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SPATIAL STATISTICS AND POINT PATTERN ANALYSIS OF EARTHQUAKE DISRIBUTION IN THE ZAGROS REGION (IRAN)

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Modeling spatial distribution of earthquakes has long been a focus of research by seismologists and statisticians. The occurrence of earthquakes can be considered as a point process, and statistical analysis of such a point process is useful for the investigation of various statistical features of seismic activity. Spatial point pattern analysis of earthquake epicenters can help us to improve our understanding about the seismicity characteristics of tectonically active regions. When the active faults in a seismically active region are hidden and the occurred earthquakes are not clearly associated with surface ruptures, these methods can reliably be used for identification and characterization of blind active faults. Furthermore, the spatial variation of seismic activity in an earthquake-prone region is closely related to both tectonic regime and fault structures of that region. In addition, the spatial distribution of this seismic activity reflects the variation of the stress regime acting over the study region.

During the past decades, point pattern analysis techniques widely have been used for exploring the internal structure of stochastic point processes such as earthquakes (e.g., Gelfand et al., 1976; Amorese et al., 1999, 2009) and in many works, the spatial statistical methods have been used to evaluate earthquake data and produce predictions for the future (Yamada et al., 2011; van Lieshout and Stein, 2012; Bray and Schoenberg, 2013; Trofimenko and Bykov, 2017). This study attempts to present a 2D spatial statistical analysis of the earthquake epicenters in the Zagros region, in order to reveal the characteristics of the distribution pattern of epicenters and to interpret the relationships between the spatial distribution characteristics and the active tectonic nature of the seismogenic structures in the region. For this study, earthquake data with high accuracies in locations (epicenter location and focal depth), spanning a period of nearly 22 years from 1995 to 2016, were extracted from the Iranian Seismological Center catalog. In order to obtain a more homogenized data catalog, and to be sure that all recorded events analyzed in this research are natural earthquakes, events with magnitude less than 3.5 were excluded in this analysis. To avoid edge effects, earthquake epicenters in neighboring regions with a distance of 0.5 geographical degree, are also taken into account.

In this research, to quantify certain aspects of the spatial pattern of seismicity, R ratio was calculated through Nearest Neighbor analysis, for the whole seismic data catalog of the region. Additionally, the autocorrelation (Moran's I index) and High/Low clustering (Getis-Ord's G general index) analysis were carried out for the earthquake epicenters of the region based on two attributes of magnitude and focal depth. The final outputs of these analyses are listed in Table 1. It should be noted that the focal depth data used in this analysis show high uncertainties, and the results should be interpreted with caution.

Table 1. Spatial statistics parameters computed for the analysis of the spatial pattern of earthquake epicenters in the Zagros region, based on the analysis of 6321 earthquakes with $M \geq 3.5$ that occurred in Iran (1995-2016).

Spatial pattern statistic	Attribute	Value	z-value	Remarks
Nearest Neighbor Ratio (R)	-	0.624	- 68.0	Clustered pattern
Moran's I index	Magnitude	0.091	96.2	Spatially autocorrelated
Moran's I index	Focal Depth	0.042	53.4	Spatially autocorrelated
Getis-Ord's G index	Magnitude	0.026	5.6	High value clustering
Getis-Ord's G index	Focal Depth	0.021	4.3	High value clustering

As can be seen in Table 1, the value of R ratio calculated for the distribution of earthquake epicenters (0.624) and its related z-value (- 68.0) indicates a completely clustered distribution pattern. The results of the Moran's I index analysis for magnitude (I = 0.091) and focal depth (I = 0.042) of earthquakes, as attributes, and their related z-values (Table 1), indicate that for both of these variables, a considerable spatial autocorrelation is seen. This means that there is a significant spatial clustering of high values of magnitudes and focal depths associated with the earthquake epicenters in the study region. Obviously, this spatial autocorrelation is stronger for magnitude as an attribute, than for focal depth. Furthermore, the results of Getis-Ord's G index analysis for magnitude (G = 0.026) and focal depth (G = 0.021) of earthquakes, as attributes, and their related z-values (Table 1), indicate that a high value clustering is observed in this clustering pattern. This means that both for magnitude and focal depth, as attributes, high values show higher intensities in clustering.

The results of this research are summarized as follows:

(1) The Nearest Neighbor Analysis results indicate a completely clustered pattern of earthquake epicenters for the whole region of Zagros and also indicate that earthquakes with greater magnitudes and focal depths show higher clustering intensities. This fact that earthquakes with greater magnitudes and focal depths show higher degree of clustering can be explained by this fact that large and deep earthquakes nucleate on major active faults often with a remarkable spacing, while the smaller and shallower earthquakes occur on minor faults showing less localizations.

(2) The Moran's I analysis indicates that both for magnitude and focal depth a spatial autocorrelation is observed. This autocorrelation degree is higher for magnitude (as an attribute) than for focal depth.

(3) High/low clustering (G Index) results indicate a significantly high clustering meaning that the high values of magnitude and focal depth (as attributes) show more intensity in clustering (as confirmed in nearest neighbor analysis).

Finally, in regions such as Zagros which surface fault ruptures associated with earthquakes is extremely rare and most information about the active faulting comes from earthquakes, the spatial point pattern analysis can be a very powerful tool to discriminate the seismicity linked to a particular fault and to easily reveal the trend of major hidden (blind) active faults.

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