Physics-based Simulator of Short- and Long-Term Seismicity: application to the Central Apennines Region

Maura Murru[1], Roberto Carluccio[1], Rodolfo Console[1], Giuseppe Falcone[1], Matteo Taroni[1], and Paola Vannoli[1]

[1]Istituto Nazionale di Geofisica e Vulcanologia

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Abstract

The application of a physics-based earthquake simulation algorithm to the central Apennines region, where the 24 August 2016 Amatrice earthquake (Mw6.2) occurred, allowed the compilation of a synthetic seismic catalog lasting 100,000 years, and containing more than 300,000 M [?] 4.0 events, without the limitations that real catalogs suffer in terms of completeness, homogeneity and time duration. The seismogenic model upon which we applied the simulator code, was derived from the DISS 3.2.1 database (http://diss.rm.ingv.it/diss/), selecting all the fault systems that are recognized in the central Apennines region, with a total of 54 fault rectangular segments. The physical model on which the last version of our simulation algorithm is based includes, besides tectonic stress loading and static stress transfer as in the previous versions, also the Rate & State constitutive law. The resulting synthetic catalog exhibits typical magnitude, space and time features, which are comparable with those of real observations. These features include (i) an earthquake magnitude distribution departing from the linear Gutenberg-Richter distribution in the moderate and higher magnitude range, (ii) long–term pseudo-periodicity of strong earthquakes and (iii) short- and medium-term earthquake clustering. We found in our synthetic catalog a clear trend of long-term acceleration of seismic activity preceding M [?] 6.0 earthquakes and quiescence following those earthquakes. A typical aspect of the observed seismicity in Italy and of the Central Apennines region in particular, is the occurrence of multiple events of M [?] 5.5 earthquakes close to each other in space and time. A special attention was devoted to verify if the synthetic catalog includes this feature. On this purpose, we applied a specific code written in "Mathematica" to count the number of multiple events contained in a seismic catalog under a quantitative definition, finding that the synthetic catalog contains a large number of multiple events but not as frequently as in the real catalog. Lastly, as an example of a possible use of synthetic catalogs, a ground motion prediction equation was applied to all the events reported in the synthetic catalog for the production of PSHA maps (in terms of PGA).

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[1,*]Maura Murru, [1]Roberto Carluccio, [1,2]Rodolfo Console, [1]Giuseppe Falcone, [1]Matteo Taroni , [1]Paola Vannoli

[1]Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy – [2]Center of Integrated Geomorphology for the Mediterranean Area, Potenza, Italy

*maura.murru@ingv.it

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SUMMARY. A newly developed physics-based earthquake simulation algorithm was applied to a seismogenic model in the Central Apennines Region. This model was derived from the last version of the *Database of the Individual Seismogenic Sources* (DISS), from which 54 seismogenic faults have been recognized. This simulator allowed the compilation of a synthetic seismic catalog lasting 100,000 years, and containing more than 300,000 events of $4.0 \le M \le 7.4$, without the limitations that real catalogs suffer in terms of completeness, homogeneity and time duration. We verify if the clustering features of this catalog are similar to those that characterize the historical and instrumental catalogs obtained from real observations. Our attention was focused on short-and medium-term seismicity patterns with particular reference to the occurrence of multiple events (events with similar magnitude, in a limited space and time window).

1. A NEWLY DEVELOPED PHYSICS-BASED EARTHQUAKE SIMULATOR

We applied to the geological model, composed by 54 fault systems redrawn from DISS (2018) (**Fig. 1**), a new version of the simulator that we applied in *Console et al.* (2017, 2018). This updated version includes, besides tectonic stress loading of each fault, according to observed slip rate, and static stress transfer, also the *Rate & State* constitutive law (*Dieterich* 1994). The nucleation point and occurrence time for earthquakes is determined randomly by a stochastic procedure, rather than by a deterministic rule. The obtained synthetic catalogs provide realistic features of earthquake clustering and a sort of Omori law after strong earthquakes, not achieved by the other previous versions. The faults were discretized in cells of 0.75 km x 0.75 km. The smallest magnitude generated by an earthquake that breaks a single cell is ≅ 3.75 with a slip of 0.029 *m* and a seismic moment equal to 0.50E+15 *Nm*, assuming a stress drop of 3.0 *MPa*.

Three free parameters basically control the nucleation point, propagation and stopping of a rupture in the simulator algorithm:

- $A\sigma$ (*Rate & State* constitutive law), affects the probability of earthquake nucleation following the co-seismic stress change due to previous events;
- "Strength Reduction" (*S-R*) reduces the effective strength on the edges of an already nucleated rupture; its increase encourages the growth of ruptures;
- "Aspect Ratio" (*A-R*) discourages the propagation of a rupture beyond very long lengths. It is relevant only if it is smaller than the ratio between the length and the width of the considered fault, and produces significant effects in the large magnitude range of the frequency-magnitude (*F-M*) distribution.

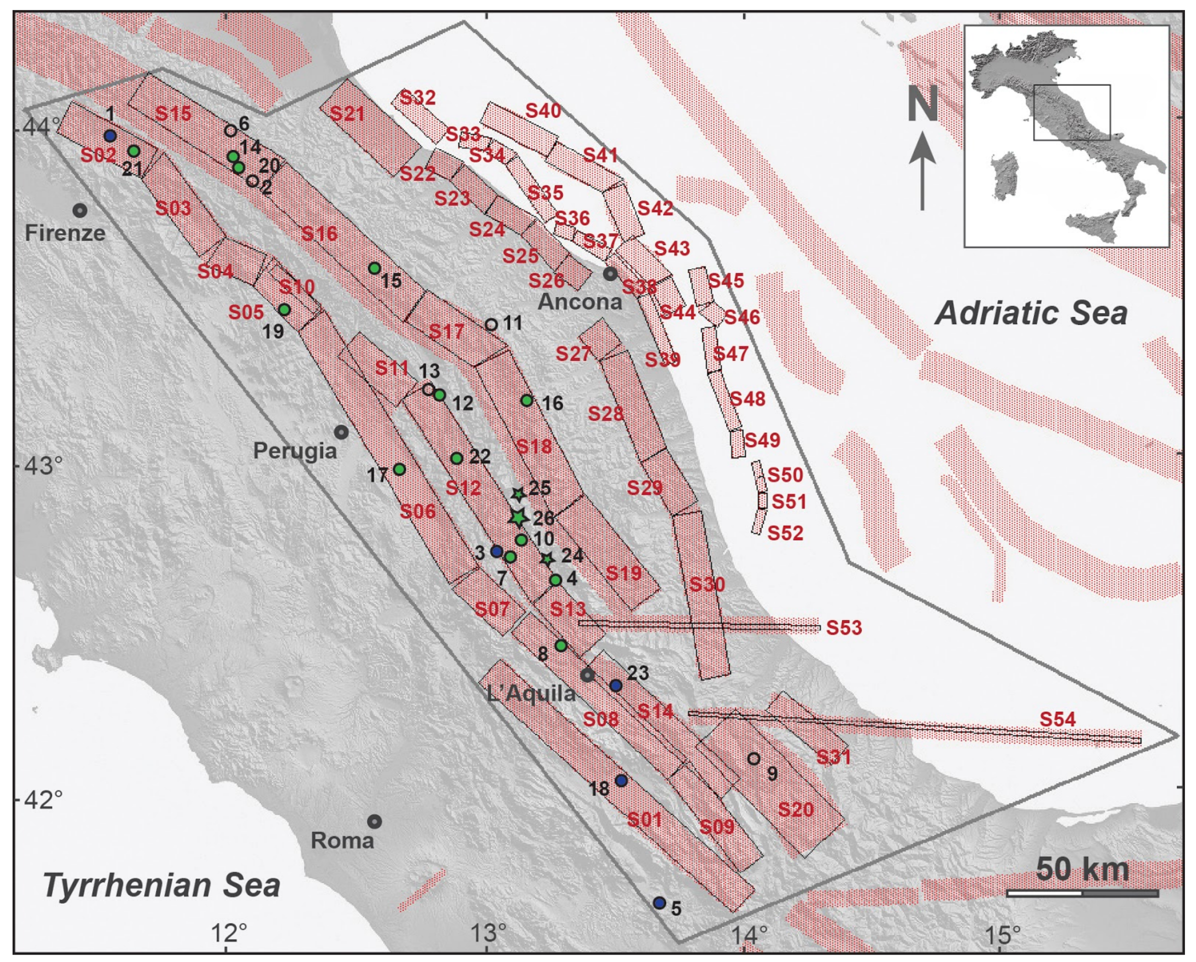

Fig. 1. Seismotectonic setting of the study area showing the projections on the ground surface of the Seismogenic Fault Systems specifically developed for this study (*DISS Working Group*, 2018; www.diss.rm.ingv.it/diss/). The 23 epicenters of the CPTI15 catalog and the 3 events of the 2016-2017 seismic sequence both with $M_w \ge 6.0$ are shown by circles and stars, respectively

2. A NEW ALGORITHM FOR CLUSTERING ANALYSIS OF MULTIPLE EVENTS

An algorithm for the clustering features was specifically developed on a Mathematica platform. The procedure analyzes a given seismic catalog working on comparisons between time ordered couples of events *A*-to-*B*, where event *A* precedes *B*. The four following criteria are checked for catching a multiple event: 1) magnitude M_A of A event; 2) temporal distance $t_B - t_A$; 3) spatial distance *d* (A,B) of hypocenters; 4) magnitude differences for $M_B - M_A$.

The search of multiple events is based on the following arbitrary criteria: each earthquake with $M_0 \ge 5.5$ is considered coupled with the following ones only if it is in the range of magnitude $M_0 - 0.5 \le M \le M_0 + 0.5$, within a time delay $t_B - t_A$ according to the *Gardner and Knopoff* (1974) empirical rule applied to the first earthquake of a couple and a maximum distance *d* (A,B) given by the sum of the radii given by the *Gardner and Knopoff* (1974) rule applied to both earthquakes of the same couple. According to this algorithm the same earthquake is not allowed to be assigned to more than one multiple event.

3. APPLICATION TO THE CENTRAL APENNINES REGION

The first steps of the simulator application were aimed to the optimization of the three free parameters ($A\sigma$, *S-R* and *A-R*) through an empirical trial-and-error learning method, following the criterion of obtaining synthetic catalogs whose features were as similar as possible to those of real catalogs.

The main criteria were the *F-M* distribution and clustering properties of the seismicity, with particular emphasis given to the latter, taking into account the frequent occurrence of multiple events observed in the seismicity of the study area.

The effect of each of the three free parameters was analyzed fixing two of the parameters and letting the third one to change in a range of possible values. After these tests, we adopted the values of $A\sigma$ = 0.05 MPa, *S-R* = 0.15 and *A-R* = 10 for running the simulator over a period of 100 kyr, preceded by a warm up period of 20 kyr not used in the output catalog.

4. COMPARISON BETWEEN THE SYNTHETIC AND OBSERVED CATALOGS

Taking into account the different time length of the synthetic (100 kyr) and observed (CPTI15 in the completeness interval for $M \ge 5.0$, 367 yrs) catalogs, and the respective number of multiple events, we can obtain a comparison between the two catalogs as reported in **Table 1**. The annual seismic moment, M_0 (5.44E+17 *Nm/yr*) obtained from the observed catalog, corresponds to the seismic moment released by just an event of *M* about 5.75 per yr. If we consider the 100,000 yr synthetic catalog we get a value of M_0, equal to 2.86E+17 *Nm/yr*, corresponding to an event of *M* about 5.58 per *yr* (**Table 1**). The largest magnitude is 7.08 (Marsica earthquake, January 13, 1915) and 7.42 for the updated CPTI15 and the simulated catalog, respectively. Possible hypotheses justifying the larger value that has been found for the real catalog could be one or a combination of 1) underestimation of the slip rates that have been considered in the fault model, 2) overestimation of the magnitude of the largest events of the real catalog.

The comparison in **Table 2** puts in evidence a clear predominance in the rate of multiple events contained in the observed seismicity, with respect to that contained in the synthetic earthquake catalog, only partially justified by the different rate of $M \ge 6.0$ earthquakes. In fact the present version of the simulator does not include rheological phenomena and viscosity of the upper mantle, which are frequently mentioned as possible causes of slow stress variations and medium-term seismicity migration.

We compare the *F-M* distribution of the synthetic catalog with the real observation of the seismicity (CPTI15 from 1650 and 1900, with different completeness intervals) (Fig. 2). The difference that can be seen between them depends on the fact that the *b*-value of the simulated catalog is not uniform in different magnitude intervals, while that of the real catalogs is close to 1.0 over the whole explored magnitude range. The difference in the low magnitude range could be ascribed to the fact that the synthetic catalog contains only events nucleated inside the main 54 seismogenic faults of the geological model, while the observed seismicity contains events generated by many small auxiliary faults.

Features	Synthetic catalog	CPTI15
Number of earthquakes of $M \ge 4.0$	308,478	na
Number of earthquakes of $M \ge 5.0$	56,021	154
Number of earthquakes of $M \ge 6.0$	2,672	18
*M*max	7.42	7.08
Annual seismic moment ($M \ge 4.0$)(*Nm/yr*)	2.86E+17	5.44E+17
Number of earthquakes of $M \ge 6.0$ rupturing only one seismogenic fault	1,907	na
Number of earthquakes of $M \ge 6.0$ rupturing at least two seismogenic faults	765	na
Largest number of seismogenic faults ruptured in one earthquake of $M \ge 6.0$	8	na
Number of multiple events ($M \ge 5.5$)	657	7

Table 1. Features of the 100,000 yr synthetic catalog, obtained fixing $A\sigma$ = 0.05 MPa, *S-R* = 0.15 and *A-R* = 10, compared with the results obtained from the CPTI15 catalog analysis (1650-2017, *M*5+)

R	Synthetic catalog (100,000 yrs)	CPTI15 catalog ($M \ge 5.0$,1650-2017)
Rate of earthquakes ($M \ge 6.0$) in 1,000 yrs	26.72	49.04
Rate of multiple events ($M \ge 5.5$) in 1,000 yrs	6.57	19.07

Table 2. Comparison between the rate of multiple events contained in the synthetic and observed seismicity

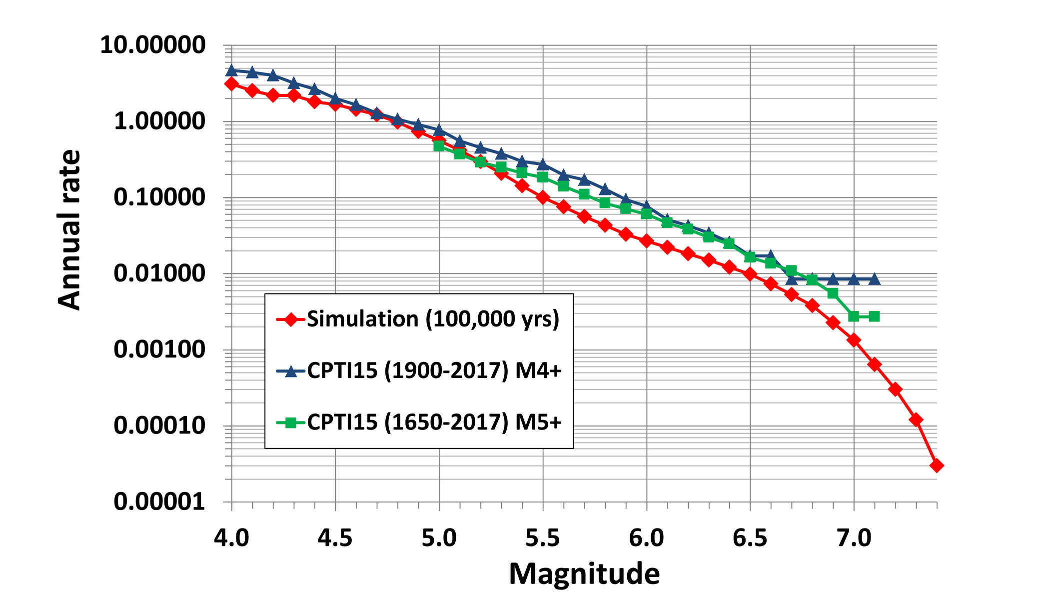

Figure 2. Cumulative *F-M* distribution of the earthquakes in the synthetic catalog, compared with those obtained from CPTI15 for the magnitude thresholds and the time intervals during which they are assumed complete

5. TEST OF POISSON BEHAVIOR

To test the Poissonicity of the inter-event times in the synthetic catalog and in particular for a few selected seismogenic faults we apply two statistical procedures: the *Lilliefors test* and the *Runs-test* (**Table 3**). If the *p*-value of both tests is larger than 0.01, we say that the catalog is Poissonian. The coefficient of variation, C_v (ratio between the standard deviation and the mean of the inter-events times) is also computed.

For the whole region the null hypothesis can be rejected for $M \ge 5.0$ and ≥5.5 (presence of a moderate clustering features, $C_v > 1.0$), and not for larger magnitudes. The Poissonicity can be rejected also for the three catalogs regarding single faults both for M≥5.0 (still in connection with clustering) and even for $M \ge 6.5$ (pseudo-periodicity). The situation is more complex in the intermediate magnitude ranges ($M \ge 5.5$ and ≥6.0) because of the superposition of the two opposite effects, producing values of C_v closer to 1.0.

Region/Fault	*M* range	*N.* of events	*p*-value (Lilliefors test)	*p*-value (Runs test)	*Cv*	Poissonian ?
Study area	$M \ge 5.0$	49,344	< 0.001	2.4E-06	1.07	No
	$M \ge 5.5$	8,682	< 0.001	0.01	0.99	No
	$M \ge 6.0$	2,319	0.02	0.05	0.94	Yes
	$M \ge 6.5$	775	0.5	0.3	0.94	Yes
S01 Marsica	$M \ge 5.0$	8,208	< 0.001	0.006	2.15	No
	$M \ge 5.5$	1,304	< 0.001	0.49	1.29	No
	$M \ge 6.0$	310	0.17	0.46	0.90	Yes
	$M \ge 6.5$	117	< 0.001	0.11	0.67	No
S12 Colfiorito-Campotosto area	$M \ge 5.0$	3,242	< 0.001	0.0002	1.57	No
	$M \ge 5.5$	493	0.27	0.50	1.02	Yes
	$M \ge 6.0$	133	0.02	0.79	0.82	Yes
	$M \ge 6.5$	46	0.001	0.09	0.75	No
S14 L'Aquila area	$M \ge 5.0$	3,490	< 0.001	0.33	1.44	No
	$M \ge 5.5$	547	0.004	0.58	0.97	No
	$M \ge 6.0$	155	< 0.001	0.57	0.72	No
	$M \ge 6.5$	70	< 0.001	0.54	0.54	No

Table 3. Results of the statistical tests of Poissonian behaviour of earthquakes of the 100,000 yrs synthetic catalog and for 3 selected seismogenic faults

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