Bollettino di Geofisica Teorica ed Applicata Vol. 56, n. 4, pp. 519-526; December 2015
DOI 10.4430/bgta0158

Seismic hazard from natural and induced seismicity: a comparison for Italy

M. Mucciarelli[1,2], E. Priolo [1], M. Santulin [1,*] and A. Tamaro [1,3]

[1] Centro di Ricerche Sismologiche, Istituto Nazionale di Oceanografia e di Geofisica Sperimentale OGS, Trieste - Udine, Italy
[2] Scuola di Ingegneria, Università della Basilicata, Potenza, Italy
[3] Dipartimento di Fisica, Chimica e dell'Ambiente, Università di Udine, Italy
[*] now at Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Milano, Italy

(Received: November 11, 2014; accepted: April 8, 2015)

ABSTRACT The seismic hazard resulting from seismicity induced by human activity is not yet regulated in Italy. The presence of a significant natural seismicity complicates the differentiation of events possibly induced by human activity from ordinary natural seismicity, while it stimulates a comparison between the ground motion that can be expected due to tectonic events and the shaking caused by man-induced events. The problem is complicated by the fact that it is not possible to compare homogeneous hazard estimates for the two classes of seismicity, since it is difficult to define the induced seismicity in terms of probabilities for a given return time. This paper provides an example of how the problem was first tackled in an Environmental Impact Assessment (EIA) procedure, and then attempts a nationwide extension of the results.

Key words: induced seismicity, seismic hazard, Italy.

1. Introduction

Italy is a country rich in hydropower reservoirs, geothermal wells, and fields of hydrocarbons extraction. However, from 1964 to 2012, only two papers were published on the problem of seismicity induced by the injection of fluids and three on the seismicity induced by dams. The historical reason for this lack of interest in the problem of induced seismicity is discussed in Mucciarelli (2013). Things changed after the Emilia 2012 earthquake sequence. The governor of the Emilia-Romagna Region appointed an international commission (ICHESE, 2014) to investigate the relationship between human activity and Emilia earthquakes. The commission concluded that it was not possible to exclude that the oil operation at Cavone could have triggered the mainshock of the Emilia seismic sequence, and suggested that further investigation had to be carried out at the site. Thus, an experiment aimed at evaluating the diffusion of the pressure field due to water injection was set up at Cavone in the following months, the so-called Cavone Monitoring Laboratory (CavoneLab). The experiment ended in mid June 2014, while at the same time a second group of experts (Astiz *et al.*, 2014) developed

ACTIVITY	SITE	PROVINCE	DOCUMENTED/ HYPOTHESISED	LOCAL MONITORING START/END
Reservoir	Pieve di Cadore	BL	D	1949/1952
	Vajont	BL	D	1962/1968
	Ridracoli	FC	D	1981/1989
	Passante	CZ	D	1981/1996
	Campotosto	AQ	H	n.d.
	Pertusillo	PZ	D	2005/2012
Geothermal	Larderello / Travale	PI	H	1978/1982
	Amiata	GR/SI	H	1982/1992
	Latera	VT	D	1978/1982
	Torre Alfina	VT	D	197871982
	Cesano	RM	D	1978/1982
Hydrocarbons	Caviaga	LO	H*	n.d.
	Cavone	MO	H	n.d.
	Montemurro	PZ	D*	2006/2014
Mining	Raibl / Cave Predil	UD	H	n.d.

Table 1 - List of Italian earthquakes related to human activities. If there are available production data correlated with seismic events, the case is considered documented. Otherwise, it is considered only hypothesised [modified from ISPRA (2014), where all the relevant references can be found except that for D*, updated as documented following Stabile *et al*. (2014), and H* that is a tectonic event according to Caciagli *et al*. (2015)].

a geodynamical model and performed numerical simulation of pressure propagation and interferences among the wells: they concluded that there was no causal relationship between fluid extraction/reinjection at Cavone and the Emilia earthquakes. After these events, the Italian government appointed two groups of scientists with two tasks: 1) to provide a “white paper” about the state of the art of induced seismicity studies in Italy, and 2) to provide guidelines for the monitoring of seismicity, ground deformation, and pore pressure for human activities that involve fluid extraction/injection deep in the ground.

Fulfilling the request of point 1, the report by the working group coordinated by the Institute for Environmental Protection and Research (ISPRA, 2014) on the level of knowledge of induced/triggered seismicity in Italy listed the cases of earthquakes attributed with more or less certainty to anthropogenic causes. In total, 15 seismic events are known, some documented and some hypothesized (Table 1). The same report also describes a few instances of publicly available monitoring data associated with documented cases of human activity that did not cause any induced seismicity.

The guidelines for monitoring (UNMIG, 2014) are focused on the actions to be taken in accordance with the changes of monitored parameters, defining a general scheme that works for subsequent levels of activation. Also, based on the experience and legislation of other countries, it is proposed to manage the reinjection activities, taking into account the possible secondary effects, such as induced seismicity, on an experimental basis, with a decision model based on pre-established thresholds also called a “traffic light system”.

To this purpose, the guidelines define the criteria that fix, case by case, the thresholds of the different levels of attention for the monitored parameters, as well as some analyses that should be done at the same time in order to confirm the cause-effect correlation [the guidelines, in Italian, can be downloaded from the following link: http://unmig.sviluppoeconomico.gov.it/unmig/agenda/upload/85_238.pdf (UNMIG, 2014)].

To respond to the interest and concern that the phenomenon of induced seismicity generates among the inhabitants of areas with a significant seismogenic potential where underground human activities are carried out, it is necessary to move from a simple description and cataloguing of events, to a hazard assessment comparable with those provided by anti-seismic codes. At present, in fact, the seismic hazard resulting from induced seismicity is not regulated in Italy. Paradoxically, the need for a good hazard assessment for induced seismicity is much more felt and clearly faced in industrial countries where natural seismicity (tectonic and/or volcanic) is moderate or almost absent, the reason being that there is no doubt that most, if not all, seismic events can be attributed to human industrial activities. In this respect, northern European countries are the most responsive, since they have both the above conditions, i.e., low seismicity and high human activity. Unlike other areas where the problem of induced seismicity recently came to the attention of the public and researchers, such as the central U.S.A. (Ellsworth, 2013) or northern Netherlands (van Eck *et al.*, 2006), Italy is a highly seismic country. The presence of significant natural seismicity complicates the differentiation of events possibly induced by human activity from ordinary natural seismicity, while it stimulates a comparison between the ground motion that can be expected due to tectonic events and the shaking caused by man-induced events.

2. Comparison between tectonic and induced seismicity hazard

The comparison between tectonic and induced seismicity hazard has became an institutional issue, probably for the first time in Italy, thanks to the Emilia-Romagna Region (RER). During the Environmental Impact Assessment (EIA) procedures for a geothermal plant at Pontegradella site in the municipality of Ferrara, RER asked the proponents to define the relationship between the hazard estimate according to Italian code provisions and known induced seismicity events, in terms of peak ground acceleration and spectral acceleration. This was asked in order to test whether the parameters adopted for the design of the proposed plant would include any phenomena of induced seismicity. The problem is complicated by the fact that it is not possible to compare homogeneous hazard estimates for the two kinds of seismicity, since it is difficult to define probabilities of occurrence of the induced seismicity in a given return time. In the absence of human activities, the probability of induced seismicity is obviously zero, something that never occurs for the natural seismicity. The time scales are not comparable, either, since many known cases of induced seismicity occurred immediately after the beginning of operations, while code hazard is estimated over long return periods (475 years or more). Finally, it is possible in many cases to control the evolution of induced seismicity before it gets to potentially damaging events through a careful management of systems, if properly monitored [see: Batini *et al.* (1985); as an example of what was done for geothermal activities in Italy].

To answer the question posed by the RER, we considered a severe-case scenario by comparing the expected values of acceleration predicted by the national code [NTC08, derived from the hazard map MPS04 described in Stucchi *et al.* (2011)] with the spectra of two induced events, supposing that in a short time after the start of the operations, without proper monitoring and management, a damaging induced earthquake may occur.

The first event that was considered comes from The Netherlands, where the extraction and re-injection of natural gas caused numerous induced seismic events, the strongest being the magnitude 3.5 event in Roswinkel, which caused non-structural damage to some houses in

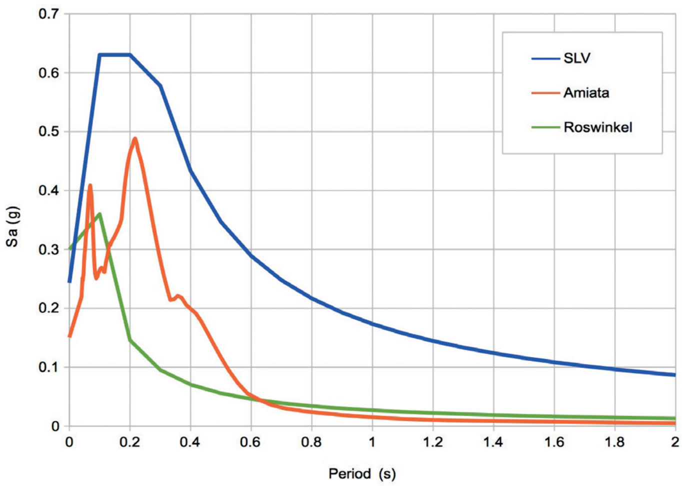

Fig. 1 - Comparison between the Dutch code for induced seismicity (Roswinkel events), the earthquake of Monte Amiata 2000 and the SLV spectrum for the municipality of Ferrara, considering a soil class C.

the vicinity of the epicentre. More information is given in van Eck *et al*. (2006), where at the conclusion of their study, they propose a spectral shape for the near-field-induced events to be accounted for in Anti-Seismic Design (ASD). It is necessary to explain why an earthquake of such a small magnitude may cause building damage: a typical characteristic of induced seismicity is a higher probability that events are shallower than with tectonic earthquakes. The reduced depth of the hypocentre produces higher acceleration (and macroseismic intensity) in the immediate vicinity of the focus and greater ground-motion attenuation away from the epicentre. A similar behaviour is found in nature with volcano-tectonic earthquakes, so in Italy the probabilistic estimates for these events use a ground motion prediction equation and an intensity-magnitude conversion different from the standard ones [see an example for the Etna volcano in Panzera *et al*. (2011)]. Also, its should not be forgotten that in areas without natural seismicity, there is usually no code requiring the construction of ASD buildings.

The second case is the earthquake that struck some localities of Mount Amiata in Tuscany on April 1, 2000. The event was recorded by the accelerometric station in Piancastagnaio and the magnitude assigned by Istituto Nazionale di Geofisica e Vulcanologia (INGV) shows a considerable discrepancy between the local magnitude (M_L=3.9) and the moment magnitude (M_W= 4.5). This difference can be attributed to the extremely limited depth of the event (2 km), and leads to the hypothesis that it is an earthquake linked to the exploitation of the geothermal field. More information about the structural damage caused by the event and the map of ground motion are provided in the paper by Mucciarelli *et al*. (2001).

The spectra of the two considered events were compared with those provided by the Italian seismic code for Ferrara (at Pontegradella site) for the Life Saving Level (SLV) spectrum (Fig. 1), corresponding to the widely accepted standard of a 475-year return period. It has to be noted that the Ferrara spectrum includes the aggravation factor from rock to soil class C, according to Eurocode 8. The recording station for the Amiata event (Piancastagnaio) is located on B* soil, according to the ITalian ACcelerometric Archive (ITACA, 2014), the superscript meaning that no V_S profile is available and the class is assigned using geological maps. Van Eck *et al*. (2006) do not differentiate their study of Dutch events by soil classes, since all the stations in The Netherlands are located on soft soil.

It can be noted that the spectrum proposed by Dutch legislation (from Roswinkel events)

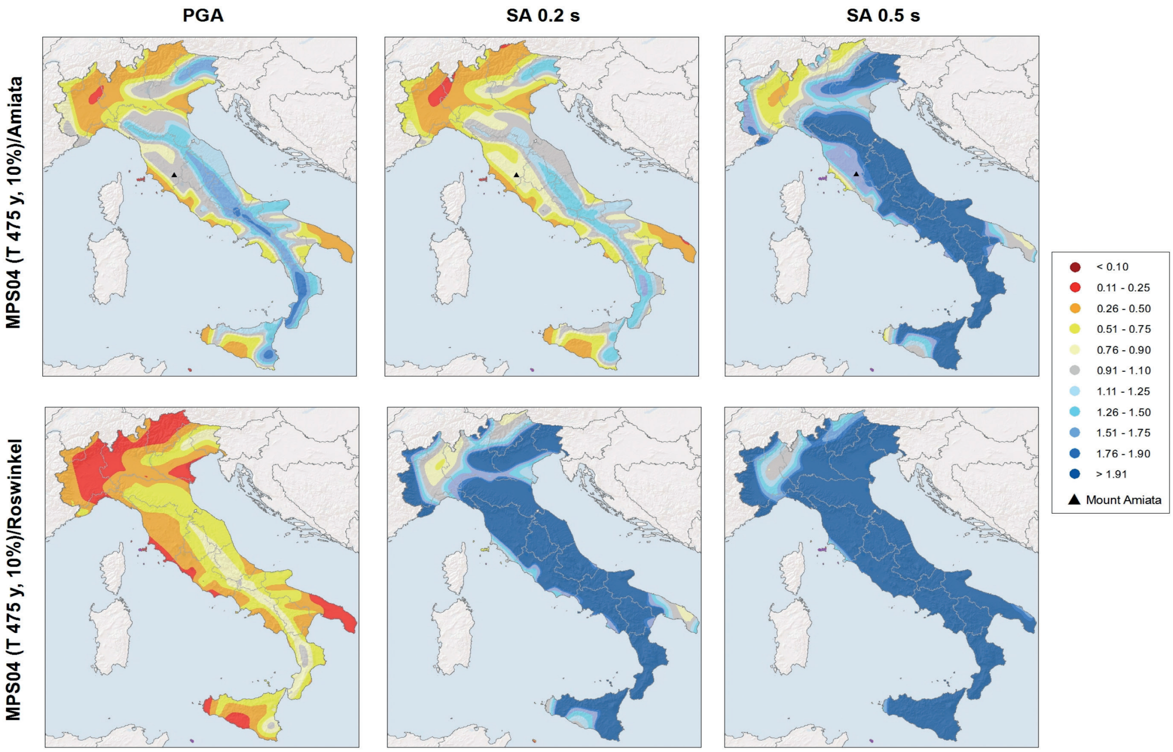

Fig. 2 - Comparison of the spectra corresponding to the Dutch legislation for induced seismicity (bottom, labelled as Roswinkel) and the earthquake of Monte Amiata 2000 (top), respectively, with the spectra with 10% probability of occurrence in 50 years for the whole Italian territory, referred as MPS04. Colours represent the value of the ratio of MPS04 to that of the two induced events, respectively. The Mount Amiata location is shown by a black triangle.

has a prevailing content at short periods and that, although it starts from a peak ground acceleration (*PGA)* anchor value slightly higher than that of the SLV spectrum, it remains far below SLV for all periods. For the Monte Amiata event, despite a richer spectrum, the recorded accelerations remain well below the SLV spectrum for all periods.

At this point, if we assume that the two considered induced events may be representative enough of induced seismicity, it makes sense to extend this approach to the entire national territory and compare the two spectral shapes with the expected values of the accelerations provided by MPS04. The first comparison was made with 10% exceedance probability in 50 years, that is, with a 475-year return period. Fig. 2 shows the ratio between the values of MPS04 divided from those from induced seismicity.

It can be seen that the Netherlands code spectra largely exceed the values of MPS04 in terms of *PGA*, but already for a 0.2 s period, MPS04 provides higher values over the entire national territory. This survey was not extended to periods longer than 0.5 s for two reasons: 1) even for this period only a very limited portion of the Piedmont Region in northern Italy shows a ratio around 1, and 2) the range up to 0.5 s comprises the fundamental period of Italian building up to 30 m (10 storeys), which are the vast majority of the national building stock (Gallipoli *et al.*, 2008). For the Amiata earthquake the case is different. The maximum extension of the territory where the spectrum of the earthquake exceeds the one expected by MPS04 is obtained for a 0.2 s period, while the extension is lower for *PGA* and decreases

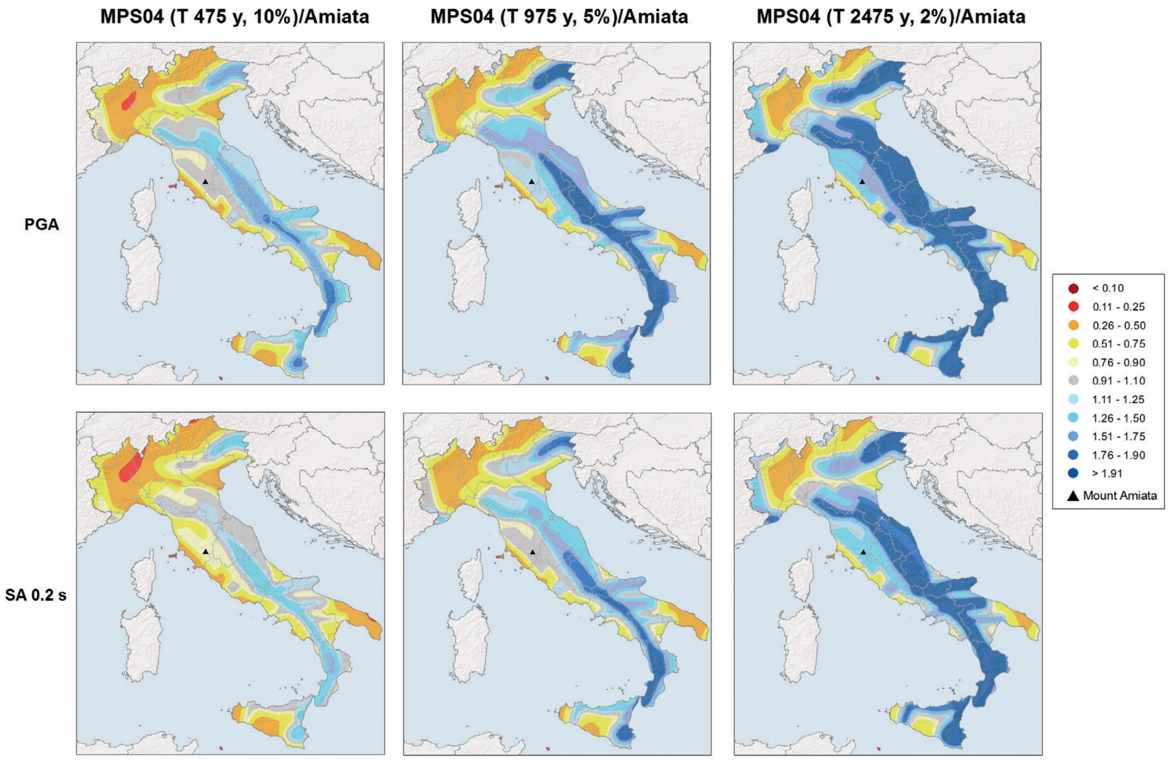

Fig. 3 - Comparison between the Monte Amiata earthquake of 2000 and the spectra with 2%, 5% and 10% probability of exccedance in 50 years for the whole Italian territory. Other details as in Fig. 2.

sharply for 0.5 s. For locations along the Apennines and in the foothills of the central and eastern Alps, natural seismicity is always prevalent. It is interesting how in Tuscany, where the earthquake occurred in 2000, the spectral ordinates are always higher than the expected values on rock along the coast and in the piedmont interior.

Since the occurrence of an event similar to Amiata 2000 brings to the exceedance of the design values for ordinary structures in a significant portion of the less seismic areas in the country, it was decided to consider two other values of interest, i.e., the 975-year return period (used for dams) and the 2475-year one (used for strategic structures). The comparison is shown in Fig. 3: the area where the values of MPS04 are higher than those expected for induced events is significantly reduced for longer return periods.

The last comparison considers the problem of protection deficit for older buildings. All the previous analyses refer to buildings designed since 2009. For older buildings, it has to be taken into account that the last Italian hazard map raised the number of classified municipalities, and thus many buildings were constructed without ASD in areas that now are considered seismic. Fig. 4 reports the comparison in terms of *PGA* between the Monte Amiata event and three periods of building construction: before1984, from 1984 to 2003, and after 2004 (actually, from 2003 to 2009 it was possible to use either new or older construction rules). It can be noted that for older buildings with a protection deficit problem, an event similar to Amiata 2000 could largely exceed any design values.

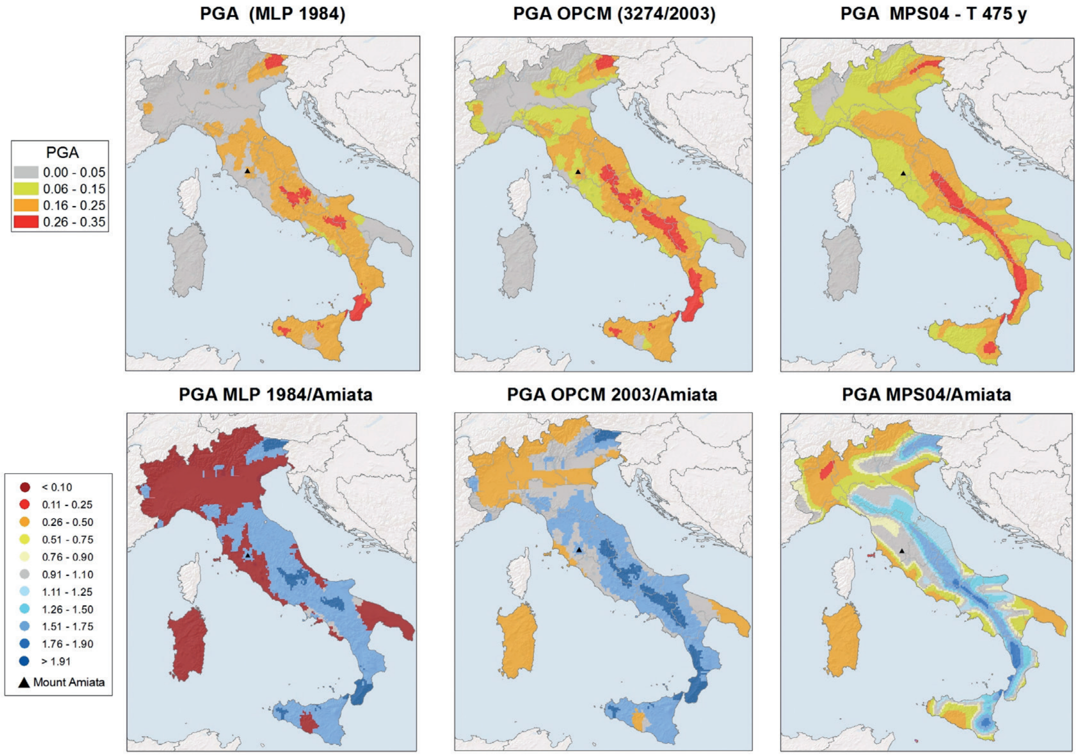

Fig. 4 - Comparison between the Monte Amiata earthquake of 2000 and the code *PGA* for the whole Italian territory, in three different periods: before1984, from 1984 to 2003, and after 2004 (left to right). Other details as in Fig. 2.

3. Conclusions

In this study, although preliminary, we suggest an approach that should be used within EIA for structures, i.e., activities that might potentially be capable of generating induced seismicity. This approach assumes that the national seismic code spectrum is compared to those of some maximum induced events. Our study shows that, in a large portion of the Italian territory, for buildings designed before 1984, an induced event may well exceed the building design acceleration limit, if any was mandatory at the time of construction.

Some suggestions can also be drawn for further development or more-in-depth analyses. For instance, we mention the special case of Sardinia, which was never classified before NTC08 and, being excluded from MPS04 calculation, is now assigned a uniform expected *PGA* equal to 0.05 g all over the island. Mulargia and Castellaro (2004), combining the data of seismic hazard with the distribution of geothermal resources in Italy, concluded that "*the area in which the exploitation of a geothermal hot dry rock system is viable is located in Sardinia, in Campidano, where temperatures at 1,000-metre depth are over 100 degrees and seismicity is virtually absent*". This is correct with regard to strong events triggered by human activity, but we must consider that stimulated geothermal energy [Enhanced Geothermal Systems (EGS)] is much more likely to cause induced seismicity than the techniques involving circulation of fluids at low and medium enthalpy, as shown by the cases that occurred in Switzerland at

Basel (Deichmann and Giardini, 2009) and at Sankt Gallen (Moeck *et al.*, 2015). An induced event, even of small magnitude, in Sardinia could cause accelerations high enough to damage buildings that were never designed to withstand earthquakes.

Acknowledgments. This study has benefitted from funding provided by the Italian Presidenza del Consiglio dei Ministri - Dipartimento della Protezione Civile (DPC) in the framework of Project DPC-INGV S2-T7. This paper does not necessarily represent DPC official opinion and policies. The calculations required by Regione Emilia Romagna for the Pontegradella site were funded by HERA Geotermia. We thank the reviewers T.A. Stabile and A. Panzera, whose comments helped to improve the manuscript.

REFERENCES

Astiz L., Dieterich J.H., Frohlich C., Hager B.H., Juanes R. and Shaw J.H.; 2014; *On the potential for induced seismicity at the Cavone oilfield: analysis of geological and geophysical data, and geomechanical modeling*. Report for the Laboratorio di Monitoraggio Cavone, 139 pp., <labcavone.it/documenti/32/allegatrapporto-studiogiacimento.pdf>.

Batini F., Console R. and Luongo G.; 1985: *Seismological study of Larderello-Travale geothermal area*. Geothermics, **14**, 255-272.

Caciagli M., Camassi R., Danesi S., Pondrelli S. and Salimbeni S.; 20015: *Can we consider the 1951 Caviaga (northern Italy) earthquakes as noninduced events?* Seism. Res. Lett., **86**, 1335-1344.

Deichmann N. and Giardini D.; 2009: *Earthquakes induced by the stimulation of an enhanced geothermal system below Basel (Switzerland)*. Seismol. Res. Lett., **80**, 784-798.

Ellsworth W.L.; 2013: *Injection-induced earthquakes*. Sci., **341**, doi:10.1126/science.1225942.

Gallipoli M.R., Mucciarelli M. and Vona M.; 2008: *Empirical estimate of fundamental frequencies and damping for Italian buildings*. Earthquake Eng. Struct. Dyn., **38**, 973-988.

ICHESE (International Commission on Hydrocarbon Exploration and Seismicity in the Emilia-Romagna region); 2014: *Report on the hydrocarbon exploration and seismicity in Emilia Region*. Regione Emilia-Romagna, E-R Ambiente, Geologia, sismica e suoli, Bologna, Italy, 213 pp., <mappegis.regione.emilia-romagna.it/gstatico/documenti/ICHESE/ICHESE_Report.pdf>.

ISPRA (Institute for Environmental Protection and Research); 2014: *Rapporto sullo stato delle conoscenze riguardo alle possibili relazioni tra attività antropiche e sismicità indotta/innescata in Italia*. Istituto Superiore per la Protezione e la Ricerca Ambientale, Roma, Italy, 71 pp., <www.isprambiente.gov.it/files/notizie-ispra/notizia-2014/rapporto-sismicita-indotta-innescata-in-italia/Rapporto_sismicita_indotta_innescata_in_italia.pdf>.

ITASA (Italian Accelerometric Archive); 2014: *Italian Accelerometric Archive version 2.0*. Istituto Nazionale di Geofisica e Vulcanologia - Protezione Civile Nazionale, Milano - Roma, <itaca.mi.ingv.it>.

Moeck I., Bloch T., Graf R., Heuberger S., Kuhn P., Naef H., Sonderegger M., Uhlig S. and Wolfgramm M.; 2015: *The St. Gallen project: development of fault controlled geothermal systems in urban areas*. In: Proc. World Geothermal Congress, Melbourne, Australia, <pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/06020.pdf>.

Mucciarelli M.; 2013: *Induced seismicity and related risk in Italy*. Ing. Sismica, **30**, 118-122.

Mucciarelli M., Gallipoli M.R., Fiaschi A. and Pratesi G.; 2001: *Osservazioni sul danneggiamento nella zona del Monte Amiata a seguito del terremoto del 1° Aprile 2000*. In: Atti X Congresso Nazionale "L'Ingegneria Sismica in Italia", Potenza-Matera, Italy, CD-Rom Edition.

Mulargia F. and Castellaro S.; 2004: *Geotermia stimolata e rischio sismico: un compromesso difficile*. In: Atti Conferenza Nazionale sulla Politica Energetica in Italia, Bologna, Italy.

Panzera F., Lombardo G. and Rigano R.; 2011: *Use of different approaches to estimate seismic hazard: the study cases of Catania and Siracusa, Italy*. Boll. Geof. Teor. Appl., **52**, 687-706.

Stabile T.A., Giocoli A., Perrone A., Piscitelli S. and Lapenna V.; 2014: *Fluid injection induced seismicity reveals a NE dipping fault in the southeastern sector of the High Agri Valley (southern Italy)*. Geophys. Res. Lett., **41**, 5847-5854, doi:10.1002/2014GL060948.

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. Seismol. Soc. Am., **101**, 1885-1911.

UNMIG; 2014: *Indirizzi e linee guida per il monitoraggio della sismicità, delle deformazioni del suolo e delle pressioni di poro nell'ambito delle attivita' antropiche*. Ministero Sviluppo Economico, Commissione Idrocarburi e Risorse Minerarie (CIRM), 38 pp., <unmig.sviluppoeconomico.gov.it/unmig/agenda/upload/85_238.pdf>.

van Eck T., Goutbeek F., Haak H. and Dost B.; 2006: *Seismic hazard due to small-magnitude, shallow-source, induced earthquakes in The Netherlands*. Eng. Geol., **87**, 105-121.

Corresponding author: Marco Mucciarelli
OGS – Istituto Nazionale di Oceanografia e di Geofisica Sperimentale
Borgo Grotta Gigante 42c, 34010 Sgonico (TS), Italy
Tel: +39 040 2140221; fax: +39 040 327307; e-mail: mmucciarelli@inogs.it