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USE OF 3-D GROUND MOTION SIMULATIONS IN ESTIMATING FUTURE ECONOMIC LOSS IN MEXICO CITY

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ABSTRACT:

The 1985 Michoacán earthquake highlighted the seismic risk in Mexico City posed by large magnitude (M>7) earthquakes at the subduction interface off the Pacific Coast of Mexico. Although more than 300 km away from the 1985 earthquake, Mexico City suffered a disproportionate amount of overall damage and loss, especially in the lakebed region. Extensive research conducted since the Michoacán earthquake has allowed a better understanding of seismic damage potential in Mexico City. However, many challenges remain in characterizing: a) ground motion attenuation in the region, b) seismic response of soft sediments underneath the city, and c) seismic vulnerability of the ever-changing building stock in the city. In this study, loss estimates for Mexico City were carried out for a selected scenario earthquake at the subduction interface off the Pacific Coast of Mexico. Instead of the conventional method, which uses empirical attenuation relationships combined with site amplification factors, we adopted comprehensive 3-D source-to-site simulations to model the ground motions. These simulations allowed a more thorough consideration of source characteristics and the complexity of seismic wave propagation from the subduction zone through the Trans-Mexican Volcanic Belt and into the Valley of Mexico. The soft sediments underlying Mexico City were represented by a finer mesh in the simulations in order to better capture the basin effects. The simulations provided ground motion time series at the surface, enabling the consideration of duration effects as well as other time and frequency domain characteristics of the resulting ground motions. In order to estimate the impact of the simulated ground motions on the buildings in Mexico City, a database of buildings exposed to the earthquake threat was compiled. Seismic vulnerability of buildings was characterized by analytical modeling of various local building types and by synthesizing damage reports from past local earthquakes. We present preliminary results from ground motion simulations of a selected scenario event and their impact on the current building stock in Mexico City in terms of damage and economic loss.

KEYWORDS: Ground motion, 3-D simulation, seismic risk, Mexico City, Valley of Mexico.

1. INTRODUCTION

Ground motion estimations are an integral part of seismic risk assessment. Conventionally, ground motions are estimated for a reference site condition (typically "firm ground") using empirical attenuation relationships. Then a site correction is applied to account for ground conditions other than the reference. For a regional analysis in which large number of sites are analysed, taking into account the site conditions is often carried out using simplified procedures such as scalar amplification factors that are applied on the ground motions calculated for the reference site conditions. These simplifications yield reasonably satisfactory ground motion estimates when the source to site path is relatively homogeneous, and the soil layers are roughly horizontal with well-defined geotechnical properties.

Mexico City has high seismic risk as demonstrated by past earthquakes, and poses a challenge in terms of estimating the risk due to: 1) complex characteristics of ground motion attenuation and wave propagation during subduction interface earthquakes, which are further complicated by the influence of the Trans-Mexican Volcanic Belt (TMVB), 2) unique seismic response of the lakebed sediments underneath the city, and 3) the seismic vulnerability of the urban building stock, which is a function of such factors as building code compliance, quality of construction, and resonance with the underlying soft sediments.

The main tectonic feature in central Mexico is the subduction zone off its Pacific coast, which has a relatively high activity rate compared to some of the other subduction zones around the world. Many large magnitude (Mw > 7.0) subduction interface earthquakes have been recorded in the various segments of the subduction zone (Santoyo et al., 2005). Although Mexico City is more than 300 km away from the subduction interface, the exceptionally efficient wave propagation and amplification through the TMVB, as well as resonance and amplification inside the Valley of Mexico, contributes to unexpectedly high levels of damage occurring in Mexico City as a result of subduction interface earthquakes. The most recent major example of this is the 1985 Michoacan earthquake, which caused $4 billion USD (1985 dollars) economic loss, mostly in Mexico City (Munich Re, 2004).

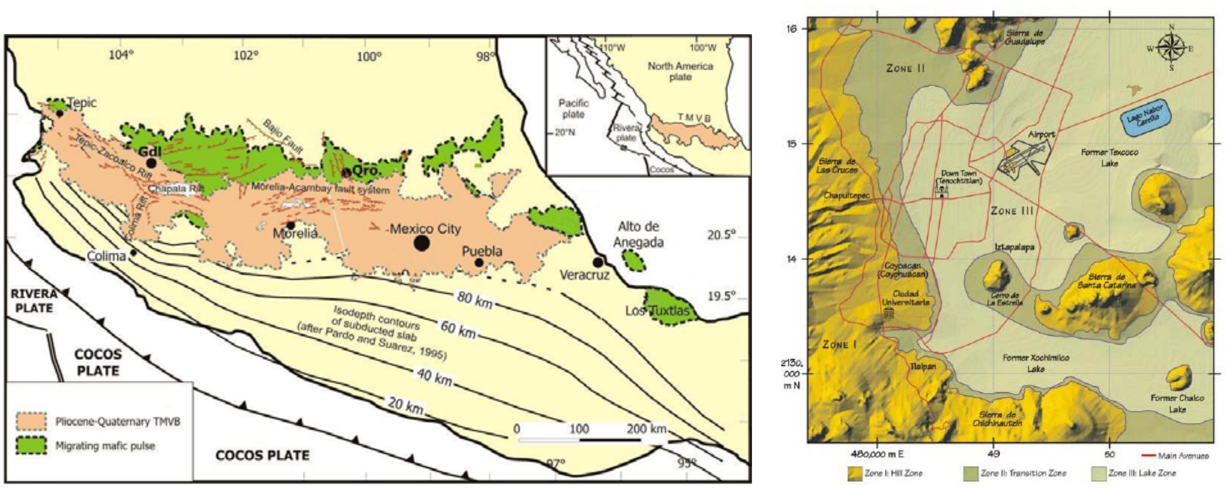

Figure 1. (a) Subduction zone and TMVB (adapted from Ferrari, 2004). (b) Mexico City microzonation. Zone I: Hill zone, Zone II: Transition zone, and Zone III: Lakebed (Flores-Estrella et al., 2007).

The Valley of Mexico, on which the greater Mexico City metropolitan area is built, is a former lakebed that went through systematic draining since the 16th century. The lacustrine valley floor is surrounded by hills dominated by volcanic tuff, and an intermediary transition zone of coalescing alluvial fans (Figure 1b). The lakebed is characterized by Mexico City clay, which is an organic clay with water content of nearly 90% and shear wave velocity as low as 50 m/s. These high plasticity clays exhibit a unique dynamic response that remains largely linear even at high strain levels. Furthermore, the duration of felt shaking in the lakebed during the 1985 Michoacan earthquake was up to 5 minutes. It has been a challenge for the geotechnical engineering and research community to fully explain and model the exceptional seismic response of the Valley of Mexico. It is widely recognized that simplified 1-D modeling of the basin response is inadequate due to inability in representing the lateral heterogeneities (Flores-Estella et al., 2007). In addition, researchers have recognized the influence of the TMVB on the ground motions observed inside the Valley of Mexico (e.g. Iida and Kawase, 2004)

To address these challenges and limitations, this study models ground motions by employing comprehensive 3-D source-to-site simulations that allow a more thorough consideration of source characteristics and the complexity of seismic wave propagation from the subduction zone through the TMVB and into the Valley of Mexico. The simulated ground motions are implemented as spectral acceleration footprints with periods from 1.3 to 4.0 sec.

2. GROUND MOTION SIMULATIONS

The 3-D source-to-site simulations comprise of a source characterization and a crustal structural model for Central and Southern Mexico that incorporates the 3-D geometry of the subduction zone, the TMVB and the Valley of Mexico. The geographical extent of the model is presented in Figure 2.

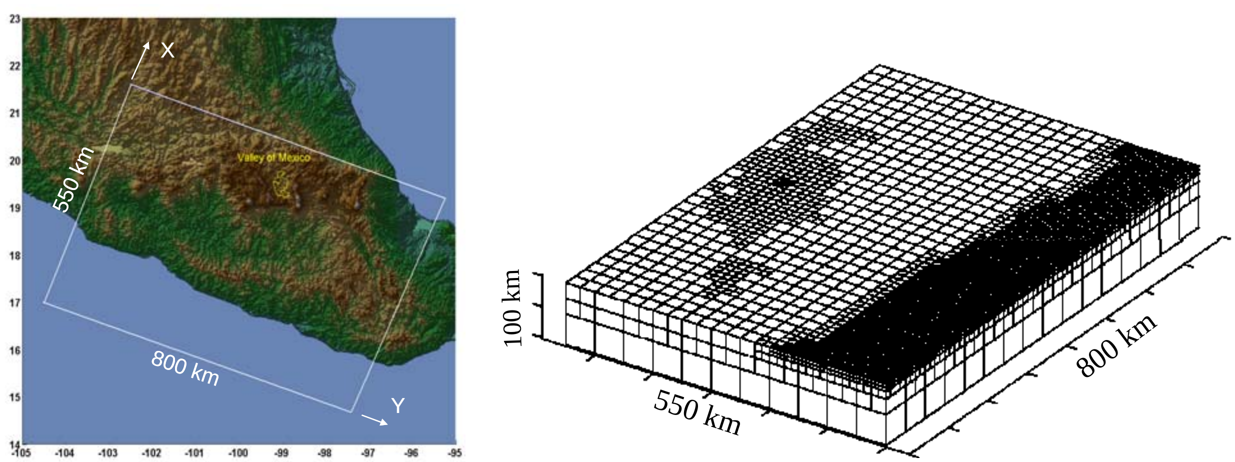

Figure 2. 3-D model of the crustal structure

The subduction zone source characteristics and crustal model are based on Pardo and Suarez (1995), Valdes and Meyer (1996), and Perez-Campos et al. (2006). The crustal structure model was supplemented with geotechnical characteristics of the Valley of Mexico such as wave velocity profile inside the Valley with shear wave velocities as low as 60 m/s .

The ground motion computations were carried out on an octree-based finite element solver (Tu et al, 2006), which combines the multi-resolution of the conventional finite element method, and the low memory requirements and good cache performance associated with the finite difference method. The resulting 3-D mesh consists of 115 million elements. The frequency resolution is 0.66 Hz (or 1.5 sec period). Since the natural period of the lakebed is 2.0 to 5.0 sec, the long-period ground motions obtained from the model are suitable to capture the response of the lakebed. The simulations were performed on Bigben, an XT3 system at the Pittsburgh Supercomputing Center.

3. BUILDING INVENTORY, EXPOSURE, AND VULNERABILITY

The building inventory distribution in Mexico City was derived from a combination of societal, economic, housing and population statistics; remote sensing data with satellite imagery; detailed damage reconnaissance from past earthquakes; and local expert judgement (e.g. on some height and construction class distributions). The majority of the buildings in Mexico City are made of reinforced concrete and reinforced (confined) masonry with some steel construction, primarily the high-rises. Note that outside of Mexico City this distribution changes significantly based on geographic location as well as degree of urbanization. Even within Mexico City, the inventory distribution varies by neighbourhood. For example, looking at two relatively close and primarily commercial neighbourhoods of Mexico City (delineated in Figure 3), roughly a third of the commercial building stock is 15 stories or higher along the strip of Paseo de la Reforma, while there are no commercial buildings in this height category in the Colonia Roma area.

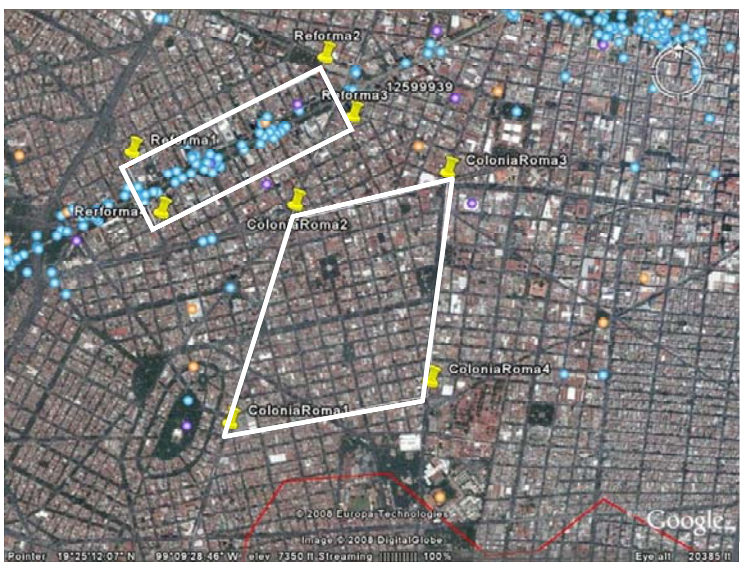

Figure 3. Two neighbourhoods in Mexico City that were used as inventory distribution examples. The zone to the north is along Paseo de la Reforma. The zone to the south is in Colonia Roma.

To develop an exposure database, unit building costs were obtained for different construction types, and applied to each construction type using average footprint size and height characteristics. Content values were estimated based on occupancy class, e.g. residential, commercial, and industrial. Thus the exposure database represents combined value of buildings and contents.

The building exposure in the states of Mexico and Distrito Federal is roughly 16 billion MXN, and it makes up about one third of the total building exposure in the country. As a comparison, these two states combined make up approximately one third of the GDP and one fifth of the population in the country.

Roughly half the total building value is from residential building exposure and the other half is from commercial and industrial combined.

Development of the vulnerability functions was carried out first by identifying the building codes that apply to different regions, and the major revisions that occurred in the seismic provisions over the years. Hysteresis models were developed to estimate non-linear dynamic response of various construction types, and these were used in incremental dynamic analyses carried out with over 400 strong motion records (PGA greater than 0.1g) obtained from the Mexican Strong Motion Database (SMIS, 1997) and Guerrero Accelerograph Network (Anderson et al., 1994).

Damage functions, developed based on analytical studies, expert judgement, and observed damage data, were constructed for various building materials, structural systems, year bands (year built), and height bands. These functions describe the amount of damage (in terms of a mean damage ratio) for a given spectral displacement. Mean damage ratio (MDR) is defined as a percentage of replacement cost.

4. RESULTS AND DISCUSSION

The 3-D ground motion simulations were carried out for a subduction interface earthquake scenario off the Pacific coast of Mexico and affecting Mexico City. For the scenario, source parameters of the 1995 Copala earthquake (Courboulex et al., 1997) were used. In order to create a scenario that would cause damage in Mexico City we scaled up the original slip by five. This scaling brought the scenario event magnitude from Mw7.3 to Mw7.8.

The wave propagation through the TMVB and Valley Mexico is presented in Figures 4 and 5, which clearly illustrate the effect of the Valley of Mexico on the amplitude, frequency and duration of the ground motion. The resulting PGV and PGA distributions in the basin are presented in Figure 6.

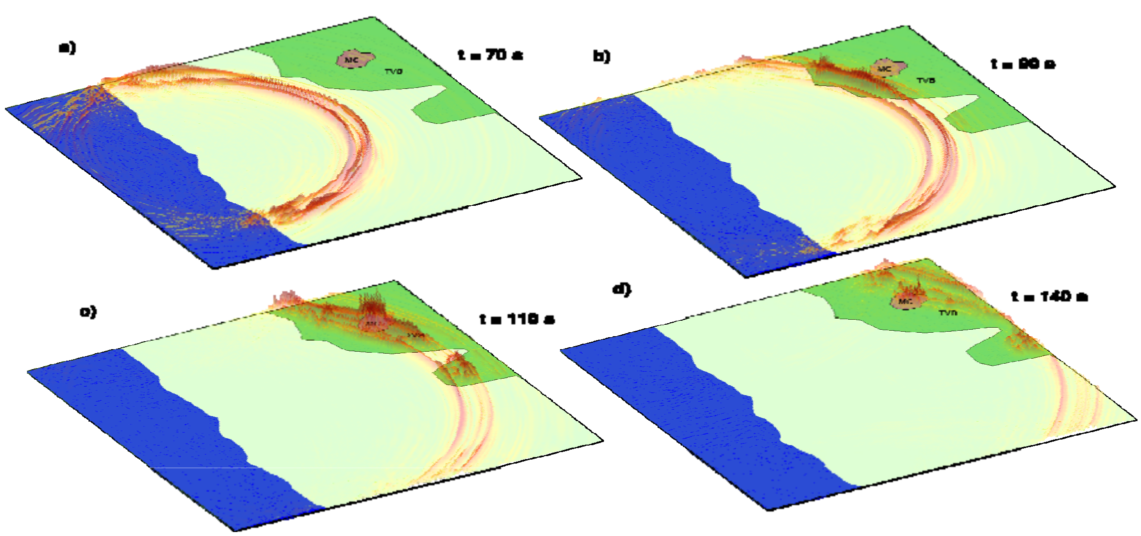

Figure 4. Snapshots of wave propagation

The snapshots in Figure 4 illustrate a time-series progression of waveforms generated at the subduction source zone off the coast, as they travel east. They illustrate the waves reaching the TMVB (dark green shaded area) at 70 seconds. The waves then enter the Valley of Mexico (brown shaded area) at 90 seconds. At 110 seconds, the waves are still inside the Valley and largely amplified. At 140 seconds, although the main wave train is past the Valley of Mexico, there are still significant wave amplitudes inside the Valley.

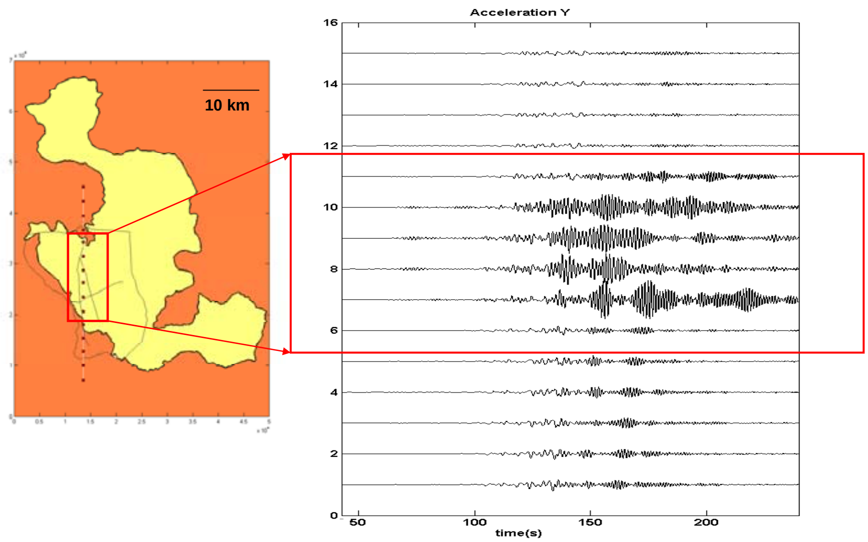

Figure 5. Simulated acceleration time series inside and outside the Valley of Mexico.

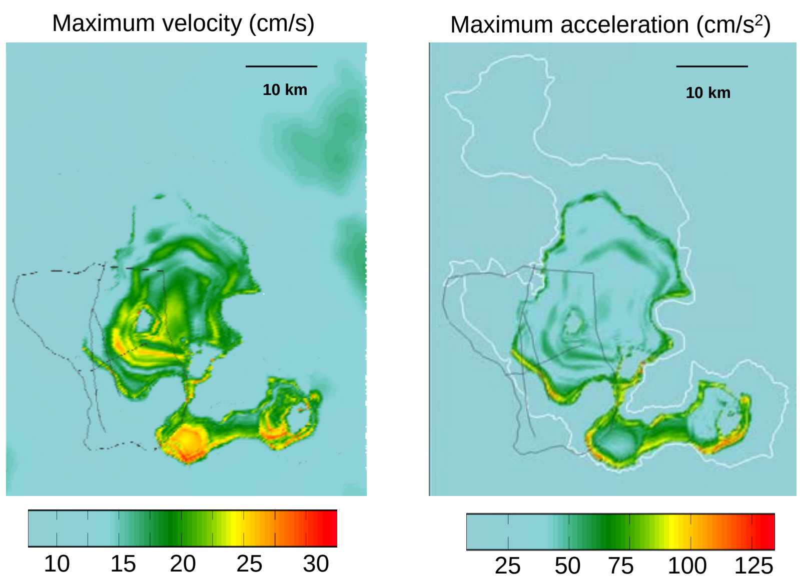

Figure 6. Maximum velocities and accelerations inside the Valley of Mexico

The maximum PGA observed in the basin as a result of the Mw7.8 scenario is around 0.13g, mostly around the edges of the basin. Highest PGV values (around 30 cm/s) on the other hand are observed both inside the basin and at the edges of the basin. Note that long-period ground motions were the main cause of damage in the basin rather than the PGA.

The spectral accelerations obtained from the simulations were used to create a series of footprints of spectral accelerations at various periods from 1.5 sec to 4.0 sec covering the range of fundamental periods of the basin. These ground motions were applied at a variable resolution grid (VRG)™, which varies from 500m inside the basin up to 5km outside the urban extent of Mexico City (Figure 7). The exposure database developed for Mexico City was distributed to this VRG using population data for residential exposures and remote sensing data for commercial and industrial exposures.

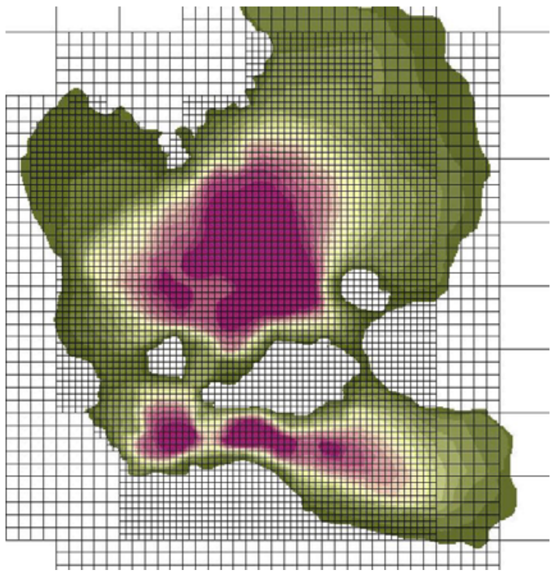

Figure 7. The variable resolution grid (VRG)™ layout in the Valley of Mexico (the smallest grid cell represents an area of 500m by 500m).

The MDR in the Valley of Mexico (the 500m by 500m grid extent) for this particular scenario is lower than 1% on average per grid cell. Total estimated economic loss due to direct damage to buildings and contents within the same area is about 40 million USD. Most of the loss (90% of the total) is in multi-family residential and commercial buildings, which include the largest proportion of high-rises with natural periods similar to the natural period of the soft sediments in the basin.

5. CONCLUSIONS

Ground motion simulations have become increasingly sophisticated and their spatial and frequency-domain resolutions have enhanced to the point that they are now able to incorporate engineering properties of the upper tens of metres of soil in detail while incorporating the broader crustal structure at a scale of tens or hundreds of kilometres. These advances in ground motion simulations allow a comprehensive source-to-site analysis rather than a combination of simplified and piece-wise characterization of the seismic source, attenuation of ground motion for firm ground conditions, and amplification of ground motion, in order to obtain the ground motions at the surface.

Incorporating 3-D simulations in seismic risk analyses has many advantages including: 1) the ability to capture variations of ground motion inside a basin that are caused by such wave propagation effects as reflection and refraction; 2) the ability to capture basin edge effects; and 3) the ability to model directivity, which is difficult to incorporate in traditional ground motion estimation methods.

This paper presents an example of how ground motion simulations can be effectively used in estimating future economic losses through scenario analyses. Although the scenario presented in this paper is not a particularly damaging one, its purpose is to demonstrate the use of ground motion simulations in regional risk analyses. In addition to the spectral response footprints, the simulated ground motion time histories at various locations within the basin are available for use in dynamic structural analyses. We also incorporate ground motion simulation footprints in exceedence probability (EP) type risk analyses by assigning them to selected events in the stochastic event set either with full weight or weighted against other modeling alternatives.

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