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# Evaluation of Ground Motion Models for Volcanic Areas in Italy: Advancing ShakeMap Implementation

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## Abstract

In Italy, volcanic earthquakes are crucial for assessing seismic hazard, as several volcanoes pose significant risks to densely populated areas (e.g., Catania and its surroundings, Phlegraean Fields, Vesuvius). Recently, the increase in seismic activity in the Phlegraean Fields, characterized by swarms of low-magnitude earthquakes concomitant with bradyseism, has prompted a revision of the configuration of the Ground Motion Models (GMMs) used in the U.S. Geological Survey (USGS) ShakeMap software implemented in Italy for volcanic areas. In this study, we applied a cross-validation technique to evaluate the effectiveness of various GMMs available in the literature for volcanic regions, aiming to the identification of the most appropriate configuration to update and improve the ShakeMap service provided by the Istituto Nazionale di Geofisica e Vulcanologia (INGV). We compared the performance of the currently adopted GMMs [a combination of Tusa and Langer (2016) for earthquakes down to 5 km depth and Bindi et al. (2010) for deeper earthquakes] in predicting ground shaking with those developed by Tusa et al. (2020) and Lanzano and Luzi (2020). To conduct the tests, we used 100 Italian earthquakes that occurred in volcanic areas between February 2019 and May 2024, with magnitudes in the range 3.0-4.5 and depths ≤ 35 km. Among the tested models, the GMM proposed by Tusa et al. (2020) was found to provide the most accurate predictions and will be adopted for generating the INGV shakemaps.

Keywords: Ground Motion Models; Volcano earthquakes; leave-one-out analysis; shaking maps; Intensity measures

## 1. Introduction

Maps of ground shaking for significant seismic events are critical for providing rapid assessments of potential damage and population exposure, benefiting disaster risk managers and civil protection authorities. To this end, the ShakeMap software (Wald et al., 1999), developed by the U.S. Geological Survey (USGS), has proven highly effective and is widely adopted by seismic network operators globally.

In essence, ShakeMap provides a rapid and detailed mapping of earthquake ground motions, illustrating both the distribution and severity of shaking. The shaking scenarios are provided in terms of maps of macroseismic intensity and five intensity measures (IMs) – peak ground acceleration (PGA), peak ground velocity (PGV), and spectral acceleration (SA) ordinates at 0.3, 1.0, and 3.0 s, respectively. This information is essential for assessing the extent of affected areas, identifying regions potentially most impacted, and enabling quick loss estimation. The reliability of ShakeMap products lies in the use of accurate algorithms that, by leveraging high-quality recorded ground motions and any available macroseismic intensity data, can provide ground-truth constraints on shaking. Additionally, ShakeMap employs advanced interpolation techniques (Worden et al., 2018; Engler et al., 2022) and generates event-specific shaking estimates in regions with sparse or no observational data. This combined approach allows ShakeMap to deliver an accurate representation of the shaking, integrating both recorded and estimated values. More specifically, it uses ground-motion models (GMMs) to estimate shaking in areas lacking seismic recordings. The site amplifications are determined using the average S-wave velocity in the uppermost 30 meters ($V_{S30}$) as proxy.

A comprehensive explanation of how site effects are integrated into ShakeMap can be found in the detailed description provided by Worden et al. (2020).

In Italy, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) routinely produces ShakeMaps for earthquakes with magnitudes ≥3.0 (Michelini et al., 2008, 2020), a key product for the Italian Civil Protection Department (Dipartimento per la Protezione Civile – DPC), which uses these maps alongside additional data to assess impacted areas. The ShakeMap configuration at INGV (Michelini et al., 2020) adopts the latest USGS-ShakeMap version 4 software (Worden et al., 2020). This configuration includes (1) an updated VS30 map for local site effects, (2) the recently developed GMICEs of Oliveti et al. (2022b) calibrated on the data set by Oliveti et al. (2022a) for the conversion between ground motion and macroseismic intensity and (3) the GMMs selected by Michelini et al. (2020) accounting for the subdivision of Italy in different tectonic regimes (MPS19, Meletti et al., 2017). Specifically, Michelini et al. (2020) applied a cross-validation technique to evaluate the configuration's effectiveness and compare ShakeMaps generated with both the initial configuration (Michelini et al., 2008) and the latest settings.

In this study, using the same cross-validation technique of Michelini et al. (2020), we seek to refine the ShakeMap configuration for Italian volcanic regions. The need to revise the set of GMMs to be applied in the Italian volcanic areas arose from the reactivation of bradyseism in the Phlegraean Fields caldera since 2018, with an intensified rate of earthquakes per month. Just over 30 earthquakes had Md ≥ 3.5, and four Md ≥ 4; the largest was an Md = 4.4 earthquake that occurred in May 2024, according to the INGV website (https://terremoti.ingv.it/). The increase in seismic activity made available new seismic data which prompted the update of the GMMs configuration to ensure more accurate maps of ground shaking. We aim to improve ShakeMap predictions, leveraging a cross-validation technique to assess existing GMMs and identify the configurations best suited for volcanic regions in Italy.

## 2. ShakeMap Configuration

ShakeMap integrates various data sources, including recorded ground motion data from seismic stations, earthquake source parameters such as location, depth, and magnitude, finite fault for larger events, GMMs, and local site conditions.

In the current INGV ShakeMap configuration, the following GMMs are adopted for the four regions (shallow active crustal region, SACR, volcanic areas, VA, subduction zone, SZ and deep events, DE) based on the dominant tectonic regime and earthquake depth, following the GMM zonation of the new Italian seismic hazard map (Meletti et al., 2017):

- Bindi et al. (2011) for SACR (depths < 35 km), VA at depths greater than 5 km, and the SZ for event depths between 0 and 35 km.
- Tusa and Langer (2016) for shallow earthquakes (depths < 5 km) in the VA.
- Bindi et al. (2014) for events deeper than 35 km in the DE and for events between 35 and 70 km in the SZ.
- Abrahamson et al. (2016) for deep events (depths > 70 km) in the SZ.

SACR covers the entire Italian territory, the VA include Mount Etna, the Aeolian Islands, Pantelleria island, the Alban Hills and the Campania volcanic complex that in turn includes Ischia island, the Phlegraean fields, and Vesuvius; SZ corresponds to the southern Tyrrhenian and Ionian sea and is characterized by deep earthquakes (from 35 to ~500 km) within the Calabrian slab; DE extends throughout Italy although the events occur primarily in the northern Apennines.

ShakeMap integrates local site amplifications using a grid of uniformly distributed $V_{S30}$ values, typically spaced at intervals of 30 or 60 seconds along latitude and longitude. When only soil site classifications (e.g., Eurocode 8 [EC8] categories) are available, they are converted to corresponding VS30 values based on EC8 classification. The $V_{S30}$ map used in the INGV ShakeMap is generated by assigning $V_S$ velocities to the EC8 A-C site classes based on the geological map of Italy and combining this data with the $V_{S30}$ values (obtained from geophysical tests and topographic slopes) from the station file in the engineering strong-motion (ESM) database (Luzi et al., 2019; https://esm.mi.ingv.it/). A detailed explanation of how site effects are incorporated into the INGV ShakeMap can be found in Michelini et al. (2020).

Moreover, Ground Motion to Intensity Conversion Equations (GMICEs) are used to transform macroseismic intensities into ground-motion parameters and vice versa. Although D'Amico et al. (2025) derived an empirical relationship between macroseismic intensity and PGA for Mt. Etna, the INGV ShakeMaps in this work are produced using the GMICEs developed by Oliveti et al. (2022b), as they are calibrated for the entire Italian territory and for all the IMs of interest.

In addition to GMMs, intensity prediction equations (IPEs) are essential in ShakeMap for supplementing the typically sparse and incomplete intensity data in the intensity maps. IPEs estimate site intensity based on the earthquake's magnitude and distance, allowing macroseismic intensity to be incorporated as a native ground-motion parameter. Specifically, the INGV Shakemap adopts the Virtual IPE (VIPE), a combination of selected GMMs and associated GMICEs, which offer the same interface and behavior of an IPE. VIPE acts as a hybrid model, combining the predictive capabilities of GMMs with observed intensity data to produce a more comprehensive representation of earthquake shaking.

In this work, to the purpose of identifying the most suitable GMMs for use in volcanic regions at depths ≤ 35 km, three different combinations of GMMs, calibrated for Italy on different datasets, are tested for VA (Table 1):

- TEST1: Tusa and Langer (2016), hereafter TL16, for shallow earthquakes (depths < 5 km) and Bindi et al. (2011) for earthquakes at depths greater than 5 km. This configuration is currently implemented in ShakeMap at INGV (Michelini et al., 2020).
- TEST2: Tusa et al. (2020), hereafter TLA20, for shallow earthquakes (depths < 6 km) and Bindi et al. (2011) for earthquakes at depths greater than 6 km.
- TEST 3: Lanzano and Luzi (2020), hereafter LL20, for both shallow (depths < 5 km) and deep (depths > 5 km) earthquakes, using two separately implemented functional forms, respectively.

For TEST1, it is noteworthy that Michelini et al. (2020) opted to use Bindi et al. (2011) instead of TL16 for VA for earthquakes between 5 and 35 km depth. This followed from the application of a ranking procedure that showed more appropriate the adoption of the Bindi et al. (2011) in this depth range. In contrast, for TEST2, two different GMMs were to be used anyhow because TLA20 is exclusively calibrated for shallow earthquakes.

| Name | Code | Area | Horizontal Component | Magnitude Range | *R* type | $R_{max}$ [km] | $Z_{max}$ [km] | Site Class |
|---|---|---|---|---|---|---|---|---|
| Tusa and Langer (2016) | TL16 | Mt. Etna | GM | 3.0-4.8 ($M_L$) | $R_{epi}$ | 100 | 30 | EC8 site categories |
| Tusa et al. (2020) | TLA20 | Mt. Etna | GM | 3.0-4.8 ($M_L$) | $R_{hypo}$ | 100 | 6 | EC8 site categories |
| Lanzano and Luzi (2020) | LL20 | Mt. Etna, the Aeolian Islands and Ischia island | GM | 3.5-4.9 ($M_W$/$M_L$) | $R_{hypo}$ | 200 | 27 | EC8 site categories |

**Table 1.** List of candidate GMMs for application to shallow earthquakes in VA.

## 3. Validation of the GMMs

In this section, we evaluate the accuracy of the selected GMM combinations in predicting ground motions for VA at recording stations. For this purpose, we use an iterative cross-validation approach, commonly referred to as leave-one-out analysis (Tomczak, 1998; Hofierka et al., 2007; Worden et al., 2010; Michelini et al., 2020; Oliveti et al., 2024). This method involves the following procedure for each recorded IM.

Choose a target earthquake and, for each recording station, perform the following steps iteratively:

1) Exclude the IMs recorded at the selected station from the dataset.
2) Use the ShakeMap procedure to predict the IMs at the excluded station, utilizing data from all other stations.
3) Calculate the difference between the logarithms of the observed and predicted IMs at the excluded station.

This procedure is repeated for all the earthquakes selected for the validation.

The validation dataset comprises earthquakes with magnitudes in the range of $3 \leq M \leq 4.5$ and depths ≤ 35 km, occurring between February 2019 and May 2024 (see Data Sharing and Resources). It includes 100 earthquakes (Figs. 1 and 2), resulting in 4839, 4900, and 4872 IMs [PGA, PGV, SA(0.3), SA(1.0), and SA(3.0)] after outlier removal (i.e., log10(IM_observed / IM_predicted) > |1|) using TEST1, TEST2 and TEST3 GMM sets respectively (Fig. 3). The IMs and event metadata were obtained through the INGV web services (see Data Sharing and Resources). It is important to acknowledge that the use of different magnitude types – such as duration magnitude ($M_d$), local magnitude ($M_L$), and moment magnitude ($M_w$) – can influence ground motion prediction, particularly in volcanic or shallow earthquake contexts, where non-standard source characteristics and path effects may be more pronounced. Nevertheless, the ShakeMap system incorporates a correction mechanism in the form of an empirical bias term (Worden et al., 2020). This term adjusts the ground motion predictions to account for systematic discrepancies between observed shaking and model-based estimates for each specific event. This feature helps to mitigate the uncertainty introduced by the choice of magnitude type. Moreover, in the case of the Phlegraean Fields, where $M_d$ is typically adopted due to the nature of the seismicity and the characteristics of the local network, the potential impact of magnitude-related

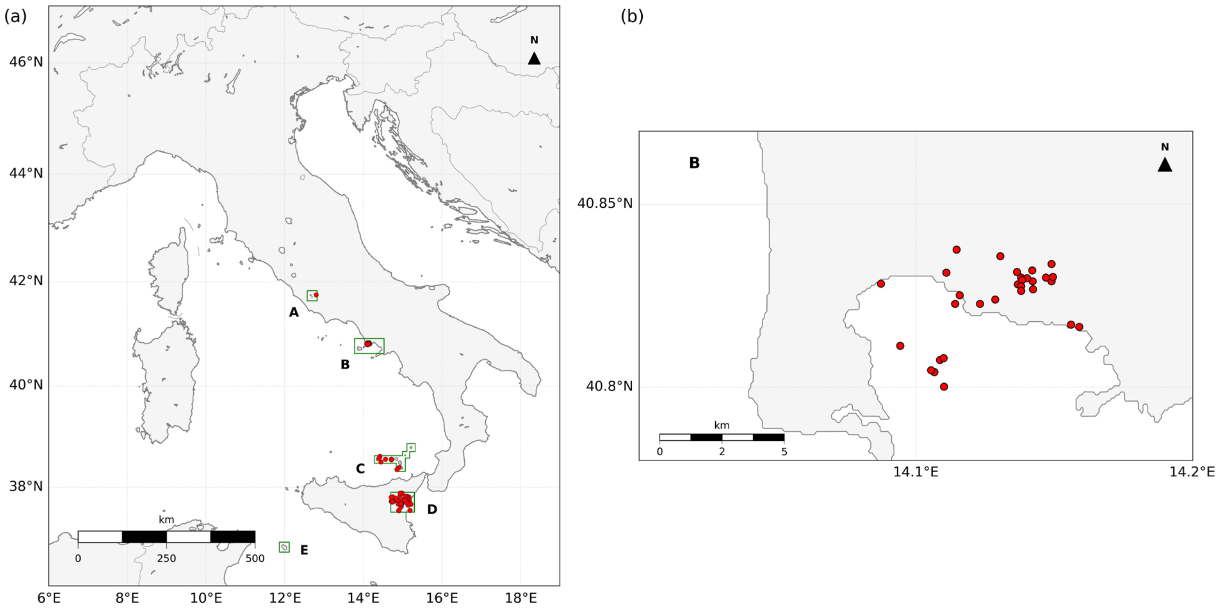

**Figure 1.** (a) Spatial distribution of the 100 earthquakes (white solid circles) used for cross-validation analysis in applying ground-motion models (GMMs) within Italian volcanic areas. The regions defined by polygons represent the volcanic areas (VA): the Alban Hills (A), the Campania volcanic complex that includes Ischia island, the Phlegraean fields, and Vesuvius (B), the Aeolian Islands (C), Mount Etna (D) and Pantelleria island (E). The polygons are defined by the INGV Seismic Monitoring Center, which is responsible for detecting and identifying earthquakes occurring within the national territory or in neighboring areas. (b) Map showing the locations of the 30 events (white solid circles) selected for this study in the Phlegraean Fields.

biases is further reduced by the dense distribution of seismic stations, enabling more accurate calibration of the empirical bias and better spatial constraint of the shaking.

We selected only earthquakes from February 2019 to avoid including events used in the datasets for calibrating the three GMMs examined. This choice was needed to verify that the GMMs are accurate in predicting ground motions at recording stations for new earthquakes, ensuring the calculation of reliable ground shaking maps. For the same reason, the GMM recently proposed by Iervolino et al. (2024) for the Phlegraean Fields was excluded from the tests, as it was calibrated using ground motion recordings from 65 events that occurred between March 2022 and May 2024. Moreover, the model is not yet usable for ShakeMap purposes, as it does not cover all the IMs of interest. The 100 selected earthquakes cover all the VA examined in this study, except for Pantelleria (see Figs. 1 and 2). Specifically, 62 earthquakes occurred at Mount Etna; 30 earthquakes in the Phlegraean fields; 7 earthquakes in the Aeolian Islands; one earthquake in the Alban Hills. Our dataset includes 42 shallow events (SE), with depths less than 5 km and 58 deep events (DE), with depths greater than 5 km (see Table 2 for details). This distinction is essential because different GMMs were applied based on earthquake depth (see Section 2), each calibrated to account for the varying attenuation with distance characteristic of shallow and deep events. Furthermore, the seismicity in some VA, such as Mt. Etna or the Phlegraean fields, presents a peculiar scenario where relatively small but shallow earthquakes can cause significant damage on a local scale (Lanzano and Luzi, 2020). For these reasons, this study focuses on observations near the epicenter to evaluate the ability of the selected GMMs to predict ground shaking in the near-source region of shallow earthquakes.

The results of the cross-validation analysis for all earthquakes are shown in Fig. 3, while Fig. 4 presents the results specifically for shallow earthquakes focused on the near-source region, i.e., with epicentral distance ≤ 20 km (Fig. 4a-c) and also disaggregated by individual volcanic areas (Fig. 4d-i). This selection implies a significant reduction in the size of the data set on which we can base our analysis, from around 4900 points to just ~ 650. Differences between observed and predicted IMs are displayed using boxplot representations. Boxplot is a method for graphically depicting groups of numerical data through their quartiles. In Fig. 3, we find that the median value for all IMs is close to zero, indicating that, overall, the three combinations of GMMs discussed in Section 2 do not exhibit significant systematic bias when considering both shallow and deep events. More specifically, in all three

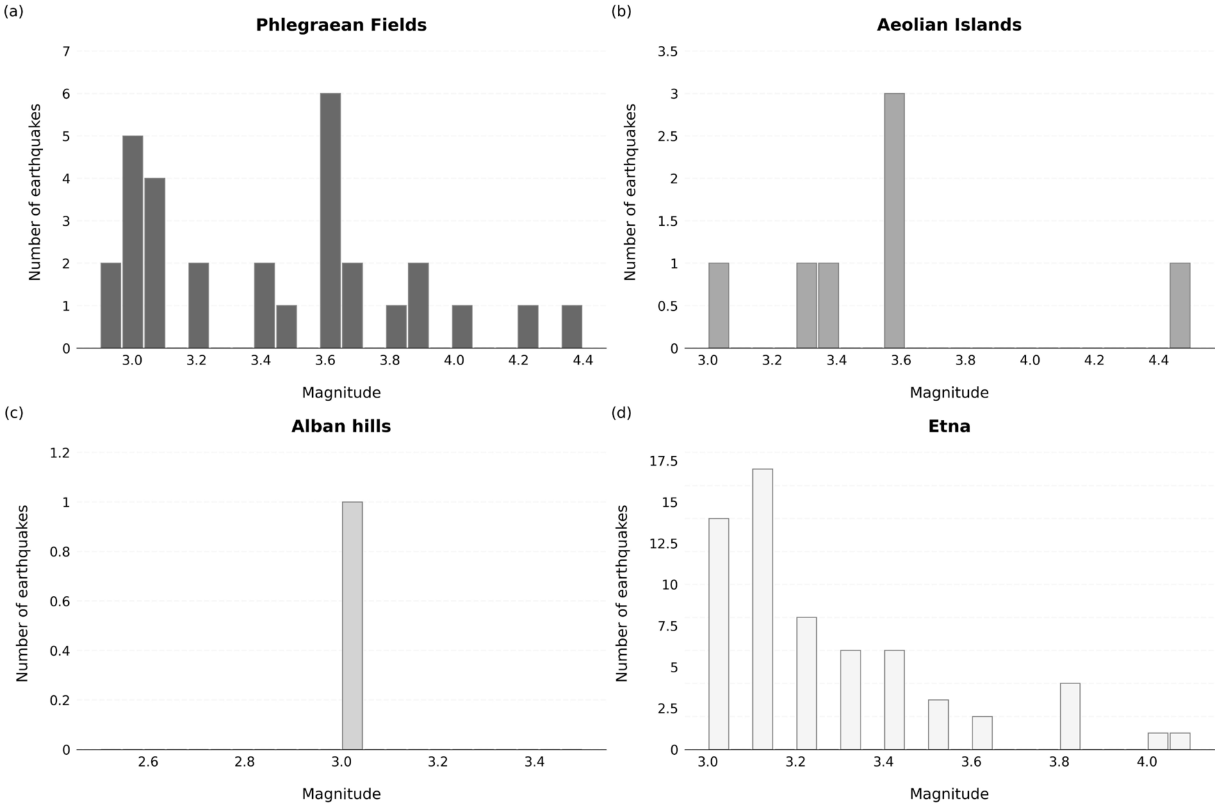

**Figure 2.** Distribution of earthquakes in the validation dataset by magnitude for each volcanic area: (a) the Phlegraean fields, (b) the Aeolian Islands, (c) the Alban Hills and (d) Mount Etna (D).

| Area | Number of SE | Number of DE | Records | $M_{\text{min}}$ | $M_{\text{max}}$ | $Z_{\text{min}}$ [km] | $Z_{\text{max}}$ [km] | $R_{\text{min}}$ [km] | $R_{\text{max}}$ [km] |
|---|---|---|---|---|---|---|---|---|---|
| The Phlegrean fields | 30 | 0 | 1872 | 3.0 | 4.4 | 1.4 | 4.5 | 1.2 | 226.5 |
| The Aeolian Islands | 1 | 6 | 451 | 3.0 | 4.5 | 3.1 | 20.9 | 9 | 198 |
| The Alban Hills | 0 | 1 | 27 | 3.0 | 3.0 | 10 | 10 | 10.2 | 130.2 |
| Mount Etna | 11 | 51 | 3259 | 3.0 | 4.1 | 0 | 30.6 | 4.9 | 219.1 |

**Table 2.** Characteristics of the validation dataset used for the leave-one-out analysis, selected from the INGV webservice (Data Sharing and Resources). Magnitude values are reported in Mw, ML, or Md.

cases, a slight overprediction can be observed for PGA, PGV, and SA(0.3). When only the data from shallow events within 20 km of the epicenter are selected (Fig. 4a-c), a differentiation in the median values is observed when using TL16 (Fig. 4a), TLA20 (Fig. 4b), and LL20 (Fig. 4c). In particular, both TL16 and TLA20 show better predictions for all IMs compared to those in Fig. 3, as evident in both the median and interquartile range's values. Conversely, the negative median values for LL20 indicate an overprediction of the level of ground shaking calculated by ShakeMap. Additional tests were conducted to investigate the behavior of the calculated residuals for SE within 20 km of the epicenter at Mount Etna (Fig. 4d-f) and in the Phlegraean Fields (Fig. 4g-i), respectively. The results for the Aeolian Islands are not shown, since the validation dataset includes only one shallow event.

When the cross-validation analysis is disaggregated to focus on the 30 shallow events in the Phlegraean Fields near-source area (Fig. 4g-i), the median values are found to be very close to zero with TL16 and TLA20, replicating what was already observed for the total of 42 events (Fig. 4a-c). In contrast, the results for LL20 indicate that ShakeMap overestimates the intensity values compared to the observed data. This behavior could be attributed to the fact that the GMM proposed by Lanzano and Luzi (2020) was not calibrated with a dataset including earthquakes

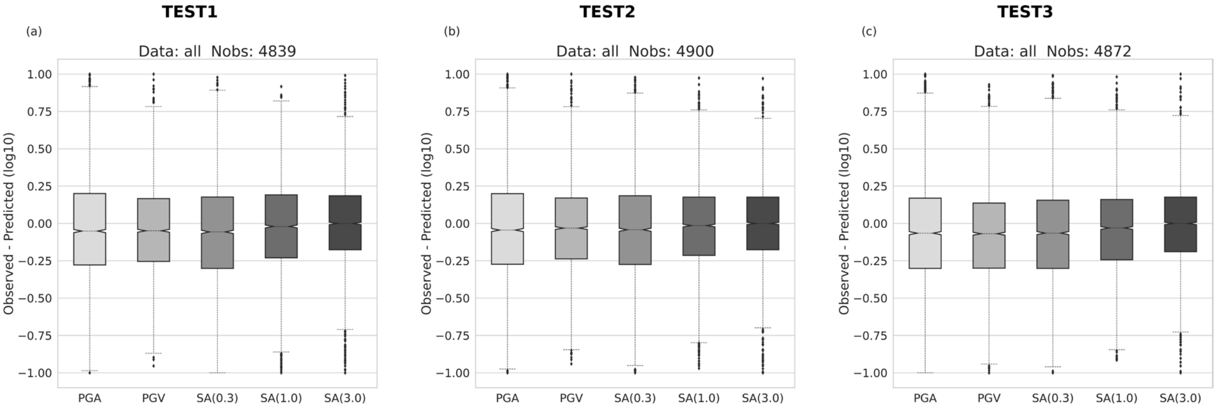

**Figure 3.** Boxplot diagram of the differences between the base-10 logarithm of observed and ShakeMap predicted values from the leave-one-out analysis for the entire validation dataset (100 earthquakes) using: (a) TEST1: Tusa and Langer (2016) (TL16) for shallow earthquakes and Bindi et al. (2011) for deep earthquakes, (b) TEST2: Tusa et al. (2020) (TLA20) for shallow earthquakes and Bindi et al. (2011) for deep earthquakes, and (c) TEST3: two separate functional forms of Lanzano and Luzi (2020) (LL20), for shallow and deep earthquakes, respectively. The units for peak ground acceleration (PGA) and spectral acceleration (SA) are log(percent-g) and for peak ground velocity (PGV) are log(cm/s). (Boxplot is a method for graphically depicting groups of numerical data through their quartiles. The box boundaries span the second and third quartile (25% and 75% of the data) and the whiskers correspond to 1.5 IQR [interquartile range, Q3-Q1 in which Q3 and Q1 are the first and third quartile, respectively.

from the Phlegraean Fields although this limitation is equally applicable to the other two models, which show, however, better performance in predicting the ground shaking.

Focusing on the validation results for SE at Mount Etna within 20 km of the epicenter, Fig. 4d-f shows that the three selected configurations result in distributions of differences between observed and predicted values that exhibit underprediction for all considered ground motion parameters. This general behavior can be explained by the relatively small number of PGM data for SE at Mount Etna within the validation dataset, compared to the higher availability of IMs for the Phlegraean Fields. Specifically, the validation dataset includes only 11 SE for Mount Etna, representing approximately one-third of the 30 SE available for the Phlegraean Fields. This trend may also be attributed to the tested GMMs and ShakeMap using different proxies to account for local site amplifications. Whereas ShakeMap employs a uniform Vs30 grid, generated as described in Section 2, Tusa and Langer (2016) and Tusa et al. (2020) classified all recording sites based on Vs30 as follows.

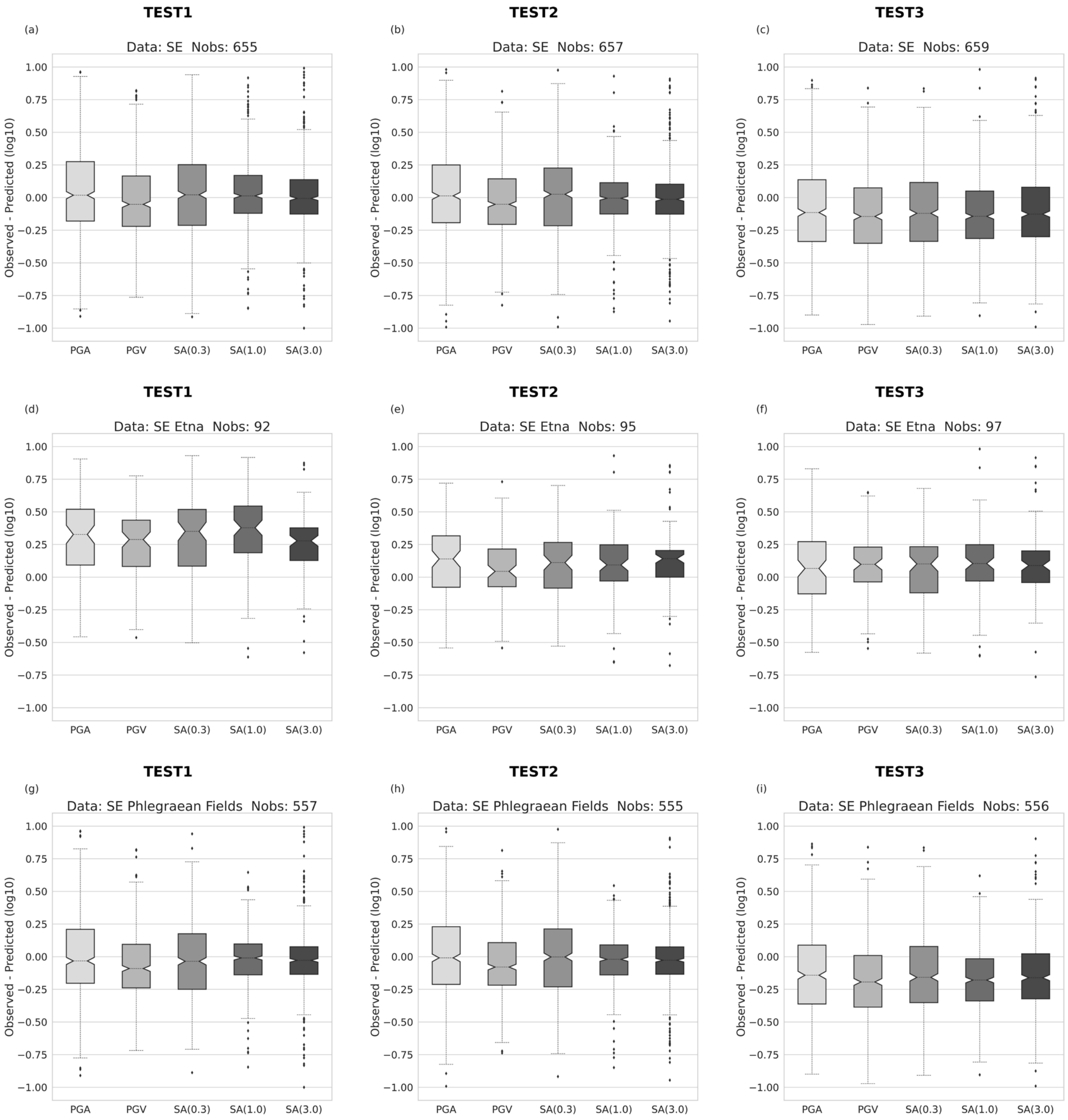

**Figure 4.** Boxplot diagrams of results from the leave-one-out analysis for the shallow events (SE) subdivided according to the different volcanic regions using: (a-d-g) Tusa and Langer (2016) (TL16), (b-e-h) Tusa et al. (2020) (TLA20), and (c-f-i) Lanzano and Luzi (2020) (LL20). (a-b-c) all volcanic areas (VA), (d-e-f) Mount Etna, (g-h-i) the Phlegraean fields. See the caption of Fig. 3 and Section 3 for details.

For Catania, they relied on seismic logs and EC8 soil classes (Gresta and Langer, 2002), while for other areas, they applied a broader classification using Sicily's geolithological map, incorporating data from the Geoportale Nazionale and the Italian strong-motion archive (ITACA, Luzi et al., 2019). In particular, the configuration based on TL16 in Fig. 4d shows larger discrepancies in terms of bias and greater uncertainties, likely due to the calibration dataset, which lacks sufficient IMs at shorter distances, as detailed at the end of the section. In contrast, the associated interquartile range for the other two GMMs are comparable to those found for the entire dataset.

To explore the behavior of the calculated residuals with increasing magnitude at closer stations, our leave-one-out cross-validation analysis was applied on a subset of the dataset. Specifically, SE with magnitudes greater than 3.5 were selected, resulting in a subset of 16 earthquakes from the dataset, 15 of which occurred in the Phlegraean Fields and 1 in the Aeolian Islands. As in previous analyses, we focused on IMs within an epicentral distance of 20 km to evaluate the robustness of predictions in the near-source region. The boxplot diagrams in Fig. 5 illustrate the distribution of residuals across all configurations and stations. The TLA20 model (Fig. 5b) shows the best predictive performance, with residuals close to zero for most IMs with the exception of PGV and SA (3.0), that display a slight overprediction.

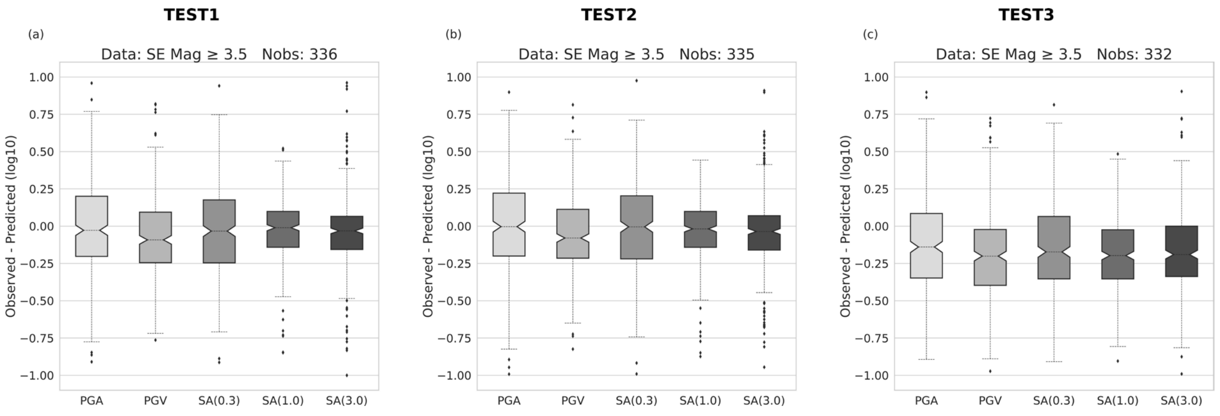

**Figure 5.** Boxplot diagrams resulting from the leave-one-out analysis for shallow earthquakes with M ≥ 3.5 using (a) Tusa and Langer (2016) (TL16), (b) Tusa et al. (2020) (TLA20), and (c) Lanzano and Luzi (2020) (LL20). See the caption of Fig. 3 and Section 3 for details.

Overall, our results indicate that TEST2 is preferable in predicting IMs for SE in the near source-region of VA within the ShakeMap algorithm. Figure 4 shows that the median values for both TL16 (Fig. 4a) and its updated version, TLA20 (Fig. 4b), are close to zero, indicating minimal systematic bias in both configurations. Between the two, however, the interquartile range associated with TLA20 is smaller than that of TL16, suggesting that TLA20 produces less scatter in the residuals compared to TL16. In particular, TLA20 shows better performance when considering only SE at the Mount Etna volcano (Fig. 4e). In fact, although both TL16 and TLA20 are calibrated using earthquakes from Mount Etna, TL16 performs well in the far field but underestimates ground shaking for events with magnitudes exceeding the calibration range, especially in the near field (Tusa et al., 2020). The better predictive capability of TLA20 likely results from the dataset used for its calibration, which, compared to that of TL16, provides a 30% increase in the amount of PGM data at shorter distances within 20 km (Tusa et al., 2020). Similarly, the difference in predictive performance between TLA20 and LL19 observed in this study can largely be attributed to the characteristics of the datasets used for their calibrations. The LL19 dataset is primarily composed of records at distances exceeding 80 km, with only 40 records available at epicentral distances less than 20 km. In contrast, TLA20 is calibrated using a dataset of 49 shallow events from Mount Etna and 1600 records, nearly half of which were collected within 20 km of the earthquake hypocenters (Tusa et al., 2020). As result, the LL19 attenuation law shows limited predictive accuracy in this study, with a clear tendency to overestimate observed PGMs, as also reported by Tusa et al. (2020).

In the following, as an example, we present the PGA shakemaps obtained from the three different configurations tested in this study (TEST1, TEST2 and TEST3) for the Md 4.4 earthquake in the municipality of Pozzuoli (see Fig. 6). We consider this event representative of the typical shallow seismicity occurring in the Phlegraean Fields.

The earthquake occurred on 13 March 2025 at 00:25 UTC and it was well recorded by the dense network of seismic stations. It occurred at a focal depth of approximately 2.5 km and because of its shallow depth, the event produced intense shaking, with PGA values exceeding 90 %g recorded at the near-source station CSOB. It is important to note that the values shown in the maps at the station locations (marked as triangles) do not provide the actual recorded ground motion at those stations, but the ShakeMap-estimated PGA values at the nearby points of the interpolation grid. This means that, even where station symbols appear on the map, the values displayed do not correspond to actual recordings but rather to model-derived estimates, calculated using nearby observational data and the ShakeMap interpolation algorithm applied to a spatial grid. As a consequence, the resulting shakemaps reproduce the best fitting maps of ground motion given the data available, the GMM and the bias adjustment.

We find that TEST2 (Fig. 6b) shows the best agreement with the actual recorded values at stations near the epicenter, particularly in the areas of Pozzuoli and Bagnoli. The PGA values recorded by the closest seismic stations were: COLB: 61.16 %g, CAAM: 26.12 %g, POZM: 35.87 %g, and CSOB: 91.47 %g. Among the three models, TEST2 appears to fit best the recorded values, as it can also be observed from the color scale, which more accurately reflects the intensity of ground motion in the epicentral area. In contrast, both TEST1 (Fig. 6a) and TEST3 (Fig. 6c) underestimate ground motion in the near-source area.

In summary, TEST2 outperforms the other two models in reproducing the spatial distribution of shaking, especially near the epicenter. It provides the most accurate and realistic ShakeMap representation of ground motion for this event, confirming that the use of TLA20 can improve the modeling of shallow, local events typical of the Phlegraean Fields.

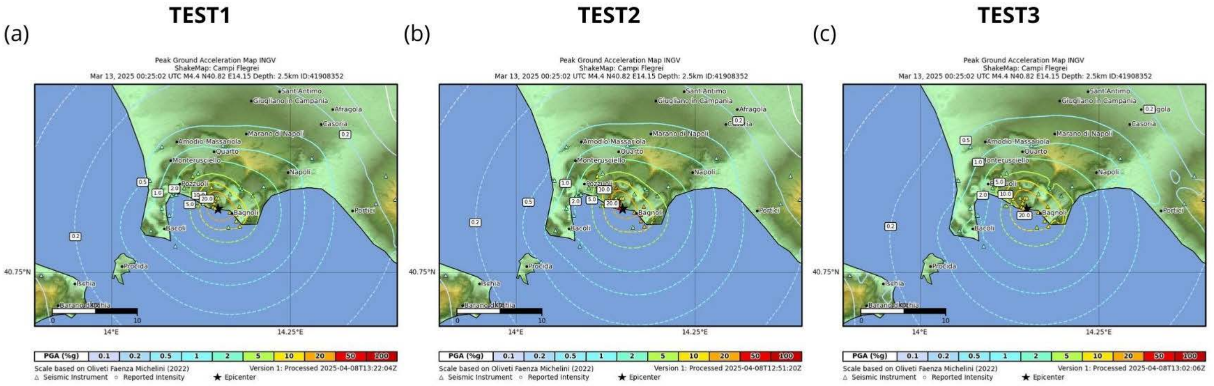

**Figure 6.** PGA shakemaps for the Md 4.4 earthquake in the municipality of Pozzuoli on March 13, 2025, generated using the three different configurations tested in this study: (a) TEST1, (b) TEST2, and (c) TEST3. In each panel, the black star indicates the epicenter and the triangles denote the seismic stations used in the analysis.

## 4. Conclusions

In this work, we evaluated the GMMs for volcanic areas in Italy that have become available in recent years by testing them against observations using the leave-one-out approach developed for shakemap testing by Michelini et al. (2020). Specifically, we analyzed the GMMs proposed by Tusa and Langer (2016), Tusa et al. (2020) and Lanzano and Luzi (2020) to identify the most appropriate attenuation law for predicting IMs [PGA, PGV, SA(0.3), SA(1.0), and SA(3.0)] within ShakeMap.

Our analysis of the residuals (i.e., the differences between the observed and predicted ground motion data) for TL16, TLA20, and LL19 shows that, overall, TLA20 provides more accurate predictions of shaking for all IMs. The leave-one-out cross-validation analysis was particularly focused on estimating the ground motion prediction capabilities for shallow earthquakes in the near field, where shallow earthquake ground motions have the major impact, from both an engineering and emergency response perspective.

In conclusion, the proposed configuration using TLA20 for shallow earthquakes (depths $< 6$ km) and Bindi et al. (2011) for earthquakes at depths ranging from 6 to 35 km, appears to provide accurate ground motion estimates for earthquakes in volcanic areas of Italy. This suggests that the ground motion model developed by Tusa et al. (2020) can be incorporated into the USGS-ShakeMap configuration currently in use at INGV (Michelini et al., 2020).

**Data Sharing and Resources.** The earthquakes have been selected from the INGV webservice (https://webservices.ingv.it/swagger-ui/dist/?url=https://ingv.github.io/openapi/fdsnws/event/0.0.1/event.yaml.) The intensity measure (IM) data are all accessible through the INGV Shakedata webservices (https://webservices.ingv.it/ingvws/shakedata/1/swagger.yml; last accessed May 2024). The U.S. Geological Survey (USGS)-ShakeMap open-source software is available on the GitHub development platform available at https://github.com/usgs/shakemap.

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## References

Abrahamson, N. A., N. Gregor and K. Addo (2016). BC hydro ground motion prediction equations for subduction earthquakes, Earthq. Spectra 32, no. 1, 23-44, doi:10.1193/051712EQS188MR.

Bindi, D., F. Pacor, L. Luzi, R. Puglia et al. (2011). Ground motion prediction equations derived from the Italian strong motion database, Bull. Earthq. Eng., 9, no. 6, 1899-1920, doi:10.1007/s10518-011-9313-z.

Bindi, D., M. Massa, L. Luzi, G. Ameri et al. (2014). Pan-European ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods up to 3.0 s using the RESORCE dataset, Bull. Earthq. Eng. 12, 1, 391-430.

D'Amico, S., R. Azzaro, G. Tusa, T. Tuvè et al. (2025). Volcano-tectonic seismicity and related hazard: a component of the multi-hazard assessment in the highly exposed region of Mt. Etna (Italy), Ann. Geophys, 68, doi:10.4401/ag-9152.

Engler, D. T., C. B. Worden, E. M. Thompson and K. S. Jaiswal (2022). Partitioning ground motion uncertainty when conditioned on station data, Bull. Seismol. Soc. Am., 112, 2, 1060-1079, doi:10.1785/0120210260.

Eurocode 8 (2004). Design of structures for earthquake resistance, part 1: General rules, seismic actions and rules for buildings, EN 1998-1, European Committee for Standardization (CEN), Brussels, Belgium, available at http://www.cen.eu/cenorm/homepage.html.

Gresta, S. and H. Langer (2002). Assessment of seismic potential in southeastern Sicily, in Risk Analysis III, C. A. Brebbia (Editor), WIT Press, Boston, Massachusetts, 617-626.

Hofierka, J., T. Cebecauer and M. Šúri (2007). Optimization of interpolation parameters using cross-validation. In Digital Terrain Modelling, R. J. Peckham and G. Jordan (Eds.), Springer, Berlin, Heidelberg, 67-82, doi:10.1007/978-3-540-36731-4_3.

Iervolino, I., P. Cito, M. De Falco, G. Festa et al. (2024). Seismic risk mitigation at Campi Flegrei in volcanic unrest, Nat. Commun., 15, 10474, doi:10.1038/s41467-024-55023-1.

Lanzano, G., and L. Luzi (2020). A ground motion model for volcanic areas in Italy, Bull. Earthq. Eng., 18, 57-76, doi:10.1007/s10518-019-00735-9.

Luzi, L., R. Puglia, E. Russo, M. D'Amico et al. (2016). The engineering strong-motion database: A platform to access pan-European accelerometric data, Seismol. Res. Lett., 87, 4, 987-997, doi:10.1785/0220150278.

Luzi, L., F. Pacor and R. Puglia (2019). ITalian ACCelerometric Archive v3.0. Istituto Nazionale di Geofisica e Vulcanologia, Dipartimento della Protezione Civile Nazionale, doi:10.13127/itaca.3.0.

Meletti, C., W. Marzocchi, D. Albarello, V. D'Amico, et al. (2017). The 2016 Italian seismic hazard model. 16th World Conf. Earthq. Eng., Santiago, Chile, January 9-13.

Michelini, A., L. Faenza, V. Lauciani, and L. Malagnini (2008). ShakeMaps implementation in Italy, Seismol. Res. Lett., 79, 688-697, doi:10.1785/gssrl.79.5.688.

Michelini, A., L. Faenza, G. Lanzano, V. Lauciani et al. (2020). The new ShakeMap in Italy: Progress and advances in the last 10 years, Seismol. Res. Lett., 91, 317-333, doi:10.1785/0220190130.

Oliveti, I., L. Faenza and A. Michelini (2022a). Inge: Intensity-ground motion dataset for Italy, Ann. Geophys. 65, DM102, doi:10.4401/ ag-8709.

Oliveti, I., L. Faenza and A. Michelini (2022b). New reversible relationships between ground motion parameters and macroseismic intensity for Italy and their application in ShakeMap, Geophys. J. Int., 231, 1117-1137, doi:10.1093/gji/ggac245.

Oliveti, I., L. Faenza, A. Antonucci, M. Locati et al. (2024). The ShakeMap Atlas of historical earthquakes in Italy: Configuration and validation, Seismol. Res. Lett., 95, 1, 21-37, doi:10.1785/0220230138.

Tomczak, M. (1998). Spatial interpolation and its uncertainty using automated anisotropic inverse distance weighting (idw)-cross-validation/jackknife approach, J. Geogr. Inform. Decis. Anal. 2, 18-30.

Tusa, G. and H. Langer (2016) Prediction of ground-motion parameters for the volcanic area of Mount Etna, J. Seismol., doi:10.1007/s10950-015-9508-x.

Tusa, G., H. Langer, and R. Azzaro (2020). Localizing ground-motion models in volcanic terranes: shallow events at Mt. Etna, Italy, revisited, Bull. Seismol. Soc. Am. 110, 2843-2861, doi:10.1785/0120190325.

Wald, D. J., V. Quitoriano, T. H. Heaton, H. Kanamori et al. (1999). Trinet ‘ShakeMaps’: Rapid generation of peak ground motion and intensity maps for earthquakes in southern California, Earthq. Spectra, 15, 537, doi:10.1193/1.1586057.

Worden, C. B., D. J. Wald, T. I. Allen, K. Lin et al. (2010). A revised ground-motion and intensity interpolation scheme for ShakeMap, Bull. Seismol. Soc. Am., 100, 3083-3096.

Worden, C. B., E. M. Thompson, J. W. Baker, A. P. Brendon et al. (2018). Spatial and spectral interpolation of ground-motion intensity measure observations, Bull. Seismol. Soc. Am., 108, 2, 866-875, doi:10.1785/0120170201.

Worden, C. B., E. M. Thompson, M. Hearne and D. J. Wald (2020). ShakeMap Manual Online: technical manual, user’s guide, and software guide, U. S. Geological Survey, http://cbworden.github.io/shakemap/, doi:10.5066/F7D21VPQ (last accessed November 2024).

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