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Spatial mapping of earthquake hazard parameters in the Hindukush–Pamir Himalaya and adjacent regions: Implication for future seismic hazard

R.B.S. Yadav [a,*], T.M. Tsapanos [b], G. Ch. Koravos [b], Yusuf Bayrak [c], Kiriaki D. Devlioti [d]

[a] Department of Geophysics, Kurukshetra University, Kurukshetra 136 119, India
[b] Aristotle University of Thessaloniki, School of Geology, Geophysical Laboratory, Thessaloniki 54124, Greece
[c] Department of Geophysics, Karadeniz Technical University, 61080 Trabzon, Turkey
[d] Finikos 6, 57013 Oreokastro, Thessaloniki, Greece

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ABSTRACT

The study deals spatial mapping of earthquake hazard parameters like annual and 100-years mode along with their 90% probability of not being exceeded (NBE) in the Hindukush–Pamir Himalaya and adjoining regions. For this purpose, we applied a straightforward and most robust method known as Gumbel's third asymptotic distribution of extreme values (*GIII*). A homogeneous and complete earthquake catalogue during the period 1900–2010 with magnitude $M_W \geqslant 4.0$ is utilized to estimate these earthquake hazard parameters. An equal grid point mesh, of 1° longitude X 1° latitude, is chosen to produce detailed earthquake hazard maps. This performance allows analysis of the localized seismicity parameters and representation of their regional variations as contour maps. The estimated result of annual mode with 90% probability of NBE is expected to exceed the values of M_W 6.0 in the Sulaiman–Kirthar ranges of Pakistan and northwestern part of the Nepal and surroundings in the examined region. The 100-years mode with 90% probability of NBE is expected to exceed the value of M_W 8.0 in the Hindukush–Pamir Himalaya with Caucasus mountain belt, the Sulaiman–Kirthar ranges of Pakistan, northwestern part of the Nepal and surroundings, the Kangra–Himanchal Pradesh and Kashmir of India. The estimated high values of earthquake hazard parameters are mostly correlated with the main tectonic regimes of the examined region. The spatial variations of earthquake hazard parameters reveal that the examined region exhibits more complexity and has high crustal heterogeneity. The spatial maps provide a brief atlas of the earthquake hazard in the region.

1. Introduction

One of the most important objectives of the earthquake hazard assessment in any seismogenic region of the world is to obtain long-term probabilities of occurrences of large earthquakes in a specific time-period. Different statistical methodologies and models have been emphasized and being used in different regions of the world to estimate earthquake hazard parameters like expected maximum magnitude, *b*-value (or β-value) of G–R relationship, activity rate, upper bound magnitude and modal values among others (Tinti and Mulargia, 1985; Kijko and Sellevoll, 1989, 1992; Pisarenko et al., 1996; Stein and Hanks, 1998; Field et al., 1999; Tsapanos et al., 2002; Tsapanos, 2003; Tsapanos and Christova, 2003; Kijko, 2004; Wheeler, 2009; Mueller, 2010; Yadav et al., 2010a,b, 2012a,b, 2013; Kijko and Singh, 2011). The theory of extreme values distribution proposed by Gumbel (1958) is one of the most popular and robust methodology that has been applied in different regions of the globe in order to estimate earthquake hazard parameters (Nordquist, 1945; Epstein and Lomnitz, 1966; Yegulalp and Kuo, 1974; Burton, 1977; Makropoulos, 1978; Makropoulos and Burton, 1985; Tsapanos and Burton, 1991; Tsapanos, 1998; Shanker et al., 2007; Bayrak et al., 2008; Yadav et al., 2012b among others). The main advantage of this method is that it does not require analysis of the complete record of earthquake occurrences, but uses the sequence of earthquakes constructed from the largest values of magnitude over a set of predetermined time intervals. The advantage of Gumbel's third asymptotic distribution (*GIII*) over first distribution (*GI*) is that it includes a parameter known as *upper-bound magnitude* (ω). The ω-value is directly related with the finite maximum stress which can be stored and released as an earthquake by the rocks of a region (Tsapanos and Burton, 1991; Tsapanos, 1997). Thus for estimation of the occurrence or expectation of extreme magnitude earthquakes using

* Corresponding author.
E-mail address: rbsybhu@rediffmail.com (R.B.S. Yadav).

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probabilistic models, the *G*III allows an appropriate and natural physical interpretation. Burton (1979) applied this methodology in southern Europe through India to estimate earthquake hazard parameters. Tsapanos and Burton (1991) estimated earthquake hazard parameters using this method for some specific regions of the world and prepared contour maps of most probable maximum magnitudes in next 85 years. Later, Tsapanos (1997) evaluated upper-bound magnitudes in the subduction zones of the Circum-Pacific region. Bayrak et al. (2008) used this method for 24 seimogenic regions in Turkey and surroundings to estimate upper-bound magnitude. Yadav et al. (2012b) applied this method in 28 seismogenic regions in the Hindukush–Pamir Himalaya to estimate upper-bound magnitude and 100-years magnitude.

In the present study, Gumbel's third asymptotic distribution (*G*III) is applied in the Hindukush–Pamir Himalaya and adjacent regions bounded by latitude 25°–40°N and longitude 65°–85°E (Fig. 1). The study region comprises one of the most seismically active regions of the Himalaya which has experienced two great earthquakes of magnitude M_S 8.7 (M_W 7.8) occurred in twentieth century in 1902 and 1905 at the Caucasus and Kangra–Himanchal Pradesh (India) region, respectively (Gutenberg and Richter, 1954; Yadav et al., 2012a). In addition to these, it has also experienced several large to moderate earthquakes in past hundred years including the Hindukush earthquake of M_W 7.6 (M_S 7.8) in 1921, the Quetta (Pakistan) earthquake of M_W 7.7 in 1935, the Uttarkashi and Chamoli earthquakes of M_W 6.8 and 6.5 in 1991 and 1999, respectively and most devastating earthquake of the Kashmir Himalaya of M_W 7.6 in 2005 (Figs. 1 and 2). The study region is located in all seismic zones V, IV, III and II on the seismic zoning map of India (Bureau of Indian Standards (BIS), 2002) with magnitudes exceeding 8, 7, 6 and 5, respectively. According to the Global Seismic Hazard Assessment Program (GSHAP), this region has been classified as a zone of high hazard with peak ground acceleration (PGA) ranging from 0.45 to 0.50 g for a 10% probability of exceedance in 50 years (Bhatia et al., 1999). The seismic hazard in the examined region has been studied by various researchers using different statistical techniques (Kaila et al., 1972; Kaila and Rao, 1979; Khattri et al., 1984; Shanker and Sharma, 1998; Parvez and Ram, 1997, 1999; Shanker and Papadimitriou, 2004; Tripathi, 2006; Shanker et al., 2007; Thingbaijam et al., 2009; Yadav, 2009; Yadav et al., 2010a,b, 2011, 2012a,b, 2013). The previous studies of estimation of earthquake hazard parameters were based on the regional scale. A detailed study of earthquake hazard parameters was carried out by Yadav et al. (2012a,b) for 28 seismogenic source zones using maximum-likelihood estimate of Kijko–Sellevoll method (Kijko and Sellevoll, 1992) and *G*III distribution method. Later, Yadav et al. (2013) applied Bayesian statistics in the examined region to estimate the earthquake hazard parameters (maximum regional magnitude M_{max}, *b*-value of G–R relationship and seismic activity rate) and different earthquake magnitudes in next 5, 10, 20, 50 and 100 years. The study of earthquake hazard estimation in examined region needs a robust and stable statistical and/or probabilistic technique to map the earthquake hazard parameters at micro level that will be directly useful in preparing probabilistic seismic hazard map of the examined region.

The present study deals with the spatial distribution of earthquake hazard parameters like the annual mode, the *t*-years mode and the maximum expected magnitude of not being exceeded in *t*-years at a stated probability level. For this purpose, the whole examined region has been divided in cells of 1° longitude X 1° latitude and the three parameters (ω, u and λ) of *G*III asymptotic distribution were determined for each cell along with aforementioned earthquake hazard parameters. The study also aims to search correlation between estimated earthquake parameters and the associated tectonics of the examined region. The results of this analysis will be useful to produce a brief atlas of regional earthquake hazard maps.

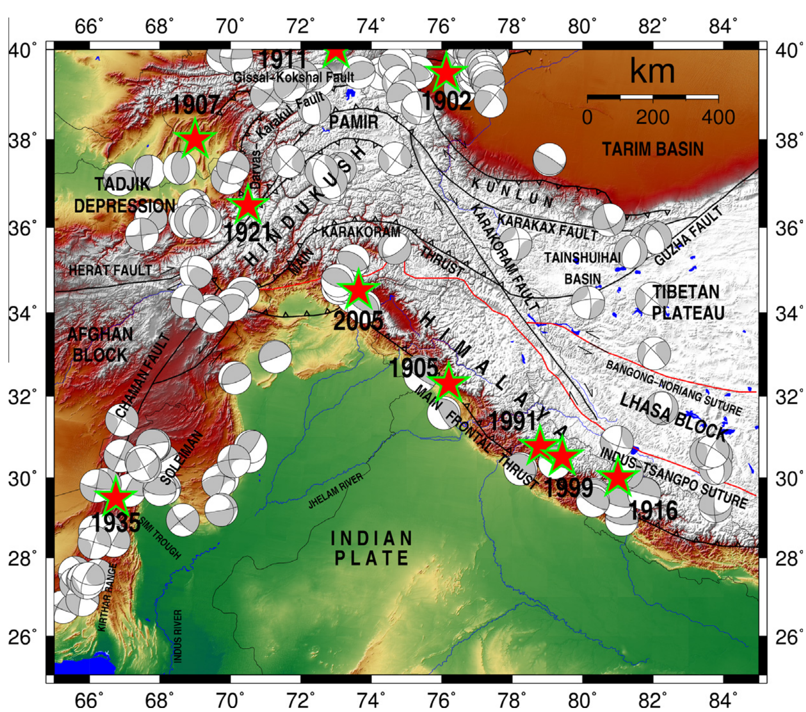

Fig. 1. Tectonic and geomorphological map shows the fault and fold systems in the Hindukush–Pamir Himalaya and adjoining region (after Koulakov and Sobolev, 2006; Yadav, 2009; Yadav et al., 2010a). Focal mechanism solutions of shallow earthquakes $M_W \geqslant 5.5$ obtained by Harvard GCMT catalogue during 1976–2010 are also shown with gray color beach ball in the map revealing the style of faulting in different parts of the region. Stars show the important earthquakes occurred in the study region and discussed in the manuscript.