FEASIBILITY STUDIES TOWARDS A PROBABILISTIC SEISMIC HAZARD ANALYSIS FOR HYDROCARBON EXTRACTION AND WASTEWATER INJECTION ACTIVITIES

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In recent years, great efforts have been devoted to the study of the human-induced earthquakes, owing to the effect that these earthquakes can have in terms of seismic hazard. In the past, different authors proposed classification schemes for distinguishing different mechanisms for fluid-induced seismicity generation (see, e.g. McGarr 2000). For example, it has been suggested that when the anthropic activities are responsible for a very small part of the stress field perturbations, the seismic events can be classified as "*triggered*", while when the anthropic activities are responsible for the most of stress perturbations driving to the event occurrence, it can be classified as "*induced*". In practice, we can rather consider that it may exist a continuum of cases depending on both the characteristics of technological operations and the local stress state.

Outstanding features of induced seismic sequences is that events can be very shallow and seismicity rates may have a non-stationary character as a consequence of trends in industrial activity. The purpose of our analyses is to implement probabilistic seismic hazard analyses when considering possible effects of georesource development activities. It is recognized that the hazard implications of shallow, small-to-moderate events at short hypocentral distances merit careful evaluation. In implementing a probabilistic seismic hazard framework that takes into account possible seismicity induced by the exploitation of georesources, it is necessary to (1) assess the rate at which seismic events occur (considering both the natural and the induced components) and identify a possible relationship between induced seismicity rate and parameters characterizing the anthropic activity; (2) quantify the scaling laws dominating the size distribution of the seismic events (including the proper evaluation of event magnitudes and the determination of the maximum event size), and (3) evaluate the ground motion prediction equations governing the seismic energy attenuation processes.

The induced seismic sequences associated with the injection of fluids can be observed both during and after fluid injections. Seismicity rates observed during the injection phases show a different temporal behavior if compared with the one usually observed after the end of injection phases. During injection phases, seismicity is usually "clustered" in time and space and shows non-stationary behavior. Non-stationarity is generally associated with the variability of the forcing associated with fluid injection. However, it is also possible that the induced events produce local stress changes that, in turn, can influence the evolution of the seismic sequence. Therefore, the complexity of the spatial and temporal distribution of the induced seismic sequences is probably linked to the combined contribution of different correlated processes such as the perturbations caused by fluid injection and the interactions between events. During the injection phase, the seismic sequence can be modelled assuming that the dominant factor for the generation of induced seismicity is the disturbance of stress caused by the injection of fluids (e.g., Langenbruch *et al*., 2011; Garcia-Aristizabal, 2018). In particular, in this application, we are considering the method proposed by Garcia-Aristizabal (2018), which models the inter-event distribution between earthquakes, allowing the parameters of the probabilistic model to vary according to covariates chosen among the factors that characterize the injection of fluids (such as the injection rate).

Besides the spatio-temporal behaviour, another key feature of the earthquake occurrence is the frequency-magnitude distribution, and, specifically for this case, the analysis is done at the local scale and in relation to the industrial activity. The starting point of this analysis is the use of a homogeneous data set, but the calculation of the magnitude of small events is a complex and challenging task. We are therefore interested in implementing reliable methods for magnitude

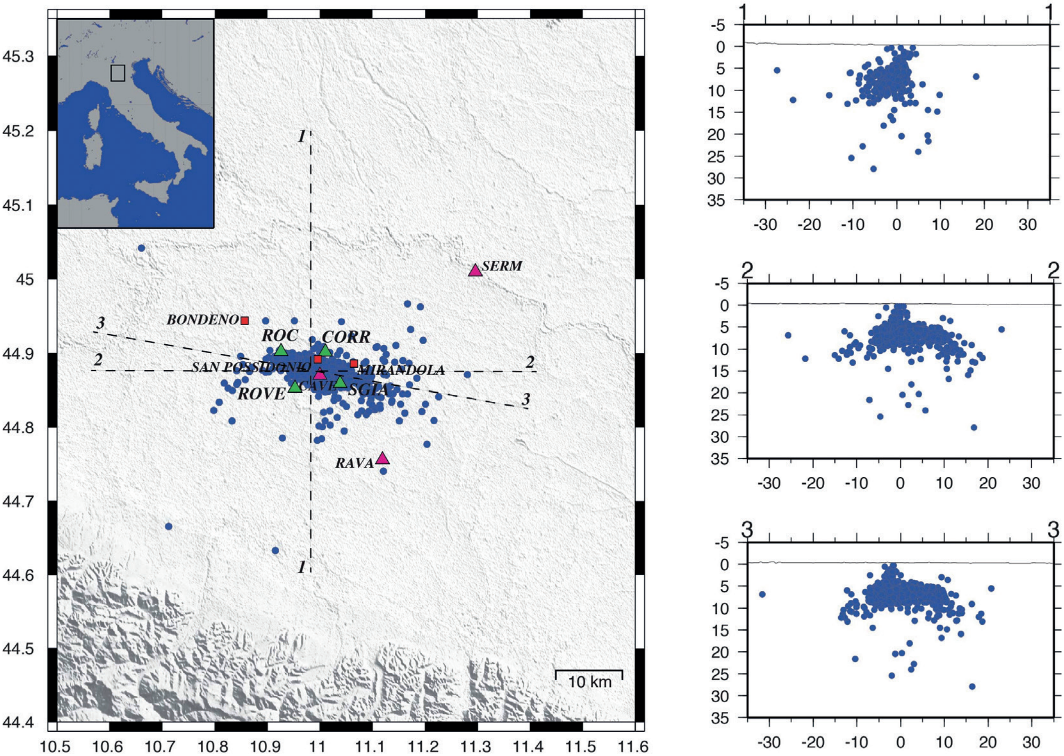

Fig. 1 - Seismicity distribution of about 1000 earthquakes recorded between 2010 and 2017 by the Cavone oil field seismic network (green triangles) in the area. Blue dots show the locations of the earthquakes, pink triangles indicate the Italian National Seismic Network operated by Istituto Nazionale di Geofisica e Vulcanologia (INGV) and the red squares indicate the main cities. Three cross sections (1, 2, 3) show the earthquake distribution at depth along the dotted lines in the main map.

calculation, for which we use an approach based on the maximization of the signal-to-noise ratio by using a technique recently proposed by Malagnini and Munafò (2018), Malagnini and Dreger (2016) and Munafò *et al*. (2016). We calculate the moment magnitude, Mw, of each single event present in the data set, separating the contribution of the seismic source, the site and the regional crustal attenuation (namely, body-wave geometrical spreading g(r), crustal attenuation parameter Q(f), residual systematic attenuation parameter k, as in Munafò *et al*., 2016). Using this approach it is possible to estimate Mw in a clear and unambiguous manner.

Among a number of sites in which we expect to implement the proposed analyses, we are particularly interested in considering as case study the Cavone oil field (Emilia Romagna region, Italy) because of the availability of microseismic data that has been shared within the context of the experimental implementation of the National Guidelines for monitoring (ILG, Indirizzi e Linee Guida), and according to the agreement among the MISE, INGV, Assomineraria and Società Padana Energia. The Cavone oil field is located in the E–W trending sector of the Ferrara arc belonging to the external fold-and-thrust system of the Northern Apennines belt, completely buried by thick Quaternary sediments of the Po plain. The Cavone oil field produces from a Mesozoic carbonate reservoir at a depth of about 2900m. The reservoir lies within an anticline displaced by reverse faulting, in a fold-fault system verging North, intersected by thrust faults oriented E-W.

This site has been thoroughly investigated by different teams after the 2012 Emilia seismic sequence to evaluate the potential of triggering/inducing seismic events by the industrial activities carried out at the field (wastewater reinjection in particular). For example, the report of the ICHESE (International Commission on Hydrocarbon Exploration and Seismicity in the Emilia region; ICHESE, 2014) concluded that it is highly unlikely that the activity in the Cavone oil field was able to produce stress variations to "induce" the 2012 Emilia sequence; furthermore, they concluded that with the available data it is not possible to test nor to exclude a contribution of the hydrocarbon exploitation for "triggering" the activity. In another study, which includes geomechanical field studies performed after the ICHESE report, Astiz et al. (2014) concluded that except within a few hundred meters of the injector well, the fluid pressure within the reservoir is dominated by the net depletion of the field due to oil production, and that the 2012 Emilia sequence was purely correlated to tectonic stress release, rather than triggered by industrial activities performed at the Cavone oil field. Our interest in this case study is to deeply analyse the microseismicity in the surroundings of this field; to perform this task, we have availability of a catalog of about 1000 events recorded in this zone between 2010 and 2017 (thus including the 2012 Emilia seismic sequence) by the Cavone oil field network (Fig. 1). The ultimate goal of our analysis is the implementation of methods for time-dependent probabilistic hazard assessment. An adequate method for non-stationary probabilistic seismic hazard analysis, associated with performance-based criteria to assess potential impacts of induced seismicity (if any), may constitute the base for the implementation of objective mitigation actions. In this framework, of ultimate objective is to propose possible alternatives to the "classical traffic light" methods (for example Bommer et al, 2006) which are based on fixed thresholds of magnitude exceeded during industrial operations.

Acknowledgements. Research supported by *Accordo Operativo 2018-19 INGV - MISE/DGS-UNMIG*. We thank Società Padana Energia for seismic and industrial data.

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