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Synthesis of instrumentally and historically recorded earthquakes and studying their spatial statistical relationship (A case study: Dasht-e-Biaz, Eastern Iran)

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ABSTRACT

Earthquake catalogues are the main source of statistical seismology for the long term studies of earthquake occurrence. Therefore, studying the spatiotemporal problems is important to reduce the related uncertainties in statistical seismology studies. A statistical tool, time normalization method, has been determined to revise time-frequency relationship in one of the most active regions of Asia, Eastern Iran and West of Afghanistan, (a and b were calculated around 8.84 and 1.99 in the exponential scale, not logarithmic scale). Geostatistical simulation method has been further utilized to reduce the uncertainties in the spatial domain. A geostatistical simulation produces a representative, synthetic catalogue with 5361 events to reduce spatial uncertainties. The synthetic database is classified using a Geographical Information System, GIS, based on simulated magnitudes to reveal the underlying seismicity patterns. Although some regions with highly seismicity correspond to known faults, significantly, as far as seismic patterns are concerned, the new method highlights possible locations of interest that have not been previously identified. It also reveals some previously unrecognized lineation and clusters in likely future strain release.

1. Introduction

Earthquakes are one the most important natural disaster, therefore, it is critical to prioritize several sites and locations based on the maximum magnitude which is most likely to happen in those regions. A key feature of this presentation is that each event relates to a particular location in space and time. Geostatistics provides a set of statistical tools for incorporating spatial coordinates in data processing. Geostatistics is not simply applied to geoscience problems, but it is instead a rapidly evolving branch of applied mathematics which can be applied in seismology to propose different seismicity patterns. Once investigators have established that their data provides adequate quantity and quality estimation, geostatistics can provide powerful analytical tools that result in better interpolation results. Application of geostatistics in seismology and earthquake engineering goes back to the late 1980s. Carr and Glass (1989) applied geostatistical tools to map the ground motion peak horizontal acceleration recorded during the 1971 San Fernando, and the 1983 Coalinga, California earthquakes. They used kriging method to map Peak Ground Acceleration (PGA) for the aforementioned earthquakes. However, smoothing is one of the main drawbacks of kriging method, which can be decreased by validating the variograms (a spatial tool for assessing the spatial regression, introduced mathematically later in the material and method section). Another pioneer researcher in geostatistics and seismology applied cokriging method to detect the porosity from seismic data (Doyen, 1988). Haas and Dubrule (1994) and Sen and Stoffa (1991) are other researchers who combined the geostatistics theory with the related seismology field in the early nineties. Geostatistical simulation method was then applied to study relationships among the magnitudes of seismic series (Torcal et al., 1999a). Also, the application of geostatistics on seismic data has been detailed in a book (Dubrule, 2003). Therefore, the application of geostatistics in several fields related to seismic data has been used for the past three decades.

As far as studying long-term earthquake occurrence is concerned, earthquake catalogues are the main sources of information. Seismicity catalogues are the basic and fundamental products that an agency running a seismic network provides and are the primary

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sources for most studies related to seismicity. An ideal earthquake catalogue records the occurrence of all earthquakes in the magnitude range important to the characterization of future earthquake hazard. In practice, earthquake catalogues are incomplete and contain uncertainty which may be reviewed in the both spatial and temporal domains (Ceus-SSC, 2008).

The pioneering study by Gutenberg and Richter (1944) proposed the simplest, nevertheless very useful, earthquake recurrence relationship as given in Eq. (1). The earthquake recurrence model of Gutenberg and Richter (1944) was derived by compiling the earthquake catalogue in southern California and sorting them by the total number of earthquakes exceeding different magnitudes (Gutenberg and Richter, 1944). The total number of earthquakes exceeding each magnitude is normalized by the total time span covered by the earthquake catalogue:

$$\mathrm{Log10(Nm) = a\text{-}bm} \tag{1}$$

Where

Nm is the mean annual rate of exceedance of specific magnitude (m),
m is the estimated magnitude, and
a, and b are seismic parameters which should be determined by the statistical methods.

Being a logarithmic relationship, Eq. (1) implies exponential probability distribution to compute the probability of mean annual exceedance rates of earthquakes in the study area. The parameter 10a in Eq. (1) represents the mean annual number of events above mmin, describing the minimum seismic activity rate in the study area known as a magnitude of completeness. Thus, large “a” implies higher seismic activity. The slope, b, defines the ratio of small to large magnitude events. A steep slope means the dominancy of smaller magnitude events with respect to larger magnitudes.

In contrast, smaller b values indicate a higher contribution of large magnitude events to the seismic activity of the considered seismic source (Sucuoğlu and Akkar, 2014).

As far as the temporal domain is concerned, the earthquake catalogues are severely incomplete in establishing the global seismic networks. In the other words, the occurrence of 2000 small earthquakes in 2015 should not be compared to the occurrence of an only moderate earthquake happened in 19th century. Therefore, Gutenberg- Richter relationship explained above can be negatively influenced unless significant time period and its uncertainties for each magnitude range is reviewed. Therefore, it is of crucial importance to assign a significant time period to each magnitude range. A statistical method of time normalization method has been introduced in this paper to decrease the temporal uncertainty in the earthquake catalogue.

In addition, the data deficiency in the spatial domain also exists in current earthquake catalogues. Some remote areas (e.g. deserts) had no significant number of historical earthquakes prior to 1963 and they still have no seismic networks even in the local scale. However, obtaining information about the seismicity of these areas is critically important. Synthetic catalogues are normally considered an interesting response to this problem. In recent years, Monte Carlo simulation, developed by randomizing key hazard paramaters of the eqrthquate events in the instrumental seismiticty catalogue, has been applied to a significant number of synthetic catalogues (Kythreoti, 2002). A study carried out by Kythreoti (2002) concluded the key hazard parameters are the earthquake magnitude. The magnitude of a new event in the synthetic catalogue will be given by the following equation:

$$\mathrm{M_R = M_0 \pm (e \times N_R)} \tag{2}$$

Where $\mathrm{M_R}$ is magnitude value of new random event, $\mathrm{M_0}$ is an original magnitude mentioned in the catalogue, e is the error and $\mathrm{N_R}$ is a random number based on uniform distribution (Khan et al., 2012; Milutinovic et al., 2013). Another researcher (Milutinovic et al., 2013) also ran a seismic hazard workshop and allocated an important part of his lecture to present Synthetic Earthquake Catalogue. However, the given studies have not paid a significant amount of attention to the spatial location of each event; consequently the spatial relationship among all the data has been neglected. According to this fact, an algorithm which considers a spatial relationship among the parameters would give rise to more reliable results. An algorithm which considers a spatial relationship among the parameters will provide useful insights through calculating an artificial catalogue in a region where there are limited events despite the high seismicity pattern of that region (Jalali and Ramazi, 2014).

Accordingly to the issues examined in this paper (i) summarize the seismic properties of one of the most seismic areas in Iran, Dashte Bayaz (ii) outline the processes which are needed to combine and utilize different catalogues (iii) illustrate the uncertainties in time domain of the earthquake catalogue and revises the G-R relationship (iv) demonstrate the uncertainties in spatial domain and attempt to reveal seismic patterns which are likely to be responsible for future seismic activities.

1.1. An introduction to the seismicity of Dashte Bayaz seismotectonic province

The Dashte Bayaz region has been the site of several large earthquakes in the 20th century and had previous notable historical activity. The distribution of destructive earthquakes gives an overview into the patterns of active deformation in the Dashte Bayaz region. The area located in eastern Iran which has a common border with Afghanistan (Fig. 1(a)). Mentioned earlier in this section, several great earthquakes have been triggered in the area in the past centuries. Fig. 1(b) shows the earthquakes which have occurred in the area. The number of earthquakes with the magnitude greater than 5 as well as documented earthquake events and faults and active fault system is particularly significant which indicates the high seismicity potential of this area. (Fig. 1(b) and (c)).

The modeling of earthquake source parameters by instrumentally recorded seismic body waves also provides useful information about the distribution of faulting on short time-scales, and the nature of this faulting at depth. The most important historical and instrumentally recorded seismic activities are summarized in Table 1. North of 34◦N, the dominant structures are the Doruneh and Dashte Bayaz left-lateral strike slip faults, which are thought to accommodate lateral shear by rotating clockwise, away from the direction of maximum shortening (Walker et al., 2004). The Dashte Bayaz fault system may accommodate a large proportion of the 20 mm right-lateral shear between Iran and Afghanistan (A. Tzanis., 1999; Walker et al., 2004). Therefore, statistical and geostatistical studies of this region can be useful for the both countries. Also, the methods can be expanded to the other areas with different seismicity rates which suffer from incomplete data in their earthquake catalogues.

According to Table 1, the largest instrumentally recorded earthquakes (31 August 1968 and 27 November 1979) ruptured the entire 120 km length of the Dashte Bayaz fault zone. The earthquake of 1968 was a catastrophic earthquake affecting a wide region north of Dashte Bayaz (Walker et al., 2004). In this region almost all the houses collapsed completely, killing 1230 out of 1670 inhabitants. Damage decreased rapidly away from this region. To