Follow up to: Ground motion, estimated shaking, and structural response at Campi Flegrei during bradyseism [by Cito et al., doi 10.1002/eqe.4303]

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Abstract

The seismic swarm at Campi Flegrei, which was analyzed in Cito et al.[1] is still going on at the time of writing, and a series of relevant seismic events occurred after publication. Moreover, a number of recordings from events occurred in the period analyzed in the paper was recently made available. The goal of this letter is to briefly update all the engineering analyses, and the collected ground motion database, to account for all this new information.

Introduction

After the publication of the paper, which deals with earthquakes featuring duration magnitude (M_d) equal to or larger than 2.5 recently occurred at Campi Flegrei, a number of events of relevance occurred. Most notably, a doublet event,[2] which was attributed $M_d = 4.6$ occurred on March 13th 2025 in the most seismically active zone of the caldera, close to the city of Naples. This event, not only is the largest magnitude event during the current bradyseism crisis, but also – if reliability of some of the recordings will be ultimately confirmed – led to the largest peak ground acceleration (PGA), even recorded in Italy so far, according to some studies.[3]

In addition, several earthquakes and associated recorded shaking data, occurred between 2023 and 2024, yet not considered in Cito et al., were made available recently. The following updates all sections in Cito et al. with the new data, following the same structure and figures of the original paper. For this update to be as complete as possible, it also includes the few events with $M_d \geq 2.5$ occurred since March 16th 2022 and August 18th 2023, the latter being the starting date of considered events in Cito et al.

Added earthquakes

The updated database consists of twenty-nine events, two of which in 2022, two in 2023, nine in 2024, and the remaining sixteen in 2025. Of these events fourteen have $M_d \geq 3$ and one with $M_d \geq 4$. Figure 1 shows the epicenter of the added events (squared markers) alongside those already considered in Cito et al. (circular markers). The dashed circle is still the area approximately identified as the one experiencing uplift due to bradyseism, which is considered to be the driving force to crustal deformation causing earthquakes. The added events still reflect the two currently most seismically active areas of Campi Flegrei, the one onshore close to the Naples' border and one off-shore in the Gulf of Pozzuoli.

1 Updated ground motion dataset

The considered added earthquakes are those for which shaking recordings are made available via the *Rete Accelerometrica Nazionale* portal (https://ran.protezionecivile.it, last accessed march 2025), whereas a larger number of events with $M_d \geq 2.5$ has been detected, in the same period, by the *Osservatorio Vesuviano* (https://terremoti.ov.ingv.it/gossip/flegrei/index.html, last accessed march 2025), the local branch of the *Istituto Nazionale di Geofisica e Vulcanologia*, yet not providing ground motion data.

Table 1 provides the essential features of the source as well as the information about the waveforms available, including the number of recording stations, and the maximum peak ground acceleration, from the horizontal (H) and vertical (V) motion components. The moment magnitude (M_w) is provided using the conversion formula from the duration magnitude in Iervolino et al.[4] All the recordings for these events, and regional shaking estimations (to follow) are provided for the reader, see Data availability.

It is interesting to note that one of the two $M_d = 3.9$ events occurred in February 2025 produced recorded horizonal and vertical PGAs (unprocessed) exceeding 0.53 g. Moreover, the $M_d = 4.6$ event of March 2025 produced (unprocessed) horizontal PGA in excess of 1.1 g if the recording at the (CSOB; https://terremoti.ov.ingv.it/urbansm/flegrei/2025/44246#, last accessed March 2025) recording station will be confirmed for reliability,[5] and PGA around 0.7 g at other stations close to the source (COLB; https://terremoti.ov.ingv.it/urbansm/flegrei/2025/44246#, last accessed March 2025) and there is a station on the seafloor, not included in the released data, where a MEMS sensor recorded also a PGA in excess of 1 g (CFB3; https://terremoti.ov.ingv.it/urbansm/flegrei/2025/44246#, last accessed march 2025).

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The ground motion intensities, in terms of PGA and horizontal spectral pseudo-accelerations, Sa, at natural vibration periods $T = 0.3$ s and $T = 1.0$ s, as well as the vertical to horizontal ratios of the added (squared markers) alongside those considered in Cito et al. (circular markers) are given in Figure 2. New data are generally in line with those in Cito et al., yet with the comparatively large PGAs recorded in the last events, as discussed.

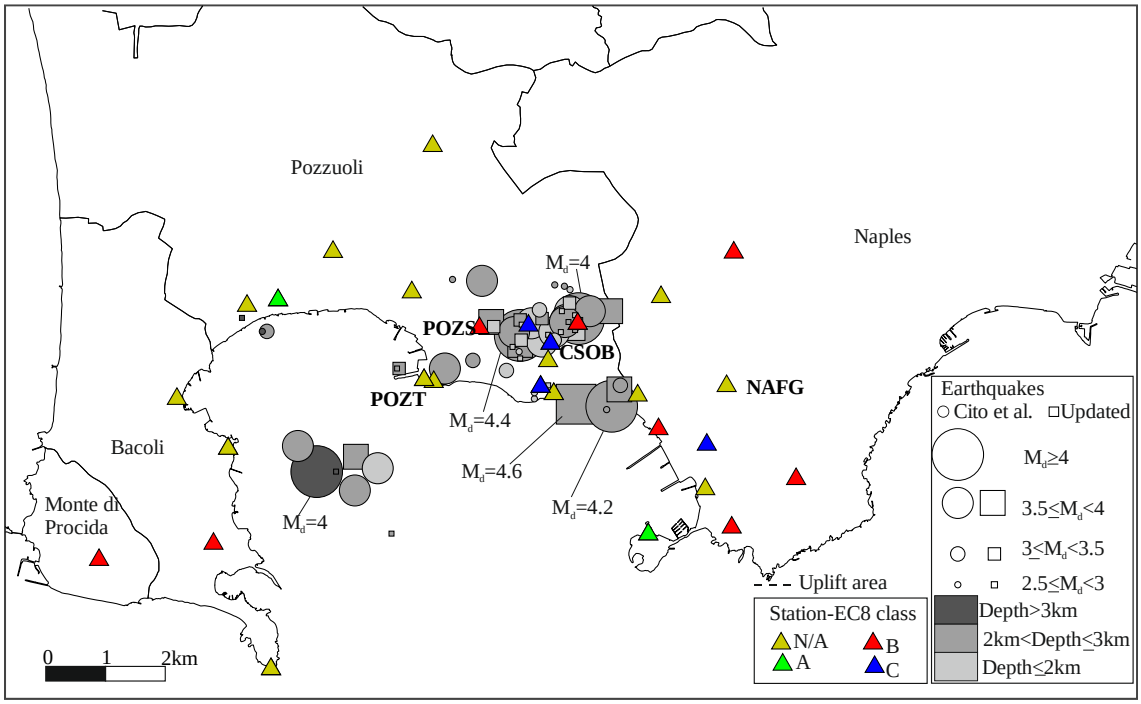

Figure 1. Map of the recording stations and epicenters, magnitudes, and depths of earthquakes included in the database; the station marker color identifies local site condition according to Eurocode 8[6] classification, while earthquake marker size and color varies with magnitude and depth, respectively.

Table 1. Date, coordinates of the epicenter, duration and moment magnitude, depth, number of three-components records, minimum and maximum recording epicentral distance, largest horizontal and vertical PGA for the events added to those in Cito et al.

Date (UTC)	Lat. [°]	Long. [°]	M_d	M_w	Depth [km]	n° of rec.	$R_{epi,min}$ [km]	$R_{epi,max}$ [km]	$PGA_{max,H}$ [g]	$PGA_{max,V}$ [g]
16/03/2022 14:14:34	40.827	14.140	3.5	3.1	3	24	0.9	97.7	0.132	0.064
29/03/2022 17:45:32	40.831	14.156	3.6	3.1	3	9	2.1	29.5	0.061	0.058
08/05/2023 2:28:34	40.830	14.138	3.4	3.0	3	17	0.7	86.5	0.123	0.063
08/05/2023 22:33:17	40.826	14.137	2.8	2.5	2	7	0.6	7.7	0.040	0.027
21/01/2024 9:35:04	40.808	14.102	2.6	2.3	4	11	2.2	7.5	0.017	0.015
04/04/2024 5:14:36	40.823	14.114	2.9	2.6	3	15	0.6	5.9	0.072	0.057
04/04/2024 5:32:56	40.823	14.114	3.2	2.8	3	4	4.4	63.4	0.004	0.003
06/04/2024 11:59:31	40.798	14.113	2.5	2.3	3	16	2.6	18.7	0.015	0.009
14/04/2024 8:01:43	40.829	14.138	2.8	2.5	2	19	0.7	61.3	0.065	0.051
16/04/2024 3:38:05	40.830	14.150	2.5	2.3	3	15	0.9	8.9	0.028	0.026
20/05/2024 19:46:14*	40.826	14.138	3.9	3.4	3	33	2.7	98.2	0.025	0.016
20/05/2024 22:55:54	40.820	14.144	2.8	2.5	0	16	0.4	12.8	0.018	0.018
08/06/2024 2:10:16	40.828	14.146	2.7	2.4	2	1	1.6	1.6	0.016	0.007
17/01/2025 16:53:50	40.829	14.133	3	2.7	2	29	0.2	82.4	0.187	0.107
05/02/2025 10:00:32	40.829	14.149	2.7	2.4	3	24	0.1	8.7	0.079	0.053
13/02/2025 15:34:22	40.831	14.149	2.5	2.3	2	24	0.2	8.9	0.077	0.085
13/02/2025 22:18:28	40.831	14.146	2.6	2.3	2	24	0.3	8.7	0.056	0.036
16/02/2025 14:30:02	40.810	14.106	3.9	3.4	3	68	1.7	99.3	0.121	0.056
16/02/2025 22:45:12	40.833	14.148	3	2.7	2	27	0.4	39.6	0.084	0.054
16/02/2025 23:19:52	40.829	14.148	3.9	3.4	2	64	0.1	98.5	0.530	0.344
17/02/2025 7:12:10	40.830	14.142	3	2.7	3	28	0.4	75.2	0.136	0.075
17/02/2025 7:14:11	40.824	14.138	2.8	2.5	2	24	0.5	7.7	0.060	0.041
17/02/2025 16:53:24	40.828	14.144	2.7	2.4	2	25	0.2	29.5	0.100	0.059
17/02/2025 17:15:54	40.830	14.148	2.6	2.3	3	23	0.5	8.7	0.063	0.045
09/03/2025 23:59:14	40.8303	14.0833	2.6	2.3	4	23	0.2	8.8	0.072	0.021
11/03/2025 2:04:09	40.827	14.1382	3	2.7	2	37	0.5	86.6	0.269	0.112
13/03/2025 0:25:02	40.8175	14.149	4.6	3.9	3	76	0.4	99.5	1.142	0.577
14/03/2025 18:44:10	40.8197	14.1575	3.5	3.1	3	45	0.9	97.2	0.175	0.189
15/03/2025 12:32:27	40.8297	14.1323	3.9	3.4	3	70	0.2	98.0	0.237	0.127

*Sixty-eight stations recorded during this event, but waveforms were provided for only thirty-three of them. Among these thirty-three, data recorded by the POZS station, having the larger PGA, is missing.

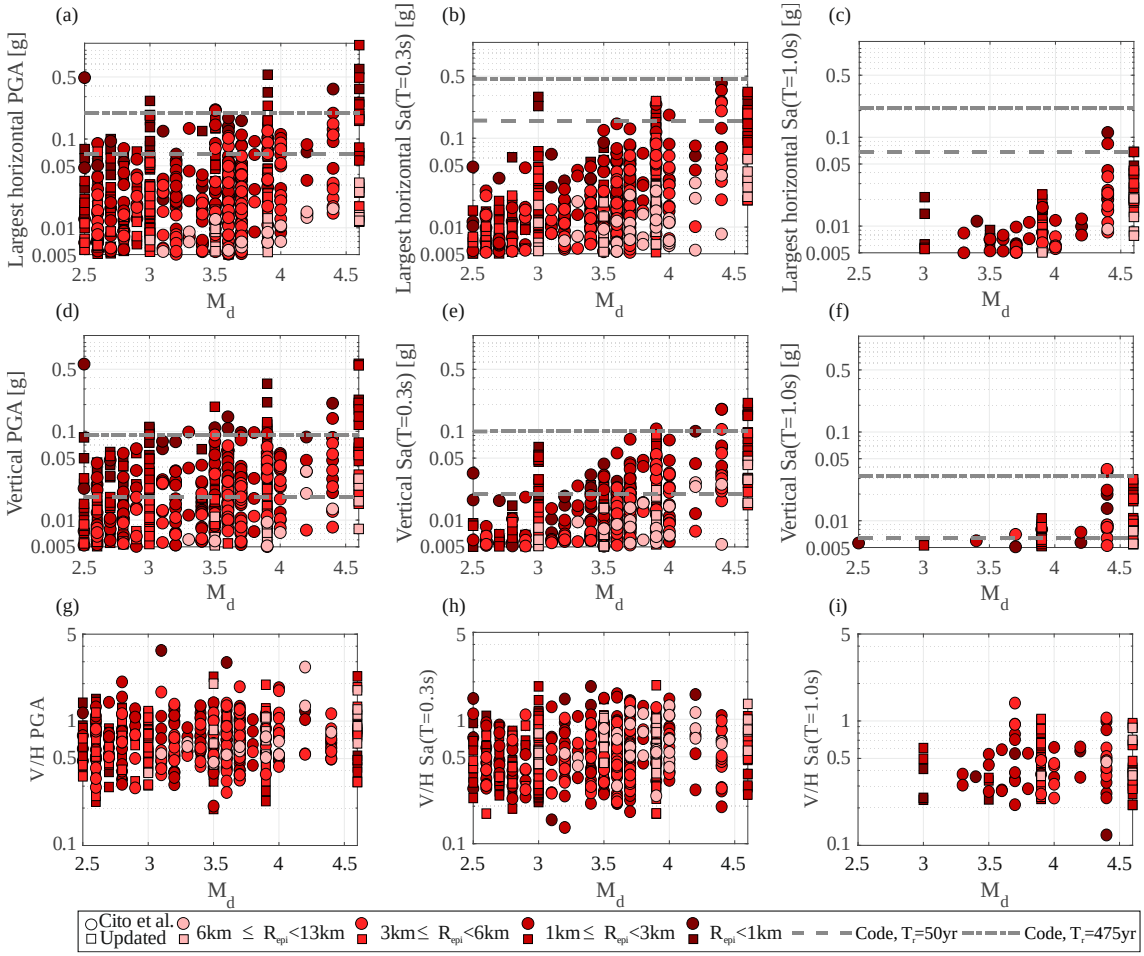

Figure 2. Recorded shaking, as a function of event magnitude and epicentral distance, in terms of largest horizontal PGA, $Sa(T = 0.3\ \text{s})$, $Sa(T = 1.0\ \text{s})$ (a-c), and vertical PGA, $Sa(T = 0.3\ \text{s})$, $Sa(T = 1.0\ \text{s})$ (d-f). Ratio between vertical and largest horizontal intensities are given in panel g-i. The marker's color identifies the interval to which R_{epi} belongs for the record in question: $R_{epi} < 1$ km; $1\ \text{km} \leq R_{epi} < 3$ km; $3\ \text{km} \leq R_{epi} < 6$ km; $6\ \text{km} \leq R_{epi} < 13$ km.

Figure 3 provides the recorded pseudo-acceleration spectra at three recording stations at an increasing average distance from the epicenters of all events, already considered in Cito et al. In this figure the added spectra are identified via blue lines except the largest magnitude event of March 2025 which is the clack continuous line. The same trend of attenuation with distance of structural seismic actions observed in the old data appears, with the spectra of the largest magnitude event standing out, also due to the relative closeness of its epicenter to the NAFG station.

2 Shaking maps

The maps of estimated shaking were computed for the added events as described in Cito et al. The individual horizontal and vertical maps are available at the link provided in the data availability section.

These shaking maps were used to update the *shaking envelope* which is provided in Figure 4. The first column of the figure now reports the shaking median estimates for the $M_d = 4.6$ event. Comparing the envelope with figure 4 of Cito et al., it emerges that the added events affect the maximum recorded intensities, this is especially due to the largest event occurred so far. The same also applies in terms of vertical ground shaking, at least when considering PGA in Figure 5.

3 Structural response

The same two equivalent single-degree-of-freedom (ESDoF) systems representing unreinforced masonry (URM) and reinforced concrete (RC) buildings conforming to the current code, as in Cito et al., were subjected to the sequence of events in which the events of Table 1 are added. Such sequences are shown in Figure 6, where the added shakings are shown in blue. Figure 7 shows the resulting hysteresis' for the URM ESDoF, because the latter slightly changes at the POZS because of the $M_d = 4.6$ event, whereas the RC system remains elastic at all considered stations. This confirms that despite the relatively high ground motion intensity at vibration periods tending to zero, recorded at some stations, the plastic engagement, at least, of code-conforming structures is limited, if any at all.

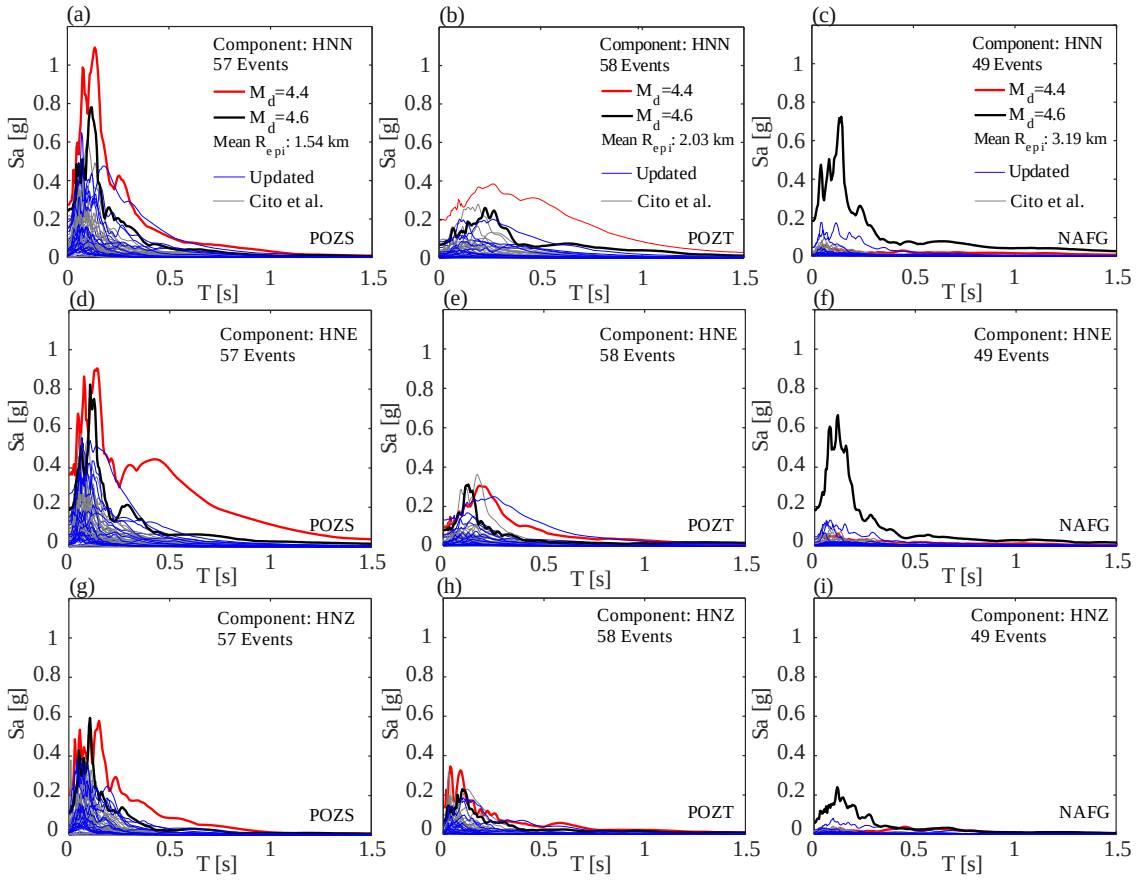

Figure 3. Pseudo-acceleration (5% damped) response spectra at POZS (a,d,g) POZT (b,e,h) and NAFG (c,f,i) stations. Panels a-f refers to the horizontal components of ground motions, while panels g-i represent spectra for vertical component. (The spectra for the $M_d = 4.4$ event and that for $M_d = 4.6$ are plotted in red and black, respectively, to distinguish.)

4 Final remarks

This short document considered twenty-nine earthquakes with $M_d \geq 2.5$, occurred between 2022 and the first half of March, which were added to the dataset of Cito et al. It emerged the following.

1. The added events all occurred in the two zones of Campi Flegrei where most events of the current seismic swarm occurred. One event has the largest duration magnitude recorded so far, being equal to 4.6. It occurred in the eastern part of the caldera, relatively close to the city of Naples.
2. The ground motion intensity of these added events is generally in line with those shown in Cito et al., yet the largest magnitude event caused the largest PGAs of the swarm so far, which may include the largest PGA recorded in Italy.
3. Structural response of equivalent single degree of freedom systems, corresponding to code-conforming URM and RC buildings, confirms that, despite the high frequency intensity of these events, the non-linear engagement is limited for the URM system close to the epicenters and is null in all other cases and for the RC system.

All data used in this study are made available for further analysis and will be updated, subject to authors resources, as the seismic swarm during bradyseism at Campi Flegrei unfolds.

Data availability

Ground motion records, metadata, and estimated shaking maps for all the considered events are available at http://wpage.unina.it/iuniervo/CampiFlegrei_EQ_Records.

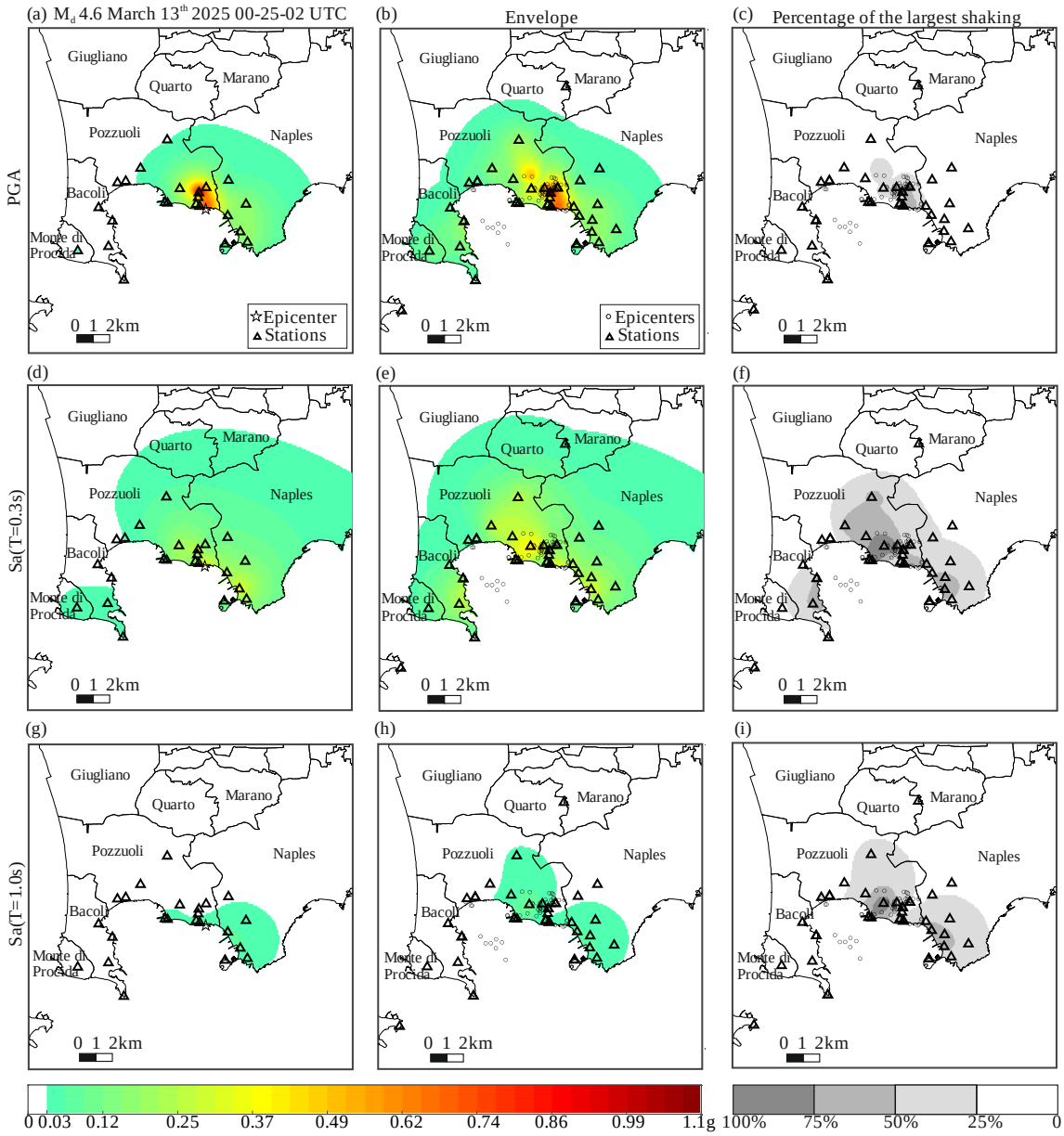

Figure 4. Median shaking due to the $M_d = 4.6$ event of March 2025, in terms of largest horizontal PGA (a), $Sa(T = 0.3\text{ s})$ (d), $Sa(T = 1.0\text{ s})$ (g), and shaking envelope of all $M_d \geq 2.5$ earthquakes (b,e,h). Estimated shaking from the envelope in terms of fraction percentage with respect to the maximum value in the envelope map for PGA (c), $Sa(T = 0.3\text{ s})$ (f), $Sa(T = 1.0\text{ s})$ (i).

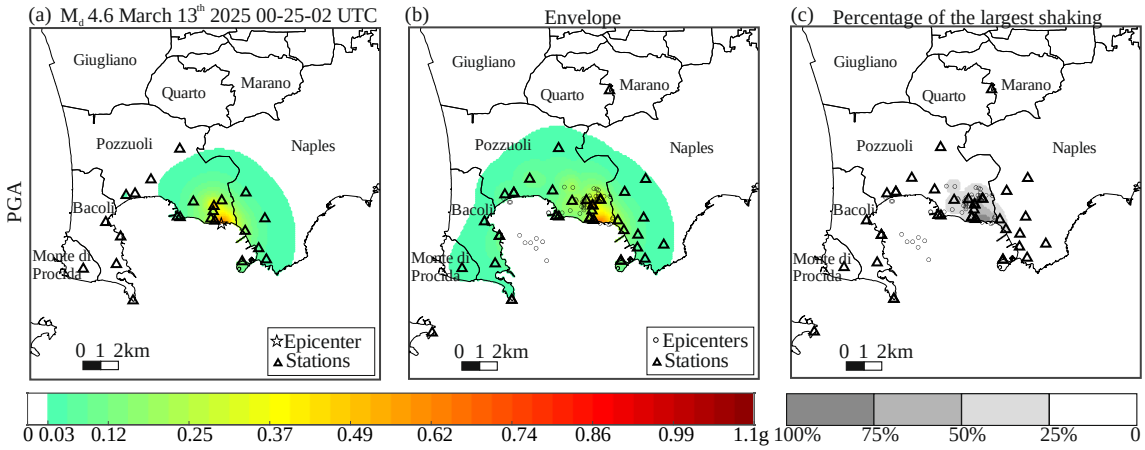

Figure 5. Median shaking due to $M_d = 4.6$ event, in terms of vertical PGA (a), and shaking envelope of all $M_d \geq 2.5$ earthquakes (b). Estimated shaking normalized by the largest value in the envelope map (c).

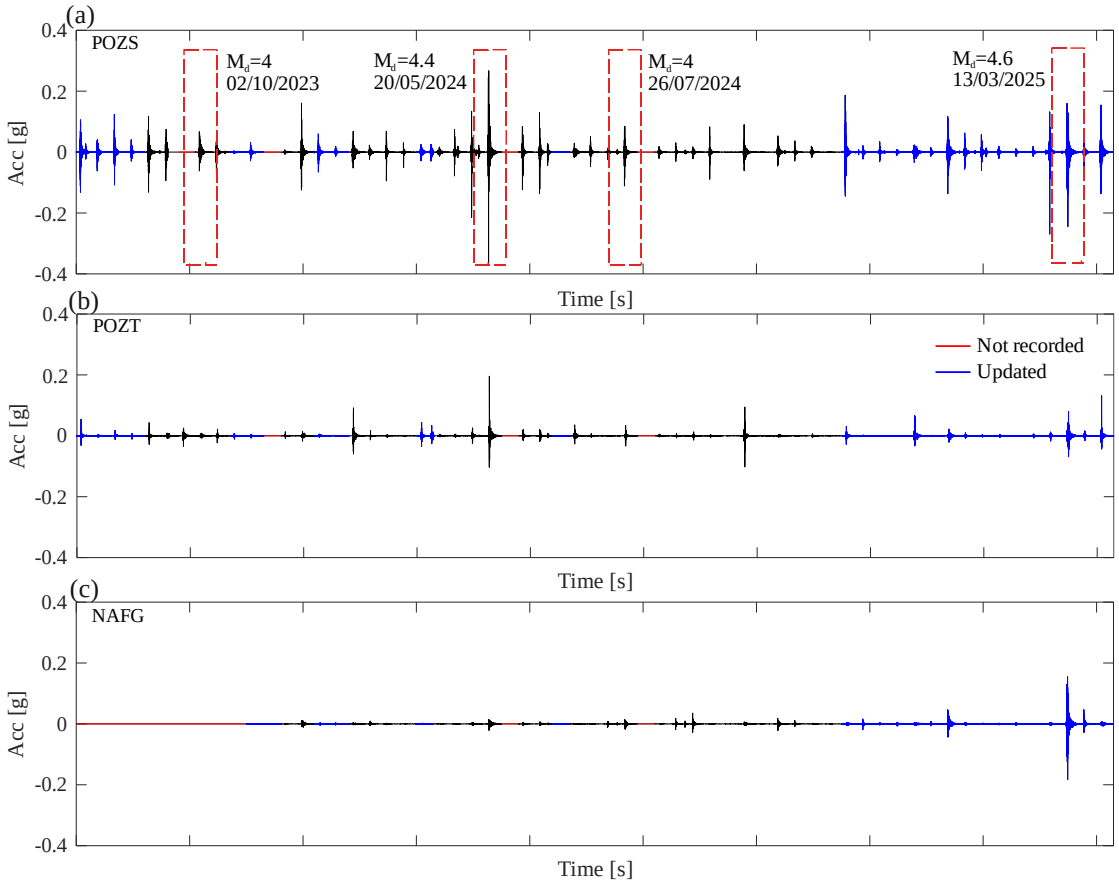

Figure 6. Horizontal components with largest PGA recorded for each event from 16/03/2022 to 15/03/2025 at POZS (a), POZT (b) and NAFG (c) station. In the panel (a) events with M_d equal or larger to 4 are highligted.

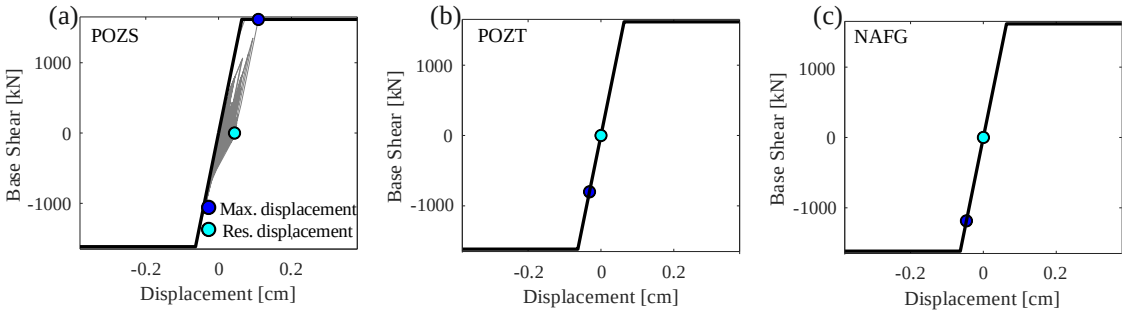

Figure 7. ESDoF system of the URM structure subjected to the accelerograms from the $M_d \geq 2.5$ earthquakes recorded at POZS (a), POZT (b), and NAFG (c) stations.

References

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