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CLUSTERING-BASED ANALYSIS OF GROUND MOTION DIRECTIONALITY: PRELIMINARY INTENSITY MEASURES AND HYPOCENTRAL CORRELATIONS IN THE ITALO-BALKAN PENINSULA

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Abstract. *Earthquake ground motion parameters exhibit significant variability when considering the simultaneous interaction of horizontal components and their orientation within the horizontal plane. Traditionally, these effects have been analyzed by evaluating each direction independently and establishing probabilistic correlations. This study proposes an alternative approach that unifies the Cartesian components of ground motion into a single framework, exploding an extensive dataset of recorded seismic events from the Italian and Balkan peninsulas. By representing all response ordinates in polar coordinates, this method effectively captures the variability across all horizontal orientations as a function of the rotation angle relative to the azimuth of maximum response. A convex hull approach is employed to determine the shape of the grouped ground motion, using the newly proposed maximum rotation-independent principal ground acceleration as a reference. These results were then used to approximate a simplified ellipsoidal envelope model for correlating the maximum rotation-independent principal ground acceleration with its orthogonal component, denoted b value. Some seismological classifications and Intensity Measures AI-driven clustering were performed to highlight underlying parameters and propose a generalized expression for the location under study. By incorporating these directional effects, which are often overlooked in probabilistic seismic hazard analyses and in the majority of building codes, the findings provide a refined framework for*

preliminarily estimating ground motions directionality. These findings enhance seismic design and retrofitting by correlating structural orientation and earthquake directionality, improving resilience and performance.

1 Introduction

Throughout the 20th century, earthquakes have been a major area of study for scientists and governmental organizations due to their devastating effects, including loss of life, economic instability, and widespread social disruption. To address these challenges, various national institutions have been established to consolidate seismic knowledge, enhance infrastructure resilience, and incorporate advancements in earthquake and structural engineering.[1]

Geologically, the Eurasian and African plates are largely stable, with the exception of specific regions where intense tectonic activity such as subduction, collision, and rifting occurs. While seismic activity remains relatively low in central and northern Europe due to their position within the stable interior of the Eurasian plate, the southern areas including the Alpine belt, the Messina Strait, the Balkan Peninsula, and the Hellenic Arc lie along active fault systems. These zones are particularly vulnerable to earthquakes and also face a considerable tsunami threat.[2]

Over the past century, the Italian and Balkan regions have experienced more than 400 major earthquakes with destructive consequences. Notable events include the Skopje Earthquake (1963), the Friuli Earthquake (1976), the Irpinia-Basilicata Earthquake (1980), the L'Aquila Earthquake (2009), and the Amatrice Earthquake (2016).[3, 4] These disasters emphasize the urgent need for improved seismic resilience in these high-risk areas. The seismic hazard posed by their tectonic setting is further aggravated by dense urban populations and aging infrastructure, much of which is historically significant and not designed to withstand modern seismic loads.[5]

Seismic-resistant design in these regions has traditionally relied on response spectrum methodologies outlined in European seismic codes such as Eurocode 8 (EC8). These regulations establish design spectra based on site-specific conditions, including soil classification, but they do not explicitly account for ground motion directionality. Instead, seismic demands are typically considered uniform in both horizontal directions, adjusted using reduction factors derived from combination rules. However, research has increasingly demonstrated that the directionality of seismic waves and their incidence angle significantly influence structural response, suggesting the need for a more rigorous approach.[6]

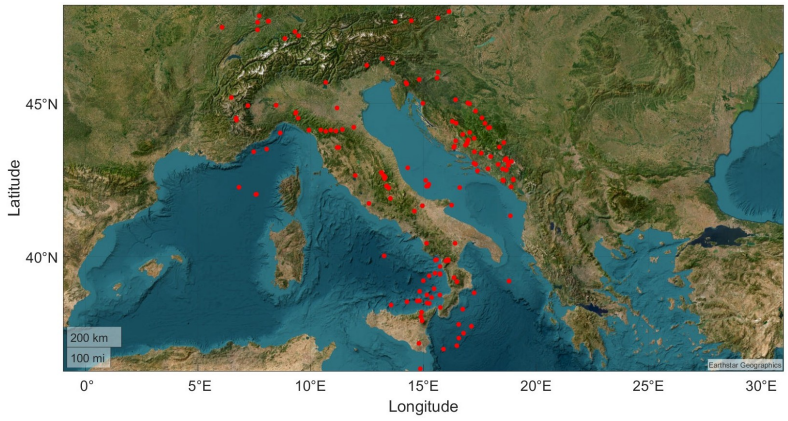


Figure 1: Geographic location of database Ground Motions' Epicenters

In contrast, international seismic codes, such as those from the American Society of Civil Engineers (ASCE) and the New Zealand Horizon Earthquake Risk Provisions (NHERP), adopt a more refined methodology by explicitly addressing the bidirectional nature of ground motion. These frameworks recommend independent analysis of seismic forces along both principal hor-

izontal directions. Studies indicate that the angle at which seismic waves strike a structure is a key factor in determining its response, especially in near-fault environments where ground motion intensity varies significantly depending on orientation. This variability makes directional amplification an essential consideration in seismic design.[7]

To address these concerns, this study explores a preliminary orientation-independent approach to ground motion analysis in the Italian and Balkan regions. Utilizing a comprehensive dataset of over 2,800 earthquake recordings (illustrated in Fig. 1).

This study examines the relationship between seismic directionality and epicentral-hypocentral parameters in the region. Starting from the U.S. seismic regulations that explicitly consider directionality effects, it adopts a similar conceptual framework. However, instead of focusing on spectral response calculations, at this stage it prioritizes the analysis of directional characteristics in recorded ground motions to develop an independent approach for computing principal and orthogonal seismic components, incorporating local parameters and seismic intensity measures.

2 Rotation-Independent Models Ground Motion Directionality

Two primary methodologies have been established for quantifying horizontal ground motion (GM) intensities. Building on the fundamental principles underlying these models, this study introduces an alternative formulation that aligns with the framework of Ground Motion Prediction Models (GMPMs) used for the Geometric Mean Rotation-Independent (GMRotI) approach. These approaches consider both recorded GM components along two orthogonal directions to derive a scalar intensity measure, ensuring robustness across varying orientations. [8]

To determine the best ground motion intensity measure for GMPMs, taking into account elements like probabilistic assessment of seismic hazards [7], seismological characteristics [8], and spatial range of inference [9]. ROTD100 and ROTD50 are among the most popular rotation-independent spectral acceleration metrics, both measure orientation-independent spectral acceleration at a specific Period. They differ only in whether it is considered the median spectral acceleration for all orientations or the maximum spectral acceleration (Sa) of all possible orientations.

Despite being widely used, ROTD measures only consider spectral accelerations from individual rotational orientations, which leaves out the combined impact of both horizontal components. The GMRotI50 metric, which incorporates both horizontal components to produce a rotation-independent geometric mean spectral acceleration, is developed to overcome this constraint. [10], as depicted in Eq. (1), where (S_{ax}(T,θ) and S_{ay}(T,θ) denote the spectral accelerations of the two orthogonal ground motion components at period T, rotated by angle θ.

$$S_a(T, GMROTI50) = \text{median}\left(\sqrt{S_{ax}(T,\theta)\cdot S_{ay}(T,\theta)}\right), \quad \forall\theta \in [0^\circ, 180^\circ] \tag{1}$$

Response spectrum characteristics obtained from these rotation-independent measurements are incorporated into a number of seismic guidelines and standards, such as NEHRP, ASCE, and NIST. The following sections present the analysis of the proposed Maximum Rotation-Independent Ground Acceleration model, incorporating a simplified expression that accounts

for θ variation. At this stage, the model is restricted to time history analysis.

3 Directional Variability in Ground Motion: Classification of Maximum Polar Ordinates and Earthquake Characteristics

This study analyzes 2,809 ground motion events recorded between 2009 and 2016, sourced from a subset of the Italian National Institute of Volcanology and Geophysics (INGV) database. Each record includes key event data such as epicenter, hypocenter, moment magnitude (Mw), and sampling time, along with ground acceleration in orthogonal X and Y components. Prior to analysis, the data undergoes preprocessing to reduce noise and ensure consistency. A two-stage filtering process is applied: first, a parameter Ro (Eq. (2) isolates the relevant time window for all directions; second, a bandpass filter removes low-amplitude signals below 6.5% of the maximum Ro acceleration. Instead of incrementally varying the ground motion (GM) incidence angle, this study identifies the maximum polar ordinate for each earthquake record and normalizes other readings for dimensional consistency. The maximum polar acceleration is then linked to a "principal" polar direction, and the reference system is rotated to align with the structural orthogonal coordinate system, such procedure can be appreciated in Fig. (2) for GM id. 156.

$$Ro_{(g)} = \sqrt{A_{y(g)}{}^2 + A_{x(g)}{}^2} \quad \theta_{(g)} = \tan^{-1}\left(\frac{A_{y(g)}}{A_{x(g)}}\right) \tag{2}$$

This methodology propose a polar input grouping strategy confined to Quadrant I, designed to establish a generalized expression that effectively relates the principal direction to its orthogonal counterpart. Fig. (3) illustrates the application of this approach to a ground motion (GM) record from the dataset, demonstrating its effectiveness in standardizing bidirectional excitation. The Quadrant I framework ensures consistency with loading regulations, as it preserves the structural response symmetry by subjecting each orthogonal component to excitations of equal magnitude in both positive and negative directions. Consequently, this approach remains aligned with established engineering practices and regulatory standards.

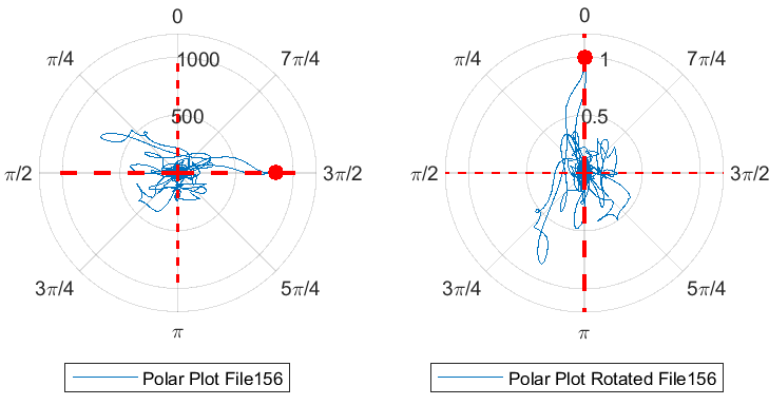


Figure 2: Coordinates Polar visualization. Initial conditions (left) and Normalization and reorientation (right) for Record id.156

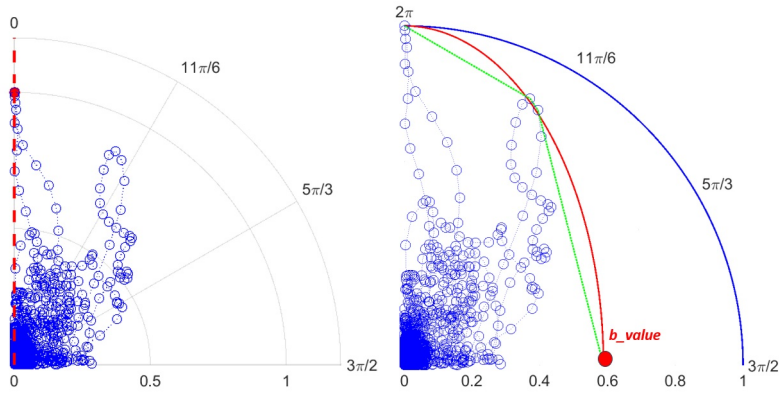


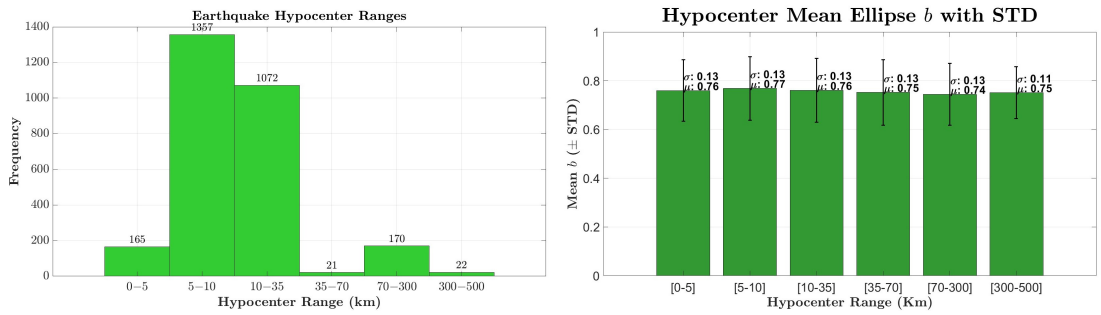
Figure 3: Grouping Quadrant 1 for Polar directionality GM record id.156

By applying Kernel Density Estimation (KDE) to each ground motion record, a consistent underlying pattern emerged across the scatter data, suggesting the potential for a generalized mathematical representation. To achieve this, a convex hull function was employed to enclose the data points, effectively delineating the distribution's boundary (**Green line** in Fig. 3). This perimeter was then used to compute an enclosed area, which was subsequently approximated using an elliptical formulation (**Red line** in Fig. 3), as expressed in Eq. (3).

$$r(b,\theta) = \frac{b_{\text{value}}}{\sqrt{(b_{\text{value}}\cos\theta)^2 + (\sin\theta)^2}} \tag{3}$$

In this representation, the shape variation is governed by a single parameter, enabling a flexible mathematical model that captures the correlation between the principal and orthogonal directions of the maximum rotation-independent ground motion intensity.

To identify correlations between the proposed rotation-independent ground motion model and the intrinsic characteristics of earthquake locations, a subsequent analysis is performed. This analysis considers all computed b values, categorizing them based on the event's hypocenter (focal depth).



(a) (b)

Figure 4: (a) Hypocenter (Focal Depths) Histogram considering a lithosphere and mantle seismological classification. (b) Mean (μ) and standard deviation (σ) for the Ellipsoidal Envelope characteristic b value under the established focal depth ranges.

The classification presented in the histogram (Fig. 4(a)) is based on the depth categorization of earthquake hypocenters within the Earth's lithosphere and mantle. The depth intervals include Shallow (0–10 km), Upper Crust (10–35 km), Lower Crust (35–70 km), Upper Mantle (70–300 km), and the Transition Zone (300–500 km) [11]. To further refine conventional seismological classifications, an additional subdivision has been introduced within the shallowest range (<10 km), distinguishing between superficial (<5 km) and very shallow (5–10 km) categories. This refinement enhances the precision of near-surface seismic event characterization.

Fig. (4 (b)) illustrates the first-order statistical parameters of the b value across the focal depth ranges classified according to the previously introduced seismological categories. The results indicate that b values remain consistent across these depth classifications, suggesting that, at this stage, seismic directionality is not directly influenced by focal depth. Consequently, the location of the seismic source within the lithosphere or mantle does not inherently dictate a predominant correlation between the principal and orthogonal directions across different depth ranges.

4 Unsupervised Machine Learning Clustering for Outlier Detection in Intensity Measures

To enhance the refinement of the classification, it has been deemed necessary to consider parameters strictly related to ground motion. Among relevant references, it has been widely acknowledged that a comprehensive understanding of an earthquake event extends beyond instantaneous measures such as Peak Ground Acceleration (PGA) or Peak Ground Velocity (PGV). While these parameters are directly related to earthquake-induced damage, they fail to fully characterize the event over its entire duration. Therefore, a more refined approach is incorporating Intensity Measures (IMs) that account for the cumulative energy transmitted throughout the seismic event rather than relying solely on peak values[12].

Specific Energy Density (SED), and Arias Intensity (AI) are key Intensity Measure parameters that integrate ground motion over time. Unlike instantaneous metrics, these measures provide a more holistic representation of seismic impact by capturing both the duration and total energy imparted to a structure. This aspect is particularly critical for structures susceptible to cumulative damage effects. SED and AI offer a more comprehensive assessment of an earthquake's overall impact. For this classification approach, they enable more meaningful dis-

tinctions between seismic events, serving as a more insightful and intrinsic reference compared to PGA or PGV, which may oversimplify the data.

Arias Intensity (AI) was introduced as an intensity measure to provide a more comprehensive quantification of earthquake energy than traditional scales such as the Richter scale or the Mercalli intensity scale. This method emphasizes the cumulative energy of ground motion, which makes it particularly valuable for assessing the potential for structural damage. By integrating the squared acceleration time history, AI offers a more holistic view of the seismic event's impact. The measure is expressed in units of velocity (m/s or cm/s), as shown in Equation (4), where g represents the acceleration due to gravity, a(t) denotes the ground acceleration time history (cm/s²), and T signifies the total duration of the ground motion.

$$AI = \frac{\pi}{2g} \int_0^T a^2(t)\, dt \tag{4}$$

Specific Energy Density (SED) is an intensity measure that quantifies the cumulative energy imparted by seismic ground motion through the integration of the squared velocity time history. In contrast to Arias Intensity, which emphasizes energy derived from acceleration, SED is more directly associated with the kinetic energy transferred to structures. This makes it particularly valuable for evaluating resonant responses in flexible or long-period systems. By squaring and integrating the ground velocity $\dot{u}(t)$ over the duration of the ground motion, SED captures the sustained energy dissipation potential of an earthquake. The measure is expressed in units of energy per unit mass (cm²/s²), as shown in Equation (5), where $\dot{u}(t)$ represents the ground velocity time history (cm/s), and T denotes the total duration of the seismic event.

$$SED = \int_0^T [\dot{u}(t)]^2\, dt \tag{5}$$

Once both intensity measures (IMs) were computed for the entire dataset, categorized according to the same hypocentral classification as in the previous section, a data clustering process was developed using the unsupervised machine learning algorithm k-means. The goal of this clustering was to identify underlying patterns in the data based considering the total energy of the events (IM's). This approach not only provides more specific information regarding the intensity of events originating at various depths within the lithosphere, but also refines the ellipsoidal envelope's characteristic b-value by isolating outlier values that deviate from the established trend within each classification.

Fig. (5) presents the mean (μ) and standard deviation (σ) of Arias Intensity (AI) for each category. Notably, the k-means clustering analysis consistently identified two distinct subgroups within each category: one representing the typical values and another comprising a small set of atypical records exhibiting AI values that deviate from the overall trend. This group of outliers significantly influences the computation of the characteristic b-value of the ellipsoidal envelope, thereby affecting the precision of the envelope estimation and, consequently, the calibration of the model.

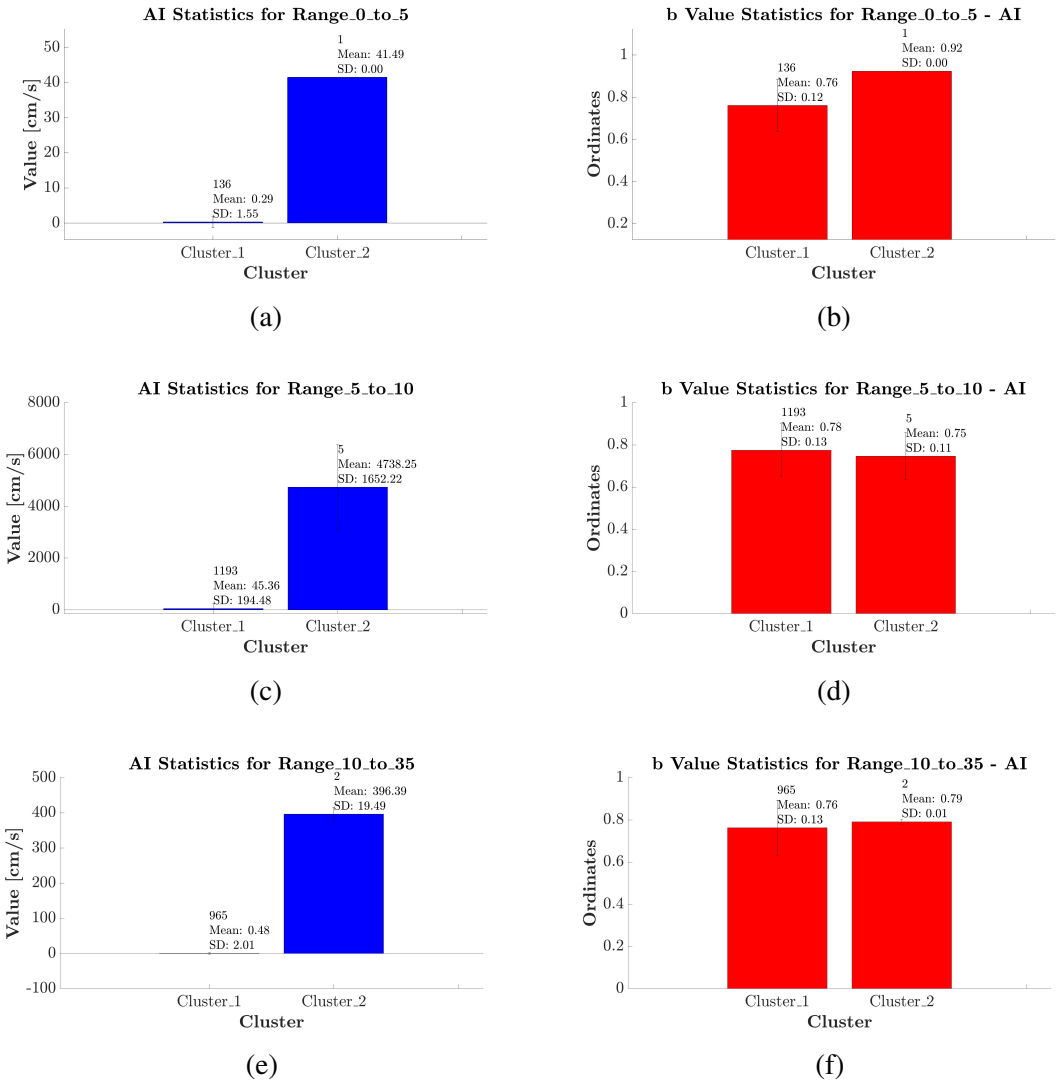


Figure 5: First-order statistics (μ and σ) for the clustering outcome considering Focal Depth Classification and Arias Intensity measure

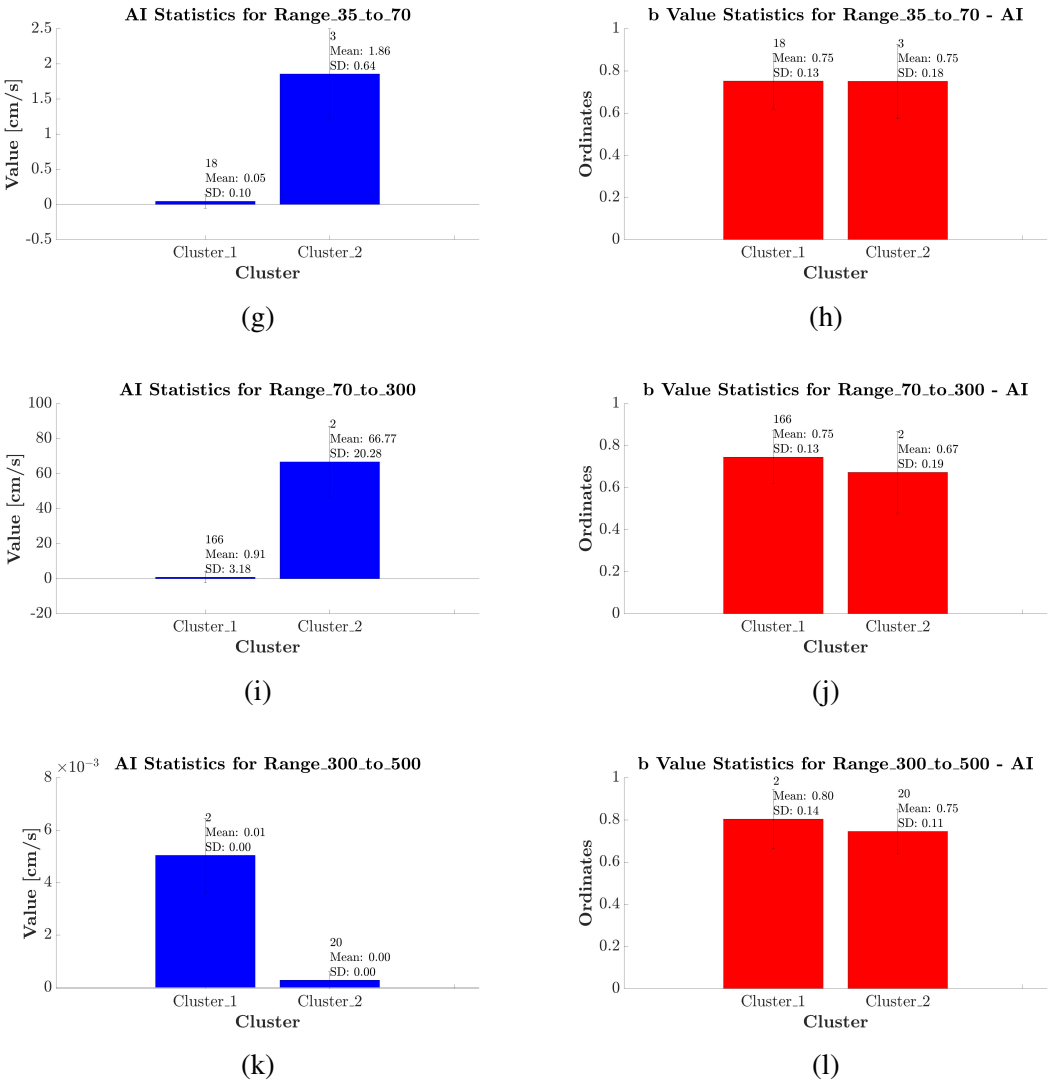


Figure 5: Continued

Similarly to what was observed in Fig. 5 for Arias Intensity, Fig. 6 presents the mean (μ) and standard deviation (σ) of Specific Energy Density (SED) for each focal-depth category. The k-means clustering analysis also revealed two subgroups: one corresponding to the typical values within each category and another consisting of a small fraction of records with atypically high SED values that deviate from the expected trend. These outliers play a crucial role in modifying the characteristic b-value of the ellipsoidal envelope, affecting the accuracy of the envelope representation.

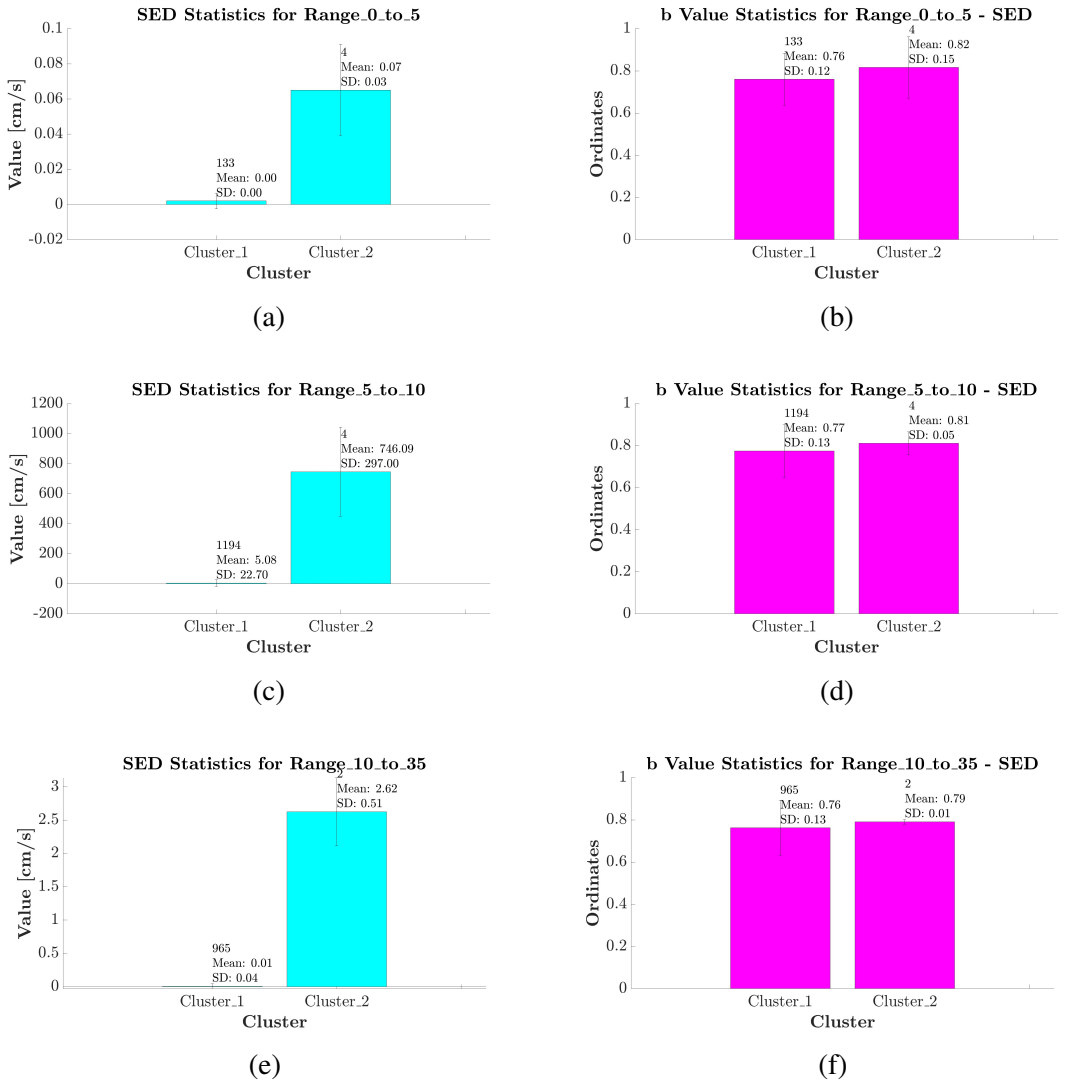
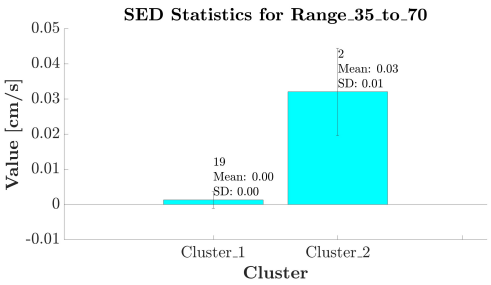
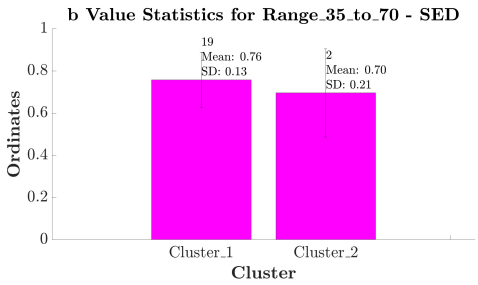


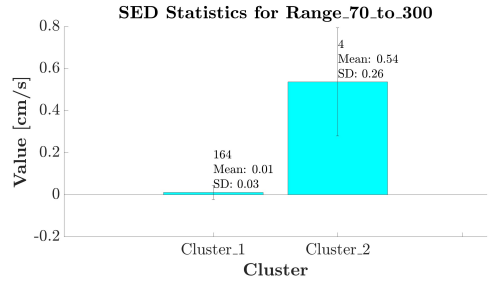
Figure 6: First-order statistics (μ and σ) for the clustering outcome considering Focal Depth Classification and Specific Energy Density measure.



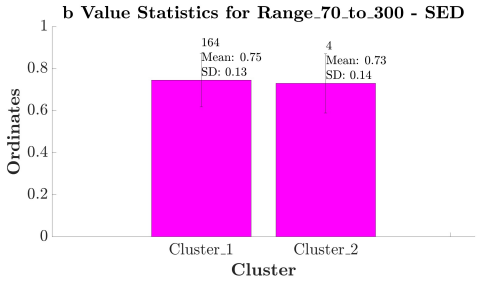
(g)



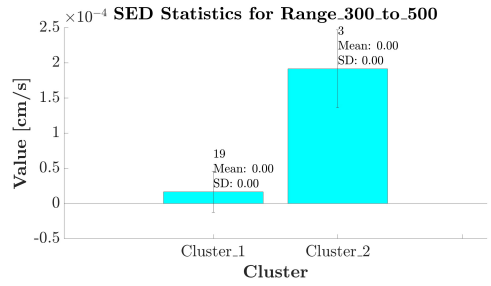
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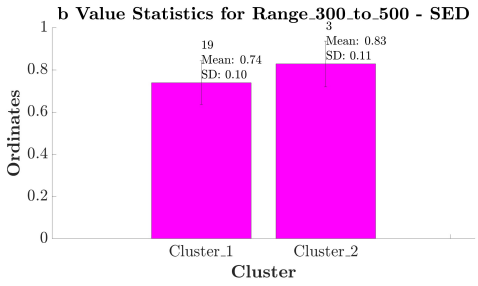
(i)



(j)



(k)



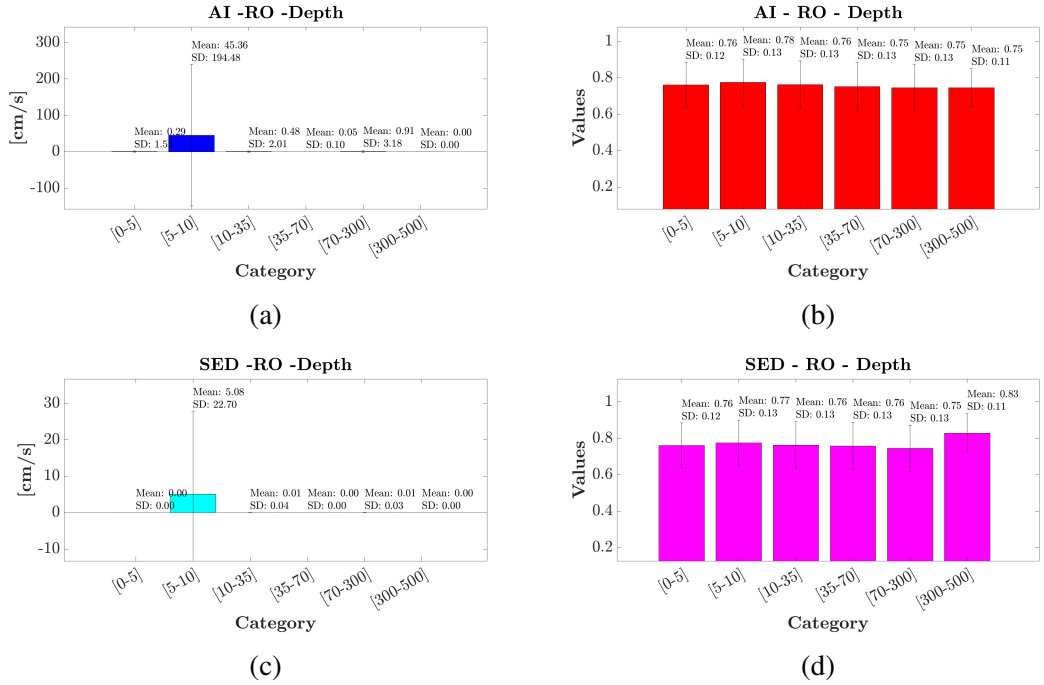
(l)

Figure 6: Continued

After analyzing Fig.s (5) and (6), which illustrate the clustered information for the ground motion dataset across the six focal-depth categories, it is evident that the most representative class for the Italo-Balkan Peninsula region corresponds to hypocentral depths ranging from 5 km to 10 km **(see Fig.s 5 (c)(d) and 6 (c)(d))**. This depth range accounts for approximately 50% of the recorded seismic events in the region, with an average Arias Intensity (AI) of around 45 cm/s and a Specific Energy Density (SED) of approximately 5 cm²/s. However, these intensity measures exhibit considerable variability, likely influenced by multiple factors such as fault type, seismic triggering mechanisms, and local soil conditions, among others. A particularly noteworthy aspect of the analysis is its connection to the characteristic b-value of the ellipsoidal envelope. This relationship, which becomes evident when considering only the in-range clustered values, will be further examined in the final section of the article.

5 Conclusions and Future Developments

The analysis of average b-values and their standard deviations, both within the general Hypocentric Classification and under the Intensity Measure-based clustering, indicates that a definitive standardization for hypocentral depths for the Italian and Balkan peninsulas remains inconclusive. Similarly, Arias Intensity and Specific Energy Density do not exhibit a consistent trend that categorizes the expected energy release of earthquakes at specific depth ranges.



(a) (b) (c) (d)

Figure 7: First-order statistics (μ and σ) for representative cluster considering Focal Depth Classification and Arias Intensity / Specific Energy Density in maximum rotation-independent principal ground acceleration (Ro).

However, a detailed examination of Fig.(7), consistently highlights that for the Hypocentral depth range of [5–10] km, the maximum rotation-independent principal ground acceleration is approximately 1.28 times greater than the polar rotation-independent orthogonal acceleration, with a dispersion of about 13%.

Furthermore, in sub-sections (a) and (c) of Fig. (7) is observed that in the [5–10] km depth category range the vast allocation of earthquake events is also associated with a higher mean energy release per event. This suggests an emerging trend that could motivate further investigation, potentially leading to unraveling ground motion behavior within the region for earthquakes originating at those depths.

At this stage, drawing definitive statements remains premature. Nevertheless, given the consistency observed in the ellipsoidal model, future research will focus on refining the clustering approach through a multi-criteria classification. This approach will not only integrate Intensity Measures but also incorporate the precise spatial coordinates of each event, potentially unveiling geological correlations related to soil conditions or fault propagation angles.

Finally, the current results on directionality confirm that the maximum rotation-independent principal ground acceleration is approximately [1.25–1.45] times greater than the polar rotation-

independent orthogonal acceleration. This insight sets the foundation for the next phase of the study, which will involve subjecting a Single-Degree-of-Freedom (SDOF) system to rotation-independent principal and orthogonal acceleration time histories to assess damage indicators and examine the coherence between principal rotation-independent inputs and structural response through Engineering Demand Parameters. If the outcomes prove promising, the study will be extended to Multi-Degree-of-Freedom (MDOF) and 3D models.

6 Acknowledgements

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