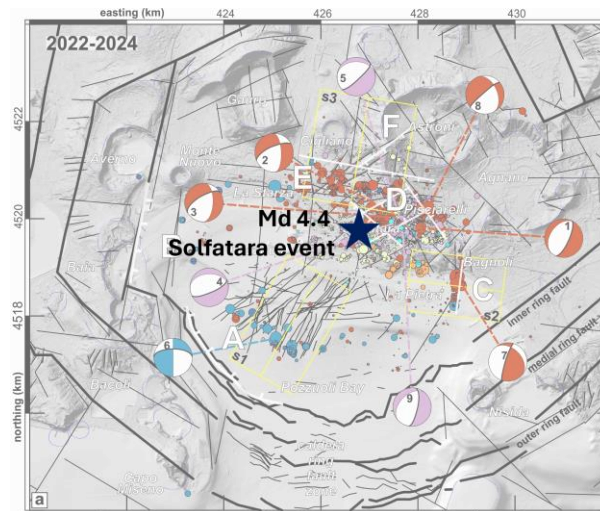


Solfatara Earthquake (20/5/2024)

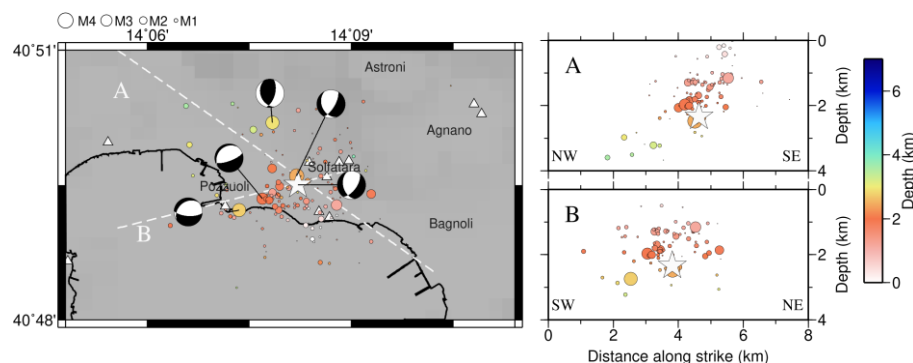
The Solfatara Earthquake

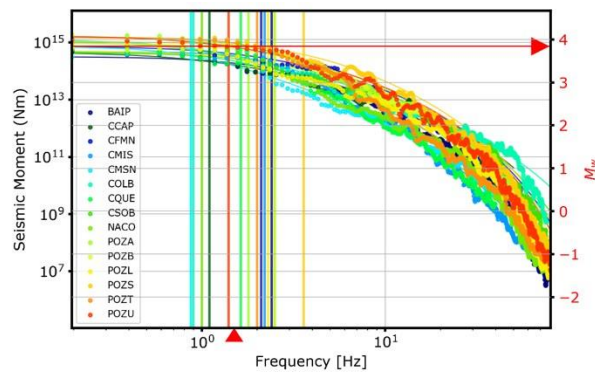
The **Md 4.4 Solfatara earthquake** occurred on **May 20, 2024**, at 18.10 UTC (20.10 Local Time). It was followed by a Md 3.9 event in the same area and hundreds of smaller magnitude events.



Absolute locations:

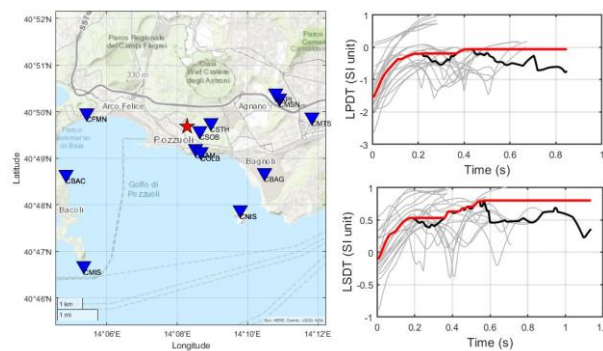
We performed the absolute location of 166 events occurred between 20th and 21th May. We used NLLoc (Lomax, 2009) and 1D P- and S-wave models optimized for the area (Vanorio et al. 2005). The location of main event (white star in figure) is constrained with 56 arrival times (31 P and 25 S), GAP 90°, RMS 0.06 s and horizontal and vertical location errors of 300 m. Considering the entire catalog, the rms are lower than 0.1 s and the location errors are within 1 km. In Figure we show the absolute locations of the 166 events, coloured by depth, and the focal mechanisms of events with magnitude higher than 3. The hypocenters are aligned along the SW-NE direction and located within 0 and 4 km depth. The focal mechanisms of the main event and the M 3.9 event, nearly co-located, are very similar and the seismicity distribution is coherent with the focal plane dipping toward W.





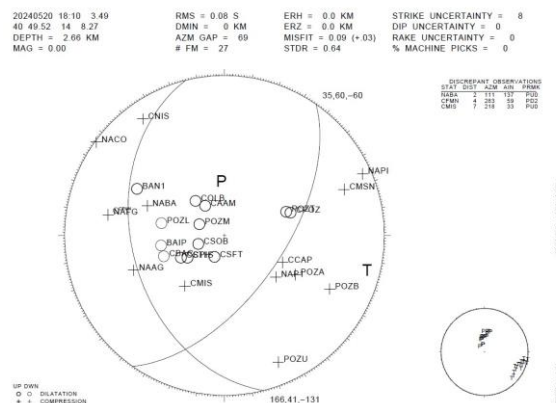
Source parameters

We computed source parameters from spectral modelling of waveforms of **15 stations** of the network (Supino et al., 2019). The resulting average moment magnitude is **$M_w 3.9 \pm 0.1$** . Source radius has been estimated to be **380 ± 20 m**, using the model *Kaneko & Shearer (2014)*. This resulted in a stress drop of **6.0 ± 1.0 MPa**.



Time domain source properties

Assuming a triangular moment-rate function, and circular rupture model, the earthquake source properties: moment magnitude (**3.6 ± 0.4**), circular rupture radius (**0.9 ± 0.3 km**), slip (**0.8 ± 0.5 m**), stress drop (**0.2 ± 0.1 MPa**), and rupture velocity (**2.3 ± 1.1 km/s**) are determined for this event implementing a straightforward and parametric approach based on the time evolution of the P- and S-wave amplitudes through the updated version of the software EASOt-AP (Zollo et al., 2021; Nazeri and Zollo, 2022).

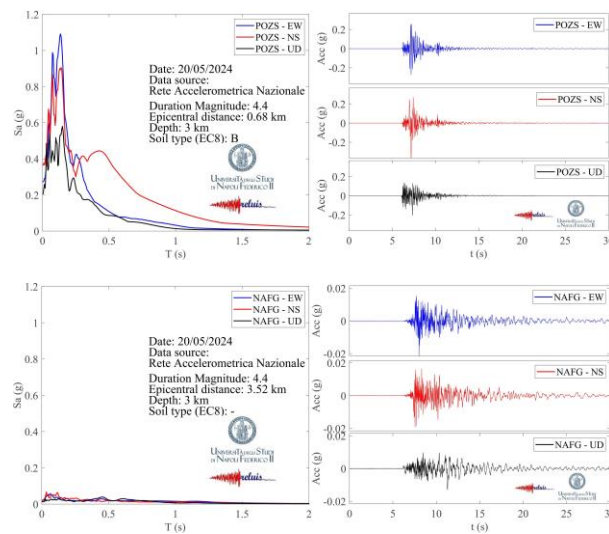


Focal mechanism

The focal mechanism has been estimated by using FPFIT. We manually measured the 27 used P-wave polarities. The maximum distance between source and receivers is of about 7 km. We obtained a well constrained focal mechanism solution, with a parameter uncertainties within 8°, showing a nearly pure normal fault mechanism. Following the same approach, we obtained the focal mechanisms for the four events with magnitude larger than 3.

Response spectra

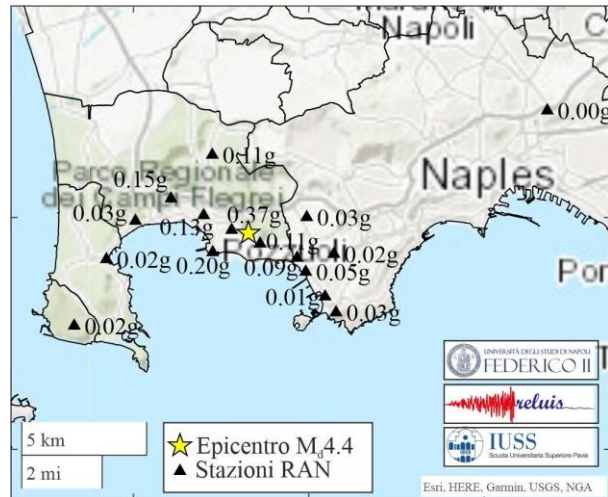
Pseudo-acceleration spectra (5% damped) of the Md4.4 Solfatara earthquake recorded at the epicenter (station POZS, Pozzuoli, epicentral distance 0.68km, B soil type according to Eurocode 8) and a few kilometers away (station NAFG, Fuorigrotta, Naples, epicentral distance 3.52km). As expected, a strong attenuation with distance was observed.



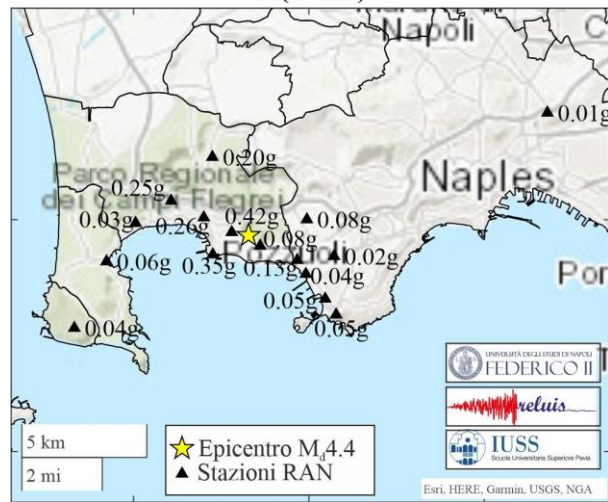
Recorded shaking

The maps show the station belonging to the national monitoring network *Rete Accelerometrica Nazionale* or RAN (<https://ran.protezionecivile.it/IT/index.php>) that are within 15 km from the epicenter of the Md4.4 earthquake occurred on May 20. In the maps, the largest shaking in terms of PGA and two pseudo-spectral accelerations, 5% damped, between those associated with the two horizontal components recorded at each station, is given. It is observed that intensities recorded in the municipality of Naples are one order of magnitude lower than the largest intensity recorded close to the epicenter in Pozzuoli.

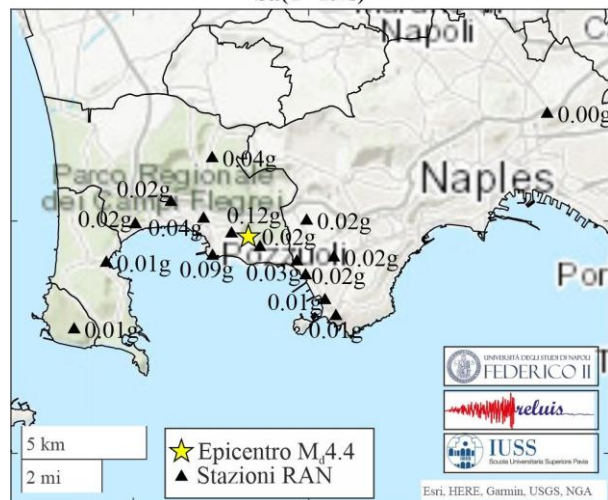
PGA

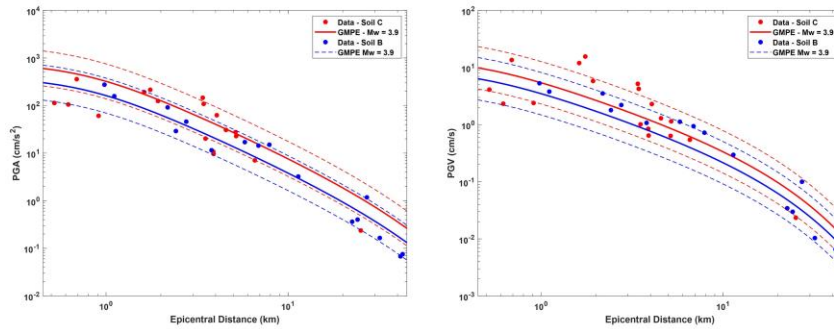


Sa(T=0.3s)



Sa(T=1.0s)





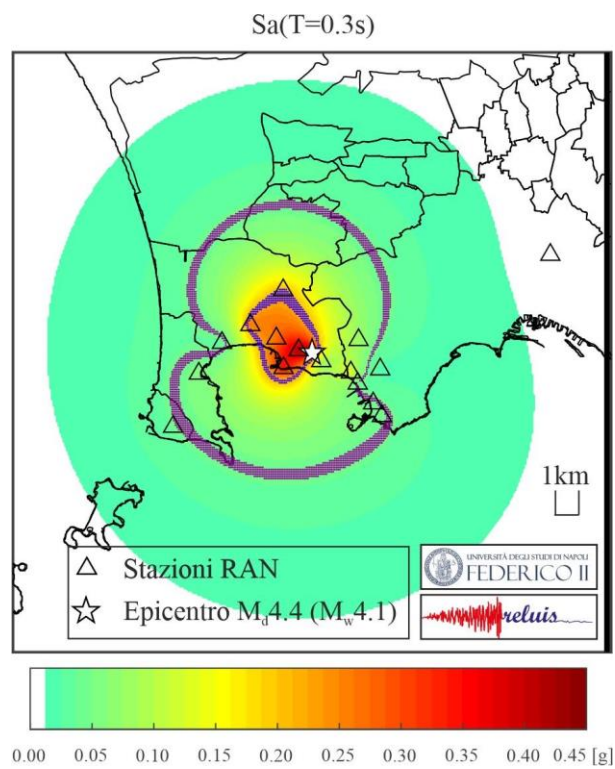
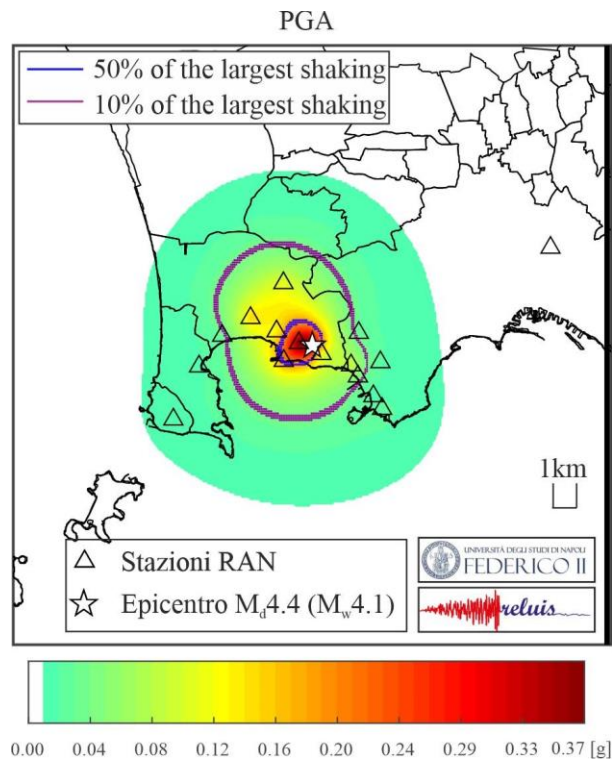
Attenuation

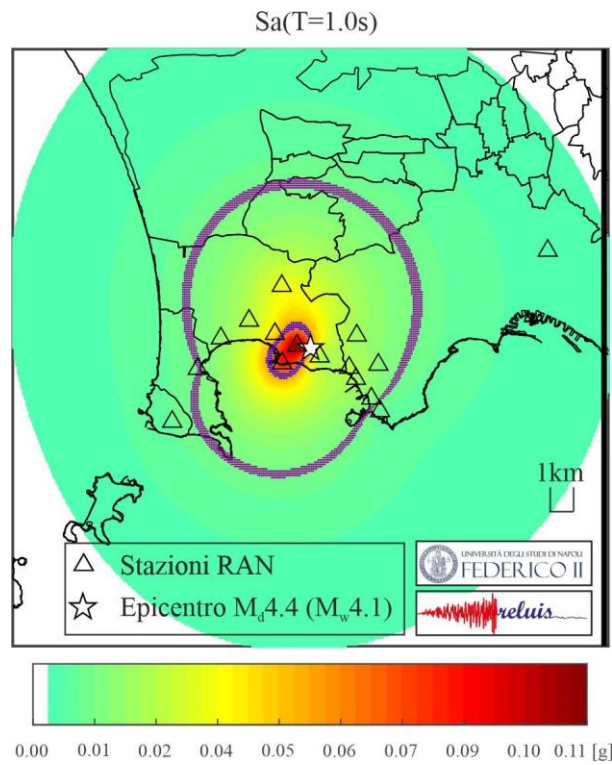
Peak Ground Acceleration (PGA panel a) and Peak Ground Velocity (PGV panel b) as a function of distance and station soil classification. Data are compared with **local attenuation laws** calibrated using events until October 2023 and **extrapolated at Mw 3.9**. Dashed lines represent uncertainty of attenuation law. **Recorded PGA and PGV are consistent with estimated values.**

Expected shaking (in terms of PGA and two pseudo-spectral accelerations, 5% damped) conditional on ground motion intensity measures recorded at the stations of the *Rete Accelerometrica Nazionale* or RAN (conditional gaussian multivariate model), earthquake and magnitude location .

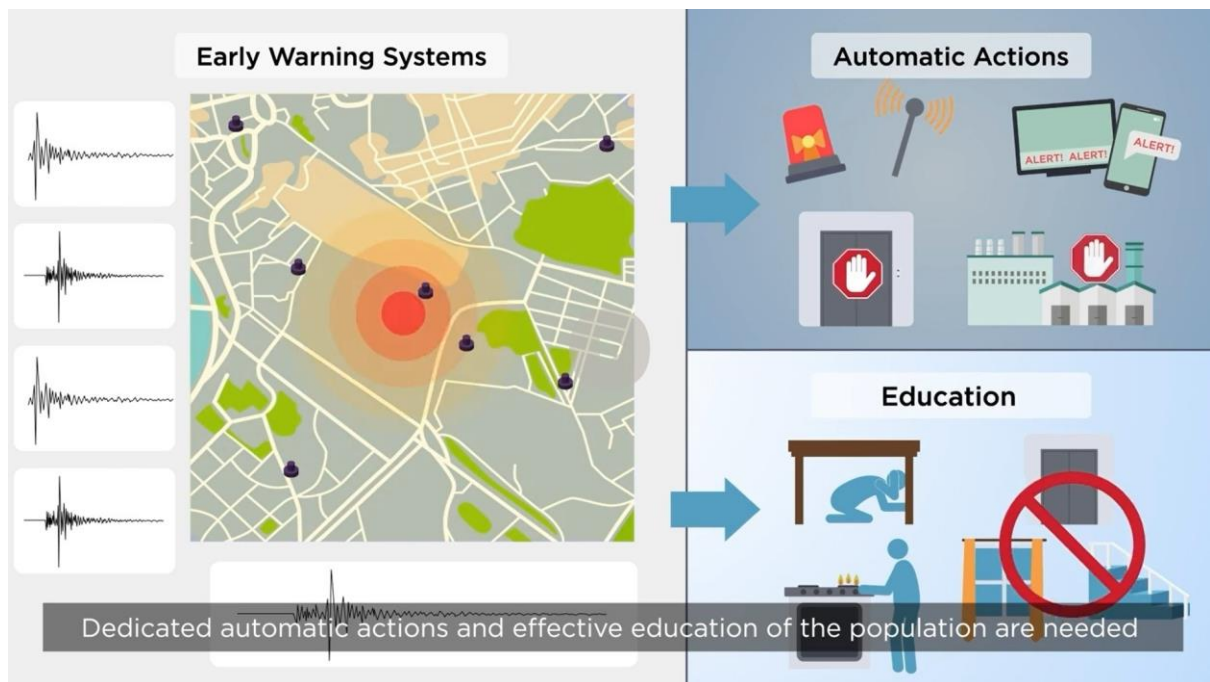
Analyses were developed using the previously introduced ground motion model developed ad-hoc for the area of Campi Flegrei. A recently developed relationship between moment magnitude (Mw) and duration magnitude (Md) suggests that Mw=3.66 when it is Md=4.4 [1]. However, Mw=4.1 was considered. Spatial correlation of the residual of the ground motion model was modelled according to literature [2]. B soil type (according to Eurocode 8) was assumed everywhere in the area.

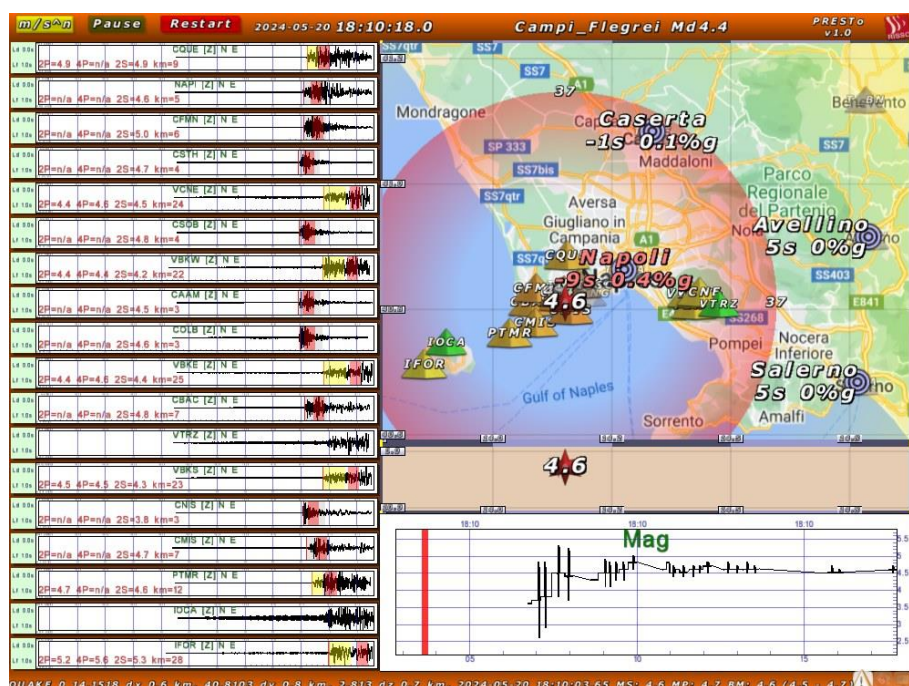
In each map, the sites where the expected shaking is 50% and 10% of the largest recorded intensity are identified by the blue and magenta contours, respectively. In the case of PGA, an estimated intensity equal to 50% [10%] of the largest shaking is found at an epicentral distance not exceeding 1.8km [5.8km]; for Sa(T=0.3s) and Sa(T=1.0s), the largest epicentral distance at which the expected intensity is 50% [10%] of the maximum value in the area is 3.7km and 2.4km [7.9 km and 8.9 km], respectively.





Earthquake Early Warning Testing



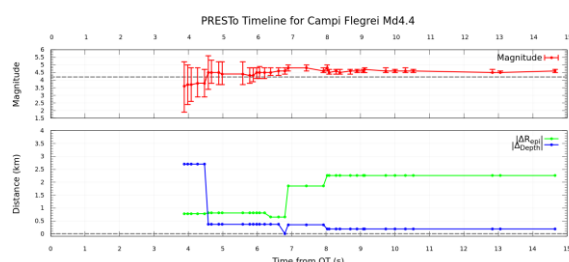


PRESTo Early Warning System (source-based)

During an off-line playback of the accelerometric waveforms from 18 stations of the INGV network, PRESTo automatically detected and characterized the earthquake and its impact at the regional scale. This is the final screenshot while processing the earthquake during the simulation. Real-time alerts are sent to target sites: location, magnitude, expected PGAs and lead-times.

First alert at OT + 4.0s (2.6s from 1st pick, 9 stations): ΔM -0.7, ΔEPI 0.8 km, ΔDEP 2.7 km

Stable alerts from OT + 6.6s (5.3s from 1st pick, 12 stations): ΔM +0.2, ΔEPI 0.6 km, ΔDEP 0.4 km



PRESTo Timeline

Time evolution of PRESTo source parameters estimates (location, magnitude) compared to the final manually revised values (INGV bulletin, dashed lines).

Parameter	Early Warning ~4 seconds	Early Warning ~14 seconds	Revised ~30 minutes
Magnitude	ML 4.5 ± 1.1	ML 4.6 ± 0.1	Md 4.4 ± 0.3
Latitude (°N)	40.823	40.810	40.828
Longitude (°E)	14.145	14.152	14.138
Depth (km)	2.6	2.8	3.0
Origin Time (UTC)	18:10:03.7	18:10:03.7	18:10:03.0

PRESTo Source Parameters Estimation

Comparison of location and magnitude estimates obtained within seconds from PRESTo vs. the manually revised INGV bulletin ones obtained ~30 minutes later.

Place	Distance (km)	Lead Time (s)	1 st PGA (%g)	Final PGA (%g)
Napoli	13	2.4	0.08	0.46
Vesuvio	22	6.1	0.03	0.15
Ischia	22	6.1	0.03	0.15
Caserta	33	10.1	0.01	0.07
Salerno	55	15.7	0.01	0.04
Avellino	56	16.2	0.01	0.04
Benevento	64	18.6	0.01	0.03

PRESTo Impact Estimation and Lead Times

The first information on magnitude, location and impact of the earthquake is released *2.6 seconds* after the first P arrival, detected at station CSTH (Campi Flegrei - Solfatara Tennis Hotel).

The table reports the *expected PGA* at the main target sites and the corresponding *lead-time* defined as the seconds passed from the first estimate of the earthquake source parameters and impact, to the arrival of the first S-waves at the target site.

INGV Bulletin Info for M>3.0						SAVE alerts @ NAPI
Data e Ora (UTC)	Magnitudo	Zona	Profondità	Latitudine	Longitudine	
2024-05-20 21:00:55	Md 3.6	Campi Flegrei	3	40.82	14.12	✓
2024-05-20 19:55:37	Md 3.1	Campi Flegrei	3	40.82	14.13	✗
2024-05-20 19:46:14	Md 3.9	Campi Flegrei	3	40.83	14.14	✓
2024-05-20 18:10:03	Md 4.4	Campi Flegrei	3	40.83	14.14	✓
2024-05-20 17:51:14	Md 3.5	Campi Flegrei	3	40.84	14.13	✓

List of SAVE alerts @ NAPI											
ID	Time	Displacement (cm)	Period (s)	Intensity	Alert Level	Magnitude	Distance (km)	Real Intensity	SAC	PGA	
112	2024-05-20 21:01:01	0.0023	0.49	3.3	III	4.0	Medium	36.0	2.1	II	
111	2024-05-20 19:50:11	0.00013	0.19	1.7	II	5.1	Unreliable	24.0	0.52	I	
110	2024-05-20 19:46:21	0.041	1.0	5.8	VI	5.1	Unreliable	24.0	4.5	II	
109	2024-05-20 18:10:10	0.06	1.1	6.1	VI	5.2	Unreliable	23.0	5.2	II	
108	2024-05-20 17:51:21	0.0042	0.78	3.8	IV	4.7	Medium	42.0	2.5	III	

Real-Time performance of the on-site Early warning system SAVE at NAPI station.

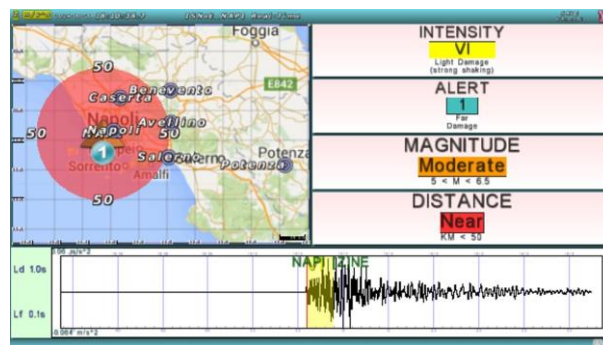
We summarize the real-time performance of the onsite EW system SAVE (on-Site Alert leVEl) running at NAPI station, which is located at the ground floor of the RISSCLab seismological laboratory, in Monte Sant'Angelo Campus. SAVE performs local estimates of Intensity, Alert Level, Magnitude and Distance through the real-time measurement of amplitude (Pd, peak displacement) and frequency (Tauc, predominant period) parameters, on the first 3 seconds of recorded P-wave signal, along the vertical component.

The figure shows the list of events from INGV bulletin (top) and the list of events detected by SAVE (bottom). Between 17:51 and 21:00 (UTC time), the INGV detected and located 5 events with Md > 3. The onsite EW system SAVE running at NAPI station identified 4 of them and missed the smallest one (Md 3.1).

Summary

- The joint analysis of the mainshock(aftershock fault mechanisms and relocated aftershocks constrains a normal faulting mechanism involving a fault bordering the western limit of the Solfatara crater at about 2.7 km depth. The fault strike is NNW oriented and dips SW with a dip of about 40°.
- The modelling of displacement spectra provides a rupture radius of 400 m and stress drop of 6 MPa as measured from the spectral corner frequency. Time-domain measurements of P and S pulse amplitude/width show a factor 2 larger rupture radius, and consequently a smaller stress drop. Combining P and S pulse durations the rupture speed is estimated to achieve a super-shear value of 2.3 km/s.

- The strong ground motion has been analyzed in terms of response spectra, attenuation vs distance and ground shaking maps. A PGA of 0.35 g has been measured near the epicenter, with a major peak of the response spectra at 0.1-0.2 sec. Peak ground motion attenuates rapidly with distance. PGA reduces by 50% with respect to the maximum less than 2km from the epicenter, and reduces by 90% with respect to the maximum in less than 6km from the epicenter.
- Regional (PRESto) and on-site (SAVE) earthquake early warning systems provided a successful alert for a M4+ and IMM V+ about 3 sec after the first P-wave arrival. The overestimates of magnitude and intensity are likely due to the inclusion of the S-wave within the used P-wave time window of analysis.



1 - The figure shows the screenshot of SAVE@NAPI during the **18:10:03, Md 4.4** earthquake.

The system was able to compute both the Pd amplitude and the Tauc parameter, and was able to provide estimates of magnitude, distance and intensity ranges.

The **estimated intensity** (through the Pd) was **VI**, while the **real Intensity** (as measured from PGV) was **V**.

The event was classified as a **moderate magnitude** event ($5 < M < 6.5$) **nearby** the station (epicentral distance < 50km).

The overestimates of magnitude and intensity are likely due to the inclusion of the S-wave within the 3s P-wave time window.

References

References

Scotto di Uccio, F., Lomax, A., Natale, J., Muzellec, T., Festa, G., Nazeri, S., Convertito, V., Bobbio, A., Strumia, C., & Zollo, A. (2024). Delineation and Fine-Scale Structure of Active Fault Zones during the 2014-2023 unrest at the Campi Flegrei Caldera (Southern Italy) from High-Precision Earthquake Locations. *Authorea Preprints*.

Iervolino I. et al. (2024) Seismic risk mitigation at Campi Flegrei in volcanic unrest (under review).

Esposito S., Iervolino I. (2012) Spatial correlation of spectral acceleration in European data. *Bulletin of the Seismological Society of America*, 102(6): 2781-2788.

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Contributors

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Useful links

[Irpinia Seismic Network](#)

