Estimation of the Seismic Hazard and The Economical Consequences for Extreme Magnitude Earthquakes

M. Chavez
Institute of Engineering, UNAM, C.U., 04510, Mexico DF, Mexico

E. Cabrera
CAOS, University Autonoma Barcelona, Barcelona, Spain

M. Ashworth, D. Emerson & Ch. Moulinec
STFC Daresbury Laboratory, Daresbury Science & Innovation Campus, Warrington WA4 4AD, UK

N. Perea
Institute of Engineering, UNAM, C.U., 04510, Mexico DF, Mexico

A. Salazar
Inst. of Geophysics , UNAM, C.U., 04510, Mexico DF, Mexico

SUMMARY:
The recent occurrences of extreme magnitude earthquakes such as: the 1985 Mw 8.01 Michoacan, Mexico, the 2008 Mw 7.9 Wenchuan, China and the 2011 Mw 9 Tohoku, Japan, which generated large number of casualties and huge economic losses, has shown that the seismic hazard estimations for their respective seismotectonic regions were grossly underestimated. Herewith, a methodology is proposed in order to estimate the probability of exceedance of the intensities of extreme magnitude earthquakes (PEI) and of their direct economical consequences (PEDEC). The PEI ´s are obtained by using supercomputing facilities and a hybrid method to generate samples of the 3D wave propagation of extreme (plausible) earthquakes scenarios. The PEDEC are computed by using appropriate vulnerability functions combined with the scenario intensity samples, and Monte Carlo simulation. An example of the application of the methodology due to the potential occurrence of extreme Mw 8.5 subduction earthquakes on Mexico City is presented.

Keywords: extreme earthquakes, hybrid synthetics, probability exceedances, economics

1. INTRODUCTION

The recent occurrences of extreme magnitude earthquakes such as the 19 September 1985 interplate Mw 8.01 Michoacan, Mexico, the 9 May 2008 intraplate Mw 7.9 Wenchuan, China and the 11 March 2011 interplate Mw 9 Tohoku, Japan (and its associated mega – Tsunami), whose estimated frequency of occurrence varies from tens or hundreds (the Michoacan event) to hundreds or thousands of years (the Wenchuan and Tohoku events), has shown that the seismic hazard estimations for their respective seismotectonic regions were grossly underestimated. The large number of casualties and huge economic losses observed for those earthquakes, calls for the development of new paradigms in order to generate better estimates, both of the seismic hazard, as well as of its consequences, and if possible, to estimate the probability distributions of their ground intensities and of their economical impacts (direct and indirect losses), this in order to implement technological and economical policies to mitigate and reduce, as much as possible, the mentioned consequences.
Herewith, a methodology is proposed in order to estimate the probabilities of exceedance of the intensities of extreme magnitude earthquakes (PEI) and of their direct economical consequences

(PEDEC). The PEI´s are obtained by using supercomputing facilities, with thousands of processors, and a hybrid method (Chavez et al., 2011) to generate broadband samples of the 3 dimensions (3D) wave propagation of extreme earthquakes (plausible) scenarios, and to enlarge those samples by using Monte Carlo simulation techniques. The PEDEC´s are computed by using appropriate vulnerability functions combined with the scenario intensity samples, and Monte Carlo simulation. An example of the application of the proposed methodology due to the potential occurrence of extreme mw 8.5 subduction earthquakes on Mexico City construction stock is presented.
The paper is divided in 6 sections, the proposed methodology is synthesized in part 2, the hybrid modeling procedure used to generate samples of broadband accelerograms is synthesized in section 3, a discussion on the main seismotectonic features of the Mexican subduction zone and the results of the hybrid modeling for the 1985 Ms 8.1 Michoacan earthquake are included in part 4, the results of the application of the proposed methodology to obtain the PEI´s and PEDEC´s for Mw 8.5 scenario subduction earthquakes on Mexico City (MC) construction stock are addressed in section 5, in the last part the main conclusions of the work are given.

2. PROPOSED METHODOLOGY TO OBTAIN THE PEIS´s AND PEDEC´s

As mentioned in the introduction the proposed methodology aims to estimate the probability of exceedance of:

1) the ground motion intensities of extreme magnitude earthquakes (PEI) and
2) their direct economical consequences (PEDEC).

The PEI ´s are obtained by using a hybrid technique (Chavez et al., 2011) to generate large samples of broadband synthetic strong ground motions, associated to the extreme earthquake plausible scenarios for the seismotectonic region of interest. The hybrid technique includes a 3D staggered finite difference wave propagation modeling of the low frequency seismograms, and the empirical Green function method (Irikura, 1986) allows the generation of the high frequency synthetics. Also, Monte Carlo simulation techniques are used to generate larger samples of maximum strong ground motion intensity parameters, such as the maximum response spectral ordinates (for a 5% of critical damping) to increase the size of their samples.

The probability of exceedance of the economical consequences, PEDEC´s, can be obtained from samples of the expected costs of the construction stock expected to be damaged by the extreme earthquake scenarios considered. The statistics of the former can be obtained by combining samples of the maximum intensities measures of the strong ground motions synthetics associated to the extreme earthquakes, ad-hoc seismic vulnerability functions and cadastral information of the construction built stock of interest. The economical consequences of the scenario earthquakes can be obtained from the expected costs of the considered built stock, and therefore of their PEDEC´s. Monte Carlo simulation techniques can also be used to generate larger samples of the expected costs to obtain the PEDEC´s.

The uncertainties in the calculations included in steps 1 and 2 of the proposed methodology, for the generation of samples of the strong ground motion synthetics, and of the associated expected costs, can (and should) be considered, as it will be shown in section 5.

3. BROADBAND MODELING PROCEDURE

A hybrid procedure (Fig. 1) combining long period and high frequency simulations (Chavez et al., 2011) was utilized for the computation of broadband synthetics accelerograms for the Ms 8.1 (Mw

8.01) Michoacan 1985 earthquake (as well as for extreme subduction Mw 8.5 earthquake scenarios) for Mexico City. The long period (< 0.3 Hz) wave field was simulated using a recently optimized 3D seismic wave propagation parallel finite difference code, that uses 2nd order operators in time and 4th order differences in space, which was successfully applied to model the wave propagation of the Wenchuan 2008 Mw 7.9 earthquake (Chavez et al., 2010) and the Colima-Jalisco 1995 Ms 7.6 (Mw 8) earthquake (Chavez et al., 2011). The high frequency (≥ 0.3Hz) synthetics were generated with the Empirical Green function (EGF) method, Irikura (1986). In this method the ground motion from a large event is expressed as a superposition of the records of small events (elementary sources). Finally, the low and high frequency synthetics are combined using matched filters (Chavez et al., 2011).

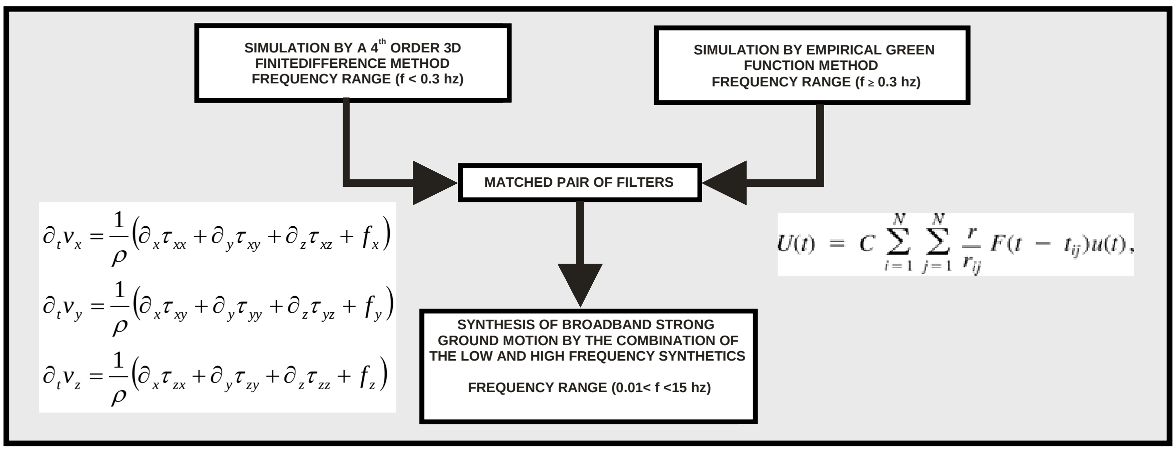

Figure 1. Hybrid procedure combining long period and high frequency simulations (Chavez et al., 2011)

4. SEISMOTECTONIC FEATURES OF THE MEXICAN SUBDUCTION ZONE AND BROADBAND SYNTHETICS ACCELEROGRAMS FOR THE 1985 Ms 8.1 MICHOACAN EARTHQUAKE

4.1 Seismotectonics of the Mexican subduction zone

The seismotectonics of the Mexican subduction region is the result of the dynamic interaction between the Cocos, Rivera, Caribean and North American plates (Fig. 2A). The Cocos and the Rivera plates are subducting the North American one and in the last century had generated the largest surficial thrust earthquakes in the region, such as the Jalisco 3 June 1932 Ms 8.2, the Ms 7.6 (Mw 8) Colima-Jalisco 9 October 1995 and the 19 September 1985 Ms 8.1(Mw 8.01) Michoacan, earthquakes (Fig. 2A). The geometry of the interacting plates is shown in Fig.2B. Recently, Perez-Campos et al. (2008), suggested that the dipping angle of the subducting plate, closer to Mexico City is ~ 75^o, instead of the ~ 30^o shown in Fig. 2B. The kinematic slip distribution of the Michoacan 1985 earthquake is shown in Fig. 2C.

4.2 Observations and modeling of the 1985 Ms 8.1 (Mw 8.01) Michoacan earthquake

The broadband hybrid modeling procedure synthesized in Fig. 1 was utilized to generate synthetic accelerograms to compare them with the ground motions recorded at Mexico City stations, such as SCT (located on compressible soils of Mexico City) for the 1985 Ms 8.1 earthquake. For the low

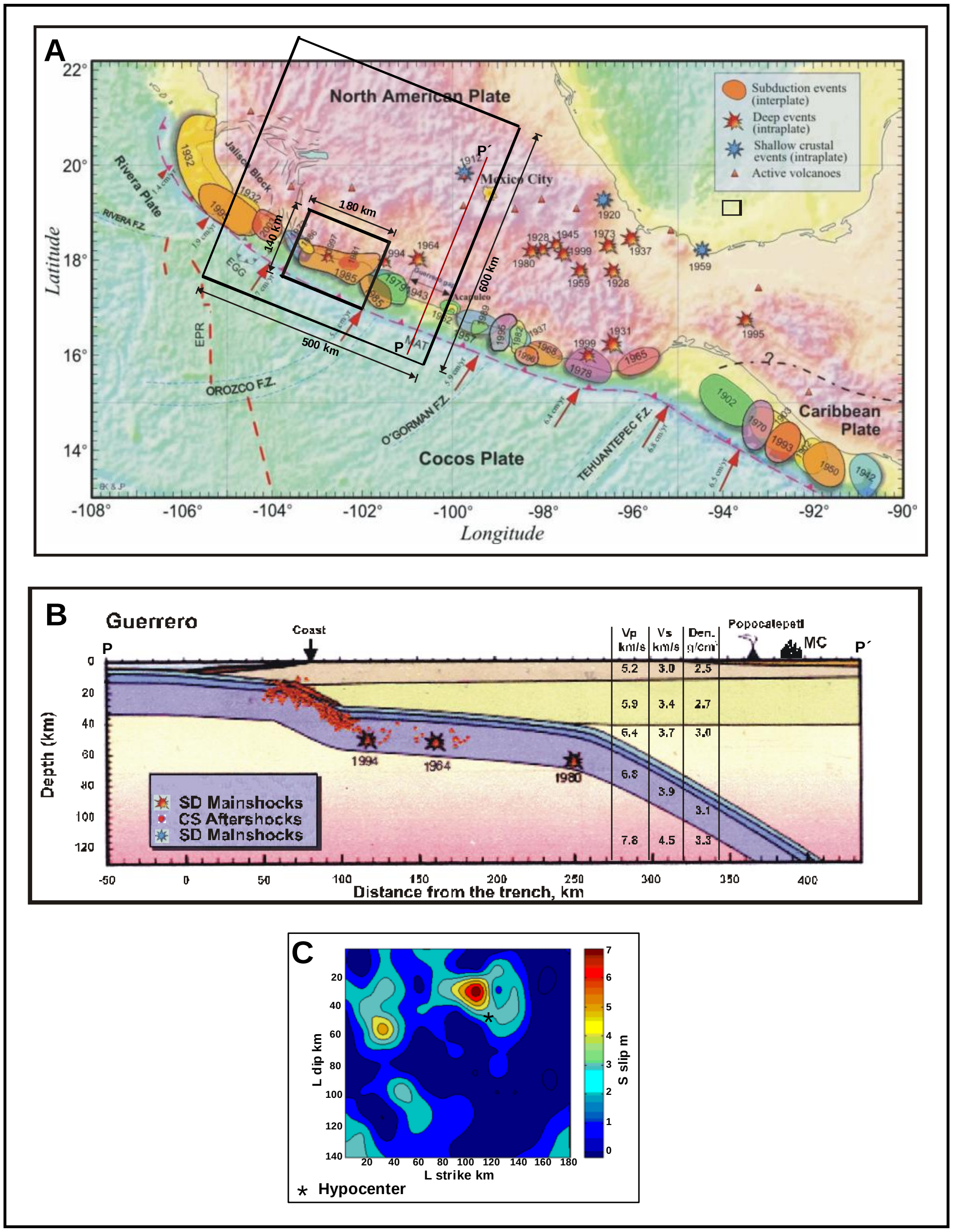

Figure 2. A) Inner rectangle is the rupture area of the 19 September 1985 Ms 8.1 earthquake on the surface projection of the 500x600x124 km^3 earth crust volume 3D discretization; B) profile P-P´; C) Kinematic slip distribution of the rupture of the 1985 earthquake. (A and B, Modified, Pacheco and Kostoglodov, 1999, and C, Modified, Mendoza and Hartzell, 1989)

frequency modeling of the 1985 Ms 8.1 Michoacan event, a 500 x 600 x 124(depth) km^3 volume was used (Fig. 2). Some modeling parameters are included in Fig. 2B and others are given elsewhere (Cabrera et al., 2007, Chavez et al., 2008). For the high frequency modeling of the 1985 event, Mexico City recordings of the 14 March 1997 Ms 7.3, 21 September 1985 Ms 7.6 and 14 September1995 Ms 7.4 subduction earthquakes were utilized. As an example of the results obtained with the procedure, in Fig. 3, the synthetic accelerograms and their associated Fourier amplitude spectra, for the SCT site N-S direction for the 1985 Ms 8.1 Michoacan earthquake are compared with their observations. Notice that the agreements between them are satisfactory, Fig. 3.

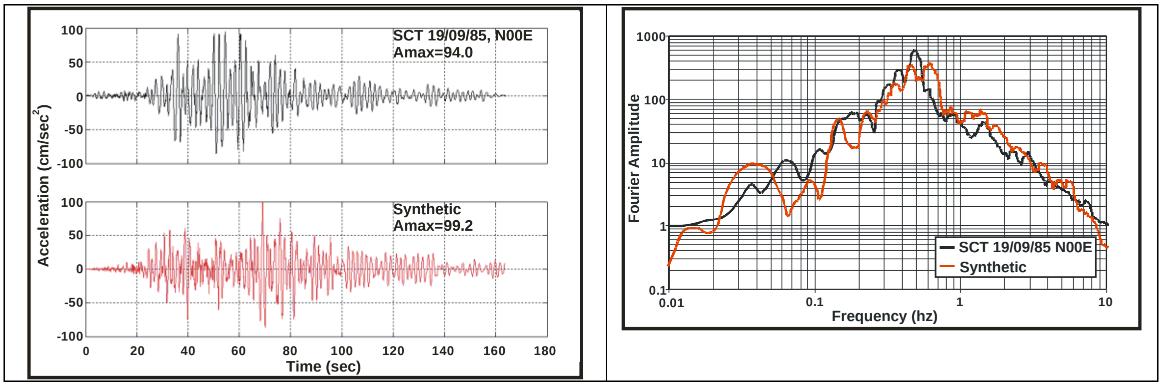

Figure 3. Observed and synthetic accelerograms and their corresponding Fouier amplitude spectra in the N-S direction at station SCT (Mexico City) for the 19 September 1985 Michoacan earthquake

5. MODELING OF Mw 8.5 SUBDUCTION SURFICIAL EXTREME EARTHQUAKE SCENARIOS FOR MEXICO CITY AND OF THEIR ECONOMICAL CONSEQUENCES

5.1 Broadband synthetic accelerograms for the extreme Mw 8.5 earthquake scenarios

Taking into account the rupture areas of the 1932 Jalisco Ms 8.2, and of the Mw 8.01 Michoacan 1985 extreme earthquakes, Fig. 2A, and the results of Suarez and Albini (2009) about the evidence of the occurrence of a magnitude 8.6 earthquake in 1787 in the Mexican pacific coast, in this work we propose scenarios for the plausible occurrence of Mw 8.5 extreme magnitude events in the Guerrero gap as shown in Fig. 4.

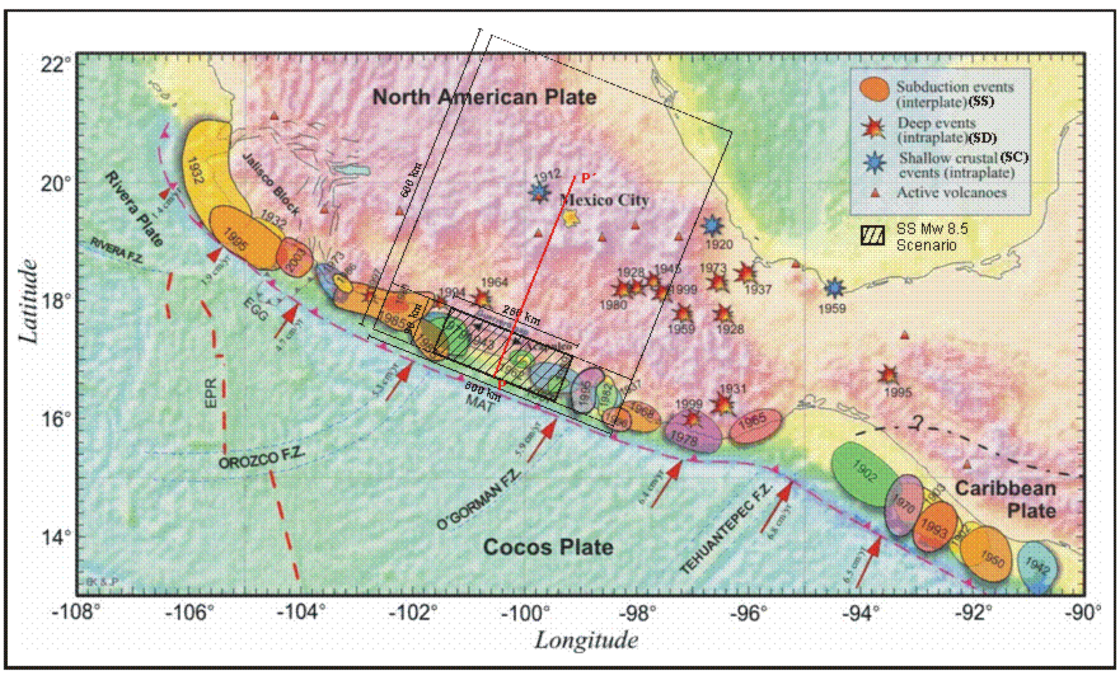

Figure 4. 3D volume (500 x 600 x 124 km^3) utilized in the 3D Finite Differences Modeling of the Mw 8.5 thrust surficial subduction Guerrero gap earthquake scenarios (Modified, Pacheco and Kostoglodov, 1999)

To generate synthetic accelerograms for the ground motions expected in Mexico City for thrust subduction surficial (TSS) Mw 8.5 extreme earthquake scenarios, the hybrid method described in section 3 was utilized. Full details on the physical and computational modeling parameters will be presented elsewhere (Chavez et al., in preparation), but some of them are very similar to the ones used for the modeling of the 1985 Michoacan earthquake (Fig. 2B). The supercomputers KanBalam, HECToR and JUGENE were used for the low frequency computation of the wave propagation of the 1985 Mw 8.01 Michoacan and the Mw 8.5 extreme earthquake scenario.
In Fig.4 the surface projection of the 500 x 600 x 124(depth) km^3 volume used for the low frequency modeling of the Mexico City scenario is presented. Their synthetic fractal slip distributions considered for the scenario ruptures are shown in Fig. 5. For the high frequency modeling, the recordings mentioned in section 4.2 and recordings of the 1985 Ms 8.1 earthquake were used. An example of the type of results obtained with the broadband acceleration synthetics for the Mw 8.5 earthquake scenarios are shown in Figs. 6 and 7. In Fig. 6 the expected values and the standard deviations of the samples of the response spectra of accelerations for the SCT site, associated to those synthetics are included for samples sizes of 10 to 50 synthetics, which include the uncertainties in the seismic source expected ruptures of the Mw 8.5 extreme earthquake scenarios shown in Fig. 5, as well as those associated to the seismic behavior of Mexico City surficial soils. The Mexico City distribution of the estimated horizontal spectral acceleration Sa (damping 5%) at 2 s, for the Ms 8.1(Mw 8.01) 1985 Michoacan earthquake and the Mw 8.5 earthquake scenario, are shown in Fig. 7, they were obtained by using the 1985 earthquake records and the synthetics at the firm soil Tacubaya site in Mexico City and the amplification factors (which includes the uncertainties in the Sa(5%) expected values), suggested by Perez-Rocha (1998).

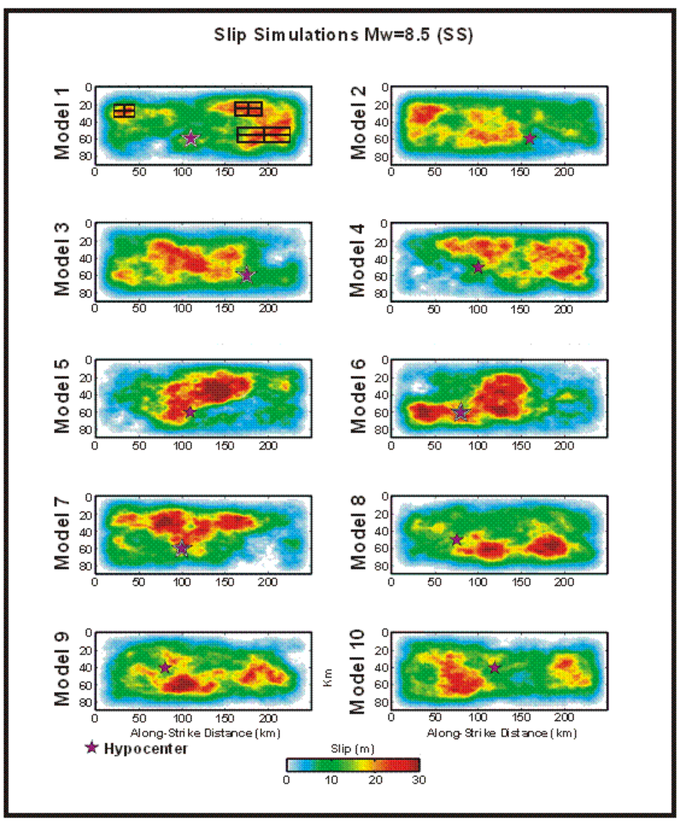

Figure 5. Fractal slip simulations (based on Mai and Beroza, 2002) of the finite seismic sources used in the hybrid modeling of the Mw 8.5 extreme Thrust Subduction Surficial (TSS) earthquake scenarios. The rectangles in model 1 are an example of the finite sources used for the Empirical Green Functions simulations

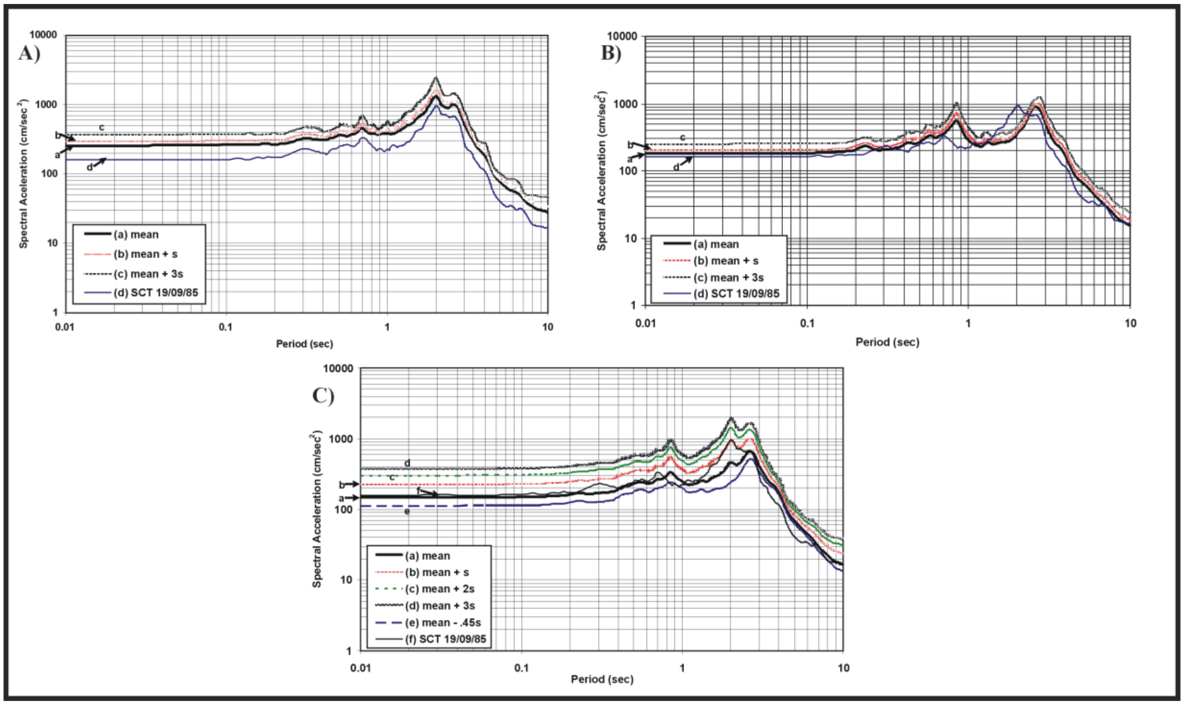

Figure 6. Statistics of sample size of 10 and 50 synthetics, for A), B) and C), respectively, of the horizontal acceleration response spectra Sa (damping 5%) for the SCT site corresponding to the synthetic accelerograms obtained for the subduction superficial Mw 8.5 scenario earthquake and assuming: A) that SCT compressive surficial soils (clays) behave as during the 19 September 1985 Mw 8.1 Michoacan earthquake, B) that SCT clays have a non-linear behaviour, C) statistics resulting from considering a 50 synthetic sample (s=standard deviation)

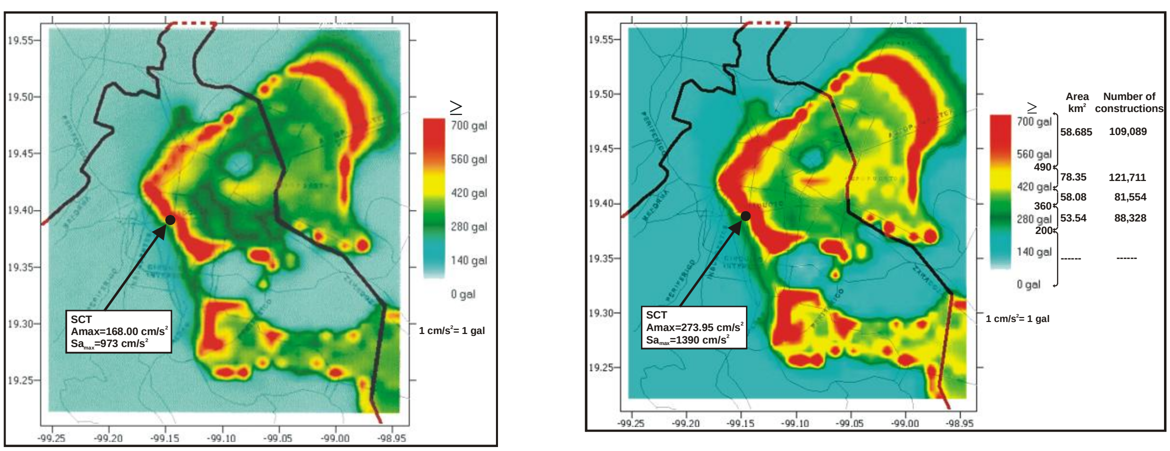

Figure 7. Left, Mexico City distribution of the estimated horizontal spectral acceleration Sa (damping 5%) at 2 s for the Ms 8.1(Mw 8.01) 1985 Michoacan earthquake. Right, the corresponding distribution for the Mw 8.5 scenario earthquake of Fig. 4. The respective maximum response spectral acceleration, Sa (5%), values for the SCT site are also included. The built area (km^2) and the number of constructions of one to three floors, located in zones with different Sa (5%) values, are also listed

5.2 Modeling of the economical consequences of the Mw 8.5 extreme earthquake scenario

Based on the information suggested by Ordaz et al., (1994) about the distribution of Mexico City built stock of 1 to 3 floors and of their seismic vulnerability, Figs. 8 and 9 were generated. Notice that in Fig. 9 the uncertainties on the vulnerability curve proposed by Ordaz et al., (1994) was incorporated by using a coefficient of variation which corresponds to the dashed curve included in this figure. The samples of the damaged built stock associated to the plausible occurrence of the Mw 8.5 earthquake scenario were obtained by using the Sa (5%) values at each of the cells shown in Fig 8, from their corresponding cell of Fig. 7 Rigth and the vulnerability curves of Fig. 9. The histograms obtained for the damaged areas and of their probability density distribution for the extreme Mw 8.5 scenario earthquake are shown in Figs. 10 and 11. Notice in Fig. 11 that for a probability of exceedance of 0.5 (mean value, m) and 6 x 10^{-4} (m + 5 standard deviations) the damaged areas are 5.32 and 21.4 km^2, respectively. A similar plot was obtained for the associated probability of exceedance of the economical consequences, PEDEC´s but is not included here for lack of space. Monte Carlo simulation techniques can be used to generate larger samples of the damaged areas, as well as of the economical consequences (Chavez et al. in preparation).

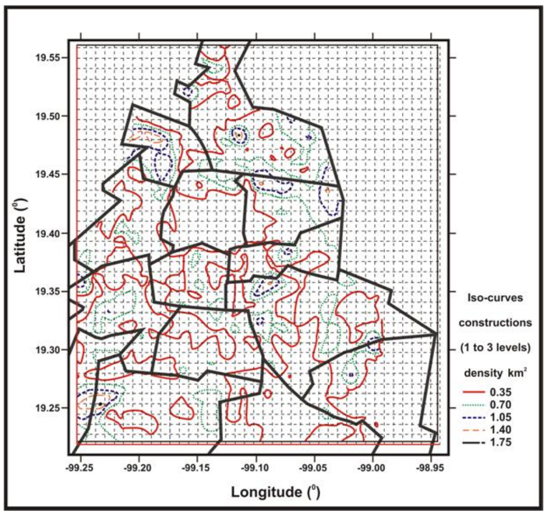

Figure 8. Mexico City 1 to 3 levels construction stock distribution used for the estimation of the probability of exceedance of the economical consequences, PEDEC´s for the Mw 8.5 earthquake scenarios

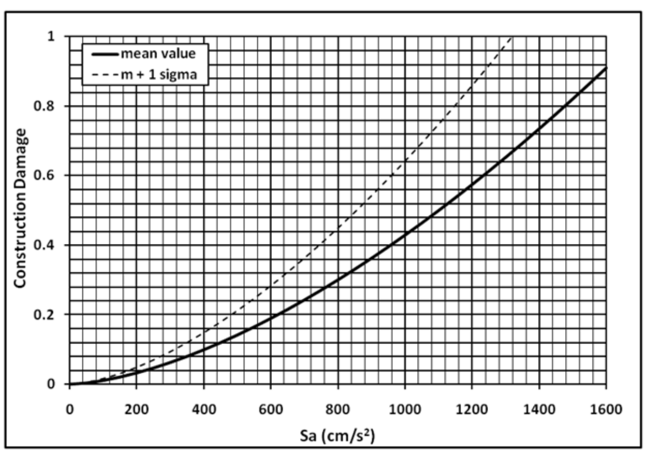

Figure 9. Vulnerability functions of Mexico City construction stock of 1 to 3 levels used for the estimation of the probability density of exceedances of the economical consequences, PEDEC´s, for the Mw 8.5 earthquake scenarios (Modified, Ordaz et al., 1994)

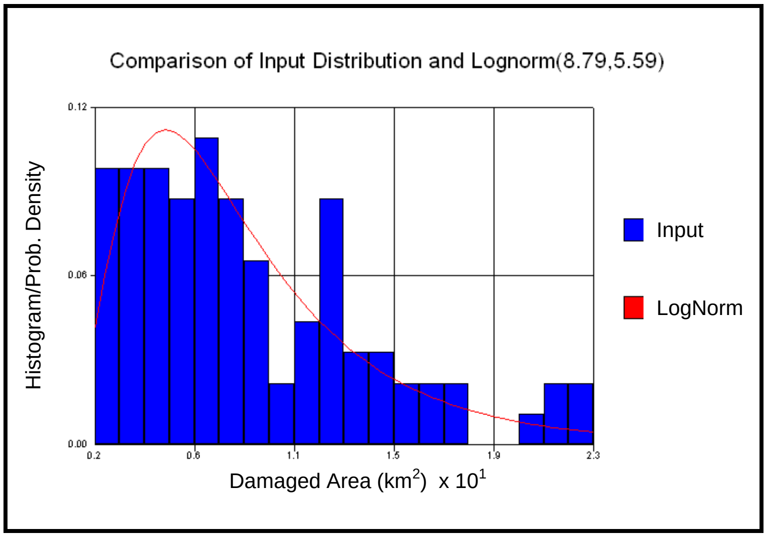

Figure 10. Histogram and fitted Lognormal probability density distribution of damaged areas in Mexico City for the Mw 8.5 earthquake scenarios

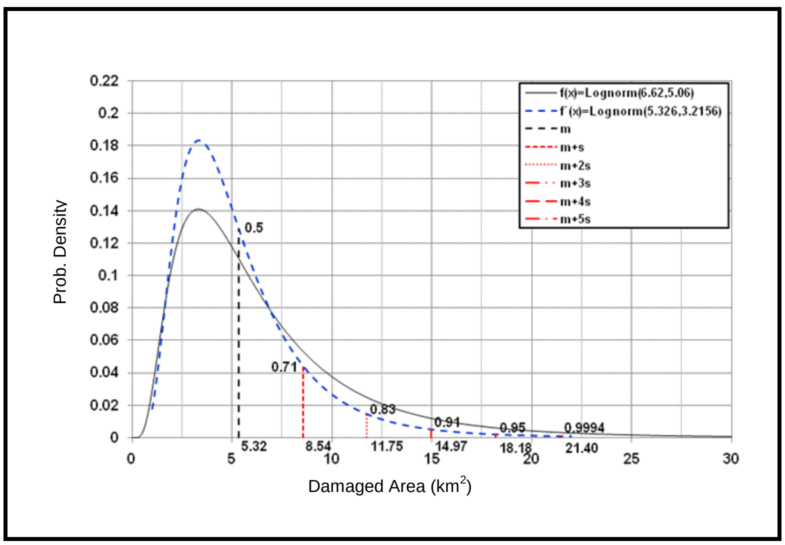

Figure 11. Lognormal probability density functions of damaged areas in Mexico City for the Mw 8.5 scenario earthquakes. The dashed curve correspond to the truncated distribution which includes the damaged areas for different probabilities of exceedances

6. CONCLUSIONS

1. A methodology is proposed in order to estimate the probabilities of exceedance of the intensities of extreme magnitude earthquakes (PEI) and of their direct economical consequences (PEDEC). The PEI´s are obtained by using supercomputing facilities, and a hybrid method to generate broadband samples of the 3D wave propagation of extreme earthquakes (plausible) scenarios. The PEDEC´s are computed by using appropriate vulnerability functions combined with the earthquake scenario maximum ground motions intensity samples, and Monte Carlo simulation. **2.** We generated broadband synthetic accelerograms, expected on Mexico City (MC) stiff and compressive soils, associated to extreme seismic scenarios for subduction surficial Mw 8.5 earthquakes. **3.** From the

Mw 8.5 extreme earthquake scenarios analyzed, we obtained the probability density functions of the intensities PEI from which upper bounds (mean + 3 standard deviations) were computed for the maximum ground accelerations, Amax, and the maximum response spectra acceleration, $Sa_{max}(5\%)$, of 125 and 400, and 400 and 2000 cm/s^2, for the strong ground motions expected in the stiff and compressible soils of MC, respectively. **4.** By using appropriate vulnerability functions for MC constructions, the cadastral information of its construction stock, and the samples of the ground motions intensities mentioned in **2**, the probability density functions of the damaged areas associated to the Mw 8.5 earthquake scenarios were computed; the respective probability density functions of the direct economical losses were obtained. **5.** We think that the results obtained with the proposed methodology could be used by the decision makers, to allocate funds, or to implement policies to mitigate the impact associated to the plausible occurrence of future extreme earthquakes.

ACKNOWLEDGMENTS

We would like to thank the support of J.L. Gordillo, the Supercomputing staff and M. Ambriz, L. Alcantara and colaborators, of DGTIC, and the Institute of Engineering, UNAM, respectively. We also acknowledge the support of R. Madariaga and M. Mai of the ENS, Paris, France and KAUST, Thuwal, Saudi Arabia, respectively. We acknowledge DGTIC, UNAM for the support to use KanBalam supercomputer, the STFC Daresbury Laboratory to use HECToR supercomputer and the PRACE European project for the grant to use the JUGENE supercomputer for one year starting in April 2011. The first author also acknowledges the support of DGAPA, UNAM.

REFERENCES

Cabrera E., Chavez M., Madariaga R., Perea N., Frisenda M. (2007). 3D parallel elastodynamic modeling of large subduction earthquakes. F. Capello et al. (eds): *Euro PVM/MPI 2007*, **LNCS 4757**, pp. 373-380, Springer- Verlag Berlin Heidelberg.

Chavez M., Cabrera E., Madariaga R., Perea N., Moulinec Ch., Emerson D., Ashworth M., Salazar A. (2008). Benchmark study of a 3D parallel code for the propagation of large subduction subduction earthquakes. Lastovesky A. et al. (eds): *Euro PVM/MPI 2008*, **LNCS 5205**, pp. 303-310, Springer-Verlag Berlin Heidelberg.

Chavez M., Cabrera E., Madariaga R., Chen H., Perea N., Emerson D., Salazar A., Ashworth M., Moulinec Ch., Wu M., Zhao G. (2010). Low frequency 3D wave propagation modeling of the Mw 7.9 Wenchuan 12May 2008 earthquake, *Bull. Seism.Soc. Am.*, **Vol 100 5B**, pp 2561-2573, doi:10.1785/012009240.

Chavez M., Olsen K. B., Cabrera E., Perea N. (2011). Observations and modeling of strong ground motions for the 9 October 1995 M_w 8 Colima- Jalisco, Mexico, earthquake, *Bull. Seismol. Soc. Am.*, **101, 5**, pp. 1979-2000, doi: 10.1785/0120100200.

Irikura K. (1986). Prediction of strong acceleration motion using empirical Green´s function, *Proc. 7^th^ JEES*, 151-156.

Mai, P.M., Beroza G.C. (2002). A spatial random-field model to characterize complexity in earthquake slip, *J. Geophys. Res*., **Vol. 107 (B11)**, 2308, doi:10.1029/2001JB000588.

Mendoza C., Hartzell S.. (1989). Slip distribution of the 19 september 1985 Michoacan, Mexico, earthquake: near source and telesismic constrains, *Bull. Seismol. Soc. Amer.*, **79**, pp 655-699.

Ordaz M., Meli R., Montoya Dulche C., Sanchez R., Perez-Rocha L.E. (1994). Bases de datos para la estimación de riesgo sismico en la ciudad de Mexico, CENAPRED, Mexico.

Pacheco J., Kostoglodov V. (1999). Seismicity in Mexico from 1900 to 1999, Servicio Sismologico Nacional, UNAM, Mexico.

Pérez-Campos, X., Kim Y., Husker A., Davis P., Clayton R., Iglesias A., Pacheco J. F., Singh S. K., Manea V. C., Gurnis M. (2008). Horizontal subduction and truncation of the Cocos plate beneath Central Mexico, *Geophys. Res. Lett*., **35**, L18303, doi:10.1029/2008GL035127.

Perez Rocha, L. E. (1998). Respuesta sismica estructural: efectos de sitio e interaccion suelo-estructura (aplicaciones al Valle de Mexico). Ph D. Thesis, Faculty of Engineering, UNAM, Mexico.

Suarez G., Albini P. (2009), Evidence for great tsunamigenic earthquake (M 8.6) along the Mexican subduction zone, *Bull. Seismol. Soc. Am.*, **99,** pp. 892-896, doi:10.1785/0120080201.