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HYPSTHER PROJECT: HYBRID GROUND MOTION PREDICTION EQUATIONS FOR PSHA PURPOSES

G. Lanzano[(1)], M. D'Amico[(2)], R. Puglia[(3)], M. Santulin[(4)], C. Felicetta[(5)], A.A. Gomez-Capera[(6)], E. Russo[(7)], M.M. Tiberti[(8)], G. Tusa[(9)], A. Scaltrito[(10)]

[(1)] *Research Fellow, Istituto Nazionale di Geofisica e Vulcanologia, giovanni.lanzano@ingv.it*
[(2)] *Research Fellow, Istituto Nazionale di Geofisica e Vulcanologia, maria.damico@ingv.it*
[(3)] *Technologist, Istituto Nazionale di Geofisica e Vulcanologia, rodolfo.puglia@ingv.it*
[(4)] *Researcher, Istituto Nazionale di Geofisica e Vulcanologia, marco.santulin@ingv.it*
[(5)] *Research Fellow, Istituto Nazionale di Geofisica e Vulcanologia, chiara.felicetta@ingv.it*
[(6)] *Researcher, Istituto Nazionale di Geofisica e Vulcanologia, antonio.gomez@ingv.it*
[(7)] *Research Fellow, Istituto Nazionale di Geofisica e Vulcanologia, emiliano.russo@ingv.it*
[(8)] *Researcher, Istituto Nazionale di Geofisica e Vulcanologia, mara.tiberti@ingv.it*
[(9)] *Researcher Fellow , Istituto Nazionale di Geofisica e Vulcanologia, giuseppina.tusa@ingv.it*
[(10)] *Technologist, Istituto Nazionale di Geofisica e Vulcanologia, antonio.scaltrito@ingv.it*

Abstract

In the last decades, the calibration of reliable GMPEs became a critical issue in Probabilistic Seismic Hazard Assessment (PSHA). NGA-East project provides a set of new GMPEs for median and standard deviation of Ground Motions (GMs) and their associated weights in the logic trees for use in PSHA for Central and Eastern North-American Region. These results include the use of synthetic data to fill the lacking of observations, especially for moderate to large earthquakes in near field conditions.

On the European side, some efforts have been made within the NERA EU Project for the calibration of physics-based GMPEs, which are particularly effective in showing important ground motion features in near source regions. Indeed, when the site is very close to the fault, the rupture processes are predominant and the finite-source effects, such as directivity, hanging wall/foot wall, radiation-pattern and slip distribution can dominate the GMs. Therefore, the empirical GMPEs are generally incapable to capture such features, because the strong motion recorded data in near source are few.

This paper explains the aims of HYPSTHER (HYbrid ground motion prediction equations for PSha purposes: the study case of souTHERn Italy) project, devoted to develop a methodological approach to retrieve ground motion prediction models, based on the integration between recorded and synthetic data. The motivation of this research is to supply the lack of instrumental observations for moderate to large earthquakes in near fault conditions.

In this framework, we will test this methodology for the study case of Southern Italy, focusing our attention on Calabria and Sicily regions. The target area has been chosen based on the expected high hazard level, despite the seismic activity has been scarce in the last decades. In addition, along the Sicily coast many critical infrastructures are present, such as chemical plants and large ports, which strongly increase the risk of technological accidents induced by natural hazards.

The results of the HYPSTHER project will be a set of Ground Motion Prediction Equations (GMPEs) for PGA, PGV and SA in the period range T=0.04-4s. Additional results include recorded and synthetic ground motion datasets. The project products can be tested and incorporated in a next generation of the Italian Seismic Hazard Maps.

Keywords: Hybrid GMPEs, Earthquake simulation, PSHA, Southern Italy

1. Introduction

The scope of the project (http://hypsther.mi.ingv.it) is the calibration of hybrid GMPEs for Southern Italy (Calabria and Sicily), based on the integration of recorded ground motion parameters with synthetic data. The motivation of this research is to supply the lack of instrumental observations for moderate to large earthquakes in near fault conditions. This is particularly relevant for target areas where the hazard level is high according to MPS04 (Italy's official seismic hazard map [1]) and the seismic activity has been low in the last decades (http://bollettinosismico.rm.ingv.it; CPTI11) [2]. The impact of these new GMPEs will be a more reliable assessment of the seismic hazard.

The work is divided in four working tasks: i) empirical flatfile generation; ii) ground motion simulation; iii) GMPEs calibration; iv) hazard assessment. The project started in July 2015 and is still on going; the total duration is 18 months (end of the project December 2016).

2. State of the art

In the last decades, the calibration of reliable GMPEs became a critical issue in Probabilistic Seismic Hazard Assessment (PSHA). For example, in the United States, two large research projects (NGA-West and NGA-East) were developed in order to provide ground motion characterization (GMC) models for different areas. In particular, NGA-East project [3] provides a set of new GMPEs for median and standard deviation of Ground Motions (GMs) and their associated weights in the logic trees for use in PSHA for Central and Eastern North-American Region. Differently from NGA-West project, where the GMPEs are retrieved only on empirical basis, NGA-East research products include the use of synthetic data to fill the lack of observations, especially for moderate to large earthquakes in near field conditions.

On the European side, in the framework of the SeIsmic Ground Motion Assessment (SIGMA; project-sigma.com) project, five GMPEs [4] were derived based on record chosen from a common strong-motion database of European and Middle-Eastern waveforms (RESORCE) [5]. Strong effort was done in order to obtain a representative dataset. Nevertheless, in areas where few significant earthquakes occurred in the recent years, although characterized by high hazard level, the integration between empirical and synthetic ground motion parameters is recommendable.

In this regard, some efforts were done in the calibration of physics-based GMPEs, which are particularly effective in showing important ground motion features in near source regions (NERA EU Project) [6, 7]. Indeed, when the site is very close to the fault, the rupture processes are predominant and the finite-source effects, such as directivity, hanging wall/foot wall, radiation-pattern and slip distribution dominate the GMCs. Therefore, the empirical GMPEs are generally incapable to captures such features, because the strong motion recorded data in near source are few.

In last years in Italy, many efforts have been made in order to develop an Italian accelerometric database (ITACA, itaca.mi.ingv.it/) [8], which also contains waveforms of seismic events of moderate to large magnitude (e.g. Friuli 1976-1977, Irpinia 1980), sometimes with a dense spatial covering in near fault conditions (e.g. L'Aquila 2009, Emilia 2012).

On the basis of the abovementioned dataset, well-established tools for the ground motion prediction has been derived [9]. Moreover, for the purpose of hazard assessment, the variability at single site was investigated [10, 11, 12], in order to reduce the standard deviation of the ground motion model.

Recently, GMPEs for specific areas of the Italian territory, as the Northern Italy, were proposed [13, 14]. In the framework of the ENEL project aimed at the seismic design of a critical infrastructure in Porto Empedocle (AG), the ground motion response in Sicily was also investigated [15].

Finally, in the framework of the MASSIMO project [16, 17], in order to provide synthetic ground-motion models for earthquakes in magnitude range and distance for which the finite-fault effects are predominant, numerical simulations by deterministic-stochastic method (DSM) [18] has been performed at selected target sites (Cosenza, Vibo Valentia and Reggio di Calabria). The analysis of the synthetic ground motion variability for the implementation of hybrid GMPEs can be integrated into PSHA procedures, as it allows to evaluate the probability of exceedance through the statistical analysis of a huge number of possible rupture scenario occurring on specific composite faults [19].

3. Methods and procedures

In the following sections, each task is described in detail.

3.1 Task 1 (WG-T1): *Empirical flatfile generation*

The main issue of the first task is the compilation of a qualified database of recorded waveforms: it will be mainly based on the Engineering Strong Motion Database (esm.mi.ingv.it) and ITACA (ITalian ACcelerometric Archive, itaca.mi.ingv.it/) [8, 20]. The accelerometric dataset will be integrated by velocimetric data, because the strong motion data are lacking and the velocimetric networks managed by INGV or other institutions are denser. Data collection includes the reviewing and processing of earthquake recordings [21] from stations on various site conditions (rock and soil) and the compilation of available metadata into a flatfile (magnitude, distance, site conditions, etc.). The metadata will be updated and completed as much as possible, in order to implement more complex functional forms for GMPEs testing and calibration.

3.2 Task 2 (WG-T2): *Ground motion simulation*

The prerogative of the WG-T2 will be to perform deterministic shaking scenarios at selected sites in order to produce a flatfile of synthetic ground motion parameters and related metadata. The main use of the numerical simulations of the ground motion is to constrain the behavior for large seismic events in near source, not represented in the database. The WG-T2 is responsible for selecting the proper methods for the numerical simulation of the ground motion [18, 22, 23] and for developing the validation requirements [24]. In this framework, we will also use fault geometry not included in the seismogenic fault database DISS3.2.0 [25]. This procedure implies the validation of empirical relationships between GMPs and macroseismic intensity.

The WG-T2 is also responsible to:

1) Define the inputs for finite-fault simulations
2) Select models for the kinematic inputs (nucleation points, rupture velocity, slip distribution)
3) Associate the more appropriate path parameters (Q, geometrical spreading).
4) Select representative 1D crustal velocity structure.

3.3 Task 3 (WG-T3): *GMPEs calibration*

The WG-T3 will develop a set of median GMPEs for Southern Italy, using the results of Tasks 1 and 2. In particular, three models will be retrieved:

i) Empirical GMPEs based on the flatfile of recorded waveforms developed in Task 1;
ii) Synthetic GMPEs based on the flatfile of simulated waveforms developed in Task 2;
iii) Hybrid GMPEs based on the flatfile integrating the recorded and simulated data;

The results of the GMPEs calibration will be compared among them and with other significant existing GMPEs. The goodness of fitting will be evaluated on the basis of the total residuals, calculated as the difference between observations and predictions. The standard deviation (σ) of the total residuals of GMPEs has a strong influence on the results of PSHA. The standard deviation values will be decomposed in the within-event and the between-event components in order to make a comparison between empirical and synthetic data. These values will be finally compared to those calculated for other regions in the world [10, 26, 27].

3.4 Task 4 (WG-T4): *Hazard assessment*

The WG-T4 will combine all the products from other tasks aiming at a series of sensitivity studies on model and/or parameters to evaluate their impact on the seismic hazard assessment. The presence of critical infrastructures will guide the choice of some significant test sites in Southern Italy as, for instance, Milazzo (ME), Priolo Gargallo (SR), Gioia Tauro (RC).

The final step will be to evaluate the impact of the use of the hybrid GMPEs in the assessment of the seismic hazard.

4. First results

4.1 Empirical flatfile

In this section, we briefly describe the results of the first task, with reference to the flatfile preparation [28].

The selection criteria are:

a) Waveforms recorded by accelerometric and velocimetric instruments;

b) Events and stations included in the following geographic range: latitude = 34°- 40° N; longitude = 10°-18° E (corresponding to Southern Calabria and Sicily);

c) Moment magnitude $M_W \geq 3.5$; in case of missing value for M_W, the local magnitude with $M_L \geq 3.5$ is considered without conversion;

d) Epicentral distance $R_{epi} \leq 200$ km.

The bulk of data come from accelerometric records of the network RAN (code IT, doi:10.7914/SN/IT), managed by Italian Department of Civil Protection, and from recording network managed by INGV (code IV, doi:10.13127/SD/X0FXnH7QfY). Minor amount of data (less than 10%) is relative to the networks MN (MEDNET Project, doi:10.13127/SD/fBBBtDtd6q), managed by INGV and YD (Calabria Appennine Tyrrhenian/Subduction Collision Accretion Network, doi:10.7914/SN/YD_2003) operating in the time interval 2003-2006.

The accelerometric records have been integrated by velocimetric waveforms by networks managed by INGV or other institutions, which are usually denser than accelerometric ones. The final dataset consists of about 3200 three-component waveforms (Figure 1, left panel), whose ~1200 accelerometric and ~2000 velocimetric, recorded by ~230 stations mainly belong to IT and IV networks (Figure 1, right panel).

All the waveforms have been manually processed using the web interface of the ESM database available at http://esm.mi.ingv.it/processing/ [29].

Event metadata have been revised. In particular, the ISIDe catalog (http://iside.rm.ingv.it) has been used to update locations and magnitudes (M_W and M_L) as well as moment tensor solutions (strike, dip and rake) and information on the geometries of the seismic source. The dataset is well sampled in terms of recordings for each bin of distances (Figure 2, left panel), but not satisfactory in terms of magnitudes: more than the 90% of the recordings belongs to the magnitude range 3.5 to 5 (Figure 2, right panel).

The areal distribution of the events is denser in the Tyrrhenian Sea and in the oriental part of Sicily region, with a cluster of low magnitude events in proximity of Mt. Etna (Figure 3, left panel). Tyrrhenian Sea events are generally characterized by deep hypocenters (Figure 3, right panel).

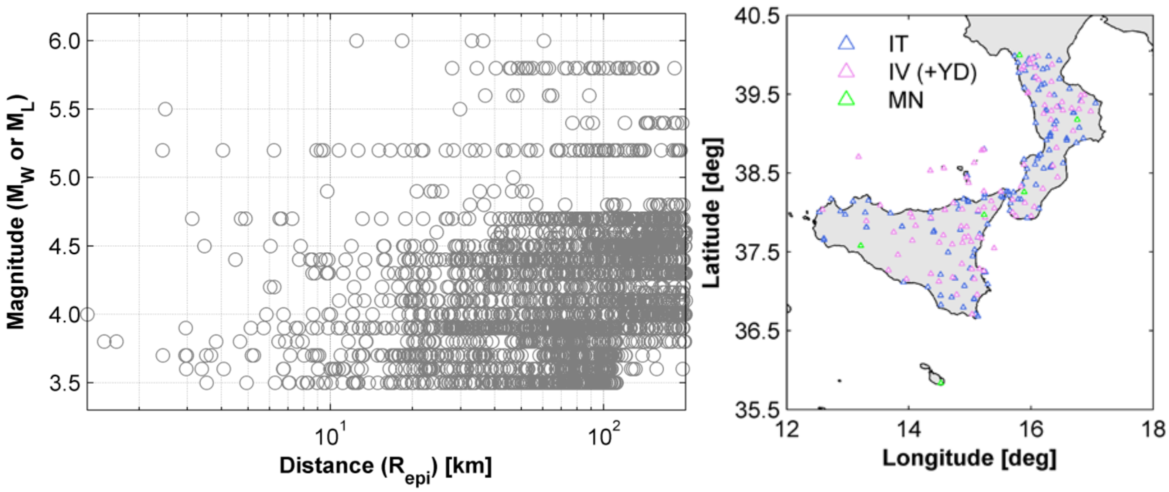

Fig. 1 – Left panel: magnitude-distance distribution of the three components waveforms included in the data-set. Right panel: map of the recording stations (~230).

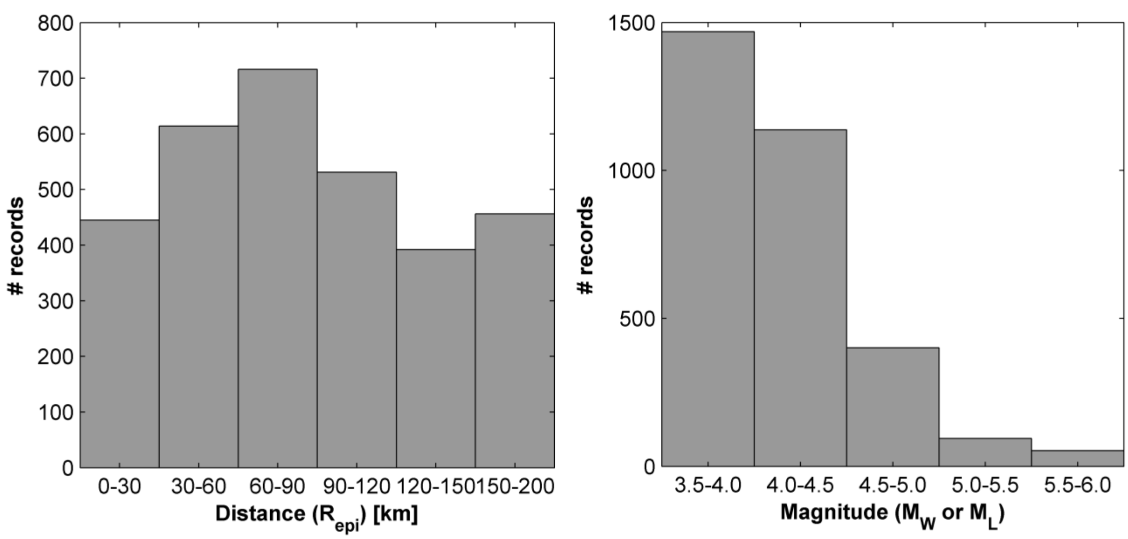

Fig. 2 – Left panel: number of records vs epicentral distance. Right panel: number of records vs magnitude ranges (M_W or M_L).

The left panel of Figure 4 shows focal mechanisms distribution. The prevalent style of faulting within the dataset is normal (NF, ~30%), however a significant number of records are associated to undefined mechanism (UN, ~30%) since information on the geometries of the seismic source are not available for such low-magnitude events.

Station metadata has been revised, by classifying the sites according to EC8 [30]. The right panel of Figure 4 shows the site classification associated to each record. Site classes marked by '*' indicate that no $V_{S,30}$ is available at the site. Therefore, the site class is attributed on the basis of geological information [31].

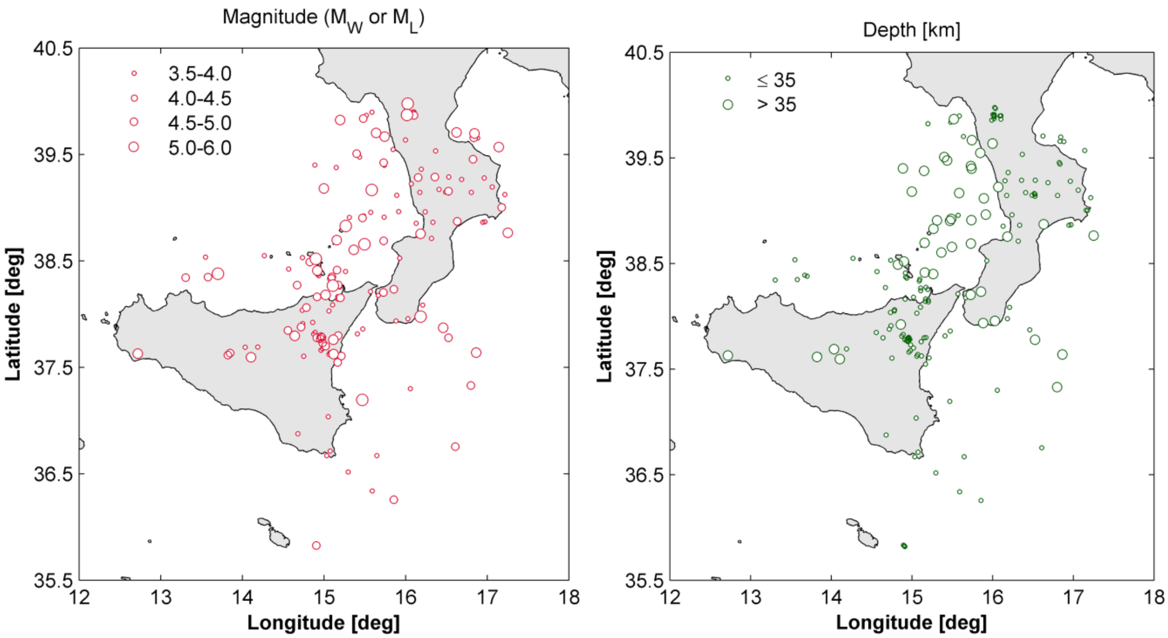

Fig. 3 – Left panel: map of epicenter locations grouped by magnitude ranges. Right panel: map of epicenter locations grouped by hypocentral depth.

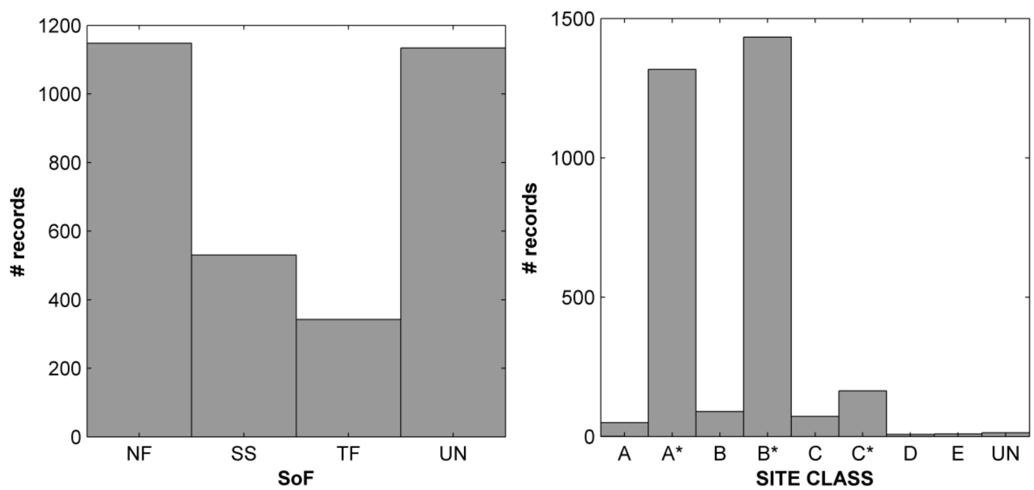

Fig. 4 – Left panel: number of records grouped by focal mechanisms (NF: normal fault; SS: strike-slip fault; TF: thrust fault; UN: undefined mechanism). Right panel: distribution of soil categories.

4.2 Ground motion simulation

To fill the gaps in the empirical flat-file, we have assembled a complementary dataset by using synthetic ground motion data. To this end, we performed a number of region-specific shaking scenarios at the bedrock (period range 0.04-4s) varying: i) magnitude of the simulated events; ii) location and kinematic parameters of individual ruptures; iii) stress parameter; iv) dip of the simulated fault; v) style of faulting.

We simulate the ground motion by means of two different simulation methods as follows:

1. Extended fault SIMulation (EXSIM) [32-34] to model a set of Generic Sources (GSs) embedded into the crust structure beneath southern Italy. GSs are not defined by geophysical or geological data. They were constructed for several moment magnitudes (from 5.0 to 7.0 with a step of 0.5), top fault depths, fault mechanisms, and dip angles. In this case we did not use equally spaced simulation grids. The geometry

of the simulation sites varies in function of moment magnitude and dip, so that the location of the phantom receivers is denser over and in proximity of the Earth's surface projection of the fault;

2. Stochastic-Method SIMulation (SMSIM) [22, 35] to model point-like sources (PLSs) characterized by lower magnitudes (3.5≤M<5.0) and source-to-site distances up to 200 km.

The regional parameters related to the propagation medium properties are fixed for all simulations. We used a 1D multilayered model considered representative of the study area in agreement with seismic imaging studies for southern Italy [36-38]. To simulate the ground motion, we considered the quality factor and the geometrical spreading obtained for the Calabria and for the Northeastern Sicily by D'Amico [39] to account a broad validity range in terms of source-to-site distances.

The simulated events are normal (NF), reverse (RF) and strike-slip (SS) earthquakes at six magnitudes (5.0, 5.5, 6.0, 6.5, 7.0 and 7.5). Dip and top depth of the simulated faults vary in function of magnitude as described in Table 1, while the strike is fixed along the North direction. Point-like source are modeled for lower magnitudes (4.5, 5.0, and 5.5). On the whole, we generated 62 different extended fault geometries and 12 point-like sources (Table 1).

Table 1 – Sources geometries and mechanisms for Generic Source Simulations

M_w	Top Depth [km]	Style of Faulting	Dip [°]	# EXTENDED/POINTS SOURCES
7.5; 7.0	1; 5	N R S	30; 60 30; 60 90	20
6.5; 6.0	5; 10; 15	N R S	45 45 90	18
5.5; 5.0	5; 10; 15; 20	N R S	45 45 90	24
4.5; 4.0; 3.5	5; 10; 15; 25	--	--	12

For GSs modelling, we used rupture fronts that radially propagate with three different constant velocities. Rupture velocities are defined in terms of percentage of the share waves velocity (Vs) of the embedding fault medium (70%; 80%; 85%). As the V_S increase with depth, the rupture velocities vary in function of fault geometries within the medium properties. We considered only one nucleation point randomly located over the fault and random distributions of slip.

In the context of the stochastic finite-fault modeling, the largest source of epistemic uncertainty in the ground motion prediction is due to the limited knowledge concerning the stress drop [32, 40], which is the main "free" input parameter that controls the level of the acceleration spectrum (> 1 Hz). For GSs simulation by EXSIM, we used 5 different values of the stress parameters (50, 100, 150, 200, and 250 bars), while for GSs simulations by SMSIM the stress drop values are randomly sampled from a normal distribution having a mean of 100 bars and a standard deviation of 40 bars. We only simulated scenario events for bedrock conditions. To this end we considered a kappa values of 0.035 s and site amplification factors for hard rock sites (NEHRP A, Vs ≥ 2000 m/s) by Atkinson and Boore [40]. For GSs we simulated the ground motion over grids of fathom receivers constructed around each simulated fault in order to have a denser distribution of station over and in proximity of the source. The geometry of the GS receivers depends on size and dip of the simulated faults.

Further detail on simulated fault ruptures will be available on HYPSTHER deliverable [41]. Figure 5 shows the magnitude–distance distribution for the empirical (grey circles) and synthetic (red and blue circles) datasets. The simulated data fill the lacks of the empirical dataset, especially for near-fault conditions and higher magnitudes (M_W>6.0).

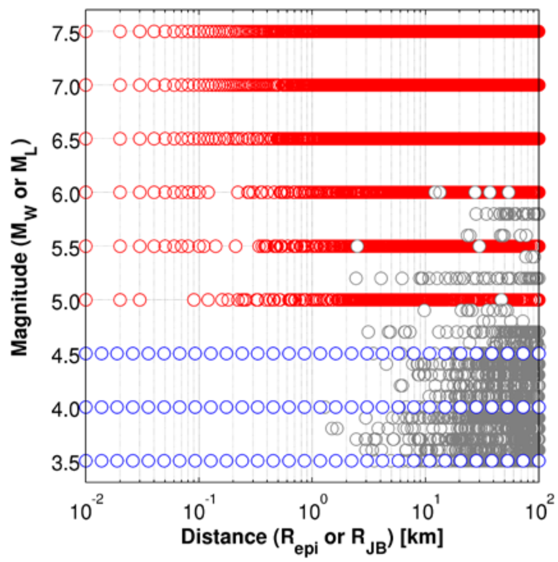

Fig. 5 – Magnitude-distance distribution : empirical data (grey circles); GS (red circles); PLS (blue circles).

Figure 6 also report the histograms of distance, magnitude and style of faulting for the GS synthetic dataset. The GSs dataset encompasses more than 180,000 strong motion data (empirical/simulated ratio is about 1/50).

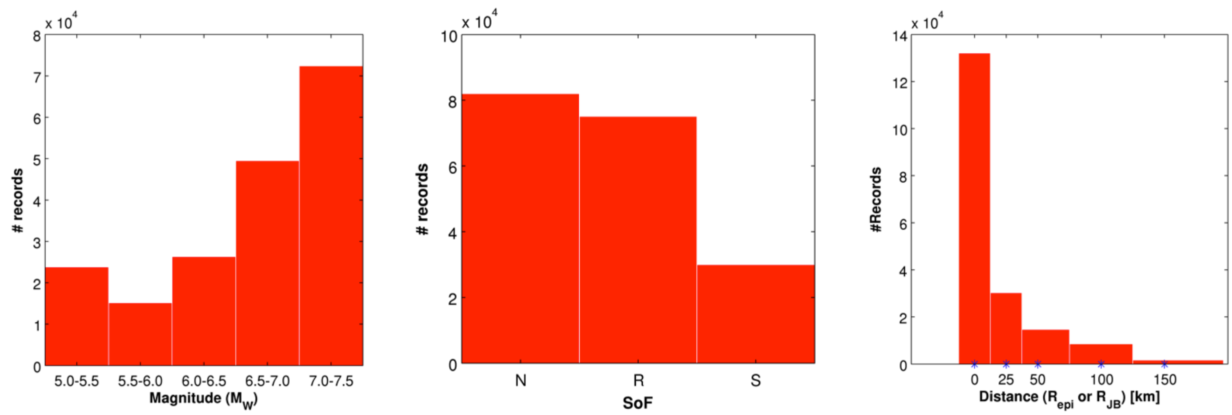

Fig. 6 –Histograms of GS synthetic dataset vs. magnitude (left), style of faulting (middle) and distance (right).

About 1/3 of the data are relative to magnitude larger than 7.0; more than half of the dataset are composed by waveforms of receivers located in the distance range 0-25km. Finally, the dataset is mainly composed by normal and reverse events, rather than strike-slip ones. Figure 7 shows the distribution of PGA, SA at 0.3s, 1s and 3s for the synthetic GSs data at magnitude 7.5. The data follow quite well a Gaussian distribution. The values of the total standard deviation (in decimal logarithm units) of the synthetic data are reported in Table 2, compared to those proposed by the most recent ground motion for Italy (ITA10, [9]). The sigma's obtained by the simulations are larger than the empirical ones, especially at lower magnitudes.

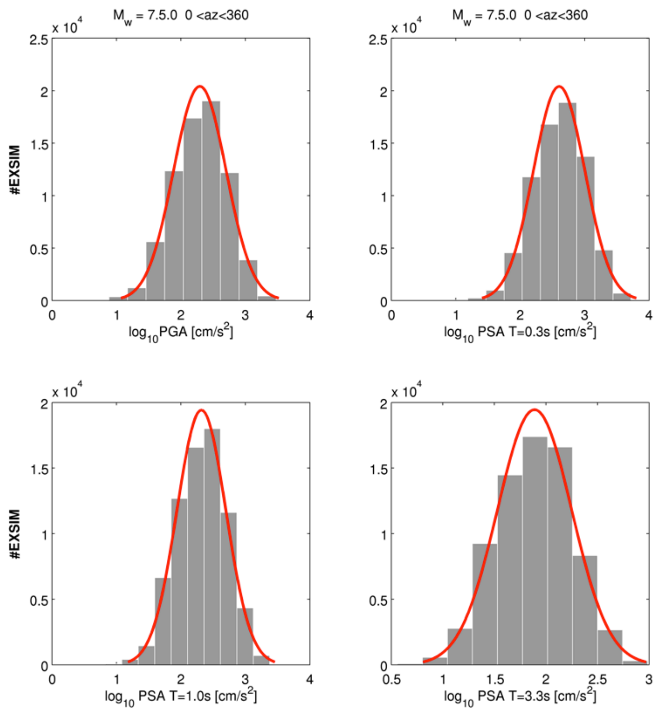

Fig. 7 – Variability of GS synthetic dataset (M_W=7.5).

Table 2 – Standard deviations of GS synthetic dataset

Dataset	PGA	SA=0.3s	SA=1s	SA=3s
M_W 7.5	0.4073	0.3983	0.3791	0.3603
M_W 7.0	0.4871	0.4733	0.4404	0.4123
M_W 6.5	0.4718	0.4525	0.4188	0.3869
M_W 6.0	0.5167	0.4879	0.4491	0.4148
M_W 5.5	0.5505	0.5091	0.4675	0.4466
M_W 5.0	0.5812	0.5297	0.4873	0.4725
ITA10	0.3370	0.3630	0.3600	--

6. Final remarks

The objective of the research project is to develop a methodological approach to retrieve ground motion prediction models, integrating recorded and synthetic data. In this framework, we choose to test this methodology for the study case of Southern Italy, focusing our attention on Calabria and Sicily regions.

This study area is characterized by high hazard levels and by the lack of empirical data needed to fully capture the peculiarities of the ground motion. In addition, along the Sicily coast many critical infrastructures are present, such as chemical plants and large ports, which strongly increase the risk of technological accidents induced by natural hazards.

The expected products of the project are a set of new hybrid GMPEs for PGA, PGV and SA in the period range T=0.04-4s. The hybrid models could be incorporated in a next generation of the MPS (Italian acronym for National Seismic Hazard Maps).

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