GRUPPO NAZIONALE DI GEOFISICA
DELLA TERRA SOLIDA

Atti del 34° Convegno Nazionale

Trieste, 17-19 novembre 2015
Palazzo dei Congressi
della Stazione Marittima

Tema 2: Caratterizzazione sismica del territorio

ISTITUTO NAZIONALE DI
OCEANOGRAFIA E DI
GEOFISICA SPERIMENTALE

TOWARDS A NEW GENERATION OF SEISMIC HAZARD MAPS FOR THE VOLCANIC REGION OF MT. ETNA

R. Azzaro[1], G. Barberi[1], O. Cocina[1], S. D'Amico[1], R. Gee[2], H. Langer[1], S. Lombardo[3], M.G. Ordaz-Schroeder[4], B. Pace[5], F. Panzera[3], L. Peruzza[2], A. Saraò[2], M.L. Suarez[4], G. Tusa[1], T. Tuvè[1]

[1] *INGV Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo, Catania, Italy*
[2] *OGS Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Sgonico (TS), Italy*
[3] *Dip. di Scienze Biologiche, Geologiche e Ambientali, Università di Catania, Italy*
[4] *UNAM Universitad Nacional Autonome de México, Mexico City, Mexico*
[5] *DiSPUTer, Università degli Studi "G. d'Annunzio" Chieti-Pescara, Chieti, Italy*

Introduction. In the last years, several seismic hazard analyses have been undertaken at Mt. Etna volcano in Sicily, Italy. These studies were aimed at estimating the capability of local faults to generate destructive earthquakes especially in the mid-term (30-5 years). Even if the areas prone to high seismic hazard have small extension, they give useful indication to establish priority criteria for seismic risk reduction action and land planning at the local/regional scale. Two main methodologies were applied in the past: the first is based on macroseismic data and uses a historical probabilistic approach (the "site approach", see Azzaro *et al.*, 2008, 2015); the second is based on a seismotectonic probabilistic approach, with time-dependent fault-based modelling, in which occurrence probabilities of major earthquakes are estimated by historic inter-event times, through a Brownian Passage Time (BPT) model combined with the time elapsed since the last event (Azzaro *et al.*, 2012b, 2013).

In the framework of INGV-DPC V3 Project, in two annual phases started in 2012 and ended in 2015, we performed a new full probabilistic seismic hazard assessment (PSHA) by using original definition of seismic sources (fault, areas, point sources), updated ground-motion prediction equations (GMPE) for this volcanic area, and referring to Poissonian and time-dependent occurrence models. Final results are given in term of maps for mid to short exposure times (10% exceeding probability in 30, 20, 10 and 5 years) and several spectral amplitudes. Site effects have been partially included too, at the very last stage of the project.

Working in a volcanic area implies new problems, usually discarded by standard PSHA, so we have tried to fix them with new analyses and original tools, as it will be briefly described hereinafter. Novelties concern both the sources parametrization, and GMPEs.

Characterization of the seismic sources. We defined the seismogenic sources related to volcano-tectonic seismicity, with increasing degree of detail and complexity. For this purpose, we used both long-term (macroseismic catalogue) and short-term data (instrumental catalogue) of the Etnean earthquakes. The latter data set consists of earthquakes recorded by the seismic network of Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo (INGV-OE) from 2005 to 2014 (Gruppo Analisi Dati Sismici, 2014; Alparone *et al.*, 2015), which have been then re-located with a 3-D model of seismic wave velocities. The conceptual tree adopted for the hazard elaborations is summarized below:

- Branch 1. Areal seismic sources with Gutenberg-Richter relationships (GR) calibrated on instrumental (*a*- *b*-values) and historical data (maximum magnitude M_{max}). This approach is similar to the one used by the Italian seismic hazard map MPS04 (Stucchi *et al.*, 2011).
- Branch 2. Fault geometry and characteristic earthquake model for major seismicity based on (a) historical and (b) geometric-kinematic approaches. Areal seismic sources for background seismicity ($M < 4.5$).
- Branch 3. Fault geometry and characteristic earthquake model for major seismicity based on (a) historical and (b) geometric-kinematic approaches. Diffused seismicity modelled by point sources with a generalized non-Poisson model, for background seismicity ($M < 4.5$).

Areal seismic zones (hereinafter seismogenic zone, SZ) represent the simplified geometry of the main seismogenic fault systems recognized in the Etnean area (Timpe and Pernicana faults, see Azzaro *et al*., 2012a). They are defined by the distribution of the earthquake epicenters of the instrumental data set and also include the sources of the strongest earthquakes occurring at Etna during the last 3 centuries. The characterization of SZs includes the estimation of the effective depth, i.e. the seismogenic layer where most of the seismic energy is released. For this purpose we calculated, for each SZ, the distribution of the number of earthquakes and the related strain release vs. depth, with steps of 1 km, using the 3-D re-located instrumental data. Results indicate that the seismogenic thickness is mainly confined in the first 7 km below sea level (b.s.l.), which is in agreement with the overall 1-D depth distribution of seismicity in the Etna area (Alparone *et al*., 2015). In particular the 3-D data set shows a clustering of hypocenters, allowing to recognize a main seismogenic layer at about 1 km b.s.l. and, in some cases, also a second layer at about 5 km b.s.l. defining the bottom of the SZs.

Seismic rates from the instrumental catalogue have been obtained for each SZ by using the ZMAP tools (Wiemer, 2001). Detailed analyses show that the structures belonging to the Timpe fault system have similar *b*-value coefficients of the GR relationship, while the Pernicana fault, though it retains about the same annual rate (*a*-value) of earthquakes, it has a much lower *b*-value.

The above frequency-magnitude distributions (FMD) were then compared with those obtained from the historical macroseismic catalogue (CMTE Working Group, 2014), covering a time-span of about 150 years for all SZs except for the Pernicana fault, whose seismic history is limited at the last 35 years. Since the extension of the two catalogues is different, FMD were normalized to one year. *b*-values calculated from the instrumental and macroseismic data sets are consistent each other, so we can affirm that instrumental seismicity occurring in a time-window of 9 years, in which no seismic swarm due to flank eruptions altered the “normal regime” of our SZs, is representative for a long-term seismogenic behavior.

In order to calculate the seismic hazard by the innovative approach of Branch 3, which uses the distributed seismicity as background model, the *a*- and *b*-value coefficients of the GR were calculated using a three-dimensional grid with inter-nodal distance of 2 km and 3 km search radius; grid nodes with less than 20 earthquakes have been discarded, and other *a*-values have been normalized accordingly to the volume represented.

For the individual faults of Etna’s eastern flank which generated major earthquakes – we consider characteristic those having an epicentral intensity $I_0 \geq$ VIII EMS (European Macroseismic Scale, see Grünthal, 1998), corresponding to magnitude $M_w \geq 4.6$ (Azzaro *et al*., 2011) - the expected M_{max} and the mean recurrence time (T_{mean}) are estimated using two different approaches: i) historical earthquake catalogue data and ii) fault data, which are representative of tectonic activity. Branches 2 and 3 fork further to take into account stationarity (Poissonian approach) or time-dependency on faults.

In the first “historical” approach, already described in Azzaro *et al*. (2012b; 2013), T_{mean} is computed by the inter-event times occurred on the same structure as defined by the fault seismic histories. Assuming that there are no significant differences between faults, we grouped all inter-event times in order to obtain a more statistically significant sample. In this approach the aperiodicity value α is obtained from the instrumental *b*-value of GR (Zoller *et al*., 2008).

As an alternative method, T_{mean} referred to major earthquakes generated by the Pernicana and Timpe faults is estimated by using the geometric-kinematic fault parameters such as 3-D dimension, kinematics and slip-rate (Azzaro *et al*., 2014). This analysis has been carried out through the software FISH, a Matlab® tool developed in the framework of the DPC-INGV S2 Project to turn fault data into seismic hazard models (Pace *et al*., 2015). The FISH code “quantifies” the seismic activity from geometry and slip-rate of a fault through different empirical and analytical scaling relationships between dimension of the source and characteristics of the expected earthquake, providing several values of M_{max} and associated T_{mean}. FISH, therefore, formally propagates the errors of magnitude and slip-rate obtaining, for the characteristic magnitude expected in each fault, the most probable value of T_{mean} with the associated standard deviation σ, and the coefficient of aperiodicity α. Finally, these values are then used to calculate the hazard rates, for a given exposure time, following a BPT probability density function (time-dependent) and a Poissonian distribution. In our application the FISH code has been customized to take into account empirical scaling relationships in volcanic worldwide domains, including the one obtained in this study for the Etna region. In particular, the calculated α values (Tab. 1) suggest a "less periodic" behavior of faults with respect to ones obtained from the intertimes analyses of historical earthquakes (~0.4, see Azzaro *et al.*, 2012b), and comparable to those derived from instrumental data (0.64-0.72 obtained by GR, see Azzaro *et al.*, 2013).

Tab. 1 - AR-FiSH output and comparison with estimations based on historical and instrumental earthquake data sets. M_{min}: minimum magnitude for which is calculated the probability of occurrence (M_{max}-sd M_{max}); BPT prob.: time-dependent probability to have an earthquake ≥ M_{min} in the next 5 years.

	Geological-kinematic				Instrumental eqs dataset				Historical eqs dataset	
Fault	**T_{mean} (yr)**	α	**M_{min}**	**BPT prob (%) 5 yr**	**T_{mean} (yr)**	Åα	**M_{min}**	**BPT prob (%) 5 yr**	**T_{mean}**	α
Pernicana (PF)	36	0.60	4.8	0.24	71	---	4.3	---	---	
Fiandaca (FF)	148	0.54	4.6	0.06	71	0.64	4.3	6.0-7.5		
S. Tecla (STF)	47	0.63	5.0	13.59	71	0.64	4.3	10.1-12.2	71.02	0.36-0.42
S. Venerina (SVF)	57	0.54	4.8	0.54	71	0.64	4.3	0.3-1.1		
Moscarello (MF)	69	0.63	5.0	7.42	71	0.72	4.3	9.1-9.3		

From source to site. The second important element of seismic hazard assessment is related to the propagation of the seismic energy from the source to the recording site. In this respect, the volcanic areas exhibit specific seismic propagation properties: the attenuation of seismic energy is very high, especially for shallow (H < 5 km) earthquakes, and GMPEs commonly used for tectonic areas are not suitable to attenuate this kind of local seismic sources. Thus, a new GMPE has been calibrated for Etna by using data recorded by the seismic network of Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo (INGV-OE). The data set consists of 91 earthquakes with local magnitude M_L ranging 3.0 to 4.8, and hypocentral distances between 0.5 km and 100 km.

The shallow events on Mt. Etna occur in peculiar geological conditions, with foci that fall into a thick sedimentary substratum with strong lateral heterogeneities. On this basis, the data set were divided into two groups: Shallow Events (SE, focal depth < 5 km), and Deep Events (DE, focal depth > 5 km). In order to compare our data to those recorded in Italy and Europe, we adopted the formulation proposed by Boore and Atkinson (2008), which is also used in the Italian standard equation "ITA10" (Bindi *et al.*, 2011). In addition to the "standard" peak ground motion parameters such as acceleration (PGA) and velocity (PGV), we also calculated empirical relations for spectral amplitude (PSA) referred to 0.1 s, 0.5 s, 1.0 s and 2.0 s periods (Tusa and Langer, 2015). For a shallow event of M = 4, at low frequencies, the corresponding spectral values are higher than those predicted by ITA10; on the other hand, PSA for higher frequencies are well below the values obtained by ITA10.

The new GMPEs for the Etna region have been finally implemented for the two softwares (Crisis, Ordaz *et al.*, 2013; OpenQuake, Pagani *et al.*, 2014) used in our analysis.

Other relevant implementations we have done concern the capability of calculation to take into account both the topography (elevation) and local site effects. The former is particularly relevant in a volcanic edifice as Mt. Etna, where earthquakes are very shallow and elevation increases sharply moving from the coast (sea level) to the Central Craters (more than 3000 meters a.s.l.), just in 20 km. At first, thanks to the cooperation with the software developer team of Crisis (by M. Ordaz and coauthors, University of Mexico City), a new release now accomplishes the general modeling of a 3D surface (effect of topography) in order to compute

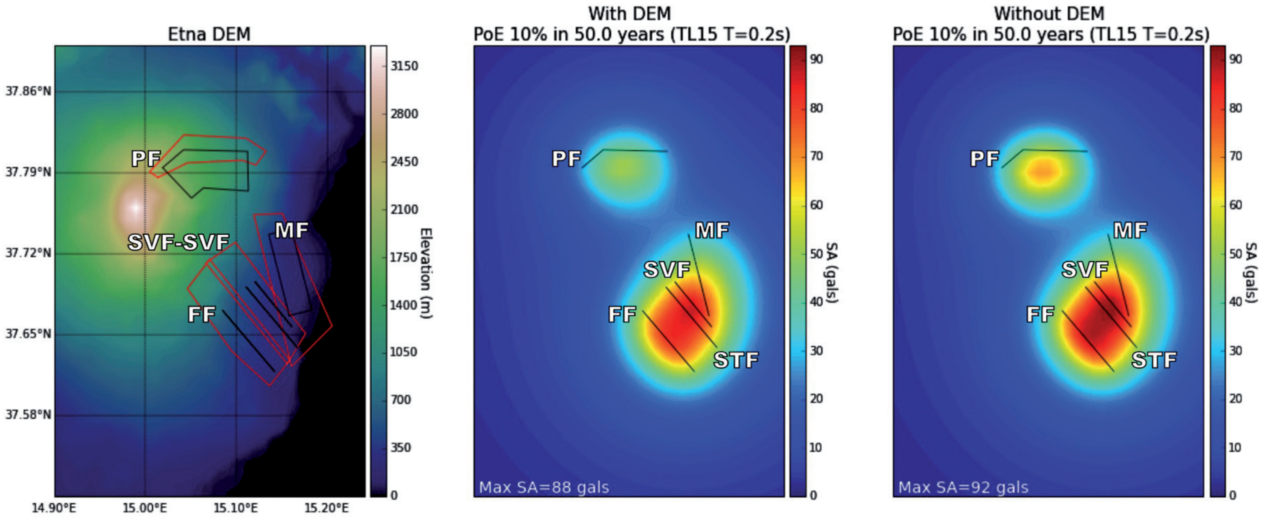

Fig. 1 – Test on topographic effects using fault sources implemented in OpenQuake. Faults (shown in black) are here modeled with arbitrary seismicity rates: TL15 means the GMPE used in the frame of INGV-DPC V3 Project after Tusa and Langer (2015). Left: Mt. Etna Digital Elevation Model; center: hazard map taking into account the DEM; right: hazard map without taking into account the DEM. Fault abbreviations as in Tab. 1.

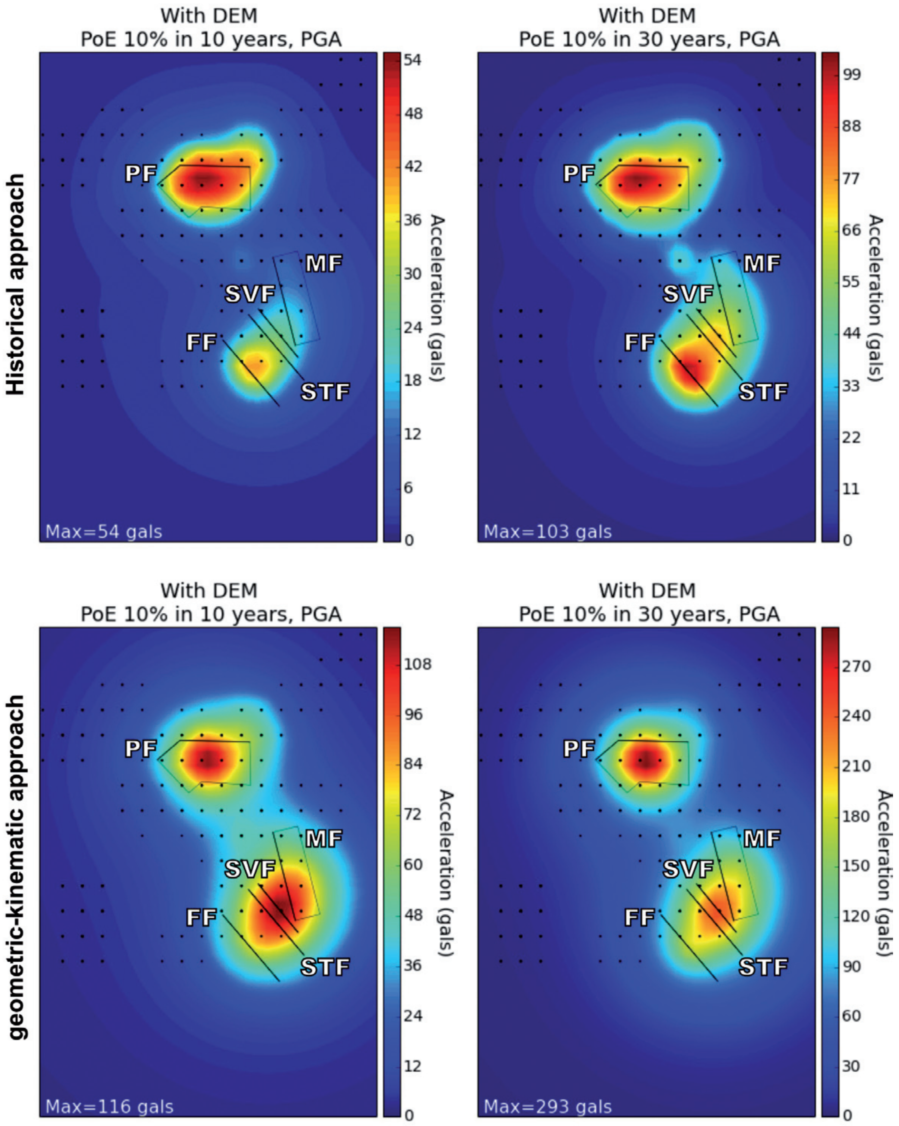

Fig. 2 – Seismic hazard maps obtained for Branch 3 by using the characterization of the seismic sources through geometric-kinematic approach or historical-instrumental earthquake data. BPT model; exceedance probability, 10%; exposure times, 10 and 30 yrs. Fault abbreviations as in Tab. 1 and Fig. 1.

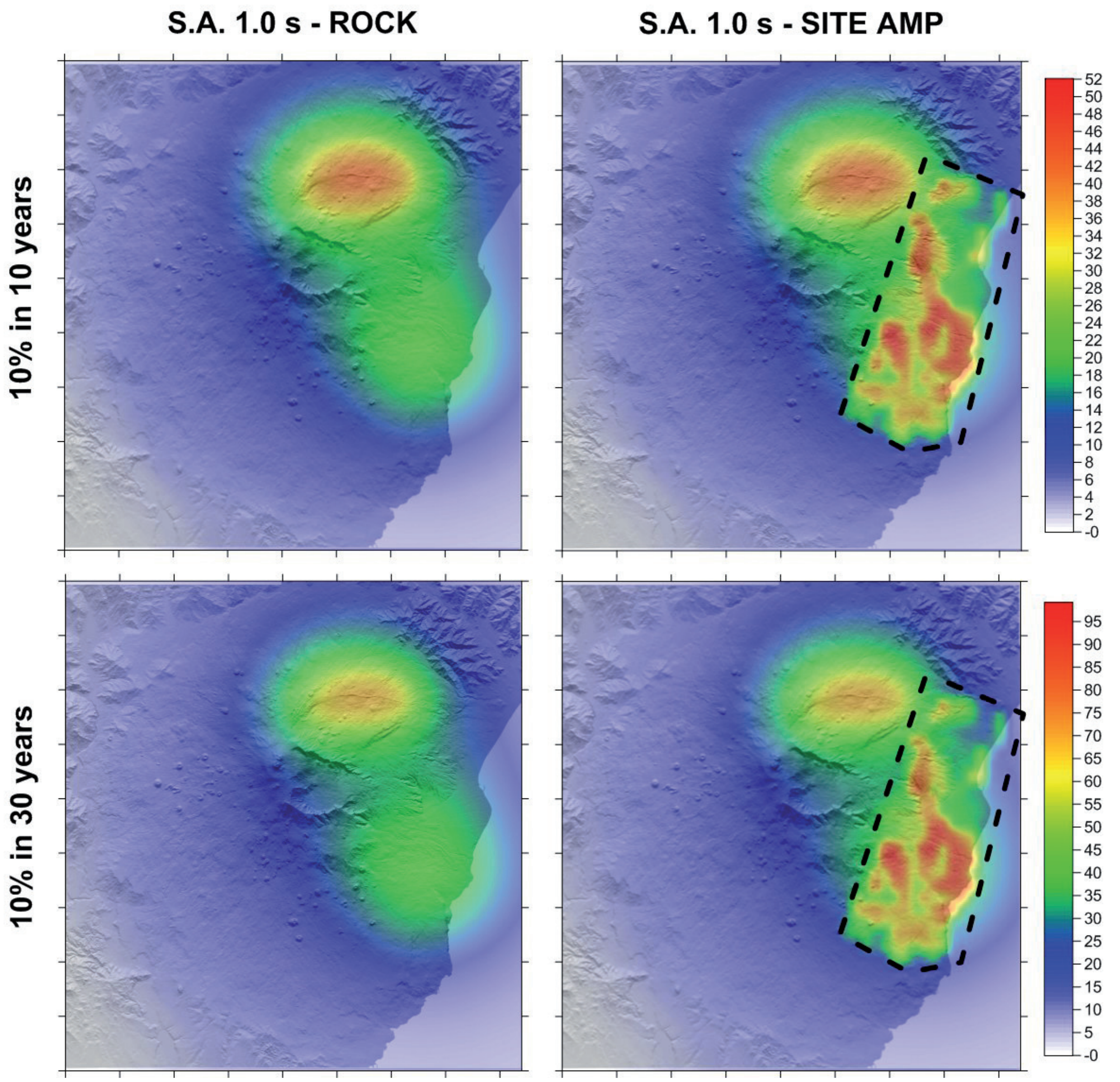

Fig. 3 – Seismic hazard maps obtained by using area sources with GR calibrated on instrumental and historical data (Branch 1), GMPE derived ad-hoc for the Etna region (Tusa and Langer, 2015) and amplification coefficients derived from site measurements (Lombardo and Panzera, RU 6 in INGV-DPC V3 Final Report, 2015). The computations have been done using CRISIS v.2015. Poisson model; exceedance probability, 10%; exposure times, 10 and 30 yrs; spectral acceleration at 1.0 s.

the proper source-site distances, essential in our case. Similar new functionalities have then been implemented in OpenQuake (by M. Pagani and R. Gee, Eucentre Pavia), the platform used by GEM (Global Earthquake Model) and SHARE Project. A synthetic example of the contribution of the Digital Elevation Model (DEM) to the hazard is shown in Fig. 1. The inclusion of a real topography influences the source-to-site distance, and thus the final results on PSHA: in the sensitivity tests performed with the Etna GMPEs, it causes a decrease of ground motion parameters that locally may reach about 20% of the expected values.

Last but not the least, the site effects play an important role on seismic hazard, and in a new generation map amplification factors obtained by instrumental measurements should be taken into account. In the INGV-DPC V3 Project, the amplification coefficients have been calibrated in a densely urbanized area of the lower eastern flank (see Lombardo and Panzera, RU 6 in INGV-DPC V3 Project Final Report, 2015), and then introduced into the computational scheme performed by Crisis.

Some results. One of the targets of the INGV-DPC V3 Project is the probabilistic assessment of seismic hazard in the Etna region due to local volcano-tectonic earthquakes. This activity represents the extension of analyses undertaken in previous projects, based on the use of macroseismic intensity data. The approach we adopted in this work follows procedures used worldwide for traditional and innovative PSHA, and considers a large data set of input parameters (geological data, instrumental seismicity, GMPE, site response etc.).

The hazard maps we computed are referred to an exceeding probability of 10% for short-mid exposure times - 5, 10 and 30 years - and do not take into account the contribution of regional seismicity, that is responsible for the maximum shaking expected in this area for an exposure period of 50 years (Stucchi *et al.*, 2011).

Fig. 2 reports some outputs of Branch 3 for 10 and 30 years, referred to the BPT model and not including the aforementioned site effects. The comparison shows that PGA obtained by using only the geometric-kinematic characterization of the seismic sources, is twice with respect the one calculated by the historical-instrumental earthquake data.

Examples of the contribution of the site amplification coefficients in a model of areal sources as depicted in Branch 1, is shown in Fig. 3. It clearly illustrates how amplification due to local site conditions can jeopardize the expected ground motion at rock reference sites, producing expected PGA values about twice with respect to the rock-reference site.

Even if these results must be considered still preliminary, they represent a first example of new generation, site-specific seismic hazard maps suitable for civil protection purpose to define priorities of retrofitting at a local scale, complementary with those calculated for the national territory.

References

Alparone S., Maiolino V., Mostaccio A., Scaltrito A., Ursino A., Barberi G., D'Amico S., Di Grazia G., Giampiccolo E., Musumeci C., Scarfì L. and Zuccarello L.; 2015: *Instrumental seismic catalogue of Mt Etna earthquakes (Sicily, Italy): ten years (2000-2010) of instrumental recordings*. Ann. Geophys., **58** (3), DOI 10.4401/ag-6591.

Azzaro R., Barbano M. S., D'Amico S., Tuvè T., Albarello D. and D'Amico V.; 2008: *First studies of probabilistic seismic hazard assessment in the volcanic region of Mt. Etna (Southern Italy) by means of macroseismic intensities*. Boll. Geof. Teor. App., **49** (1), 77-91.

Azzaro R., D'Amico S. and Tuvè T.; 2011: *Estimating the magnitude of historical earthquakes from macroseismic intensity data: new relationships for the volcanic region of Mount Etna (Italy)*. Seism. Res. Lett., **82** (4), 533-544.

Azzaro R., Branca S., Gwinner K. and Coltelli M.; 2012a: *The volcano-tectonic map of Etna volcano, 1:100.000 scale: an integrated approach based on a morphotectonic analysis from high-resolution DEM constrained by geologic, active faulting and seismotectonic data*. Italian. J. Geosc., **131** (1), 153-170.

Azzaro R., D'Amico S. and Tuvè T.; 2015: *Seismic hazard assessment in the volcanic region of Mt. Etna (Italy): a probabilistic approach based on macroseismic data applied to volcano-tectonic seismicity.* Bull. Earth. Eng., DOI 10.1007/s10518-015-9806-2.

Azzaro R., D'Amico S., Peruzza L. and Tuvè T.; 2012b: *Earthquakes and faults at Mt. Etna (Southern Italy): problems and perspectives for a time-dependent probabilistic seismic hazard assessment in a volcanic region*. Boll. Geof. Teor. App., **53** (1), 75-88.

Azzaro R., D'Amico S., Peruzza L. and Tuvè T.; 2013: *Probabilistic seismic hazard at Mt. Etna (Italy): The contribution of local fault activity in mid-term assessment*. J. Volcanol. Geoth. Res., **251**, 158-169.

Azzaro R., D'Amico S., Pace B. and Peruzza L.; 2014: *Estimating the expected seismicity rates of volcano-tectonic earthquakes at Mt. Etna (Italy) by a geometric-kinematic approach*. Gruppo Nazionale di Geofisica della Terra Solida, Atti del 33° Convegno Nazionale, Tema 1: Geodinamica, 20-25.

Bindi D., Pacor F., Luzi L., Puglia R., Massa M., Ameri G. and Paolucci R.; 2011: *Ground motion prediction equations derived from the Italian strong motion database*. Bull. Earth. Eng., **9**, 1899-1920, DOI 10.1007/s10518-011-9313-z.

Boore D.M. and Atkinson G.M.; 2008: *Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 100 s*. Earthq. Spectra, **24**, 99-138.

CMTE Working Group; 2014: *Catalogo Macrosismico dei Terremoti Etnei dal 1832 al 2013*. INGV, Catania, http://www.ct.ingv.it/macro/http://www.ct.ingv.it/macro/

Grünthal G. (ed.); 1998: *European Macroseismic Scale 1998 (EMS-98)*. European Seismological Commission, subcommission on Engineering Seismology, working Group Macroseismic Scales. Conseil de l'Europe. Cahiers

du Centre Européen de Géodynamique et de Séismologie 15, Luxembourg, 99 pp. http://www.ecgs.lu/cahiers-bleus/.
Gruppo Analisi Dati Sismici; 2015: *Catalogo dei terremoti della Sicilia Orientale - Calabria Meridionale (1999-2015)*. INGV, Catania http://www.ct.ingv.it/ufs/analisti/catalogolist.phphttp://www.ct.ingv.it/ufs/analisti/catalogolist.php
Ordaz M., Martinelli F., D'Amico V. and Meletti C.; 2013: *CRISIS2008: A Flexible Tool to Perform Probabilistic Seismic Hazard Assessment*. Seism. Res. Lett., **84** (3), 495-504, DOI: 10.1785/0220120067.
Pace B., Visini F.and Peruzza L.; 2015: *FiSH: MATLAB tools to turn Fault data into Seismic Hazard models*. Seism. Res. Lett., submitted.
Pagani M., Monelli D., Weatherill G., Danciu L., Crowley H., Silva V., Henshaw P., Butler L., Nastasi M., Panzeri L., Simionato M. and Vigano D.; 2014: *OpenQuake Engine: An Open Hazard (and Risk) Software for the Global Earthquake Model*. Seism. Res. Lett., **85** (3), 692-702, DOI: 10.1785/0220130087.
Stucchi M., Meletti C., Montaldo V., Crowley H., Calvi G.M. and Boschi E.; 2011: *Seismic Hazard Assessment (2003-2009) for the Italian Building Code*. Bull. Seism. Soc. Am. **101** (4), 1885-1911.
Tusa G., and Langer H.¸ 2015:, *Prediction of ground motion parameters for the volcanic area of Mount Etna*. J. of seismology. DOI: 10.1007/s10950-015-9508-x.
Wiemer S.; 2001: *A software package to analyze seismicity: ZMAP*. Seism. Res. Lett., **72** (2), 374-3833-170.
Zöller G., Hainzl S. and Holschneider M.; 2008: *Recurrent large earthquakes in a fault region: what can be inferred from small and intermediate events?* Bull. Seism. Soc. Am., **98** (6), 2641–2651.

PROBABILITY OF EARTHQUAKE OCCURRENCE FROM ELECTRIC ANOMALIES RECORDED BY CIEN

C. Fidani[1,2,3]
[1] *SARA electronic instruments s.r.l., Perugia, Italy*
[2] *Osservatorio Sismico "A. Bina", Perugia, Italy*
[3] *Central Italy Electromagnetic Network, San Procolo, Italy*

Introduction. The Central Italy Electromagnetic Network (CIEN) recorded strong Extremely Low Frequency (ELF) signals at the time of the Emilia earthquakes in 2012 (Fidani and Martinelli, 2015), and strong signals were recorded by the network at the time of the L'Aquila earthquakes in 2009 (Fidani, 2011a). CIEN is presently composed of 14 stations including Trasacco and Urbino which were made operative in March and May of 2014, in L'Aquila and Pesaro-Urbino provinces, respectively. The Pozzuolo del Friuli (Udine) Station from autumn 2014 and the Gubbio (Perugia) Station from January 2015 have been out of order. All 14 stations were equipped with two wide band amplifiers each in ELF with a range of 4 to 1000 Hz and in VLF with a range of 1 to 25 kHz. Whereas, four stations, Chieti, Fermo, Città di Castello (Perugia) and Urbino (Pesaro-Urbino) monitor LF in a range of 1 to 50-100 kHz. VLF and LF ranges have allowed to monitor several sub-ionospheric signals by various VLF and LF transmitters (Fidani, 2011b). Characteristic ELF signals were monitored in relation to seismic activity in Fermo, Marche Region, Italy, from January 2006 to September 2015 (Fidani, 2009). These signals were detected also during low seismic activity at the Perugia CIEN Station from October 2008 to September 2015 (Fidani, 2010). A CIEN update is shown in Fig. 1.

Increases in the seismic activity rates occurred near both Pietralunga and Massa Martana, in the region of Umbria. In the Pietralunga area, the seismic swarm started on April 15, 2010, with a shock of $M = 3.8$ (Marzorati *et al.*, 2014). The swarm started in October 2008 and it had an epicentre about 35 km north of the Perugia Station. Several shocks of $M > 3$ have occurred near the same epicentre over the following years and, at the same time, many ELF oscillations have been recorded by the Perugia Station. An increase in the seismic activity rate occurred in the Massa Martana area from mid-March 2014 and on March 26, 2014 there was a recorded shock of $M = 3$ (Bina Observatory, 2014). Its swarm epicentre was about 45 km south of the Perugia