Spatial analysis of the Italian seismic network and seismicity

Analisi spaziale della rete sismica italiana e della sismicità

Antonino D'Alessandro, Marianna Siino, Luca Greco and Giada Adelfio

Abstract Seismic networks are powerful tools for understanding active tectonic processes in a monitored region. Their numerous applications, from monitoring seismicity to characterizing seismogenic volumes and generated seismicity, make seismic networks essential tools for assessing seismic hazard in active regions. The ability to locate earthquakes hypocenters requires a seismic network with a sufficient number of optimally distributed, stations. It is important to assess existing network geometry, to identify seismogenic volumes that are not adequately monitored, and to quantify measures that will allow network improvement. In this work we have studied the spatial arrangement of the stations of the Italian National Seismic Network by means of several Point Pattern techniques The results of the point patter analysis were compare with the spatial distribution of the historical and instrument seismicity and with the distribution of the well know seismogenetic sources of the Italian peninsula. Some considerations have also been made on some models of seismic hazard of the Italian territory. Our analysis allowed us to identify some critical areas that could require an optimization of the monitoring network.

Abstract *Le reti sismiche permettono di misurare e comprendere i processi tettonici attivi in una regione monitorata. Le informazioni acquisite mediante le reti vengono utilizzate per il monitoraggio della sismicità, per la caratterizzazione dei volumi sismogenetici e della sismicità generata, di fatto sono uno strumento essenziale per la valutazione del rischio sismico. Per localizzare gli ipocentri bisogna disporre di una rete sismica con un numero sufficiente di stazioni distribuite in modo ottimale. È importante valutare la geometria della rete esistente, identificare i volumi sismogenetici che non sono adeguatamente monitorati e quantificare le misure che consentiranno il miglioramento della rete. In questo lavoro abbiamo studiato la*

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disposizione spaziale delle stazioni della Rete Sismica Nazionale Italiana attraverso diverse tecniche per lo studio dei processi puntuali. I risultati dell'analisi spaziali delle stazioni sono stati confrontati con la distribuzione spaziale della sismicità storica e strumentale e con la distribuzione delle ben note sorgenti sismiche della penisola italiana. Alcune considerazioni sono state fatte anche su alcuni modelli di pericolosità sismica del territorio italiano. La nostra analisi ci ha permesso di identificare alcune aree critiche che potrebbero richiedere un'ottimizzazione della rete di monitoraggio.

Key words: earthquakes; point process; seismic network; spatial correlation

1 Introduction

The Italian seismic network was developed immediately after the Irpinia seismic crisis in 1980. After this disastrous event, the National Seismic Network (NSN) was established. Initially, the NSN consisted of only few stations spread over Italy. In the 90s, the ING (Istituto Nazionale di Geofisica), then became INGV (Vulcanlogia), upgraded progressively the monitoring network leading, in about thirty years, to the current NSN consisting of about 500 seismic stations. Over the years, the spatial and temporal network development continued, depending on the funds availability for the purchase of the instrumentation and the implementation of monitoring nodes. As it is well known, the quality of the estimate of focal parameters depends on the density and geometry of the monitoring stations. Therefore, the development of a seismic network should be carried out according to precise criteria, designed to guarantee a rational development of the monitoring infrastructure. The most correct criterion is to adapt the seismic network, that is to increase the density of monitoring stations, in the areas with the greatest number of seismogenic structures, historical strong earthquakes and with the greater release of seismic energy observed as instrumental seismicity. Unfortunately, the development of the NSN did not follow a precise criterion, uniformly applied to the whole territory. The result is that the quality of the location and the magnitude of completeness is very inhomogeneous and sometimes does not seem to be rational or proportional to the seismic rate (Schorlemmer et al, 2010; D'Alessandro et al, 2011). This clearly can have repercussions on the quality of the seismic monitoring and studies and it is therefore necessary to identify a simple and effective criterion that could be used for the future NSN optimization. In the following, we propose a statistical approach based on the spatial distribution of the NSN, instrumental and historical seismicity, to evaluate the current degree of the network coverage and plan for future optimization.

2 Data description

We integrate seismological, geological and seismic network data in order to address the goals of the analysis, and in this paragraph they are briefly described. We restrict the study window (W) to the Italian peninsula and Sicilian land boundary because only few stations are placed in offshore areas and Sardinia island is not characterised by a high seismicity. As a matter of fact, at this point of the analysis, we want to relate the spatial distribution of the stations with the seismicity and geological information available on the mainland.

More than 500 stations of the National Seismic Network managed by the National Institute of Geophysics and Volcanology and other networks managed by other bodies are used to locate earthquakes, sending data to the central branch in Rome in real time to monitor the seismicity in Italy. The seismic network is composed by 363 stations (Figure 1a).

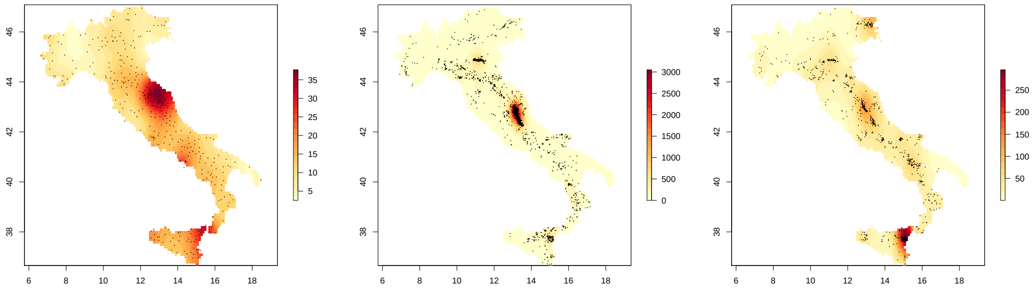
The Italian catalogue contains events since 1985 and we considered the earthquake since 2005, when the network was upgraded and earthquake location was sensibly improved. A subset of the catalogue consisting by 2936 events is analysed, selecting the earthquakes in W with a threshold magnitude equal to 3 and a focal depth less than 50 km (Figure 1b). Furthermore, the historical seismicity is selected starting from the Parametric Catalogue of the Italian Earthquakes, (Rovida et al, 2016) containing 4584 events in the time window 1000-2014; in particular, we select a subset of the events with location, magnitude and depth corresponding to the ones of the catalogue data (Figure 1c).

Additionally, we consider geological information to understand dependence between stations and the sources of earthquakes. The dataset of the Composite Seismogenic Sources (CSS) (Group et al, 2010) is plotted in Figure 2. A composite source represents a complex fault system with an unspecified number of aligned individual seismogenic sources that cannot be separated spatially. In particular for the analysis, we consider the upper edges of the composite sources that for the sake of simplicity are named faults.

The seismic stations, the catalogue events (instrumental seismicity) and the historical seismicity are treated as three spatial point patterns in the region W. Then, we use R (R Development Core Team, 2005) packages for the statistical analysis of spatial patterns of points in two-dimensional space, *spatstat* (Baddeley and Turner, 2005) and *spatstat.local* (Baddeley, 2018).

3 Main results

More formally, a spatial point pattern $\boldsymbol{\upsilon} = \{\mathbf{u}_1, \ldots, \mathbf{u}_n\}$ is an unordered set of points in the region $W \subset \mathbb{R}^d$ where $n(\boldsymbol{\upsilon}) = n$ is the number of points, $|W| < \infty$ and $d = 2$. The first-order intensity is assumed inhomogeneous ($\lambda(\mathbf{u})$) and for our point patterns is estimated non-parametrically to understand the spatial trend (Figure 1). The usual kernel estimator of the intensity function is (Baddeley et al, 2015)



(a) Stations (b) Earthquakes (c) historical seismicity

Fig. 1: Kernel estimate of intensity, with smoothing bandwidth selected by Scott's rule for: (a) the seismic monitoring stations, (b) earthquakes occurred between 2005 and 2018 and (c) the historical seismicity. In (a) and (b), the selected events have a magnitude greater than or equal to 3 and a focal depth less than 50 km. Black points are the events.

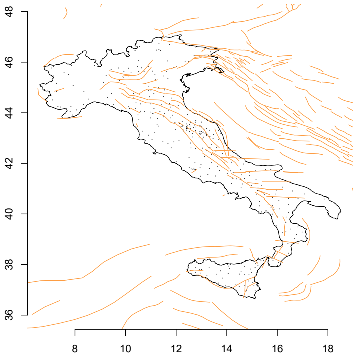


Fig. 2: Faults, upper edges of the composite sources

$$\hat{\lambda}(\mathbf{u}) = 1/e(\mathbf{u}) \sum_{i=1}^{n} k(\mathbf{u} - \mathbf{u}_i, h)$$

where $e(\mathbf{u})$ is the edge corrections and $k(\cdot)$ is a Gaussian density with standard deviation (smoothing bandwidth) equal to h.

From Figure 1a, there is a high concentration of stations in the centre of Italy and in the neighbourhood of the Vesuvio and Etna volcanoes. As for the spatial distribution of instrumental seismicity (Figure 1b), the areas with the higher number of events are in centre of Italy (referring to the Aquila sequence in 2009 and Amatrice-

Norcia-Visso sequence between 2016 and 2018) and in the north centre of Italy for the Emilia sequence in 2012. The historical seismicity (Figure 1c) indicates that most of the seismic activity in Italy is along the alpine and Apennines areas and in Sicily

In this paper, we want to study the relationship between the spatial distribution of the stations with respect to the two types of seismicity (instrumental and historical) under two aspects, their spatial dependence and the global and local characterization. With respect to the first aspect, we compute the inhomogeneous version of the bivariate K-function, to assess if the pair of point patterns are spatially dependent. As it concerns the second aspect, the global and local correlation coefficients are computed to compare the estimated intensities in Figure 1.

Generally for any pair of types i and j, the multitype K-function $K_{ij}(r)$ is the expected number of points of type j lying within a distance r of a typical point of type, i, dividing by the intensity of points of type j. It takes the form

$$K_{ij}(r) = 1/\lambda_j E\left[t(u,r,\mathbf{X}^{(j)})|\mathbf{u} \in \mathbf{X}^{(i)}\right]$$

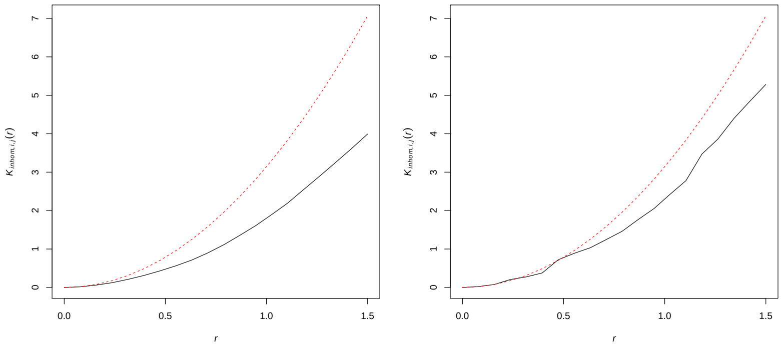
where $\mathbf{X}^{(j)}$ is the sub-process of points of type j, with intensity λ_j, and $t(\cdot)$ is the the number of points in the point pattern $\mathbf{X}^{(j)}$ that lie within a distance r of the location **u**, but not at **u** itself. If the process of type i points are independent of the process of type j points, then $K_{ij}(r)$ is equal to ϕr^2. Deviations between the empirical value of the curve and the theoretical one suggest dependence between the points of types i and j.

For instance, Figure 3a shows the K-cross where the point pattern of stations is type i and the point patterns of earthquake events from 2005 to 2018 is type j. Clearly the two point patterns are dependent and since the observed cross K-function is below the theoretical value, type j events are farther to type i events than it would be expected under complete spatial randomness. Similarly conclusions can be drawn when the K-cross is computed between the point pattern of the stations (type i) and the point pattern of historical seismicity (type j), see Figure 3a. However, for distances up to 0.5 degree, the two distributions (the station and the historical seismic events) seem to be independent.

As expected, the overall correlation between the intensity of stations with respect to the instrumental seismicity and historical seismicity is positive, the Pearson correlation coefficients are 0.423 and 0.643, respectively.

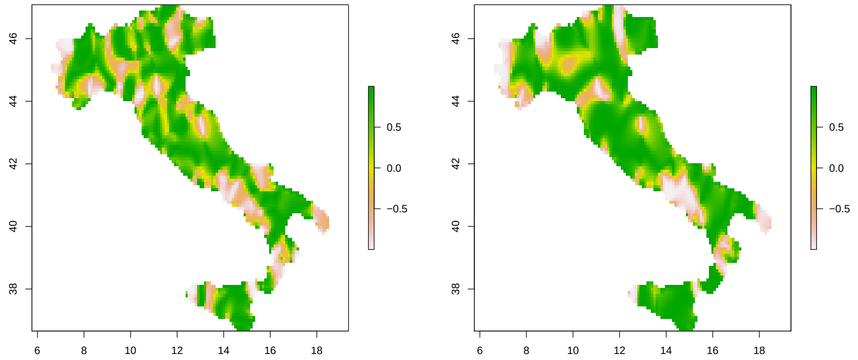
Moreover, considering the estimated intensities as raster data, we want to check if there are variations of correlation in space. Around each cell of the rasters, we define a focal squared area 5x5 and the correlation between the 25 values of each raster in this square is recorded for the central cell, see Figure 4. Comparing the two plots, it seems that there are more areas with negative correlation between the stations and instrumental seismicity (Figure 4a) than the stations and the historical seismicity (Figure 4b). It would suggest the necessity of a development of the current network, not completely concordant with the spatial seismicity evolution.

Finally, the main interest lies in deciding whether the spatial arrangement of the stations occurs more frequently near faults. The geological information in Figure 2



(a) (b)

Fig. 3: (a) The black line is the inhomogeneous bivariate K-function for the seismic station point pattern (type i) and the earthquake events from 2005 and 2018 (type j). (b) The black line is the bivariate inhomogeneous K-function for the seismic station point pattern (type i) and the historical seismicity (type j). In both the plots, the red line corresponds to the theoretical value πr^2.



(a) (b)

Fig. 4: (a) Local correlation coefficient for the raster objects, between the stations and the instrumental seismicity. (b) Local correlation coefficient for the raster objects, between the stations and the historical seismicity. In both cases, the focal squared area has a dimension 5x5.

is transformed into a spatial variables defined at all locations $\mathbf{u} \in W$, namely $D(\mathbf{u})$ distance to the nearest fault. Assuming an inhomogeneous Poisson model with a parametric log-linear form with respect to the covariate D, we estimate the following intensity

$$\lambda(\mathbf{u}) = exp(\beta_0 + \beta_1 D(\mathbf{u}))$$

where the estimates are $\hat{\beta}_0 = 2.84$ and $\hat{\beta}_1 = -1.69$.

Moreover, we obtain with local inference (Baddeley, 2017) spatially-varying estimates of the parameters of the previous inhomogeneous Poisson process model,

$$\lambda(\mathbf{u}) = exp(\beta_0(\mathbf{u}) + \beta_1(\mathbf{u}) D(\mathbf{u}))$$

This approach has the potential to detect and model gradual spatial variation of the parameters that govern the intensity of the stations and the estimates are in Figure 5.

Generally increasing the distance to the nearest fault the station intensity decreases, however according to the spatially varying slope coefficient this reduction is higher in the centre and north-east of Italy.

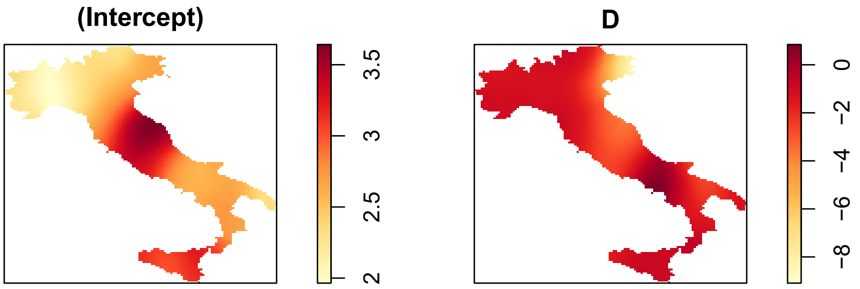


Fig. 5: Spatially varying estimates of intercept (Left) and slope coefficient (Right) from the local likelihood fit of the log-linear model to the seismic station data where the covariate ($D(\mathbf{u})$) is distance to the nearest fault.

4 Conclusions

In this paper we use statistical methods and tools ior the description and characterization of the current degree of the network coverage based on the spatial distribution of the NSN and of the instrumental and historical seismicity, in order to suggest directions for planning future optimization.

As observed from Figure 4, a further upgrade of the network allocation is necessary, in order to get homogeneous and positive correlation in all the Italian area.

In particular, for instance, along the Apennines as well as the West Sicily area, the different correlation between the NSN and instrumental and historical seismicity respectively, suggests the necessity of a network strengthening in those areas.

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