IMPLICATIONS OF STRONG GROUND MOTION COMPLEXITY FOR SEISMIC HAZARD ASSESSMENT

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ABSTRACT :

The use of deterministic ground motion simulations in seismic hazard assessment is currently a rapidly growing field of research. The advantage of such methodologies is that detailed information about the characteristics of strong ground motion can be obtained because they are based on earthquake scenarios. A method for calculating the broadband frequency ground motion due to a scenario earthquake will be presented. In our hybrid model we combine the deterministic simulation of the low frequencies with a semi-stochastic simulation of the high frequencies using empirical Green's functions. Examples from two case studies (the Dec 26, 2004 Sumatra earthquake and an expected future earthquake in the Marmara Sea) are used to illustrate the various aspects of the method. Furthermore, the effects of varying the input source and attenuation parameters on the simulated ground motion are quantified. One limitation of the deterministic methodologies is that the hazard assessment is usually conducted due to a single scenario earthquake. In many regions, however, the seismic hazard is combined from the threat of several active faults for which several scenario earthquakes can be defined with different probabilities of occurrence. Future plans towards the implementation of deterministic earthquake scenarios in probabilistic seismic hazard calculations are investigated.

KEYWORDS: Seismic hazard, ground motion simulation, earthquake scenario, deterministic seismic hazard assessment, probabilistic seismic hazard assessment

1. INTRODUCTION

In classical seismic hazard assessment, a probabilistic approach is followed by dividing the region of interest into a number of source zones and combining the ground shaking contributions from these zones based on activity rates and regional attenuation relations. This approach provides the probabilities of exceeding specified ground shaking levels within a given time, which is important information for, among others, city planers and the insurance industry. Probabilistic seismic hazard assessment (PSHA) is especially suited for studies covering large areas or areas where the hazard is controlled by several faults where the activity rates can be assessed by studying earthquake catalogues.

On the other hand, in areas where a single fault controls the seismic hazard, deterministic seismic hazard assessment through the simulation of ground motions due to a (typically worst-case) scenario earthquake can provide more detailed information about the seismic hazard. In such studies, source complexity can be taken into account and full time histories can be derived to obtain information also about duration and spectral content of the ground shaking. However, such analysis requires detailed knowledge about the kinematics and the rupture properties of the studied fault. Furthermore, the application of deterministic methodologies becomes problematic in regions where several faults control the seismic hazard. In such cases, it is necessary to combine the hazard including contributions from all source regions in the study area.

One way to exploit the advantages of both of the above methodologies is to combine a large amount of deterministic scenarios in a probabilistic manner. For example, large scale computational efforts are underway at the Southern California Earthquake Center (SCEC) to compute site specific and regional hazard based on increasingly complex numerical and physics based models of earthquake probabilities, earthquake rupture propagation, seismic wave propagation and interaction with the built environment (http://epicenter.usc.edu/cmeportal/CyberShake.html).

In this paper we present a hybrid methodology for deterministic seismic hazard assessment through simulation of strong ground motion for a scenario earthquake. Two examples are presented for the application of the methodology; one retrospect study of the Dec 26, 2004 Sumatra-Andaman earthquake and another predictive study for a potential future M=7.5 scenario earthquake in the Marmara Sea south of Istanbul. For the Marmara Sea earthquake, the effect of varying source and attenuation parameters on the simulated ground motions is also presented. Finally we include a discussion on the future steps necessary for a combination of several earthquake scenarios in a probabilistic study. Such analysis will combine the detailed knowledge of the distribution of ground motion obtained from the deterministic calculations, accounting for a range of possible earthquake scenarios affecting the studied region through a probabilistic approach.

2. METHOD

We follow the approach of Pulido and Kubo (2004) and Pulido et al. (2004), using a hybrid method for simulating the broadband ground motion. This procedure combines a deterministic simulation at low frequencies (0.1-1 Hz) with a semi-stochastic simulation at high frequencies (1-10 Hz). A finite-extent scenario earthquake source embedded in a flat-layered 1D velocity structure is assumed. The source consists of a number of asperities, which are divided into subfaults assumed to be point sources. The total ground motion at a given site is obtained by summing the contributions from the different subfaults. For the low frequencies, subfault contributions are calculated using discrete wave number theory (Bouchon, 1981) and summed assuming a given rupture velocity. At high frequencies, the subfault contributions are calculated using a stochastic method that incorporates a frequency-dependent radiation pattern by applying a smooth transition from a theoretical double-couple at low frequencies to a uniform radiation pattern at high frequencies following Pulido and Kubo (2004). Point sources are summed using the empirical Greens function method of Irikura (1986). The methodology has been validated through comparison to recorded data in previous studies by Pulido and Kubo (2004) and Sørensen et al. (2007a).

The ground motion simulations are performed at bedrock level and therefore do not take local site effects into account. This is important to keep in mind when interpreting the simulation results since local site effects may be important in the studied regions.

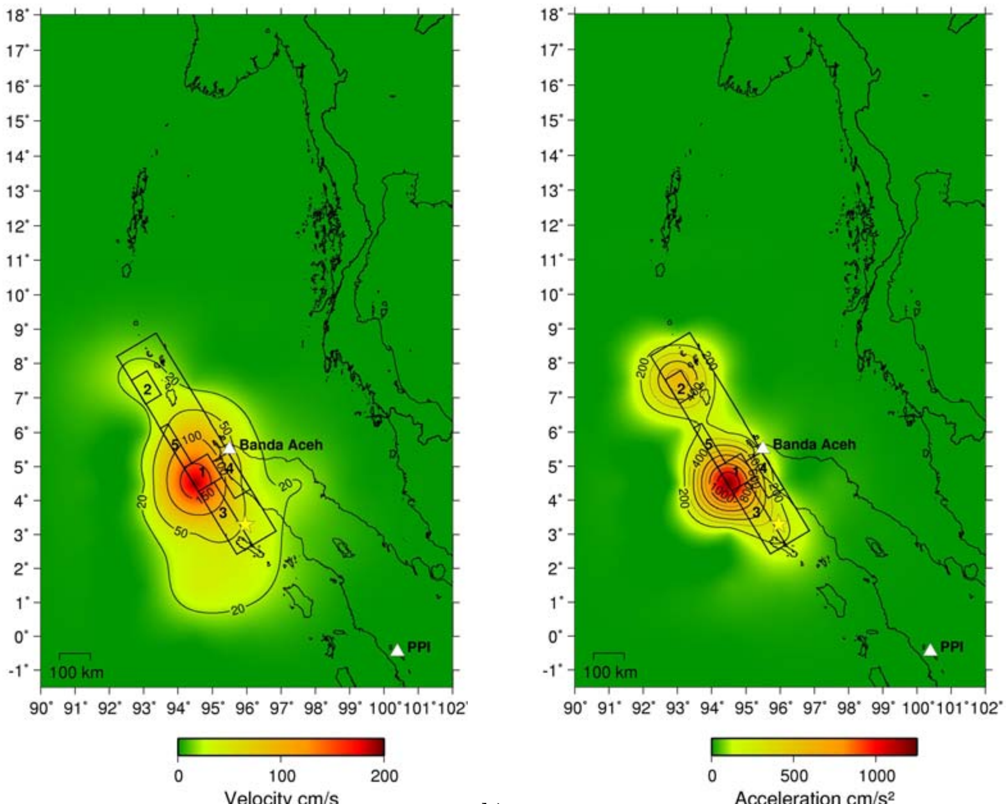
As input for the modelling, the source needs to be defined in terms of the location of the rupturing fault and its asperities together with asperity parameters such as rise time, rupture velocity, stress drop and seismic moment. Also, the properties of the surrounding crust need to be defined in terms of the velocity structure and attenuation characteristics.

3. SIMULATION RESULTS FOR THE DEC 26, 2004 SUMATRA EARTHQUAKE

On Dec 26, 2004 the most devastating earthquake in recent history occurred off the west coast of northern Sumatra. This mega-thrust earthquake with a magnitude of M_w=9.3 and the accompanying tsunami lead to the loss of more than 200 000 lives. An important question posed after the earthquake was related to the strong ground motion distribution in the region and its consequences in places like Banda Aceh where severe destruction was observed. Although much of the damage was associated with the impact of the tsunami, it is still not clear how much of the destruction was due to strong ground shaking. Therefore, the described ground motion simulation methodology has been applied to a scenario earthquake representing the Dec 26, 2004 earthquake (Sørensen et al., 2007a).

The scenario earthquake represents a simplified model based on the source inversion of Yagi (2004) published shortly after the earthquake. This source model has been modified slightly to account for the northern extension of the fault plane revealed by Lay et al. (2005), which was not included in the model of Yagi (2004) due to the limited frequency range included in this study. The resulting scenario fault rupture covers an area of 750 x 150 km and includes five asperities where high slip was observed based on the slip inversion results. Other source parameters such as rise time, rupture velocity and stress drop, and the velocity and attenuation characteristics of the surrounding crust, are taken from various sources available in the literature. For details, the reader is referred to the description in Sørensen et al. (2007a).

The simulated ground motion distribution in terms of peak ground velocity (PGV) and peak ground acceleration (PGA) is presented in Figure 1. From this figure it is clear that the strongest shaking occurred close to the rupturing fault plane and that the reverse mechanism of the earthquake has a strong effect on the directivity of the ground motion. PGV values reach up to 200 cm/sec above the fault plane and are strongest in the region near the strong asperity nr. 1 (Figure 1). On land in northern Sumatra, velocities reach values up to 100 cm/sec at bedrock level. The PGA distribution differs from the PGVs, and we observe significant PGAs over the entire fault plane. The largest values of PGA are predicted in the area around asperity 1 reaching values of 1200 cm/sec^2, but also the other asperities have a clear effect on the ground accelerations. This is important for the Nicobar Islands which have experienced strong accelerations. Largest bedrock accelerations on northern Sumatra are of the order of 400 cm/s^2. Comparison of the simulated waveforms with recordings of the earthquake show a reasonable fit even at the large distances (minimum 650 km) where data are available (Sørensen et al., 2007a).



a) b)

Figure 1 Simulated a) PGV and b) PGA distribution for the Dec 26, 2004 Sumatra earthquake. The black boxes indicate the extent of the surface projection of the fault plane and its asperities. The star shows the surface projection of the hypocenter, and the white triangles indicate the simulation sites Banda Aceh and PPI.

3. SIMULATION RESULTS FOR A SCENARIO EARTHQUAKE IN THE MARMARA SEA

The city of Istanbul is under a significant seismic hazard due to its proximity to the Marmara Sea segment of the North Anatolian Fault (NAF). During the last century there has been a westward migration of large, destructive earthquakes along the NAF with the latest events occurring near Izmit and Ducze in 1999 (e.g. Barka et al., 2002). Following these large earthquakes, there has been an increase in the Coulomb stress along the Marmara

Sea segment (Hubert-Ferrari et al., 2000) which, together with the fact that no large earthquakes have occurred here at least since 1766 (Barka et al., 2002), indicates that a large earthquake is likely to break this part of the NAF within the life time of the present city environment (Parsons et al., 2000; Parsons, 2004).

To study the effect of such an event on the city of Istanbul located ca 20 km north of the NAF, ground motions have been simulated for a M=7.5 scenario earthquake in the Marmara Sea (Sørensen et al., 2007b). The 130 km-long scenario fault plane is limited by the recently ruptured segments of the Ganos Fault (ruptured in 1912) to the west and the Izmit Fault (ruptured in 1999) to the east. The source parameters of the scenario earthquake are mainly based on observations from the 1999 Izmit earthquake, for details see Sørensen et al. (2007b).

The distribution of bedrock ground motions obtained for the scenario earthquake is shown in Figure 2. The largest accelerations are predicted in the southernmost part of Istanbul, which is also located closest to the rupturing fault. Here we can expect bedrock accelerations of 500 cm/s^2 or more in some places. There is a very strong forward directivity effect on the ground motions, which is especially evident in the PGV distribution. Largest velocities are expected in the southeastern part of the city, where we predict velocities up to 125 cm/s. Due to the forward directivity, the shaking is extended far towards east from the rupturing fault which may have important implications along the populated areas around the Izmit gulf.

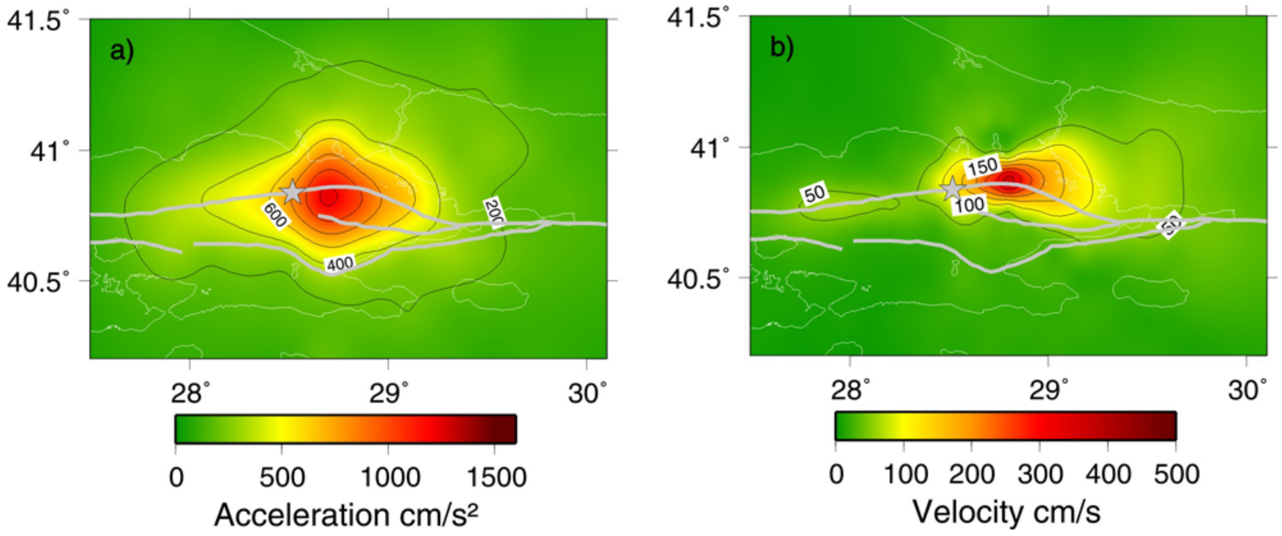


Figure 2 a) PGA and b) PGV distribution for a M_w=7.5 scenario earthquake in the Marmara sea. Gray lines indicate the locations of major faults in the area, the star shows the point of rupture initiation.

4. SENSITIVITY TO VARYING SOURCE PARAMETERS

Variation in the scenario source parameters introduces significant uncertainties in the ground motion simulations. Although increased knowledge about the rupture properties of the area in question can reduce this uncertainty it cannot be completely avoided and must be taken into account when interpreting the results of such hazard calculations. In order to quantify these uncertainties, the earthquake scenario for Istanbul described above, has been varied by changing the source and attenuation parameters one by one to demonstrate their effect on the simulated ground motions. The parameters which have been studied are the attenuation (Q), rise time, rupture velocity, rupture initiation point and stress drop. These parameters have been varied in a total of 16 scenarios (for details, see Sørensen et al. (2007b)).

Figure 3 shows the distribution of standard deviations in PGA and PGV based on all scenarios. These maps indicate that the largest variation in the ground motion occurs close to the asperities which are located adjacent to the bend of the fault plane. This is as expected since much of the variation in the ground motion is associated with the location of asperities and their rupture parameters. The variation naturally affects also the surrounding regions. The level of standard deviation of both PGA and PGV decreases gradually with increasing distance from the fault asperities. However, PGA variability is spread over a wider area compared to PGV variability.

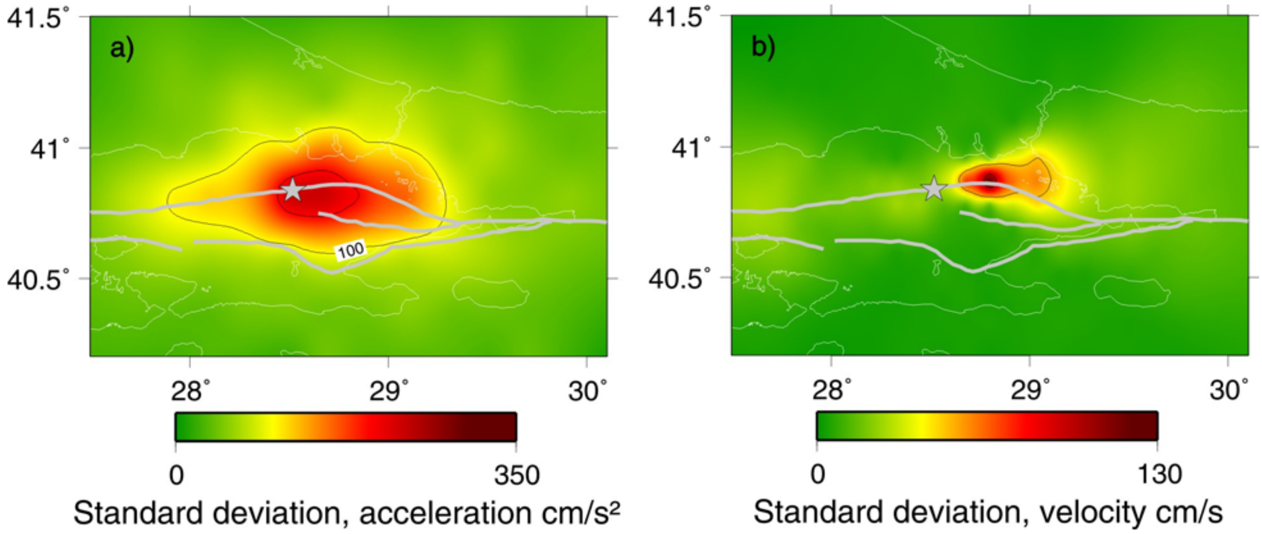


Figure 3 Spatial distribution of standard deviation of a) PGA and b) PGV based on the 16 scenarios. Major faults are shown as grey lines and the rupture initiation point as a star.

When applying seismic hazard results to engineering problems, the frequency content of the ground motion becomes an important factor in addition to the peak ground motion. The effect of the source and attenuation parameters in various frequency bands can be studied by considering the spectra of the simulated seismograms for a number of selected sites (Sørensen et al., 2007b). Such analysis shows that rise time and rupture velocity have their main effect on the low-frequency ground motions despite them entering both the low- and high-frequency calculations. This implies that even though these parameters cause large variations in the ground motion levels, their effect for engineering issues is limited in most parts of Istanbul where the building stock is more sensitive to higher frequencies. It should be noted however that due to the nature of the kinematic-based fault rupture model used in this study, that assumes these parameters are nearly uniform across the fault plane, their influence on high frequency ground motion is not fully taken into account. The location of the rupture initiation point (RIP) affects all frequencies, but the effect decreases for increased frequencies, indicating that the RIP mainly has an impact low frequencies and hence may affect large structures such as high-rise buildings. The stress drop, and especially the stress drop ratio (asperity to fault average stress drop), affects all ground motions above 1 Hz (the parameter is only introduced directly for the high frequency calculations) and thereby it is an important parameter with large impact on the level of potentially damaging ground motion, which should be given attention in future studies. The frequency dependent attenuation (Q) is another parameter only introduced for the high frequency computations. The main effect on the ground motion is due to varying frequency, and this effect increases for increasing frequency as one would expect. For the low frequency computations, attenuation is introduced through Q_p and Q_s in the velocity model. The effect of varying these two latter parameters has shown to be negligible.

In summary, we find that the most critical parameters for the ground motion modelling, in terms of ground shaking levels, are the location of the rupture initiation point, stress drop, rise time, rupture velocity and the anelastic attenuation for the studied region. However, the impact of these parameters in frequency bands of engineering interest varies. From an engineering perspective, the most important parameters are the stress drop and the location of rupture initiation. Also rupture velocity and rise time will play an important role due to their strong effect on PGV. Unfortunately, these parameters are difficult to predict for future earthquakes, but detailed studies should be made ahead of ground motion simulation, and in case of large uncertainties, extreme values should be considered in the input to the models to set bounds on the predicted ground motions.

The results of this study reveal that even if we have reliable ground motion estimation methodologies we are still limited in the prediction of ground motions from future earthquakes by our limited knowledge of the source and attenuation parameters. This limitation should always be kept in mind when interpreting ground motion simulation results. However, being aware of the uncertainties, ground motion simulations still provide a strong tool in determining seismic hazard levels in places with a high probability of exceedence.

5. COMBINING GROUND SHAKING SCENARIOS IN A PROBABILISTIC APPROACH

The methodology applied in this study can only be applied to one earthquake at a time and is therefore appropriate mainly for estimating the effects of individual “most likely” or “worst case” scenario earthquakes. In areas such as the San Francisco Bay area in northern California, where several fault structures are likely to rupture in the next large earthquake with varying probabilities (Working Group on California Earthquake Probabilities, 2003), such methodologies are of limited use. Furthermore, the purely deterministic methodologies provide no information about the likelihood of the scenario earthquake occurring.

In order to improve the seismic hazard assessment, the advantages of probabilistic and deterministic seismic hazard assessments can be combined in an approach where several ground shaking scenarios are combined using the principles of PSHA. In such an analysis, a synthetic earthquake catalogue can be generated through a Monte Carlo approach (for details, see e.g. Giardini et al., 2004) and ground shaking scenarios can be calculated for each earthquake in the synthetic catalogue. The synthetic catalogue is based mainly on active faults in the region, complemented by a source zonation with associated activity rates as in standard PSHA. Uncertainties in both the synthetic catalogue and in the earthquake source parameters can be accounted for through a logic tree approach. The ground shaking scenarios for the synthetic catalogue can be combined (for example through counting exceedances of a given ground motion level at a simulation site) and hazard curves for various percentiles can be determined.

The outlined approach is computationally very demanding and in this respect on the limit of feasibility for application to large regions. However, with the fast increase in computational power, such methodologies are expected to become state-of-the-art in the future.

6. CONCLUSIONS

We have presented a hybrid methodology for broadband ground motion simulations with application to the Dec 26, 2004 Sumatra earthquake and a potential future earthquake in the Marmara Sea. The method accounts for the complexity of the source and thereby provides valuable information about the ground shaking distribution including e.g. source directivity. Based on the work presented in the present paper, the following conclusions can be drawn:

- Deterministic ground motion simulations serve as a strong tool for assessing the seismic hazard in regions where the hazard is controlled by a single or few faults. In such cases, deterministic ground motion simulations are superior to standard PSHA.
- Ground motion simulations preformed for the Dec 26, 2004 Sumatra-Andaman earthquake indicate that significant ground shaking affected northern Sumatra, most likely causing pronounced destruction before the tsunami hit the region.
- The expected impact of a M=7.5 earthquake in the Marmara Sea on the city of Istanbul may have catastrophic consequences with the largest ground motions occurring in the southern and southeastern parts of the city. Here, ground accelerations at the level of 200-500 cm/s^2 and velocities in the range 50-100 cm/s can be expected at bedrock level.
- A sensitivity study has shown that rise time, rupture velocity, rupture initiation point and stress drop are the most significant parameters in terms of variations in ground shaking level when performing ground motion simulations. However, these parameters have their effect in different frequency bands and their engineering significance therefore varies.
- Seismic hazard assessment can be improved through the combination of deterministic ground shaking scenarios in a probabilistic manner. In this way, the detailed information obtained from the ground motion simulations can be exploited also in regions where several faults control the seismic hazard.

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