunyi-Qianmen-Liangxiang and the Tongxian-Nanyuan faults, both crossing the downtown of the metropolis. Finally in Christchurch along the causative fault of the Mw 6.2, February 22, 2011 earthquake, the most damaging event of the seismic sequence that struck Christchurch and the South Island of New Zealand between 2010 and 2011.

As presented in [5] and [6], the deterministic dataset has been integrated into a classical PSHA, based on a logic-tree framework, through the PSHAe methodology. Three different seismic hazard assessment for the three areas 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 three 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.

Furthermore the preliminary analyses accomplished, based on simple portfolios realistically distributed all over the region, show that the PMLs obtained are largely varying according to different methodologies. A substantial difference is related to the fact, albeit GAF or footprint based Hazard Maps are almost indistinguishable, a substantial difference is highlighted in PMLs obtained with the GAF or with the footprint approach. Thanks to the unique and intrinsic capability of the footprint based approach to take into account the spatial correlation of the ground motion, this method is the most interesting one for Probabilistic Seismic Risk Assessment, involving a large portfolio of assets distributed over a certain region.

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 paramount importance in modern computational seismology (e.g. [20] and [21]). A comprehensive discussion on the alternative strategies and investigations is beyond the scope of the present paper and we refer the reader to future works.

7. Acknowledgments

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