3D EARTHQUAKE GROUND-MOTION SIMULATIONS: THE CASE OF BOGOTA, COLOMBIA

A. Riaño1, J. Reyes2, J. Bielak3, L. Yamin4, D. Restrepo5, R. Taborda6, N. Pulido8

ABSTRACT

The basin beneath the greater metropolitan area of Bogota, Colombia is filled with soft materials ($V_s \leq 1$ km/s) that reach depths of up to 425 m. Located on a high plateau in the eastern cordillera of the Colombian Andes, this highly populated urban area is subject to significant seismic hazard from local and regional fault systems. Therefore, the potential amplification effects due to the presence of these deposits, as well as the effects of the surface and sub-surface topography constitute a problem of great importance. In this study, we present the advancements of the first three-dimensional (3D) earthquake ground motion simulations for the region of Bogotá. We are currently using an unstructured, octree-based, finite element parallel code that implements an explicit time-step solution of the 3D seismic wave equation due to kinematic faulting, including the effects of intrinsic attenuation. The code also implements a virtual topography method, which allows one to perform ground motion simulations incorporating explicitly the effects of the surface topography in the model. Initial tests are under development for a maximum frequency $f_{\text{max}} \leq 2$ Hz. We expect to increase $f_{\text{max}}$ to 4–5 Hz to best capture the effects of topography.

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3D earthquake ground-motion simulations: The case of Bogota, Colombia

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The basin beneath the greater metropolitan area of Bogota, Colombia, is filled with soft materials ($V_s \leq 1$ km/s) that reach depths of up to 425 m. Located on a high plateau in the eastern cordillera of the Colombian Andes, this highly populated urban area is subject to significant seismic hazard from local and regional fault systems. Therefore, the potential amplification effects due to the presence of these deposits, as well as the effects of the surface and sub-surface topography constitute a problem of great importance. In this study, we present the advancements of the first three-dimensional (3D) earthquake ground motion simulations for the region of Bogotá. We are currently using an unstructured, octree-based, finite element parallel code that implements an explicit time-step solution of the 3D seismic wave equation due to kinematic faulting, including the effects of intrinsic attenuation. The code also implements a virtual topography method, which allows one to perform ground motion simulations incorporating explicitly the effects of the surface topography in the model. Initial tests are under development for a maximum frequency $f_{max} \leq 2$ Hz. We expect to increase $f_{max}$ to 4–5 Hz to best capture the effects of topography.

Introduction

The complexity of seismic events lies in all the physical phenomena present during an earthquake, which can be summarized as follows: (1) the dynamic characteristics of the rupture of the fault, (2) the location of the fault itself with respect to the locations of interest, (3) basin effects at a regional scale, (4) soil properties and local site conditions, and (5) the presence of buildings in the area. Considering all these factors, simultaneously, constitutes a highly complex problem that leads...
to plenty of questions in seismic engineering and seismology. However, recent efforts demonstrate the need for new approaches to address the problem using approaches based on deterministic methods [1, 2]. In recent years, the use of the Finite Element (FE) and Finite Differences (FD) methods to model the propagation of seismic waves in the earth's crust and regional basins at scales of tens to hundreds of kilometers has started to gain increasing interest. Among the work teams participating, the Quake group at Carnegie Mellon University in Pittsburgh, Pennsylvania, USA, and their collaborators have been working on earthquake modeling for over fifteen years, and in the last ten years, particularly in the development of Hercules, an earthquake simulator that uses the FE method [3, 4, 5]. Hercules is a parallel program that combines an octree tree approach to generate large unstructured FE meshes (hundreds of millions to billions of elements), with highly efficient and scalable algorithms to solve the propagation of waves using a kinematic representation of the seismic fault. Hercules has been employed in the development of several simulations, including verification and validation exercises. Of interest is the fact that Hercules has already been used for a case study in Colombia. Restrepo and Bielak [5] modified the code to consider topographic irregularities of the free surface and they used Hercules in a 3D simulation of the region of the Aburrá valley and the metropolitan area of Medellín. The simulations required the development of a structural model to represent the geology of the zone (commonly called: seismic velocity model). The simulation allowed the estimation of the valley's response when subjected to rupture scenarios along a segment of the Romeral fault. Additionally, Hercules has been previously adapted to incorporate the non-linear effects of the softer soil strata into sedimentary formations and the presence of simplified building models [1]. All this together makes Hercules an ideal tool to integrate three processes that are normally studied separately: (1) the assessment of seismic hazard, (2) the simulation of the propagation of seismic waves, and (3) the analysis of the structural response of an inventory of buildings.

According to the Colombian seismic hazard study, Bogota classifies in an intermediate level of seismic hazard [6]. The principal sources of the seismic activity of the city are the Eastern frontal fault system, Benioff and Salinas. Several studies such as the Seismic Microzonation of Bogota [7], the study for the prevention of disasters in the metropolitan area of Bogota [8], and the actualization and systematization of earthquake damage scenarios for Bogota [9], lead to the conclusion that the high seismic vulnerability of the city is a consequence of the heterogeneous development of construction, particularly, that of the informal construction. Soil characteristics, seismic activity associated with the city, and the effects on the population caused by the occurrence of strong seismic events, are the motivations to develop a realistic three-dimensional (3D) simulation of seismic wave propagation.

Methodology

The region of interest is located on a high plateau in the eastern cordillera of the Colombian Andes and is bounded on the east by the eastern plains and on the west by the Bogota district area with an average topographic level of 2600 meters above sea level. The scenario contains a volume of the crustal structure of 100x50x18.75 km³ (see Figure 1), the coordinates corresponding to the bounding box of the region are shown in Table 1. The activities developed to perform a 3D large-scale simulation of the region of study can be summarized as follows: (1) simulation code tune-up, (2) models setup, (3) running simulations for different configurations and (4) data processing and analysis. A brief description of these activities is shown below.
Table 1. WGS Coordinates of the region of study (see Figure 1b).

<table>
<thead>
<tr>
<th>Corner</th>
<th>Coordinates (longitude, latitude)</th>
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<tr>
<td>B</td>
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<tr>
<td>D</td>
<td>-74.2982 5.0596</td>
</tr>
</tbody>
</table>

**Simulation code tune-up**
The first task of the project consisted of making minor adjustments to Hercules, to work with the input data formats for the region of interest. The code was modified to easily include the community velocity model of Bogota (CVM Bogota) to execute the simulations described here, and to facilitate its future use in other activities.

**Models setup**
Three basic models were defined: the subsurface model, the elevation (topography) model, and the source model. The subsurface material properties were extracted from the velocity model recently developed (in-house) to represent the structural geology of the region [10]. The domain size considered was 100 km × 50 km in surface area, and 18.75 km in depth. We used the USGS 1 arcsec (~30 m) dataset to extract the DEM for the topography model. Finally, a source model for the 2008 Quetame earthquake was created for the simulation. We used the empirical relationships between magnitude, rupture length, rupture width, rupture area, and surface displacement proposed by Wells and Coppersmith (1994) to define the seismic source.

**Running simulations with different configurations**
We are developing a series of simulations without topography to test the performance of the code that includes the CVM of Bogota. Then, we will increase the maximum frequency of the simulation to 2 Hz and run again models with and without considering the surface elevation for the seismic event considered. We expect to increase $f_{\text{max}}$ to 4–5 Hz to best capture the effects of topography.

Figure 1. Location of the region of study. (a) Colombia map identifying the region domain as a light-blue rectangle; (b) Study area of 100×50 km²; orange marker identifies the epicenter location of the 2008 Quetame earthquake.
Data processing and analysis

The results obtained in this study correspond to the first test of the velocity model recently developed for the region. The results will be compared with respect to the flat-surface solutions to gain insight into the effects that topography have on the characteristics of the ground motion. These results will be presented in terms of maps and figures showing the spatial distribution of goodness-of-fit and amplification factors. Additionally, we expect to validate the 2008 Quetame earthquake; this validation will require acquiring and processing available records as well as performing a comparison analysis on the synthetics with respect to data.

Conclusion

This extended abstract presents the advancements in the development of the first 3D large scale simulation of the region of Bogota. The scenario contains a volume of the crustal structure of 100 × 50 × 18.75 km³. The irregular topography is included by means of a Digital Elevation Model (DEM) of 30 × 30 m² resolution. We use the S-wave velocity distribution obtained from the CVM of Bogota constrained over the computational domain to a minimum of 200 m/s. In this study, the effect of the earthquake rupture and the discontinuity of the displacements that occur at the fault are modeled as a point source, a single set of balanced forces acting on a point. However, a variation in the results is expected if we assume that the rupture occurs over an extended area; in that case, it must be modeled as an extended fault. The characteristics of the seismic movement vary depending on the geotechnical properties of the soil deposits. Therefore, throughout the simulation, we expect to see substantial changes in the incident seismic wave in deep rock layers due to the seismic response of the superficial deposits of soft soil. These characteristics are modified by resonances, that are determined by the depth and seismic velocity of the near-surface sediments. We are interested in investigating the effects of a local larger magnitude earthquake originated on a fault directly linked to the topography of the region and posing high seismic hazard to the nearby communities. Consequently, in subsequent simulations, we will use extended kinematic source models.

References