Stochastic Simulation of Ground Motions Generated by Vrancea Intermediate-Depth Seismic Source

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***Abstract*—The current paper is concerned with the ground motion simulation using the stochastic method, a method that combines the parameters of the amplitude spectrum of the seismic motion with a random phase spectrum modified so that the movement would be distributed over the specific duration to the magnitude and distance of the earthquake. Using simple functions, this method incorporates the influence of seismic motion characteristic (source mechanism, seismic wave path influence and local site conditions). To see how the method can be used for Vrancea (Romania) intermediate-depth source, SMSIM and EXSIM were used to simulate the medium earthquake produced by Vrancea source on October 27, 2004.**

***Index Terms*—stochastic, Vrancea earthquakes, simulation, strong motion.**

I. Introduction

Currently, there are four main methods of predicting ground motion: motion prediction equations (the result of the method being motion parameters), stochastic modeling, Green empirical functions and numerical modeling based on physical characteristics (the last three methods result in a time domain ground motion). Hybrid methods combining numerical modeling, Green empirical functions and stochastic modeling have been used over the past years. The difficulty of earthquake simulation methods is given by the complexity of input data. If for the prediction equations it is necessary to identify the general characteristics of the seismic source, the fault geometry, the definition of the rupture (seismic moment, the tectonic mechanism, the type of sliding), for the stochastic method the characterization of the propagation path influence in terms of seismic wave speeds, mass densities and behavior of the local site conditions are needed. Numerical modeling also requires more input data: a proper characterization of the seismic source (kinematics or dynamics) and a more detailed definition of the complex geological structure that can influence the local seismic response.

II. The Essence of the Methods

A. *The empirical method of Green functions*

The method involves modeling a large earthquake (a large rupture surface) through a series of small earthquakes that represent point sources (with a similar faulting mechanism to the target earthquake) along the fault, the propagation of the rupture being accounted for through phases of delay. Basic papers in the literature on the empirical method of Green functions are Hartzell [1], Irikura [2-3], Miyake et al. [4].

B. *Stochastic simulation of ground motion*

Hanks and McGuire [5] combined spectral models of amplitudes of ground motion with the notion that high frequency movements are random. In their work, they assumed that the accelerations on a resilient semi-space are of finite bandwidth of Gaussian white noise and that the spectrum of the source is described by a single corner frequency which depends on the size of the earthquake [6,7]. Boore [8] generalized their work to allow the use of more complex, extended patterns to simulate time series and to take into account several features of seismic motion. In the literature we find, for modeling the seismic source, two popular methods: stochastic modeling as a punctual source and stochastic modeling as a finite source. Also, the source spectrum can be defined as having one or two corner frequencies.

C. *Numerical modeling. Theoretical simulations (3D)*

The most appropriate method of simulation of long-term seismic movements is the method of finite difference of the fourth row with spatial grid variables [9] and frequency dependent attenuation factor [10]. This method involves building a 3D speed model and determining the optimal mitigation parameter, resulting in 3D waves.

D. *Hybrid methods*

Hybrid simulation methods combine long-period movements of a large earthquake (simulated by deterministic methods) and short-period movements (simulated using either stochastic methods [11] suitable for small earthquakes or using empirical Green functions [3] suitable for large earthquakes). Simulated ground motion results from the summation of long-period movements and short-period movements after filtering.

III. Characteristics of Simulated Earthquake

Simulations have been made for the Vrancean (Romania) subcrustal earthquake produced on October 27, 2004, using SMSIM a program by D. Boore [12-13] and EXSIM a program by Motazedian and Atkinson [14-15], that use the stochastic simulation method with a point-source and respectively a finite-source description.

The earthquake of October 27, 2004, is a medium sized earthquake with a magnitude of 5.8 at a depth of 99 km [16] or 105 km [17]. The epicenter of this earthquake is

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45.78º N and 26.73º E longitude [16] or 45.78º N latitude and 26.73º E longitude [17]. The magnitude of the seismic fault according to Oth et al. [16] was 1.2×1.8 km and the stress drop was 75 bars [18]. From the point of view of the rupture mechanism, according to Ganas et al. [18], the earthquake was produced at a 219º strike angle, the dip being 81º, with a rake of 107º.

IV. Input Data

For the average velocity of shear waves β_s and the density in the vicinity of the source ρ, several variants are reported in the literature, so Martin et al. [19] propose $\beta_s = 4.5\ \mathrm{km/s}$ and density $\rho = 3.2\ \mathrm{g/cm^3}$ and Sokolov et al. [20] proposes $\beta_s = 3.8\ \mathrm{km/s}$ and the density $\rho = 2.8\ \mathrm{g/cm^3}$. In the simulation were considered the fallowing values the mean shear wave velocity $\beta_s = 4.5\ \mathrm{km/s}$ and the density $\rho = 2.8\ \mathrm{g/cm^3}$.

In SMSIM, simulations were made for 3 types of spectra for the source: one corner frequency source (S1) and two corner frequencies with additive spectrum (S11) and multiplicative spectrum (S12), using the models BC92 for S1 [21], H96 for S11 [22] and AB95 for S12 [23]. The corner frequency was defined according to Gusev et al. [24].

Two sets of simulations were made for the hypocentral distance one for the closest distance (*R*) from the fault to site 183km and another for effective distance (R_{eff}) taking into account the geometry of the fault 188km (obtained with reff.exe – an executable from the SMSIM program set [13]). Geometrical scattering was considered according to Pavel and Văcăreanu [25].

As for the attenuation, in the same work mentioned above, Pavel and Văcăreanu [25] determined it to have the form

$$Q(f) = 100 \times f^{1.2} \tag{1}$$

(form used in the simulations). Following the seismic wave attenuation analysis, Oth [16] found the form of the attenuation equation

$$Q(f) = 100 \times f^{0.8} \tag{2}$$

and in Pavel [26] can be found as

$$Q(f) = 165 \times f^{1.2} \tag{3}$$

A significant dependence of the earthquake magnitude parameter and local site was observed [27]. For example, for the Bucharest area, the mean value k_0 has a relatively high value of 0.071, in the area of Moldova the average value k_0 is 0.057 and in the epicentral area k_0 has an average value of 0.101. For the application, the values of the kappa parameter were considered in the work of Pavel and Văcăreanu [25]. The kappa spectral degradation parameter was calculated using the recordings of the nine earthquakes recorded by 57 seismic stations. The final value of the kappa parameter is given by the following equation

$$k = k_{event} + k_0 \tag{4}$$

where

$$k_{event} = 0.022 M_w + 0.127 \tag{5}$$

The duration of the sources was considered according to Boore [11], and the path dependent duration was considered 0.0868 used in the paper of Pavel [26]. For amplification of the location conditions, two amplification profiles were used, one resulting from the calculation performed with the NRATTLE (program from the SMSIM collection [13]) for the shear wave profile for INCERC Bucharest [28], the second is an amplification profile used in the paper of Pavel [26] resulting from the H/V method.

Table I. Average Peak Acceleration for Different Stress Values

Type of simulation using SMSIM	Arithmetic mean (cm/s^2)	Geometric mean (cm/s^2)
04sursa1RH_V75stress	17.97	17.79
04sursa1RH_V200stress	29.96	29.69
04sursa1RH_V250stress	37.27	36.90
04sursa1RH_V300stress	41.49	41.10

V. Ground Motion Simulation Using SMSIM

A. Modified parameter (calibration)

Starting from the assumption that in the simulations made by Boore [11], Pavel and Văcăreanu [25], Oth [16], Sokolov [20] the stress drop parameter was chosen higher than could be found in the specialized literature (for example, for the earthquakes of 1977, 1986 - Ganas et al., [18], Oncescu and Bonjer [29]), the stress drop parameter was changed from 75 bars to 300 bars, and 4 sets of 400 simulations for the Source 1, H/V amplification profile were made. An average arithmetic of peak simulation type acceleration ranging from 17.97 cm/s^2 to 41.92 cm/s^2 were obtained (Table I).

B. SMSIM simulations for a stress drop of 200 bars

By setting the stress parameter at 200 bars, simulations were made for the three source types, two source-station distances and for the S1 source two types of amplifications of local field conditions (NRATTLE and H/V profile). From the 400 simulation sets, an accelerogram with the closest PGA value to the average was analyzed.

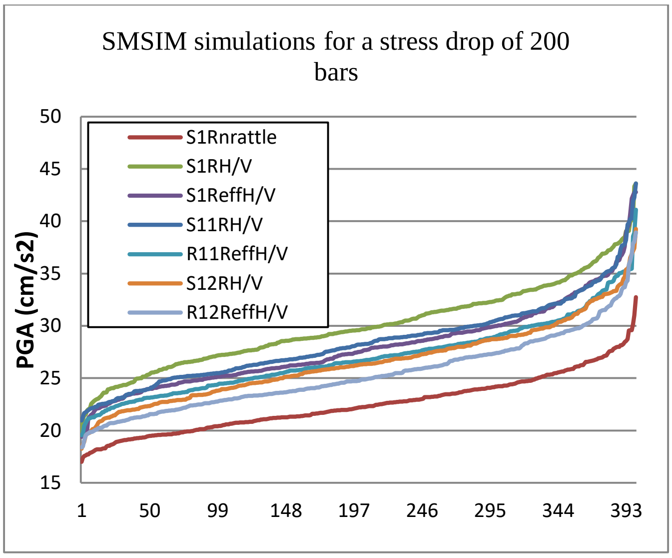

Figure 1. Variation of peak accelerations in the 400 simulations performed for the three source types and 2 local amplification types (the PAGs values were ordinated for a better illustration of the differences)

Conclusions

1. From the point of view of amplification given by local conditions, one can notice a decrease of peak accelerations about 1.35 times between the H/V and NRATTLE amplification profile.

2. Using the reference distance leads to a decrease in peak accelerations on average by 2.3 cm/s^2 for Source 1 and by 1.6 cm/s^2 for Sources 11 and 12 compared to the simulations in which the closest distance was used.

3. The significant duration of the earthquake recorded in 2004 is on average about 4 seconds longer than the simulations duration.

4. It can be seen that the mean square acceleration (parameter measuring the effects of amplitude and frequency content) is about 2.2 times higher for the simulations made using the H/V amplification profile, and for the simulation performed with the NRATTLE amplification profile is about 1.6 times higher (the difference can be explained by the large difference between peak accelerations).

TABLE II. CHARACTERISTICS OF SIMULATED GROUND MOTION OF OCTOBER 27, 2004 FOR A 200 BAR STRESS DROP

Type of simulation using SMSIM	Effective duration	Average square root	PGA (cm/s^2)	f_a (Hz)	f_b (Hz)	Obs.
Vrancea 2004 NS	21.39	3.8	30,01	0.35	0.35	*f_0 from Gusev et al [24]
Vrancea 2004 EW	20.92	3.4	29,72	0.35	0.35	
Sursa1 R H/V	16.73	7.8	30.65	0.726	0.726	f_a=f_b= =f_0
Sursa1 Reff H/V	17.1	8.1	28.36	0.726	0.726	
Sursa1 R nrattle	15.93	5.9	22.59	0.726	0.726	
Sursa11 R H/V	15.89	8.3	28.75	0.25	2.09	
Sursa11 Reff H/V	15.79	8.7	27.1	0.25	2.09	
Sursa12 R H/V	16	7.9	26.93	0.5	1.52	
Sursa12 Reff H/V	14	7.4	25.42	0.5	1.5	

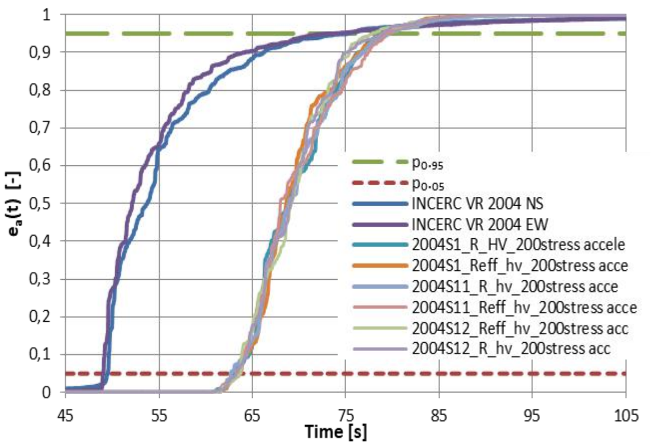

Figure 2. Cumulative energies of actual records and simulations with SMSIM

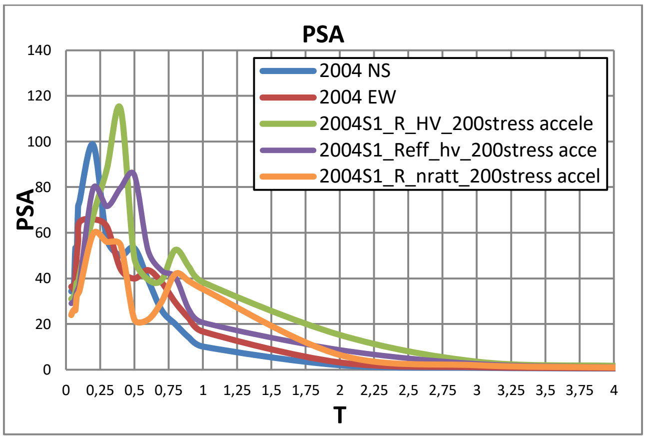

Figure 3. Comparison of the response spectra of simulations made with source S1 and the earthquake of 27 October 2004

5. Seismic energy is released faster and more abruptly through simulated ground motions than real accelerograms.

6. It can be noticed that all simulations fail to capture the 2004's earthquake peaks for periods of less than 0.25 s (frequencies higher than 4 Hz).

7. Simulations in which the reference distance was used tend to capture a peak for periods of 0.20 s (S1)–0.3 s (S11, S12). Also, for two-frequency corner sources at longer periods, amplification has a closer reduction to reality.

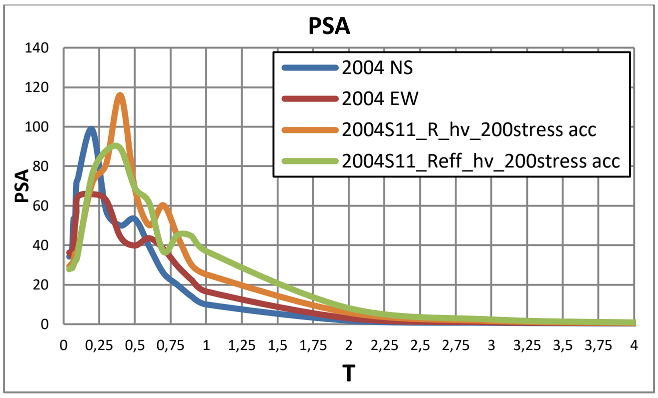

Figure 4. Comparison of response spectra of simulations made with source S11 and earthquake of 27 October 2004

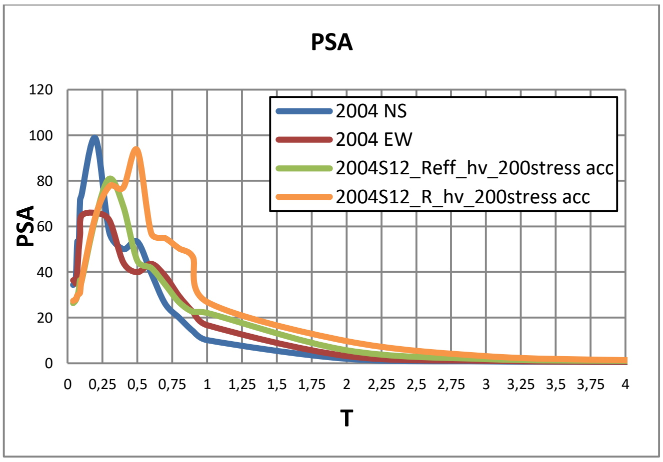

Figure 5. Comparison of response spectra of simulations made with source S12 and earthquake of 27 October 2004

C. SMSIM simulations without the influence of local site conditions

In order to observe more easily the changes in the frequency content of the ground motion simulations, there were made a second set of simulations without the amplification given by the local site conditions for the reference distance of 188 km.

Conclusions:

1. The arithmetic mean of peak acceleration on the 400 simulations for each source type are 7.50 cm/s^2 for S1, 8.08 cm/s^2 for S11 and 6.10 cm/s^2 for S12. The amplifications given by local field conditions increase the amplitudes of the movements by 3.5–4 times.
2. There remains a tendency to decrease the peak accelerations of the source 12 (multiplicative spectrum).
3. As expected, the frequency content is not altered by the amplification of local field conditions.
4. It is observed that the S12 source approaches as a normalized spectrum of recorded motion in the EW direction, although it fails to capture the amplifications for short periods.

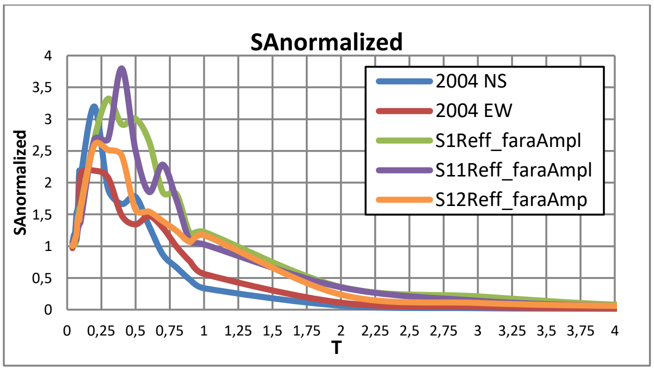

Figure 6. Comparison of normalized response spectra of simulations without the influence of local site conditions and the earthquake of 27 October 2004

D. SMSIM simulations near source

The third set of simulations is performed for a distance $R = 1\,\text{km}$ (near the source), eliminating the effects of the road from source to site.

It is observed how the frequency content is affected by the path from source to site, amplifying the movement over a larger spectrum of frequencies, with the tendency to amplify short periods.

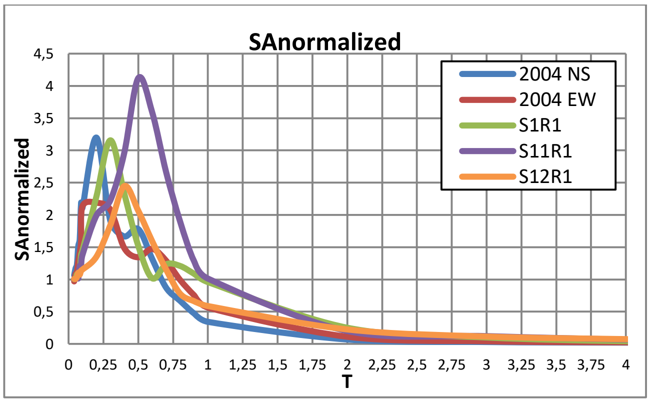

Figure 7. Comparison of normalized response sources spectra of simulation and the earthquake of 27 October 2004

E. SMSIM simulations near source for a stress drop of 75 bars and one of 200 bars

Since the stress drop parameter controls the motion frequency content quite enough and the initial simulation set was made by its variation, the four simulation set contains motions near the source with the stress drop values of 75 bars and 200 bars.

Conclusions:

1. It can be noticed that for a lower value of stress drop Source 12 manages to capture quite well the 2004's earthquake spectra.
2. Two frequency corner sources are more influenced by stress drop change.
3. Sources S1 and S12 show an increase in the duration of sources with the decrease of stress drop (from 1.37 s to 1.91 s for S1 and from 1.78 to 1.94 s for S12). For source S11 the source duration remains almost constant.
4. Decreasing the stress drop also causes a decrease in corner periods.
5. The stress drop parameter controls the frequency spectrum of the source spectrum, the use of the 75 bars value makes the peak of the spectral amplitude to be lower (closer to reality).

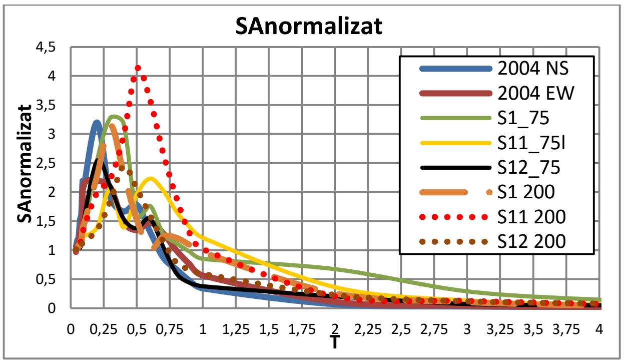

Figure 8. Comparison of the normalized response spectra of simulated sources motion with stress drops of 75 bars and 200 bars and the earthquake spectra of 27 October 2004

F. Final set of SMSIM simulations

In SMSIM, the accelerogram shape is controlled by a box or exponential filter. It greatly influences the effective duration and the average square root. In this set of simulations, it was used an exponential window from Boore's paper [11], in which $\eta = 0.01$, $\eta = 0.1$, $f_{tb=} = 2.0$, $f_{text} = 7.0$. The scatter remained at 0.4, the path duration was taken 0.09 and the stress drop 75 bar.

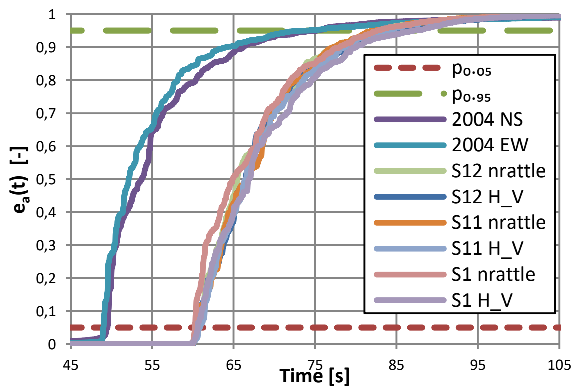

Figure 9. Comparison between the simulated cumulative energies of the final version and those of the earthquake of 27 October 2004

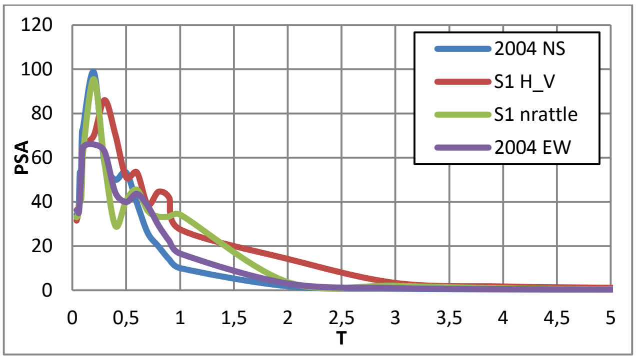

Figure 10. Comparison of the response spectra of the Vrancea earthquake of 27 October 2004 and the response spectra of the final simulations for the S1 source

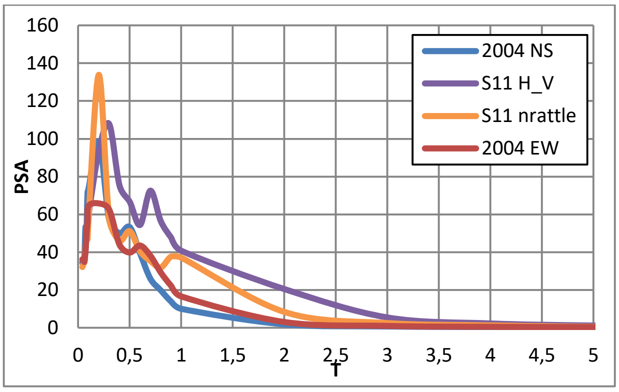

Figure 11. Comparison of the response spectra of the Vrancea earthquake of 27 October 2004 and the response spectra of the final simulations for the S11 source

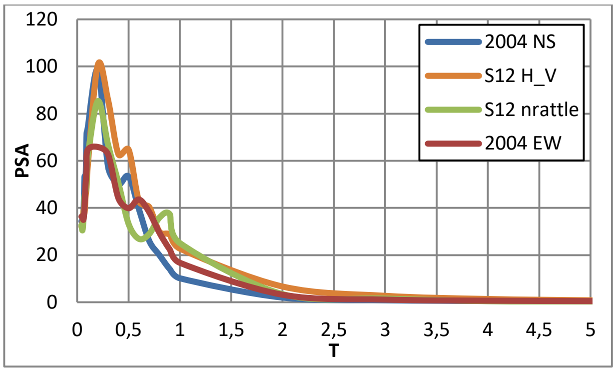

Figure 12. Comparison of the response spectra of the Vrancea earthquake of 27 October 2004 and the response spectra of the final simulations for the S12 source

Conclusions:

1. From the point of view of released energy, all sources have a power approximately 2 times greater than the normal earthquake.

2. The actual time of the simulations is also higher than the real one.

3. The amplification of the H/V profile for sources S1 and S11 increases the period at which the first spectral acceleration peak is found.

4. For sources S1 and S11, there is an increase greater than the real one for long periods.

5. From the point of view of the average of the peak accelerations on the 400 simulations, an oversize of movement can be observed, which may be due to the energy release difference given by the chosen filter, or due to the chosen geometric spraying.

TABLE III. CHARACTERISTICS OF SIMULATED GROUND MOTION OF 27 OCTOBER 2004 FOR A 75 BAR STRESS DROP, GEOMETRIC SPREADING OF 0.4 AND PATH TIME 0.09

Type of simulation using SMSIM	Average PGA	PGA of the analyzed simulation	f_a (Hz)	f_b (Hz)	Effective duration	Average square root
S1 H_V	39.68	29.82	0.52	0.52	22.88	7.92
S1 nrattle	33.13	30.86	0.52	0.52	22.4	7.08
S11 H_V	42.73	33.56	0.33	0.82	23.97	9.40
S11 nrattle	34.8	29.62	0.33	0.82	21.95	7.99
S12 H_V	36.41	31.08	0.33	1.15	25.04	7.39
S12 nrattle	31.23	29.39	0.33	1.15	22.11	6.78

6. In theory, a smaller earthquake has a larger geometric spreading, but the scatter modification for the last simulations was chosen without a research.

7. Using a more suitable filter and scaling modification based on more detailed research would most likely lead to a better fit of the simulation

VI. GROUND MOTION SIMULATION USING EXSIM

In EXSIM were made two types of simulations for each profile of local site amplification. In one type of simulation was used the static subfaults and in the other pulsing subfaults, the last eliminates the dependence of ground motion simulations on the subfaults number.

TABLE IV. CHARACTERISTICS OF EXSIM SIMULATED GROUND MOTIONS OF 27 OCTOBER 2004

Type of simulation using EXSIM	PGA	Effective duration	Average square root
2004 NS	29.82	21.39	3.84
2004 EW	30.86	20.92	3.41
EXSIM static nrattle	33.109	11.67	8.10
EXSIM static H/V	35.869	11.11	10.15
EXSIM pulse 50% nrattle	27.830	11.35	6.99
EXSIM pulse 50% H/V	25.539	12.23	7.87

1. From the point of view of released energy, using static subfaults leads to a power approximately 3 times greater than the real earthquake while the pulsing subfaults lead to a power approximately 2 times greater and the amplification of the H/V profile simulates a greater release of energy then NRATTLE profile.

2. The effective time of the simulations is almost 2 times smaller than the real one.

3. From the point of view of amplification given by local site conditions, one can notice that in both cases that H/V profile amplifies the motion around 0.6-0.7 s.

4. The pulsing subfaults type of simulation underestimates the motion from the point of view of peak ground acceleration with 2-5 cm/s^2, while the static type overestimates it with 3-6 cm/s^2.

5. Seismic energy is released faster and more abruptly through simulated ground motions than real accelerograms.

6. For all types of simulations there is a considerable spectral amplification at a period of 1 s.

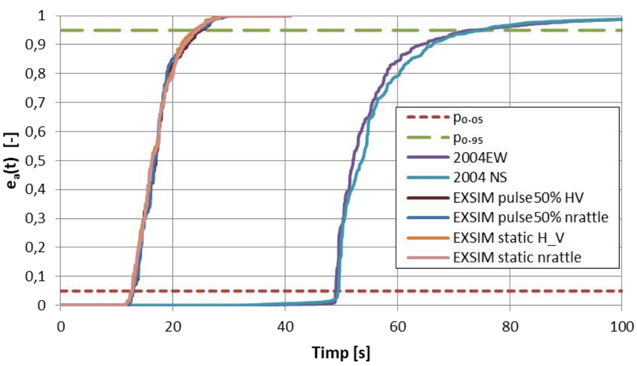

Figure 13. Comparison between the simulated cumulative energies of the EXSIM version and those of the earthquake of 27 October 2004

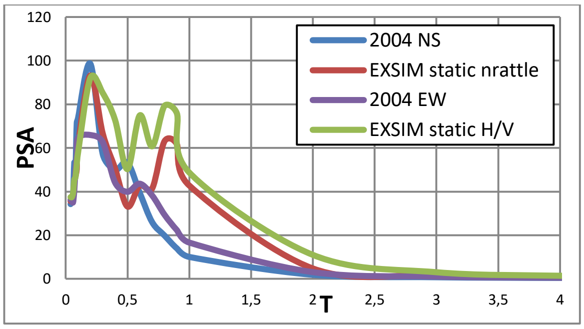

Figure 14. Comparison of the response spectra of the Vrancea earthquake of 27 October 2004 and the response spectra of the EXSIM simulations for the S12 source

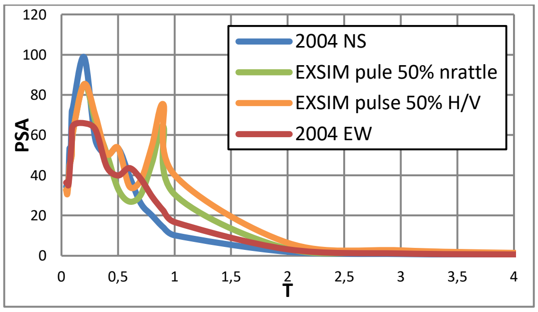

Figure 15. Comparison of the response spectra of the Vrancea earthquake of 27 October 2004 and the response spectra of the final simulations for the S12 source

VII. Conclusion

The stochastic simulations using SMSIM estimate properly the spectral shape and peak ground acceleration of the real earthquake which is a medium one, but from the point of view of the energy release the simulated motion is practically 2 times bigger. EXSIM simulations amplify the movement at a period of 1 s, but it estimates it good for small periods, the energy release is also 2-3 times greater in simulated motion. For medium intermediate-depth Vrancea earthquakes, SMSIM and EXSIM simulations give a good estimation of the motion for small periods and SMSIM for long periods too, as for the energy release both overestimate the movement.

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