3D PROBABILISTIC PHYSICS-BASED SEISMIC HAZARD MAPS FOR REGIONAL RISK ANALYSIS

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EXECUTIVE SUMMARY

Disastrous earthquakes occurred worldwide during past years revealed the extreme vulnerability of greatly populated areas to seismic hazards. The exploratory project added a contribution toward a reliable seismic risk evaluation, substantiating a future general proposal for the development of site-specific seismic scenarios through physics-based 3D models of seismic wave propagation. To be reliable, those models require a high computational burden, with a significant level of parallelization and high-performance computing resources. That is why a petascale resource of the leading-edge capability of Blue Waters is necessary. The exploratory project and the requested resources have been used to: i) evaluate and tune the software SPEED (SPectral Elements in Elastodynamics with Discontinuous Galerkin) for Blue Waters and ii) demonstrate its readiness for use in a future proposal submission. The Next Generation work will be a proposal for General Allocation, aimed to the development of 3D Probabilistic Physics-based Hazards Maps.

INTRODUCTION

A seismic event affecting a greatly populated area could lead to severe damage and economic losses. The impressive chain of disastrous earthquakes occurred worldwide during past years from Chile (Maule, MW 8.8), to Japan (Tohoku MW 9.0) and New Zealand (Darfield MW 7.1, Christchurch MW 6.2), revealed the extreme vulnerability of modern society to seismic hazards and the need to better estimate seismic scenarios. A reliable seismic risk evaluation, able to assess and reduce earthquake-induced damages and losses, is clearly needed and therefore a challenge of paramount significance. To improve the hazard assessment trough site-specific physics-based seismic scenarios definition will benefit emergency managers, planners and the public to be prepared for future earthquakes, as well as civil engineers to develop cost-effective mitigations measures and practices in structures design, construction and planning. This will allows researchers and the risk management industry to tackle the challenging task of analyzing seismic wave propagation with increased accuracy.

METHODS & RESULTS

The numerical simulation tested on Blue Waters within the allocated exploratory project have been carried on through an existing open-source high-performance software package, named SPEED: SPectral Elements in Elastodynamics with Discontinuous Galerkin (Mazzieri et al. 2013, http://speed.mox.polimi.it/). The code belongs to the family of the spectral element methods (SEM), a powerful, well-established, numerical technique naturally suited for three-dimensional seismic wave propagation analyses. SPEED allows seismic wave propagation modelling through visco-elastic heterogeneous three-dimensional media, both on the local and regional scale. SPEED reproduces the propagation path of the seismic wave through complex geological structures and localized superficial irregularities, such as alluvial basins and civil engineering infrastructures. The code is written in Fortran90 using its pseudo-object oriented features. It takes advantage of the hybrid parallel programming based upon the Message Passing Interface (MPI) library relying on the domain decomposition paradigm and the OpenMP library for multi-threading operations on shared memory. The mesh generation may be accomplished using a third party software, e.g. CUBIT (http://cubit.sandia.gov/) and load balancing is facilitated by graph partitioning based on the METIS library (glaros.dtc.umn.edu/) included in the package.

The allocated resources have been used to: i) Setup the software SPEED on Blue-Waters; ii) evaluate/tune the code SPEED for Blue Waters with short tests (tutorials); iii) Eevaluate/tune the code SPEED for Blue Waters with tests at full machine scale. Figure 1 shows an example of the results of tests at full machine scale. The spatial variability of peak ground East-West and North-South velocity has been estimated by 3D numerical simulation referring to the 22 February 2011 (MW 6.2) Christchurch, New Zealand, earthquake, based on the available numerical model for that area (Guidotti et al., 2011)

The results of the exploratory project will be used to substantiate a future general proposal, a discussed in the Next Generation Work Section. The allocated resources in the exploratory project have been used to evaluate how the code SPEED use the major systems elements of Blue Waters, e.g. the memory hierarchy, the communications network, the computational elements, the GPU nodes and the I/O subsystem. We evaluated and tuned the code SPEED for Blue Waters and demonstrated the readiness of SPEED for use in a future proposal submission. In addition, the tests performed on Blue Waters confirmed the excellent scalability features of the code.

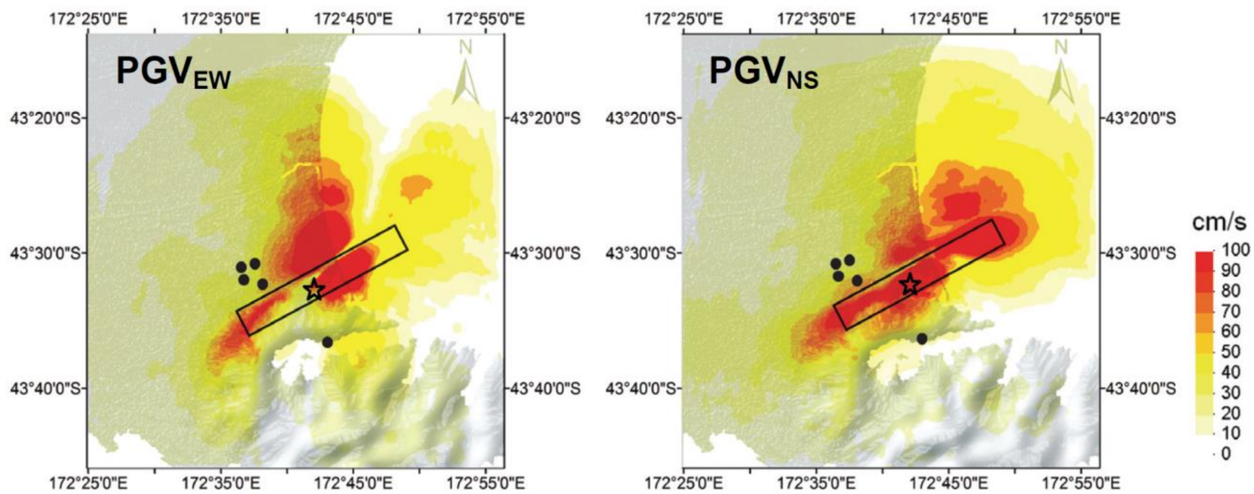

Figure1. Spatial variability of peak ground velocity as estimated by 3D numerical simulation referring to the 22 February 2011 (MW 6.2) Christchurch, New Zealand earthquake.

WHY BLUE WATERS

In recent years, fostered by the ever-increasing progress in computational algorithms and resources, physics-based numerical modeling of the seismic response of complex earth media has gained major relevance in seismic hazard analysis. Among the most appealing features of a physics-based 3D models of seismic wave propagation, there is the possibility to capture in its entirety the complex coupling of: i) directivity pulses, ii) 3D basin effects (Figure 1), iii) topographic effects, iv) wave scattering, and v) nonlinear soil response, especially in the near-source of an earthquake. Accounting for all these features within a single computational model requires a high computational burden (in terms of CPU time and RAM occupation), with a significant level of parallelization and high-performance computing (HPC) resources. That is why a petascale resource of the leading-edge capability that Blue Waters represents was necessary to address this research. To perform our 3D seismic wave propagation simulation would have been infeasible without Blue Waters' resources. Blue Waters, allowing the run of hundreds of simulations, is essential in a future proposal submission, to generate the predictions needed for 3D probabilistic physics-based hazard maps.

NEXT GENERATION WORK

The exploratory project allowed us to evaluate and tune the software SPEED (SPectral Elements in Elastodynamics with Discontinuous Galerkin) for Blue Waters and to demonstrate its readiness for use in a future proposal submission. As Next Generation work, we are developing a proposal for General Allocation aimed to the development of 3D Probabilistic Physics-based Hazards Maps. These maps will help address the problem of the seismic risk, contributing to a comprehensive understanding of earthquake physics and effects. The next generation work will follow two main steps.

First, we develop a 3D physics-based seismic model of the Metro Memphis Statistical Area (MMSA), which is near one of the highest seismic hazard area in central and eastern United States, the New Madrid Seismic Zone (NMSZ). Moreover, the presence of a thick layer of sediments beneath the Metropolitan area of Memphis could determine ground motion amplification phenomena, not accurately captured by ground motion prediction equations. This model is intended to give a comprehensive understanding of the seismic wave propagation through complex media over a large area, leading to more accurate, physics-based, site-specific seismic hazard maps to use towards the resilience assessment of spatially distributed large networks. In addition, it helps better explain the spatial variation of ground motions for different kinds of soil conditions where dense array data are scarce. The numerical simulation will be carried on through Blue Waters and the tested code SPEED. The simulation of spatial and temporal seismic wave propagation in such a complex area will be of a significant help to the understanding of the underlying process of earthquakes as well as engineering applications, which require accurate input seismic excitations.

Second, we investigate the predictive power of physics-based methods in seismic hazard analysis, introducing a probabilistic procedure based on the developed detailed 3D finite element model of the MMSA and a suitable surrogate model. Using the 3D model, a deterministic analysis considering a limited (in terms of magnitude, distance and ground motion variability) number of scenarios selected from the large suite of possible scenarios enhance results of probabilistic hazard study. The simulations performed with the 3D model are designed, in terms of quantity and input parameters, to provide sufficient data to build a surrogate model. Based on the chosen 3D physics-based seismic scenarios, the surrogate model allows the generation of a new set of scenarios with a significant reduction in computational burden. The ensemble of scenarios coming from the metamodel and the surrogate model are used for the development of 3D Probabilistic Physics-based Hazards Maps.

PUBLICATIONS

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