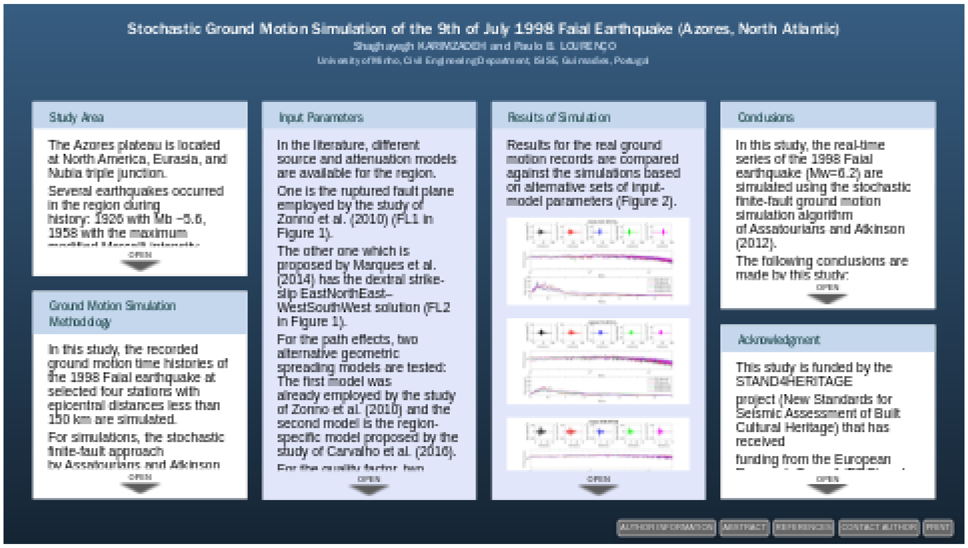
Stochastic Ground Motion Simulation of the 9th of July 1998 Faial Earthquake (Azores, North Atlantic)



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PRESENTED AT:

STUDY AREA

The Azores plateau is located at North America, Eurasia, and Nubia triple junction.

Several earthquakes occurred in the region during history: 1926 with Mb ~5.6, 1958 with the maximum modified Mercalli intensity (MMImax) of X, and 1998 with a moment magnitude (Mw) of 6.2.

The 1998 Faial earthquake occurred between the islands of Faial and Pico in the Azores plateau.

The earthquake caused severe structural damage in Faial and Pico with the MMImax of VIII (Matias et al., 2007).

The earthquake was recorded at five strong ground motion stations (Figure 1).

Table 1 lists detailed information on the stations.

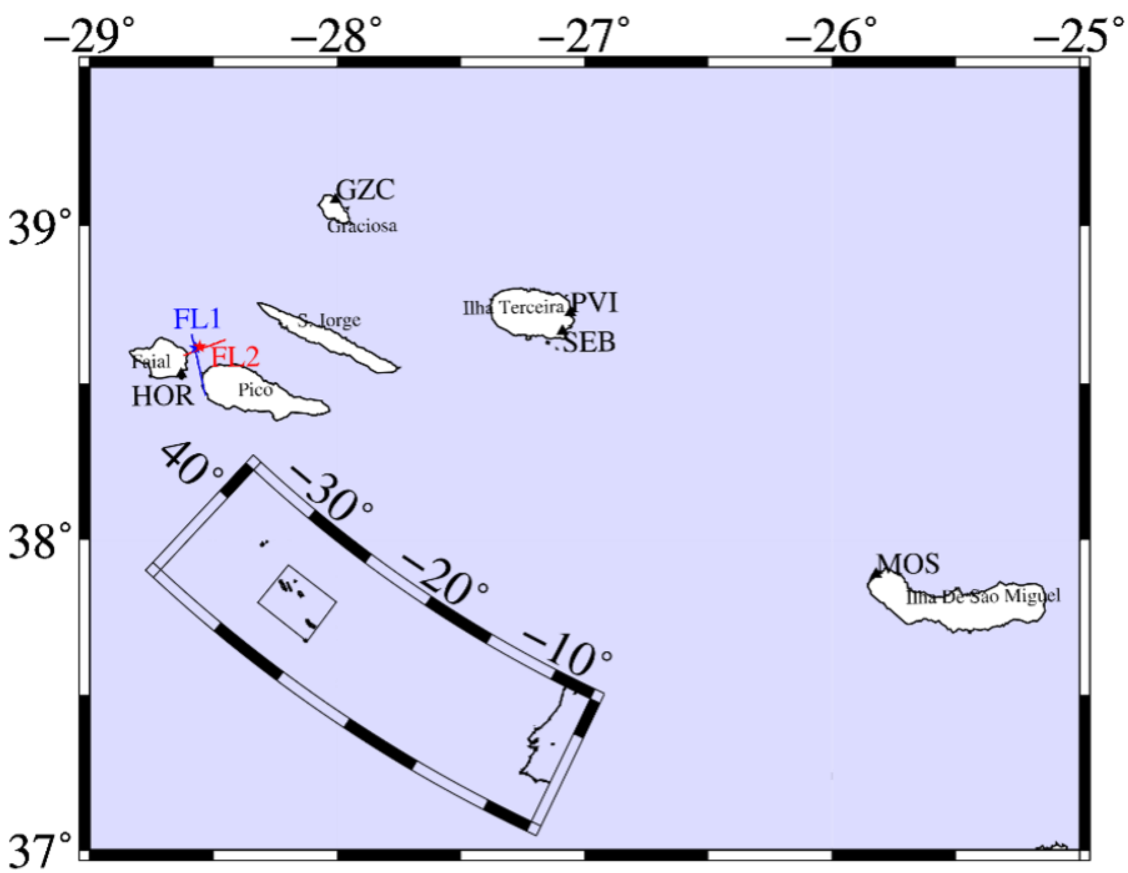


Figure 1. Study area with the two alternative potential faults (FL1 and FL2) and their corresponding epicenters as shown by stars

Table 1. Information of the stations that recorded the 1998 Faial earthquake (Mw=6.2)

Station Code	R_{epi}	Latitude	Longitude	PGA-EW (cm/s^2)	PGA-NS (cm/s^2)	PGV-EW (cm/s)	PGV-NS (cm/s)
GZC	72	39.084	-28.006	17.76	14.62	0.91	1.02
PVI	132	38.726	-27.057	8.32	10.06	0.76	0.73
HOR	11	38.53	-28.63	418.10	399.16	31.94	37.39
MOS	254	37.892	-25.822	4.08	5.10	0.15	0.19
SEB	129	38.668	-27.088	17.17	21.73	1.40	1.98

- Among these stations, the highest shaking level was recorded at the near-field station, HOR, with an epicentral distance of 11 km.
- At the other far-field stations, lower shaking levels were observed.

GROUND MOTION SIMULATION METHODOLOGY

In this study, the recorded ground motion time histories of the 1998 Faial earthquake at selected four stations with epicentral distances less than 150 km are simulated.

For simulations, the stochastic finite-fault approach by Assatourians and Atkinson (2012) is employed.

In this method, the fault plane is considered as the grid of smaller sub-sources.

Each sub-source is considered as a point source with an ω^{-2} source spectrum (Boore,1983; 2003).

Each sub-source ruptures with an appropriate time delay depending on the distance of the sub-source from the hypocenter.

The contribution of sub-sources is summed in the time domain as follows:

$$A(t) = \sum_{i=1}^{N} H_i Y_i(t + \Delta t_i + T_i) \quad (1)$$

where A(t) is the total seismic signal at time t, N is the total number of sub-sources, *Y* is the seismic signal of i^{th} sub-source as the inverse Fourier transform of the i^{th} sub-source spectrum (Boore, 2003; 2009), Δt_i is the sum of fracture initiation and time delay due to the distance of the i^{th} sub-source from the hypocenter, T_i is the fraction of the rise time considered for additional randomization, and H_i is the normalization factor of the i^{th} sub-source introduced for conservation of energy.

Hi is calculated as follows:

$$H_i = M_0 / M_{0i} \sqrt{\sum_j [f_0^2 f_j^2/(f_0^2 + f_j^2)]^2 / N \sum_j [f_{0i}^2 f_j^2/(f_{0i}^2 + f_j^2)]^2} \quad (2)$$

where f_0 is the corner frequency of the entire fault plane, f_j is the j^{th} frequency ordinate, M_0 is the total seismic moment, and M_{0i} and f_{0i} are, respectively, the seismic moment and corner frequency of the i^{th} sub-source as follows:

$$M_{0i} = (M_0 \times s_i)/(\sum_{i=1}^{N} s_i) \quad (3)$$

$$f_{0i} = 4.9 \times 10^6 \beta_s (\Delta\sigma/(p \times M_0)^{1/3} \quad (4)$$

where,

$$p = \begin{cases} N_R/N & \text{if} \quad N_R < N \times PP \\ PP & \text{if} \quad N_R \geq N \times PP \end{cases} \tag{5}$$

In equation (3), s_i represents the slip of the i^{th} sub-source. In equation (4), N_R represents the total number of sub-sources that is activated when the i^{th} sub-source triggers and $\Delta\sigma$ is the stress drop in bars. The term PP is the pulsing percentage.

INPUT PARAMETERS

In the literature, different source and attenuation models are available for the region.

One is the ruptured fault plane employed by the study of Zonno et al. (2010) (FL1 in Figure 1).

The other one which is proposed by Marques et al. (2014) has the dextral strike-slip EastNorthEast–WestSouthWest solution (FL2 in Figure 1).

For the path effects, two alternative geometric spreading models are tested: The first model was already employed by the study of Zonno et al. (2010) and the second model is the region-specific model proposed by the study of Carvalho et al. (2016).

For the quality factor, two different models are tested: The model employed by Zonno et al. (2010) and the region-specific model of Carvalho et al. (2016).

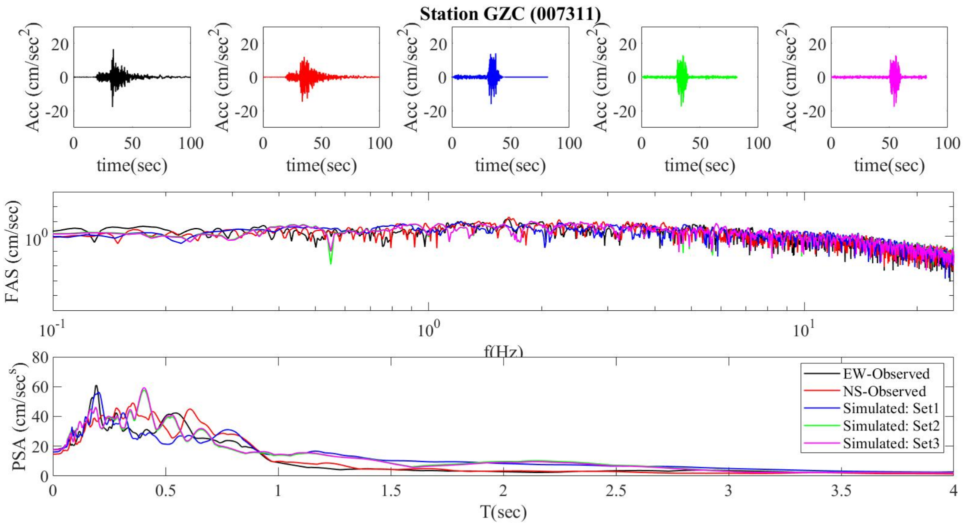
As a result of testing different models in the simulations, three sets of the input-model parameters are verified: Set 1, Set 2, and Set 3 (Table 2).

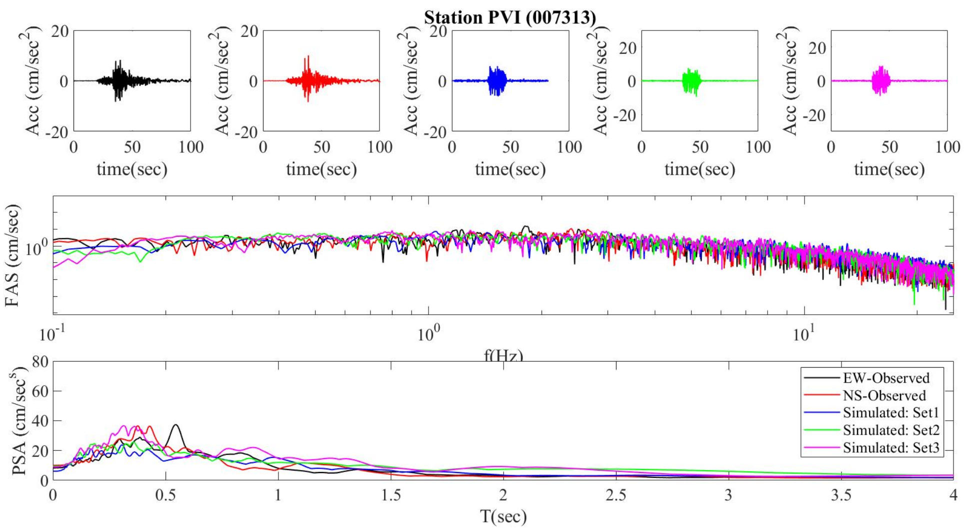
Table 2. Information on the verified input-model parameters

Parameter	Set 1	Set 2	Set 3
Fault Type	right-lateral SS (FL1)	right-lateral SS (Marques et al., 2014)	right-lateral SS (Marques et al., 2014)
Mw	6.2 (Zonno et al., 2010)	6.2 (Marques et al., 2014)	6.2 (Marques et al., 2014)
Fault Length (km)	16.5 (Zonno et al., 2010)	12 (Marques et al., 2014)	12 (Marques et al., 2014)
Fault Width (km)	9.4 (Zonno et al., 2010)	5.5 (Marques et al., 2014)	5.5 (Marques et al., 2014)
Strike	165° (Zonno et al., 2010)	84° (Marques et al., 2014)	84° (Marques et al., 2014)
Dip	85° (Zonno et al., 2010)	83° (Marques et al., 2014)	83° (Marques et al., 2014)
Epicenter	38.640 N, -28.590W (Zonno et al., 2010)	38.618N, -28.555W (Marques et al., 2014)	38.618N, -28.555W (Marques et al., 2014)
Depth of Fault (km)	4 to 6 (Dias et al., 2007)	6 (Marques et al., 2014)	6 (Marques et al., 2014)
Depth to top of Fault (km)	1.1 (Dias et al., 2007; Matias et al., 2007)	5 (Marques et al., 2014)	5 (Marques et al., 2014)
Geometric Spreading	$R < 30$ R^{-1} $else$ $R^{-0.5}$ (Zonno et al., 2010)	$R < 18$ R^{-1} $18 < R < 30$ R^{0} $R > 30$ $R^{-0.5}$ (Carvalho et al., 2016)	$R < 18$ R^{-1} $18 < R < 30$ R^{0} $R > 30$ $R^{-0.5}$ (Carvalho et al., 2016)
Duration model	T0+0.1R (Zonno et al., 2010)	T0+0.1R (Zonno et al., 2010)	T0+0.1R (Zonno et al., 2010)
Quality Factor	$Q(f) = 239f^{1.06}$ (Olafsson et al. 1998; Carvalho et al., 2008)	$Q(f) = 76 \pm 11f^{0.69\pm0.09}$ (Carvalho et al., 2016)	$Q(f) = 76 \pm 11f^{0.69\pm0.09}$ (Carvalho et al., 2016)
Pulsing Percent	50 (Zonno et al., 2010)	50 (Zonno et al., 2010)	50 (Zonno et al., 2010)
Window Type	Boxcar	Saragoni	Saragoni
Shear Wave Velocity (km/s)	3.5 (Zonno et al., 2010)	4.2 (Carvalho et al., 2016)	4.2 (Carvalho et al., 2016)
Rupture velocity	2.8 (Zonno et al., 2010)	3.57 (Carvalho et al., 2016)	3.57 (Carvalho et al., 2016)
Density(g/cm3)	2.8 (Carmichael, 1980)	2.86 (Carvalho et al., 2016)	2.86 (Carvalho et al., 2016)
Damping	5%	5%	5%
Hypo Loc.	8.25, 4.7	5.0, 1.0	5.0, 1.0
Slip Weigth	Random	Random	Random
Stress Drop (bars)	50 (Mohammadioun and Serva, 2001)	90 (Carvalho et al., 2016)	90 (Carvalho et al., 2016)
Iseed	309	309	309
Crustal Amplifications	Joyner and Boore (1997)	Joyner and Boore (1997)	Assatourians and Atkinson (2012)
Soil Amplifications	Joyner and Boore (1997)	Joyner and Boore (1997)	Joyner and Boore (1997)
Kappa	0.075±0.02 (Carvalho et al., 2016)	0.075±0.02 (Carvalho et al., 2016)	0.075±0.02 (Carvalho et al., 2016)

RESULTS OF SIMULATION

Results for the real ground motion records are compared against the simulations based on alternative sets of input-model parameters (Figure 2).





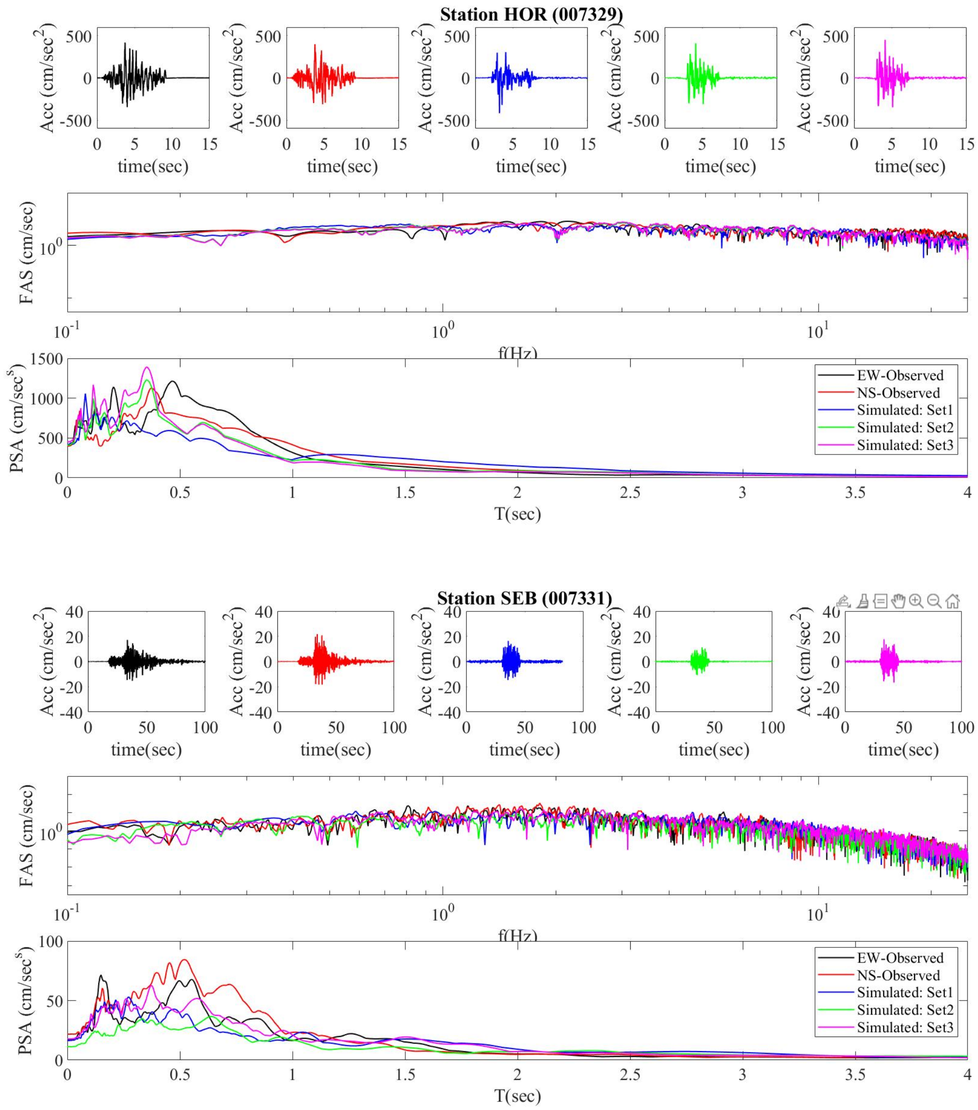


Figure 2. Real and simulated full-time series, FAS, RS at the stations

Results reveal that all three sets of simulated ground motion records are in good agreement with the real records in the entire time, frequency, and period domains.

Next, for validation of the simulations, the goodness of fit (GOF) scores are evaluated using the following formula (Olsen and Meyhew, 2010):

$$GOF = 100 * erfc[NR], where,$$

$$NR = 2|R_{simulated} - R_{real}|/(R_{simulated} + R_{real}) \quad (6)$$

The results for the GOF scores are listed in Table 3.

Table 3. GOF scores between the real and simulated records

Station	Set 1		Set 2		Set 3	
	GOF	Fit Type	GOF	Fit Type	GOF	Fit Type
GZC	65	Very Good Fit	65	Very Good Fit	65	Very Good Fit
PVI	73	Very Good Fit	70	Very Good Fit	65	Very Good Fit
HOR	74	Very Good Fit	73	Very Good Fit	74	Very Good Fit
SEB	72	Very Good Fit	53	Fair Fit	75	Very Good Fit

The statistical results mostly demonstrate the validity of simulations in the category of very good fits compared to the real records from different seismological aspects.

CONCLUSIONS

In this study, the real-time series of the 1998 Faial earthquake (Mw=6.2) are simulated using the stochastic finite-fault ground motion simulation algorithm of Assatourians and Atkinson (2012).

The following conclusions are made by this study:

- Comparison of the real and simulated records in the time and frequency domains reveals that the simulations are generally in agreement with the real-time histories.
- Evaluation of the GOF scores in terms of frequency, energy, and amplitude content of records reveals that the three sets of simulated ground motion records are seismologically acceptable fits when compared to the real-time series.
- When the GOF scores are considered, most of the fits are categorized as very good fit (65≤GOF≤85).
- Finally, the verified input-model parameters can be utilized and calibrated for simulating region-specific scenario earthquakes in future studies.

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ABSTRACT

Earthquakes are among the most destructive natural disasters, resulting in a huge number of fatalities and economic losses all over the world. For regions with limited number of seismic networks or for regions where there is a seismic gap to produce large magnitude and destructive earthquakes, ground motion simulation approaches provide alternative region-specific time histories for potential events. Region-specific simulations require modeling and calibration of input parameters in terms of source, path and site effects. Verification of these parameters is a challenging task and can be accomplished through comparing the real time histories of the past events against the simulated data. In this study, the recorded time histories of the 9th of July 1998 Faial earthquake (Mw=6.2) at available stations are simulated with the stochastic finite-fault ground motion simulation approach based on a dynamic corner frequency concept. For ground motion simulations, alternative region-specific source, path and site models are employed and tested. The best model is proposed through goodness of fit score which is evaluated through the complementary error function in terms of various seismological parameters between the real and simulated record sets. These seismological parameters include peak ground acceleration peak ground velocity, the ratio of peak ground velocity to peak ground acceleration, Arias intensity, cumulative absolute velocity, acceleration spectrum intensity, modified acceleration spectrum intensity for the period range of 0.1 to 2.5 seconds, velocity spectrum intensity, Housner intensity, significant duration, bracketed duration, Fourier amplitude spectra within the frequency range of 0.1 to 25 Hz and pseudo response spectra within the period range of 0 to 4 seconds. The simulation results demonstrate that for the event of interest the input parameters are verified, and the fits between the real and simulated time histories are satisfactory.

Keywords: The 1998 Faial Earthquake, Azores- North Atlantic, Stochastic finite-fault Ground Motion Simulation method, Goodness of Fit Score

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