UNIVERSITÀ DEGLI STUDI
DI NAPOLI FEDERICO II

Aftershocks' effect on design seismic actions in Italy

Iunio Iervolino
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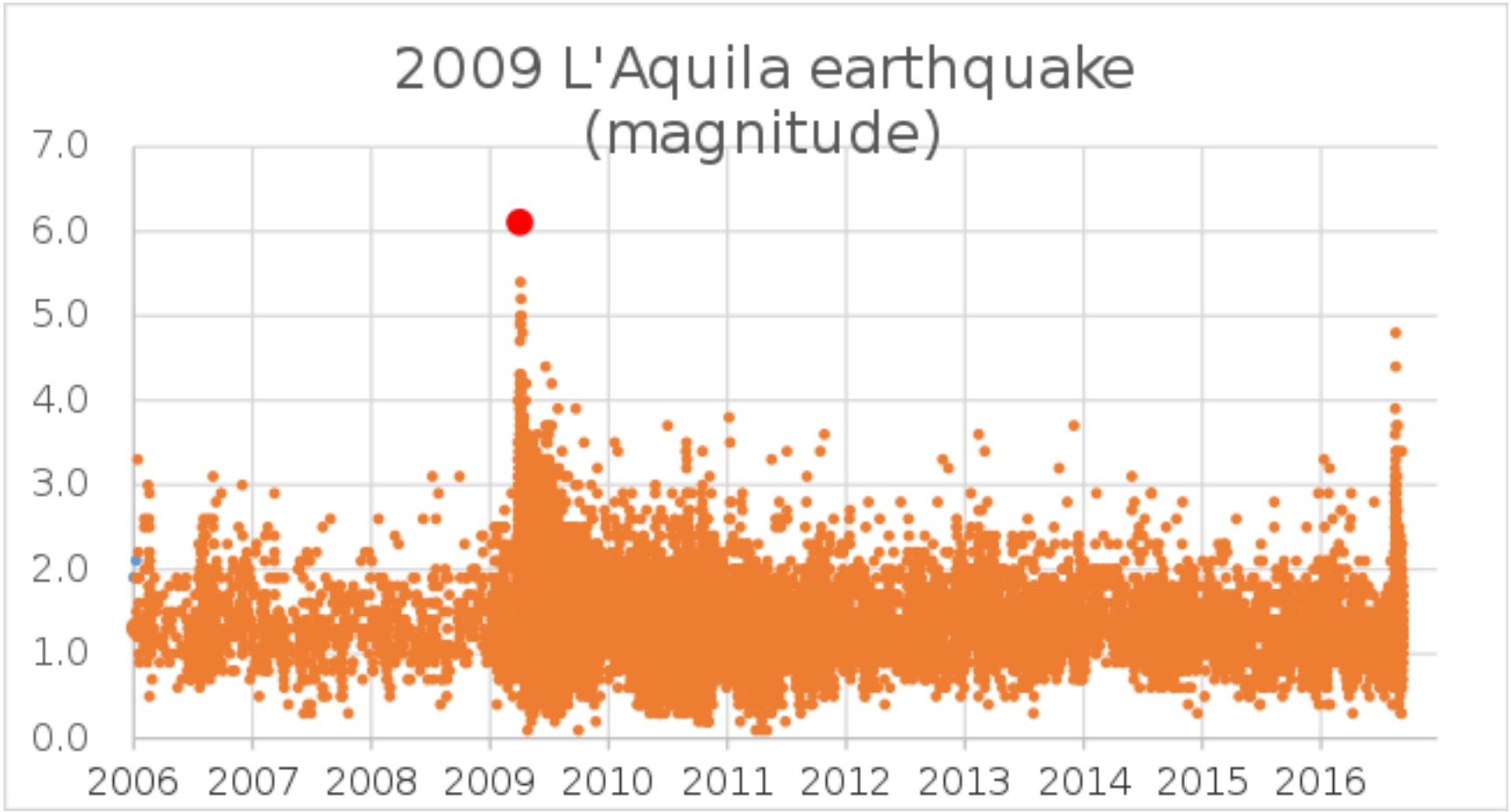


Why a declustered catalog?

1. **Incompleteness with respect to aftershocks.**
2. **Ease of use of the Homogeneous Poisson Process.**
3. **Negligibility of aftershocks for seismic risk (?).**

Classical-hazard integral (after Cornell, 1968; McGuire, 1974…)

Probability of exceedance in a generic earthquake: $P[IM > im]$

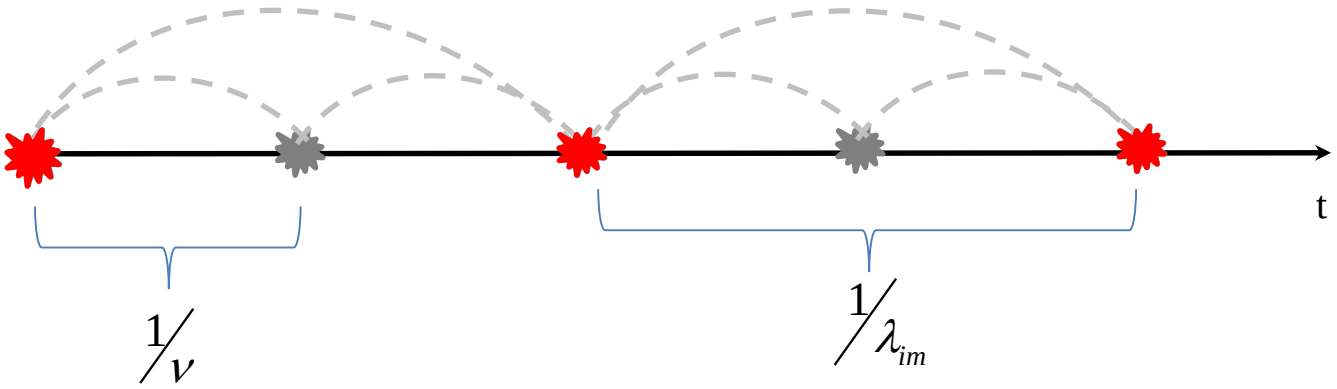
Rate of earthquakes causing exceedance

$$\lambda_{im} = \nu \cdot \int_{r_{min}}^{r_{max}} \int_{m_{min}}^{m_{max}} P[IM > im \mid x, y] \cdot f_{M_E, R_E}(x, y) \cdot dx \cdot dy$$

Rate of occurrence from declustered catalog (mainshocks)

GMPE

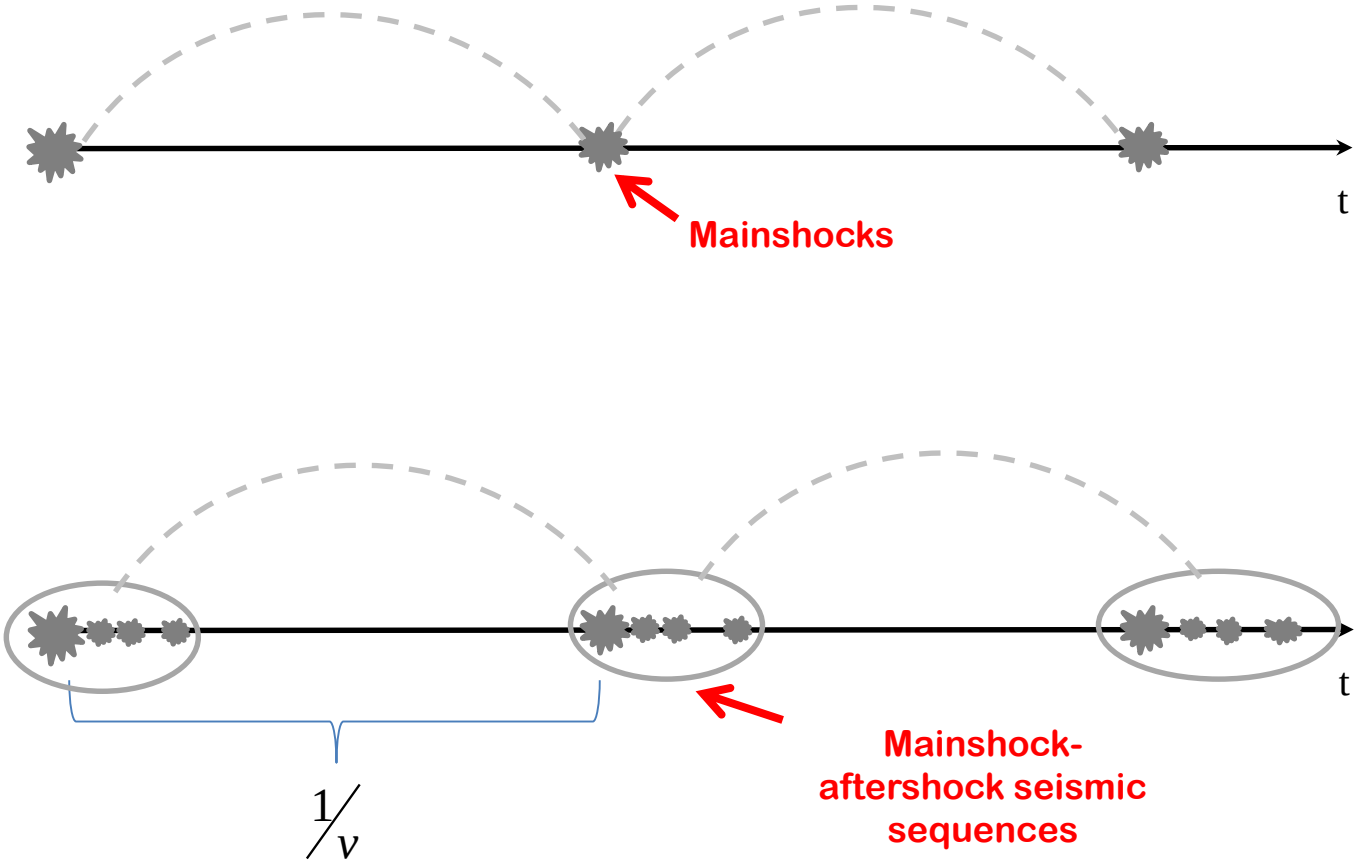
Distribution of source features



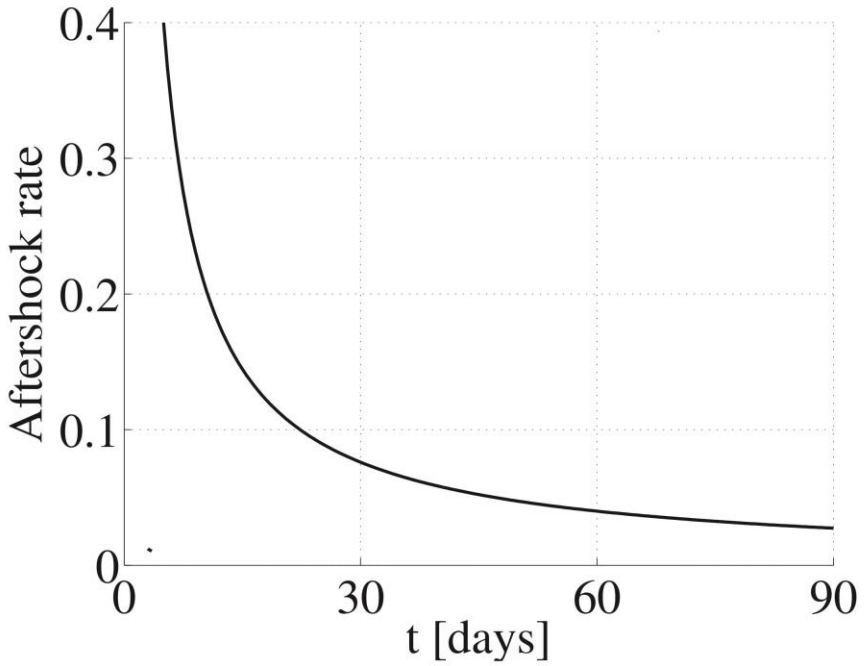
Motivation/Goal

- PSHA is built on declustered catalogs (it allows to use the homogeneous Poisson process for earthquake occurrence).
- It is known that major earthquakes are followed by aftershock sequences.
- The exceedance of the *im* can occurr not only in the mainshock but also in the aftershocks.
- If the effect of afteshocks on the annual rate of exceedance of the *im* is significant, it may be of engineering interest to include it in hazard analysis so not to underestimate the design risk.
- The goal is pursued with the least modifications possible to the hazard integral and still considering a declustered catalog.

Mainshock-aftershock sequences occur at the same rate of mainshocks (after Toro and Silva, 1996; Boyd, 2012)



Aftershock probabilistic seismic hazard analysis (after Yeo and Cornell 2009)



Aftershock-hazard integral

$$\lambda_{im|m}(\tau) = \nu_{A|m}(\tau) \cdot \iint_{M,R} P[IM > im \mid w,z] \cdot f_{M,R}(w,z) \cdot dw \cdot dz \cdot d\tau$$

To include aftershocks in classical hazard the probability that the *im* is exceeded in the aftershocks sequence must be accounted for

$$\lambda_{im} = \nu \cdot P\left[IM > im \cup IM_{\cup A} > im \right] =$$

$$= \nu \cdot \left\{ 1 - P\left[IM \le im \cap IM_{\cup A} \le im \right] \right\} =$$

$$= \nu \cdot \left\{ 1 - \iint_{M,R} P\left[IM \le im \mid x, y \right] \cdot P\left[IM_{\cup A} \le im \mid x, y \right] \cdot f_{M,R}(x, y) \cdot dx \cdot dy \right\} =$$

GMPE

Probability that zero aftershocks exceed IM in the sequence

Distribution of source features (mainshocks)

$$P\left[IM_{\cup A} \le im \mid x, y \right] = e^{-\int_0^{\Delta T_A} \nu_{A|x}(\tau) \cdot \iint_{M,R} P\left[IM \le im \mid w, z \right] \cdot f_{M,R}(w, z \mid x, y) \cdot dw \cdot dz \cdot d\tau}$$

Sequence-based probabilistic seismic hazard analysis (SPSHA)*

$$\lambda_{im} = \nu \cdot \left\{ 1 - \iint_{M,R} P\left[IM \le im \mid x,y\right] \cdot e^{-\int_0^{\Delta T_A} \nu_{A|x}(\tau) \cdot \iint_{M,R} P\left[IM \le im \mid w,z\right] \cdot f_{M,R}(w,z \mid x,y) \cdot dw \cdot dz \cdot d\tau} \cdot f_{M,R}(x,y) \cdot dx \cdot dy \right\}$$

Still rate of mainshocks

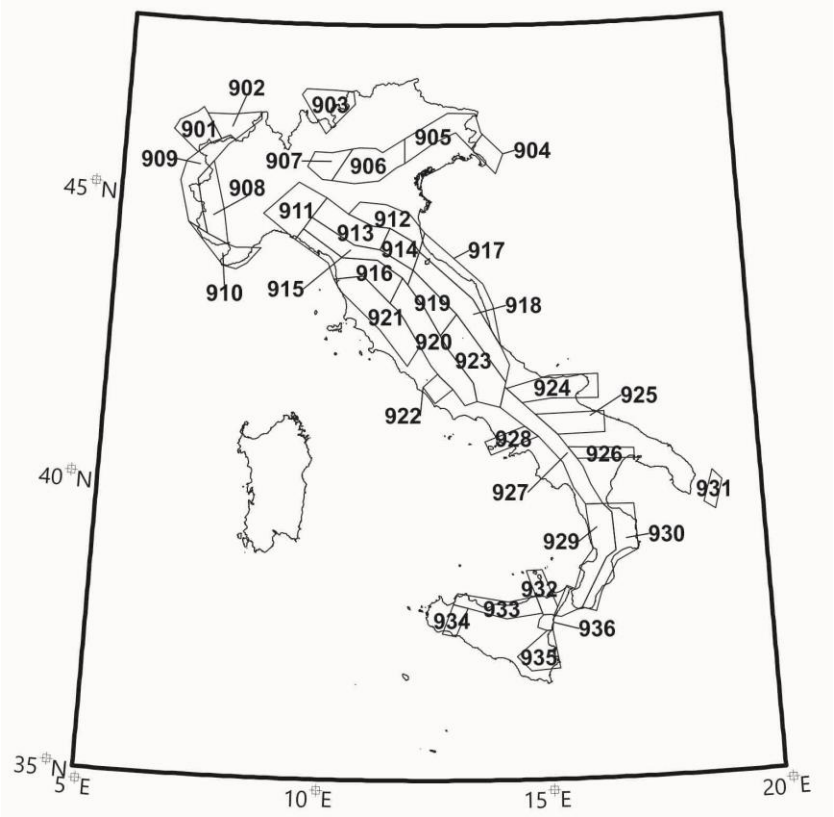
GMPE

Probability of not exceeding the IM threshold due to aftershocks

Distribution of source features (mainshocks)

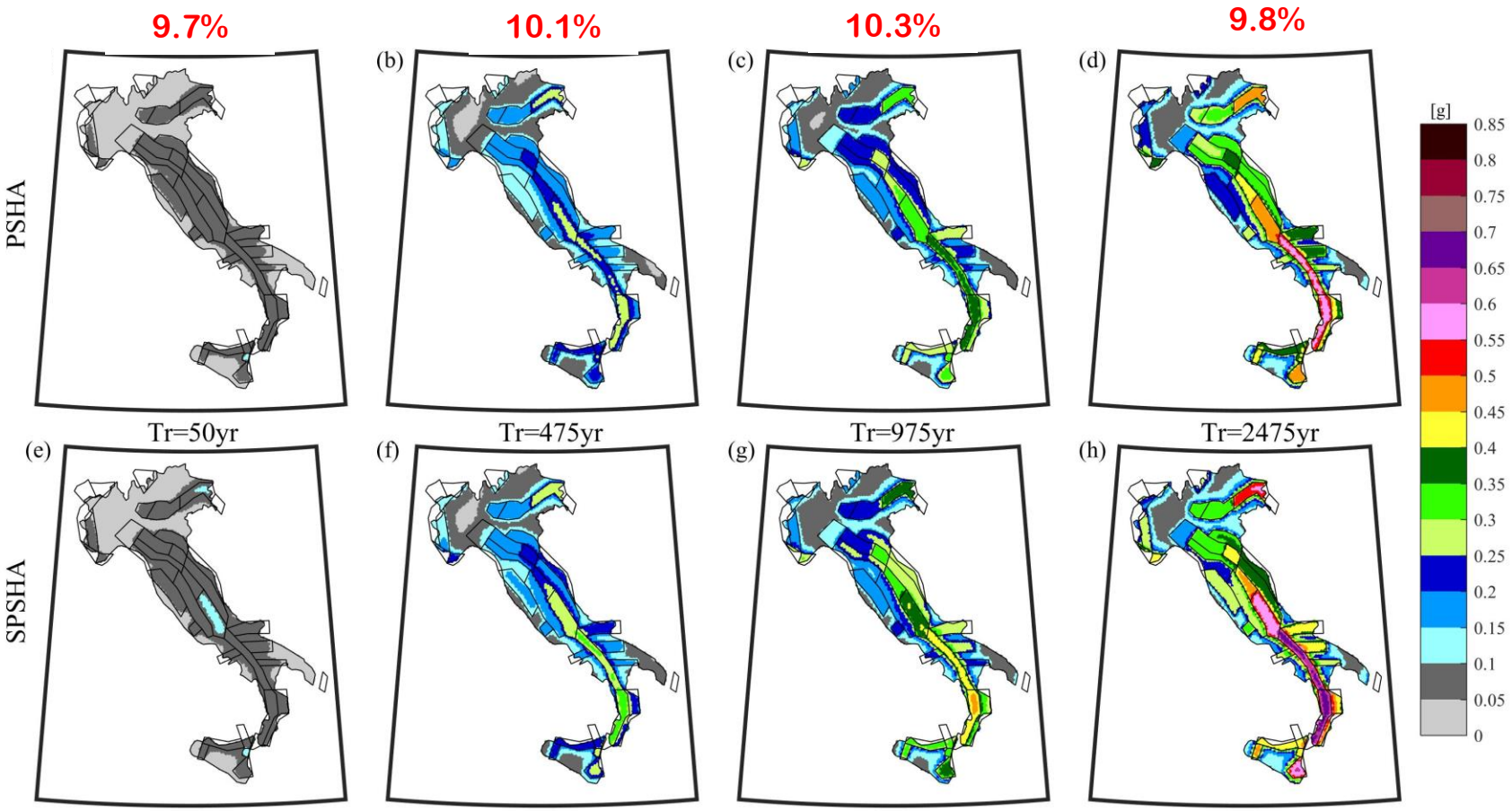
*Iervolino, Giorgio, Polidoro (2014). Sequence-based probabilistic seismic hazard analysis. Bull. Seismol. Soc. Am., 104: 1006-1012.

Application to Italy



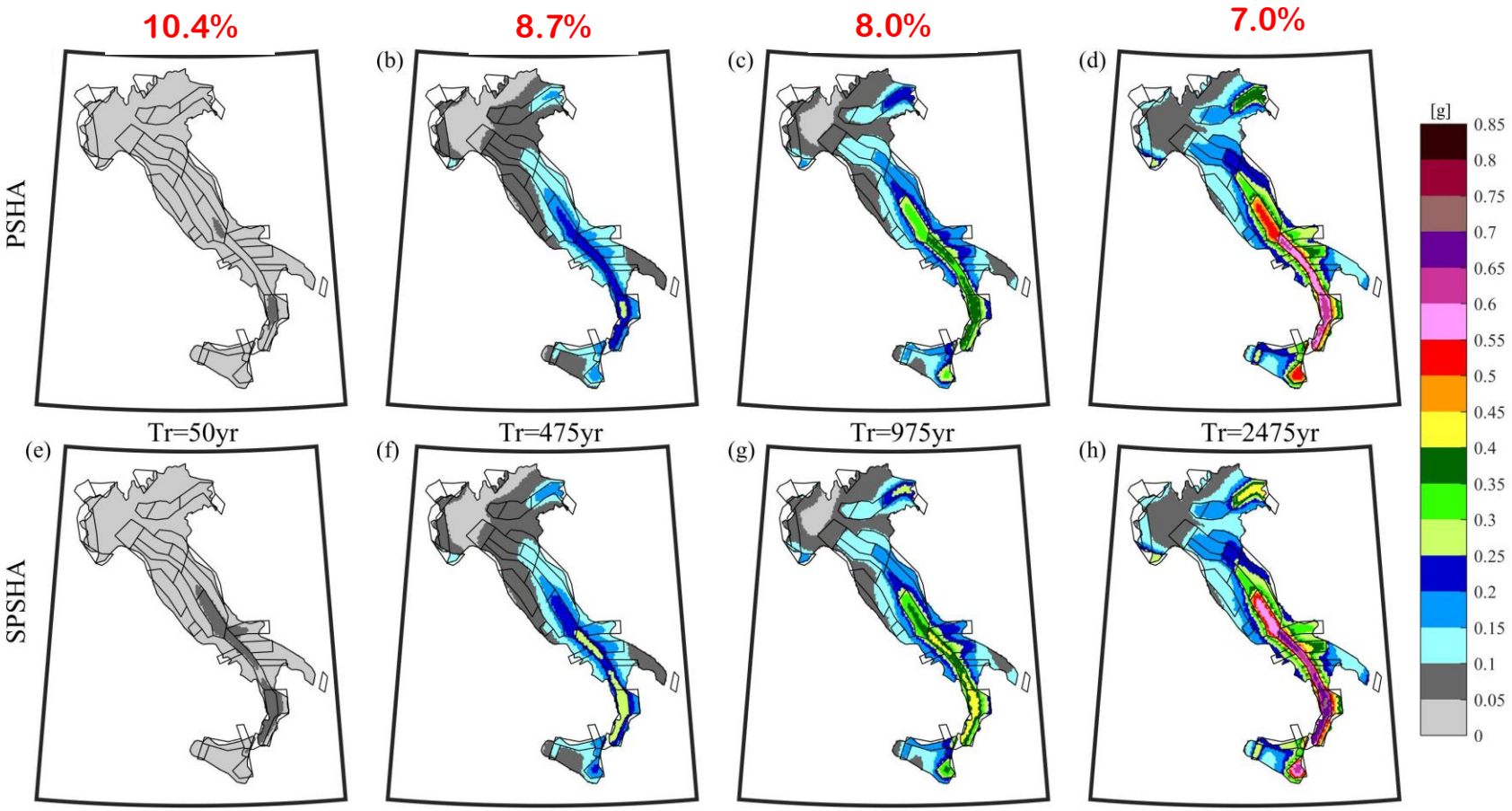
- Source model of the Italian hazard map (MPS04) branch 921 of the logic tree (Stucchi et al., BSSA, 2011);
- The generic aftershock sequence modified Omori law parameters from Lolli and Gasperini (J. Seismol., 2002);
- Relationship between earthquake magnitude and aftershock area from Utsu (1970).

PSHA vs SPSHA in terms of PGA*



*Iervolino I., Chioccarelli E., Giorgio M., (2018) Aftershocks' Effect on Structural Design Actions in Italy. Bull. Seismol. Soc. Am. 108: 2209–2220.

PSHA vs SPSHA in terms of Sa(T1s)*



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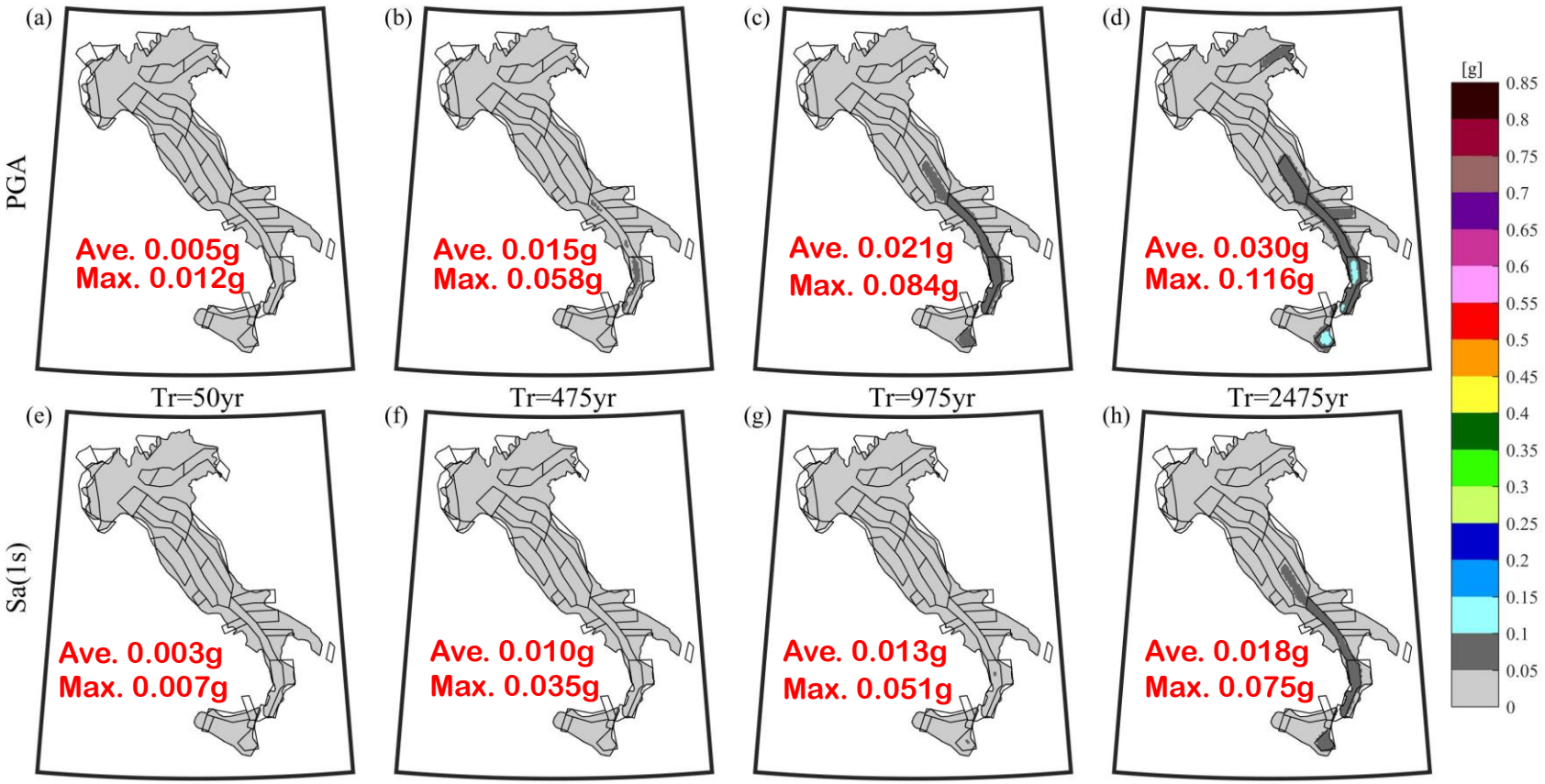
Differences*



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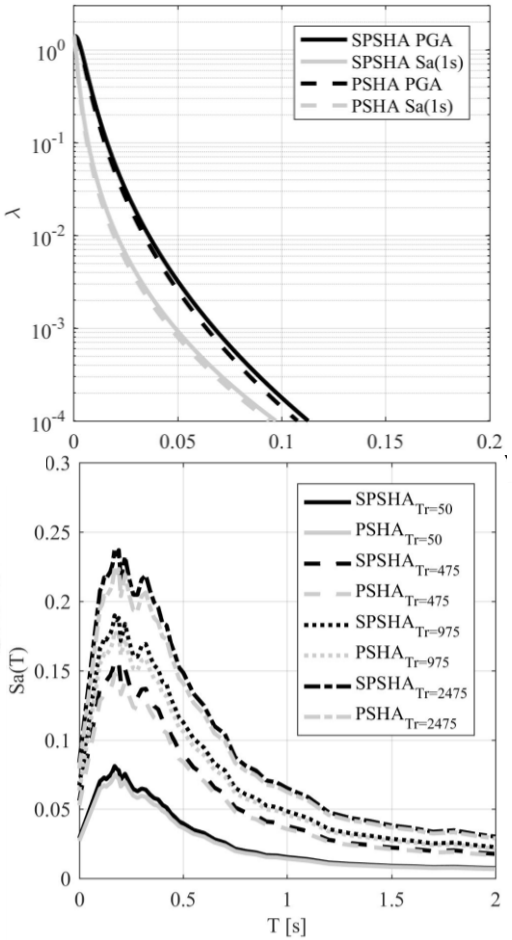
The case of Milan and L'Aquila*

Milan

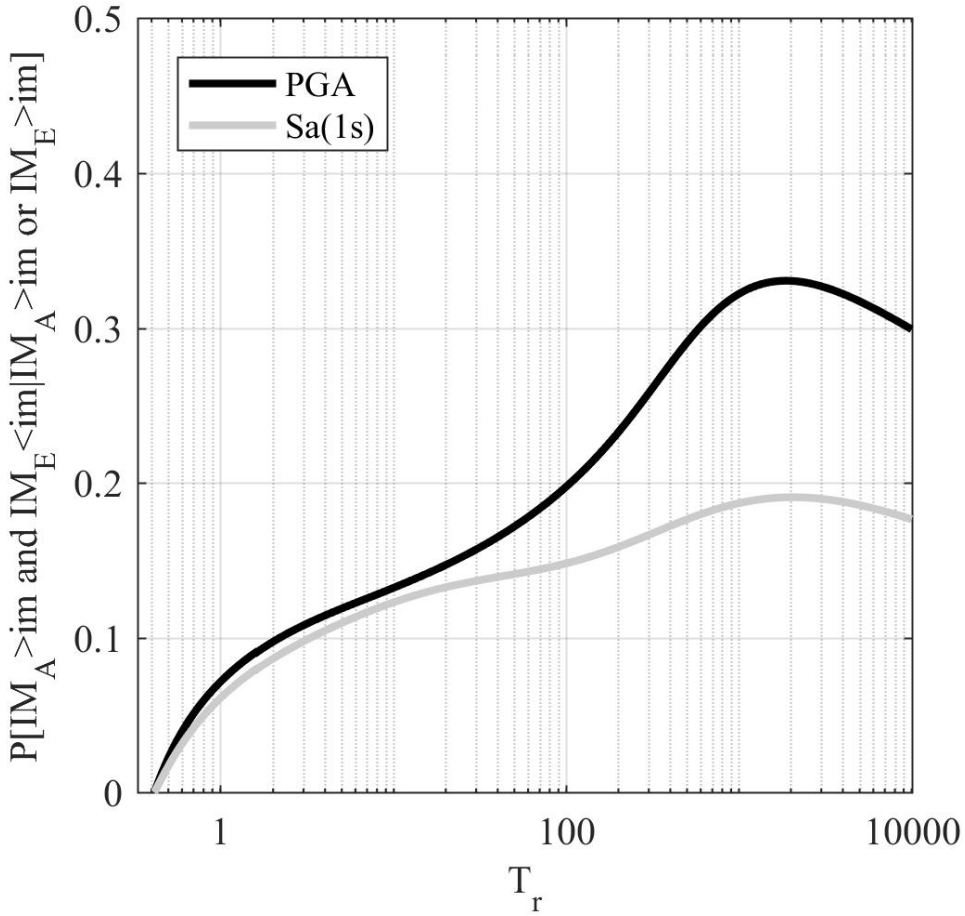


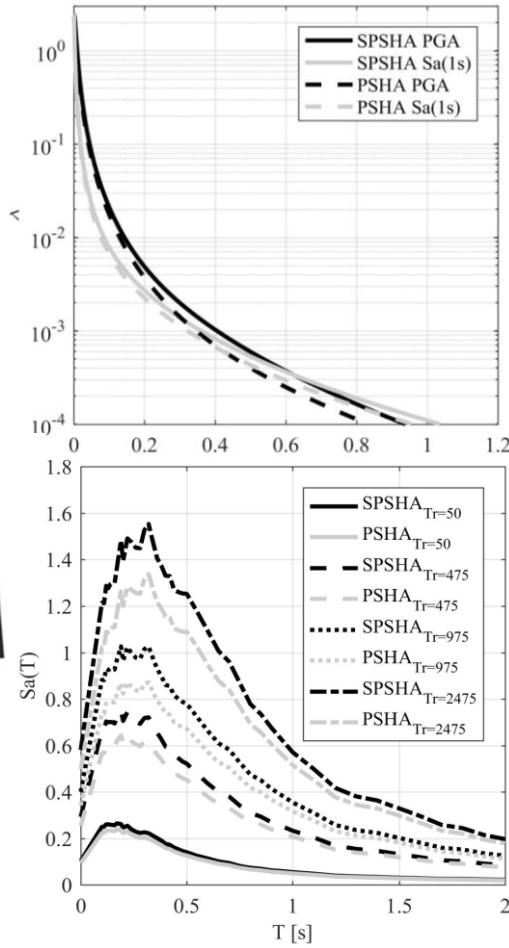
(SPSHA-PSHA)/PSHA [%]				
	Tr=50yr	Tr=475yr	Tr=975yr	Tr=2475yr
PGA	7.5	6.5	6.2	5.7
Sa(1s)	8.3	6.1	5.4	4.5

*Iervolino I., Chioccarelli E., Giorgio M., (2018) Aftershocks' Effect on Structural Design Actions in Italy. Bull. Seismol. Soc. Am. 108: 2209–2220.

The case of Milan and L'Aquila*

(SPSHA-PSHA)/PSHA [%]				
	Tr=50yr	Tr=475yr	Tr=975yr	Tr=2475yr
PGA	9.9	15.6	17.6	17.2
Sa(1s)	10.3	12.6	12.3	10.9





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Summary

- In 2014 a probabilistically rigorous reformulation of the hazard integral to account for the contribution of aftershocks was formulated.
- The model is based on the occurrence of sequences with the same rate of mainshocks and the occurrence of aftershocks is modeled via the modified Omori law (combination of PSHA and APSHA).
- **The rate of occurrence of a mainshock-aftershocks cluster is the same of the mainshocks, thus the catalog is the same of the classic calculation (declustered).**
- SPSHA was applied to Italy based on the source model for the official hazard map, the preliminary results show average increases around 10% and largest effects in more hazardous areas.

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Utsu (1970)

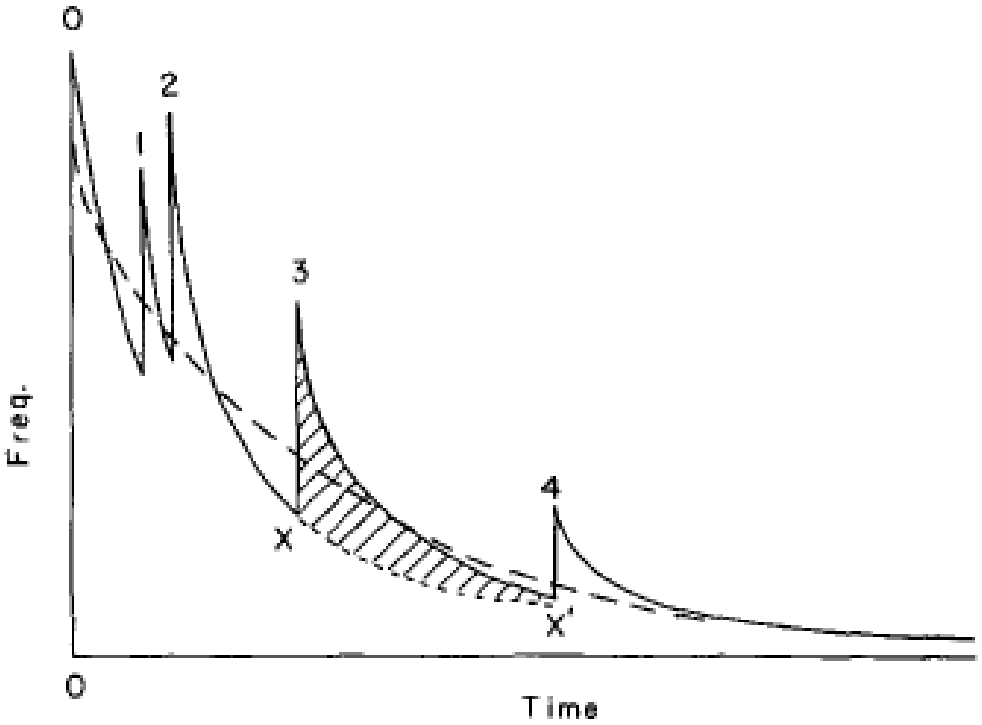
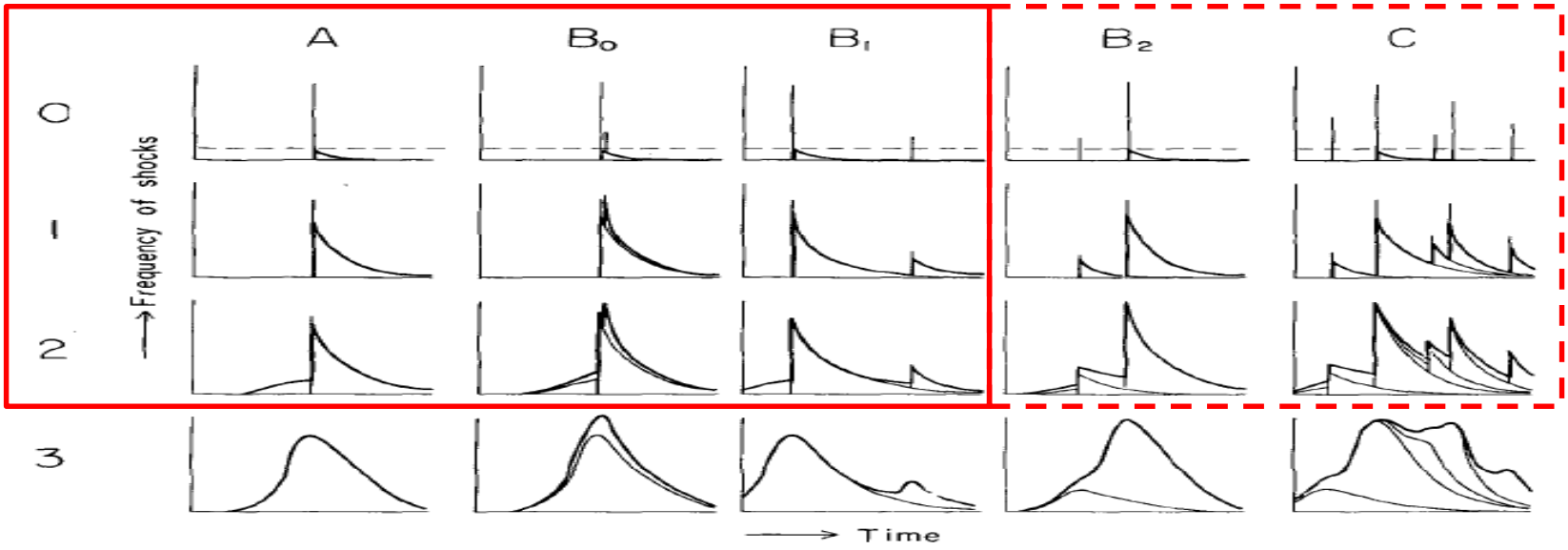


Fig. 105. A schematic graph of Type 1-C aftershock sequence. The borken line represents the curve for the modified Omori formula fitting the whole sequence. The shaded area indicate the secondary aftershocks triggered by shock 3.



	A	B₀	B₁	B₂	C
0	Single event *	(Doublet)*			Multiplet *
1	Main shock – aftershock series				#
2	Foreshock – main shock – aftershock series				#
3	Swarm				

Fig. 75. Types of earthquake sequences. Length of the vertical bar represents the size of the "main shock".
* When the events above the broken line only are observed.
# If one main shock has exceedingly large magnitude, the sequence is no more called swarm.

Utsu (1970)