Earthquake Hazard and Risk Assessment Based on Unified Scaling Law for Earthquakes: State of Gujarat, India

IMTIYAZ A. PARVEZ,[1] ANASTASIA NEKRASOVA,[2] and VLADIMIR KOSSOBOKOV[2,3,4]

Abstract—The Gujarat state of India is one of the most seismically active intercontinental regions of the world. Historically, it has experienced many damaging earthquakes including the devastating 1819 Rann of Kachchh and 2001 Bhuj earthquakes. The effect of the later one is grossly underestimated by the Global Seismic Hazard Assessment Program (GSHAP). To assess a more adequate earthquake hazard for the state of Gujarat, we apply Unified Scaling Law for Earthquakes (USLE), which generalizes the Gutenberg–Richter recurrence relation taking into account naturally fractal distribution of earthquake loci. USLE has evident implications since any estimate of seismic hazard depends on the size of the territory considered and, therefore, may differ dramatically from the actual one when scaled down to the proportion of the area of interest (e.g. of a city) from the enveloping area of investigation. We cross-compare the seismic hazard maps compiled for the same standard regular grid $0.2° \times 0.2°$ (1) in terms of design ground acceleration based on the neo-deterministic approach, (2) in terms of probabilistic exceedance of peak ground acceleration by GSHAP, and (3) the one resulted from the USLE application. Finally, we present the maps of seismic risks for the state of Gujarat integrating the obtained seismic hazard, population density based on India's Census 2011 data, and a few model assumptions of vulnerability.

Key words: Gujarat, seismic hazard, unified scaling law, seismic risk.

1. Introduction

The Gujarat region is located within the tectonic plate of India; about 500 km from a transform plate boundary (Bendick et al. 2001) is seismically one of the most active regions in India. The reliable assessment of seismic hazard of Gujarat is a major issue, particularly after the catastrophic Bhuj earthquake happened on January 26, 2001 (Mw7.7) resulting in a huge loss of lives (above 20,000 fatalities). There are many studies on seismic hazard assessment of Gujarat region in the recent past (e.g., Petersen et al. 2004; Tripathi, 2006; Yadav et al. 2008; Shukla and Choudhury, 2012; Chopra et al. 2013; Magrin et al. 2016) based on probabilistic and deterministic approaches. Petersen et al. (2004) studied the sensitivity of seismic hazard to three fault source models for the Kachchh region, Gujarat and observed the recurrence intervals of 266–533 years on one of these faults. Tripathi (2006) worked out a probabilistic hazard assessment for Kachchh region, Gujarat. Yadav et al. (2008) extended the same by studying the probability of occurrence of earthquakes in the three regions of Gujarat, namely Kachchh, Saurashtra, and Mainland Gujarat region, during a specified time interval for different elapsed times on the basis of observed time intervals between earthquakes using three stochastic models. Chopra et al. (2013) evaluated the seismic hazard in the Gujarat region by simulation and from the scenario hazard maps; they illustrated the spatial distribution of various parameters like peak ground acceleration, characteristics site frequency, and spectral acceleration for different periods. In the recent study by Magrin et al. (2016), Neo-Deterministic Seismic Hazard Assessment (NDSHA) has been used to define the seismic and tsunami hazard scenarios for the territory of Gujarat. This study allows considering a wide range of possible seismic sources as a starting point for deriving scenarios by means of full waveforms modeling using current computational

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[1] CSIR Fourth Paradigm Institute (Formerly Centre for Mathematical Modelling and Computer Simulation), Bangalore, India. E-mail: parvez@csir4pi.in
[2] Institute of Earthquake Prediction Theory and Mathematical Geophysics, RAS, Moscow, Russian Federation.
[3] Institut de Physique du Globe de Paris, Paris, France.
[4] International Seismic Safety Organization, ISSO, Arsita, Italy.

resources and physical knowledge of the seismic waves' generation and propagation processes. In addition to the regional seismic hazard studies of Gujarat, the region has also been covered in hazard assessment studies at national scale (e.g. Khattri et al. 1984; Bhatia et al. 1999; Parvez et al. 2003). Khattri et al. (1984) indicate the peak ground acceleration (PGA) in kachchh region ~ 0.4 g with 10% probability of being exceeded in 50 years. As per Global Seismic Hazard Assessment program (GSHAP), Bhatia et al. (1999) concluded that this region has the PGA values in the range of 0.16–0.24 g with 10% probability of exceedance in 50 years, which was greatly underestimated as became evident from the observed ground shaking in the 2001 Bhuj earthquake. Hough et al. (2002) estimate near field ground motions of approximately 0.8 g for the Bhuj 2001 event from the compilation of the Modified Mercalli Intensities using the MMI–PGA empirical relationship, which compared well with (Parvez et al. 2003; de Nardis et al. 2014). However, none of these studies have been used to implement the associated seismic risk for the region.

The basic law of seismicity, the Gutenberg–Richter recurrence relation, is applied in a modified form in the present study involving a spatial term (Nekrasova et al. 2015):

$$\log N(M, L) = A - B(M - 5) + C \log L,$$

where $N(M, L)$ is the expected annual number of earthquakes of a certain magnitude M within an area of linear size L. The parameters A, B, and C of this Unified Scaling Law for Earthquakes (USLE) in the Gujarat and surrounding regions have been assessed by applying the SCE algorithm (Scaling Coefficient Estimation) described in (Nekrasova and Kossobokov 2005a, b; Nekrasova et al. 2011). The deterministic approach has been used to map the local value of the expected peak ground acceleration (PGA) derived from the USLE-estimated maximum magnitude with 10% chance of exceedance in 50 years. We not only combined and compared the seismic hazard from various probabilistic and neo-deterministic models but also integrated it with the population density data available after the 2011 Census to assess the seismic risk of Gujarat region. It should be noted that as a matter of fact PGA is a poor indicator for assessing

damage and risk due to earthquake (Klügel 2008). In our study, PGA was selected only for the comparison with all other standard methods that are relying on this parameter.

2. Brief History of Seismicity of Gujarat Region

From the available literature, the Rann of Kachchh major earthquake occurred in Kachchh region on June 16, 1819. Based on the reported intensity, Johnston and Kanter (1990) assigned $M_w \sim 7.8$. This was a significant earthquake felt over an area of nearly one million square miles. It is also well known for its great destructive power and intense ground deformation capability in the history of intraplate earthquakes. Analysis of the survey report showed that it ruptured the earth's surface in NW–SE direction for nearly 75 km (Oldham, 1926), creating the Allah Bundh fault (i.e., a dam erected by God). Other significant earthquakes are Rann of Kachchh (M 6.0, 1903) and Anjar (M 6.0, 1956) in Kachchh region. In Saurashtra, the Paliyad (M 5.5, 1938) sequence of 1938 was important where approximately 200 shocks were felt in this sequence (Bapat et al. 1989). Northern region of the Gujarat state had experienced moderate seismicity in the past. Amongst them, Mt. Abu (M 5.0, 1909, M 5.5, 1969) and Palanpur (M 5.0, 1962) are reported. The other important events are Ahmedabad earthquake (M 5.0, 1864), Baruch (M 5.0, 1970), and Rajula (coastal Saurashtra, M 5.2, 1993).

In the recent past, January 26, 2001 Bhuj earthquake ($M_w \sim 7.7$, epicenter: 23.419°N, 70.232°E, depth: 16 km) occurred in Kachchh Basin and was one of the most destructive earthquakes in terms of causality and socio-economic losses. A total of 20,072 people lost their lives and millions got injured; more than a million houses were damaged in 7904 villages of Gujarat state. Surface manifestation of such rupture is likely to be a broad zone of distributed uplift and subsidence with secondary surface faulting and cracking (Wesnousky et al. 2001; Lavecchia et al. 2012). Aftershocks survey report presented by GSI reported about 2000 small aftershocks during January 29 to February 28, 2001. Singh et al. (2004) estimated radiated energy of 2.1×10^{23}

erg and the corresponding slip velocity at the center of the fault of 156 cm/s. They also reported a high static stress drop of about 200 bars, which is a common feature for large intraplate earthquakes.

2.1. Methodology

Molchan et al. (1997) have described that the seismic reality evidences many contradictions to the model assumption of a stationary Poisson point process with annual rate of $N(M)$, which according to the well-established Gutenberg–Richter law is parameterized in a log-linear form. Introducing sequences of main events and their associates (fore- and after-shocks) superimposed with hypothetical distributions of the associate size, time, and location may eventually lead to complications of the existing hypotheses. Therefore, estimation of $N(M)$ at a given site of interest remains the basic source of erroneous seismic hazard assessment (Kossobokov and Nekrasova 2012), as well as the basic source of inadequate seismic engineering decisions (Davis et al. 2012).

The results of the global and regional analyses (Keilis-Borok et al. 1989; Kossobokov and Mazhkenov 1994; Kossobokov and Nekrasova 2003, 2007; Nekrasova and Kossobokov 2002, 2003, 2006; Kossobokov 2005; Nekrasova 2008) imply that the recurrence of earthquakes at a seismically prone site, for a wide range of magnitudes M and sizes $L \in (L_-, L_+)$, can be described as Unified Scaling Law for Earthquakes (USLE) by the following formula:

$$N(M, L) = 10^A \times 10^{B \times (5-M)} \times L^C, \qquad (1)$$

where $L \times L$ is a square embedding seismic locus, and A, B, and C are constants. An alternative formulation using the inter-event time distribution, we can denote the relationship as USLE (Bak et al. 2002; Christensen et al. 2002). The algorithm for Scaling Coefficients Estimation, named SCE, is described in detail (see e.g. Nekrasova et al. 2015).

The long-term estimates of the USLE coefficients can be used to characterize seismic hazard in a rather traditional terms of maximum expected magnitude and/or macroseismic intensity, Peak Ground Acceleration (PGA), etc.; specifically,

- The values of A, B, and C are obtained for grid points of a regular $l \times l$ mesh of centers of the $L_0 \times L_0$ cells of interest, where $L_0 \in (L_-, L_+)$ is the predefined constant used in the analysis of sizes.
- Formula (1) is used for magnitude ranges from M_- to M_+ with Δm-magnitude step calculate the expected numbers of events in T years in the cells of interest, $N_T(M, L_0) = T \times N(M, L_0)$. The maximum magnitude has been estimated for each cell with the expected number $N_T(M, L_0) \geq p\%$ and assign the intensity or PGA value that corresponds to this maximum magnitude.

The value of hazard assigned to a cell of interest is presumed in such a way that it indicates an estimate of the traditional one with the $p\%$ probability of exceedance in T years.

2.1.1 Direct Implications for Seismic Hazard and Risk Estimates

The risk estimates of any kind result from a convolution of the hazard with the exposed object under consideration along with its vulnerability

$$R(g) = H(g) \otimes O(g) \otimes V(O(g)),$$

where $H(g)$ is hazard at location g, $O(g)$ are the objects at g exposed to this hazard, and $V(O(g))$ is the vulnerability of these objects (Nekrasova et al. 2015). It is important to note that g could be some area, a line, or a point on or under the Earth surface and that distribution of hazards, as well as objects of concern and their vulnerability, could be time-dependent, each and all resulting from a complex problem-oriented assessment (Stoppa and Berti 2013). Furthermore, the convolution $\otimes$ could be much more complicated operation than usually accepted product of terms.

The key role in the risk assessment is related to the choice of a probability model describing the occurrence of earthquakes in a specified space–magnitude–time volume $V = \{g, M, t\}$. A rough description of the leading features for long-term seismic activity is usually provided by assuming the flow of events $(g, M, t) \in V$ to be a stationary point Poisson process with annual rate of $N(M)$ that contradicts seismic reality.

By applying USLE that generalizes the Gutenberg–Richter recurrence relation to evident patterns

of distributed seismic activity, one can demonstrate that the traditional estimations of seismic risk for cities and urban agglomerations are usually underestimated. In fact, any estimate of seismic hazard rate (e.g., $N(M)$) depends on the size of territory that is used for averaging and, therefore, may differ dramatically when scaled down to the proportion of the area of interest (Nekrasova et al. 2015). For example, the coefficient C at Los Angeles is about 1.21 both as estimated by Okubo and Aki (1987) for the system of faults in Southern California and as computed by applying the SCE algorithm to one of the best regional earthquake catalogues; scaling down in proportion to the area from the entire Southern California of about 400 km to the region of Los Angeles about 40 km in length underestimates the recurrence rate by a factor of $(L_{SCA}/L_{LA})^2/(L_{SCA}/L_{LA})^{1.21} = 10^{0.79} = 6.2$. By analogy, the underestimation of seismic hazard in a region of about 40 km long at Petropavlovsk-Kamchatsky from the area of Kamchatka about 700 km in length where C = 1.26 rises to a factor $(L_K/L_{PK})^2/(L_K/L_{PK})^{1.26} = 17.5^{0.74} = 8.3$. A comprehensive analysis of seismic hazard at 1140 cities and urban agglomerations in seismic regions worldwide due to scaling in proportion to the area (Nekrasova and Kossobokov 2005c) reveals in addition to abovementioned cases' potential underestimation of a factor of 5.4 for Tokyo (Japan), 7.2 for San Francisco (USA), about 20 for Ulan-Ude (Republic of Buryatia, Russian Federation), etc.

Such a discrepancy in evaluation of seismic hazard propagates non-linearly into erroneous estimations of risks. An error in rate of a factor of 6 (in assumption of $B = 1$) corresponds to an error about 0.8 in magnitude, which explodes exponentially in underestimation of seismic energy release by a factor 15 corresponding to a factor above 4.5 for expected fatalities, etc. (Wyss et al. 2012).

2.2. Data

2.2.1 Seismic Data

We consider the territory of Gujarat region within 20°–26°N and 66°–75°E, same as the territory used by Magrin et al. (2016) aimed at neo-deterministic seismic hazard estimation of the region. The coefficients of USLE are evaluated by applying the SCE algorithm to the sample of about 150 normal depth seismic events with magnitude 4.8 or more reported in USGS/NEIC Global Hypocenters Database System (GHDB 1989), for the period 1965–2015, and the hierarchy of areas with linear size of 8°, 4°, 2°, 1°, 1/2°.

2.2.2 Seismic Hazard Model Data

For the purposes of comparison with other SHA maps for the this study, we use peak ground acceleration (PGA) values for the territory of Gujarat region provided by the following four seismic hazard assessment maps

(a) the design ground acceleration (DGA) map for Gudjarat,
(b) the design PGA values adjusted to return period of 475 years corresponding to 10% chance of exceedence in 50 years (DGA10%),
(c) the design PGA values adjusted to return period of 2475 years corresponding to 2% chance of exceedence in 50 years (DGA2%).

The three design ground acceleration (DGA) maps are based on the neo-deterministic seismic hazard assessment, NDSHA (Panza et al. 2001), of PGA values at the grid points of a regular $0.2° × 0.2°$ mesh. The DGA map was provided by the standard NDSHA method not limited in time, while DGA10% and DGA2% maps were obtained by integrating earthquake recurrence into NDSHA (Magrin 2012) for the return periods of 475 and 2475 years, respectively (i.e., same as considered in compilation of the PSHA maps).

(d) the final Global Seismic Hazard Assessment Program (GSHAP) map of PGA values with 10% chance of exceedence in 50 years (GSHAP10%) corresponding to return period of 475 years.

The PGA values of GSHAP have been obtained by the probabilistic seismic hazard analysis (PSHA) methodology and presented as the final Global Seismic Hazard Map (Shedlock et al. 2000; Giardini et al. 2003) available as an ASCII file GSHPUB.dat at http://www.seismo2009.ethz.ch/GSHAP/) are provided on the $0.1° × 0.1°$ regular grid for seismically

active regions of the Globe including the territory of Gujarat. The data from the GSHAP database have been smoothen for the purpose of comparison, bringing at the same standard regular grid $0.2° \times 0.2°$ over the Gujarat territory.

2.2.3 Population Data

We have considered the population density data for the territory of investigation to generate the seismic risk model using India's Census 2011 data. Figure 1 presents the map of the population density distribution (P). The values on the regular grid $0.2° \times 0.2°$ mesh are obtained by summing up the four values from the India's Census 2011 provided for a finer grid with $0.05° \times 0.05°$ mesh.

2.3. Mapping Seismic Hazard Based on the USLE Approach

One can see in Fig. 2 the map of the empirical density distribution function of seismic activity, ρ, based on the counts of magnitude 4.8 or greater earthquakes within a cell of the $0.25° \times 0.25°$ grid.

We have obtained the reliable estimation of the USLE coefficients on the Gujarat region territory for the 23 cells listed in Table 1. The coefficient A ranging from -1.7 to -1.3 corresponds to the recurrence of strong earthquakes (with magnitude 6.0) from about 1 in 50 years to 1 in 20 years. The coefficient B spreads from 0.52 to 0.65 which low values may be due to the great 2001 Bhuj earthquake and its aftershocks that
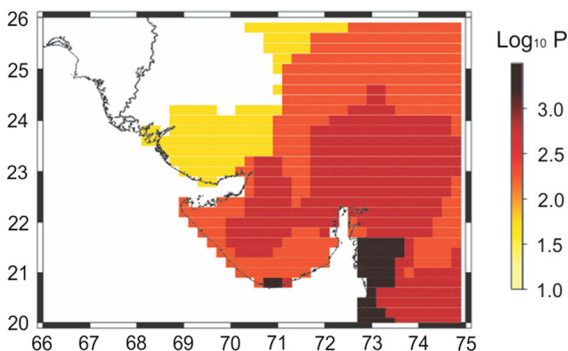

Figure 1
The population density map (P in individuals per km squared) based on India's Census 2011 for the Gujarat territory
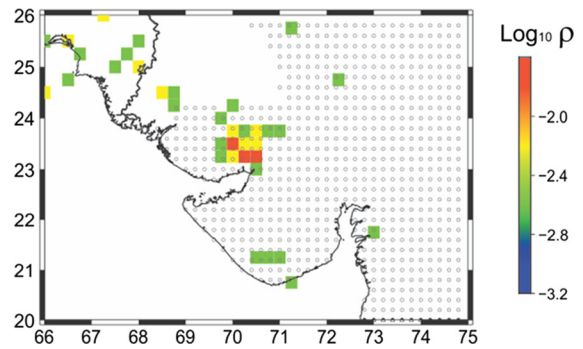

Figure 2
The map of the empirical density distribution function of seismic activity

dominate in the available catalog (about 35% of the total in the 600-km circle and 94% in the 100-km circle centered at epicenter of the great shock). The coefficient C ranges from 0.6 to 1.1. The lowest values of C have three cells located on the latitude 21.25°N and may correspond to the isolated source of seismic activity marked with moderate earthquakes of magnitude $M_w = 4.9$ and 5.1 on November 6, 2007 and $M_w = 5.1$ on October 20, 2011.

The USLE coefficients were used for estimation and mapping the expected maximum magnitude M_{max} with a 10% chance of exceedence in 50 years following the procedures suggested in (Parvez et al. 2014). Specifically, for each $0.25° \times 0.25°$ color-coding cell at seismic location on a regional map (Fig. 2), we have applied Eq. 2 to calculate the expected numbers of events from magnitude ranges M_j in 50 years, i.e., $N_{50}(M_j, 0.25°) = 50 \times N(M_j, 0.25°)$, and then find the maximum magnitude, $M_{10\%50years}$, with the expected number $N_{50}(M_{10\%50years}, 0.25°) \geq 10\%$. Figure 3 shows the map of the M_{max} values assigned in such a way. Naturally, these are the estimates of traditional maximum magnitude with 10% chance of exceedence in 50 years. However, the estimated $M_{10\%50years}$ values appear in conflict with actual M_{max} in the period of instrumental observations. Such a discrepancy indicates high level of uncertainty in any of probabilistic assessment of seismic hazard related to very short period of observations in relation to return time of earthquake extremes. On the other hand, it may also be indicative of the long-term variability of seismic process in the regions of low

Table 1

The USLE coefficients at seismically active cells

#	Latitude	Longitude	A	σ_A	B	σ_B	C	σ_C	$M_{10\%50years}$	M_{max}
1	25.75	71.25	−1.45	0.011	0.65	0.008	0.92	0.013	7.0	4.8
2	24.75	72.25	−1.52	0.014	0.54	0.002	0.89	0.015	7.1	5.3
3	24.25	70.00	−1.49	0.009	0.64	0.010	0.88	0.010	6.9	4.3
4	24.00	69.75	−1.50	0.009	0.64	0.013	0.91	0.012	6.9	4.8
5	23.75	70.00	−1.65	0.017	0.57	0.003	1.09	0.022	6.5	4.4
6	23.75	70.25	−1.66	0.018	0.56	0.001	1.09	0.024	6.5	4.4
7	23.75	70.50	−1.56	0.016	0.55	0.002	0.95	0.020	6.9	5.4
8	23.75	70.75	−1.47	0.009	0.56	0.001	0.83	0.011	7.2	5.3
9	23.75	71.00	−1.40	0.011	0.55	0.002	0.77	0.012	7.4	5.9
10	23.50	69.75	−1.53	0.012	0.58	0.007	0.95	0.016	6.9	4.9
11	23.50	70.00	−1.60	0.020	0.55	0.003	0.99	0.026	6.7	5.5
12	23.50	70.25	−1.67	0.012	0.55	0.001	1.05	0.016	6.6	8.0
13	23.50	70.50	−1.55	0.019	0.54	0.001	0.91	0.023	7.0	5.5
14	23.25	69.75	−1.46	0.013	0.56	0.002	0.88	0.015	7.1	4.7
15	23.25	70.00	−1.63	0.024	0.56	0.002	1.05	0.030	6.6	6.1
16	23.25	70.25	−1.63	0.018	0.55	0.002	1.02	0.023	6.7	4.8
17	23.25	70.50	−1.51	0.018	0.55	0.001	0.91	0.019	7.0	4.6
18	23.00	70.50	−1.51	0.017	0.55	0.002	0.91	0.019	7.0	4.4
19	21.75	73.00	−1.37	0.021	0.53	0.004	0.72	0.021	7.6	5.4
20	21.25	70.50	−1.27	0.015	0.52	0.005	0.58	0.019	8.0	5.1
21	21.25	70.75	−1.30	0.018	0.53	0.004	0.64	0.023	7.8	4.9
22	21.25	71.00	−1.33	0.011	0.54	0.003	0.68	0.014	7.7	4.7
23	20.75	71.25	−1.36	0.015	0.55	0.002	0.74	0.018	7.5	5.0
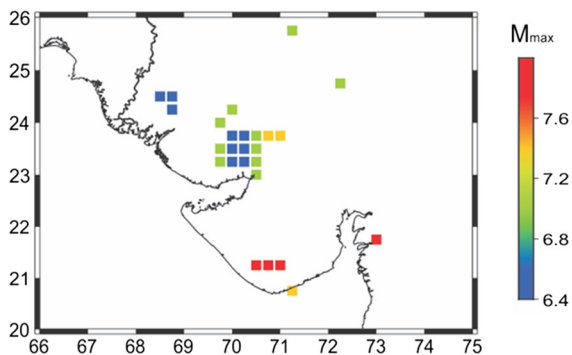
Figure 3
The seismic hazard map in terms of M_{max}

macro-block is formed with the Kachchh Graben on the North, the Cambay Graben on the East, and the Bombay Graben on the South, each of which is recognized as the 1st rank morphostructure. Notably, the Bombay Graben extends to the Arabian Sea, the Narmada-Son Lineament, which is crossing the entire subcontinent and is associated with the Gondwana Graben (Bhatia et al. 1994; Kayal 2003; Rao et al. 1992). By and large, the potential active seismogenic structures are well studied in this region.

This map has been used to estimate the seismic hazard in terms of expected ground shaking. Specifically, in the following paragraphs, the semi-empirical relation linking the interdependence among the peak ground acceleration (PGA), earthquake magnitude, and distance to hypocenter for the regions under investigation determined by Parvez et al. (2001) from strong motion data available was used to produce seismic hazard map of the Gujarat region.

Figure 4a shows the seismic hazard map in terms of PGA determined for each source point from Fig. 3 (Table 1) using the empirical formula (2) for acceleration produced by a source of $M = M_{10\%50years}$ as inspired from Parvez et al. (2001)

B and C, so that the regions of recent discharge would possess underestimated values of M_{max} while the quiescent regions—the overestimated ones. In particular, the high values of $M_{10\%50years}$ on the latitude 21.25°N could be justified by tectonics and geomorphology: the southern and northern boundaries of the Kathiawar (also known as Saurashtra) Peninsula tectonic block are of the same geomorphic rank and, presumably, may have the same seismic potential as the one exposed in the 2001 Bhuj earthquake (Rantsman et al. 1996; Bhatia et al. 1994). This

$$\mathrm{Acc}(M, D) = \mathrm{const} \times g \times D^{-1.5} \times \exp(M - 5), \quad (2)$$

where D is the source-receiver distance on a $0.2° \times 0.2°$ grid, $\mathrm{const} = 6$, $g = 9.81 \text{ m/s}^2$ is the gravity constant, and $\exp(x)$ is the natural exponent of x. The maximum of acceleration values computed at a grid point is assigned to it. We have opted the minimum and maximum distances of 10 and 500 km, respectively.

3. Discussion

Figures 4b–e provides the alternative seismic hazard maps of the Gujarat region for an overall comparison. These are the *deterministic* design ground acceleration (DGA) map (Fig. 4b) based on the neo-deterministic seismic hazard assessment (Panza et al. 2001) along with its modifications (DGA10%, DGA2%) adjusted by Magrin et al.
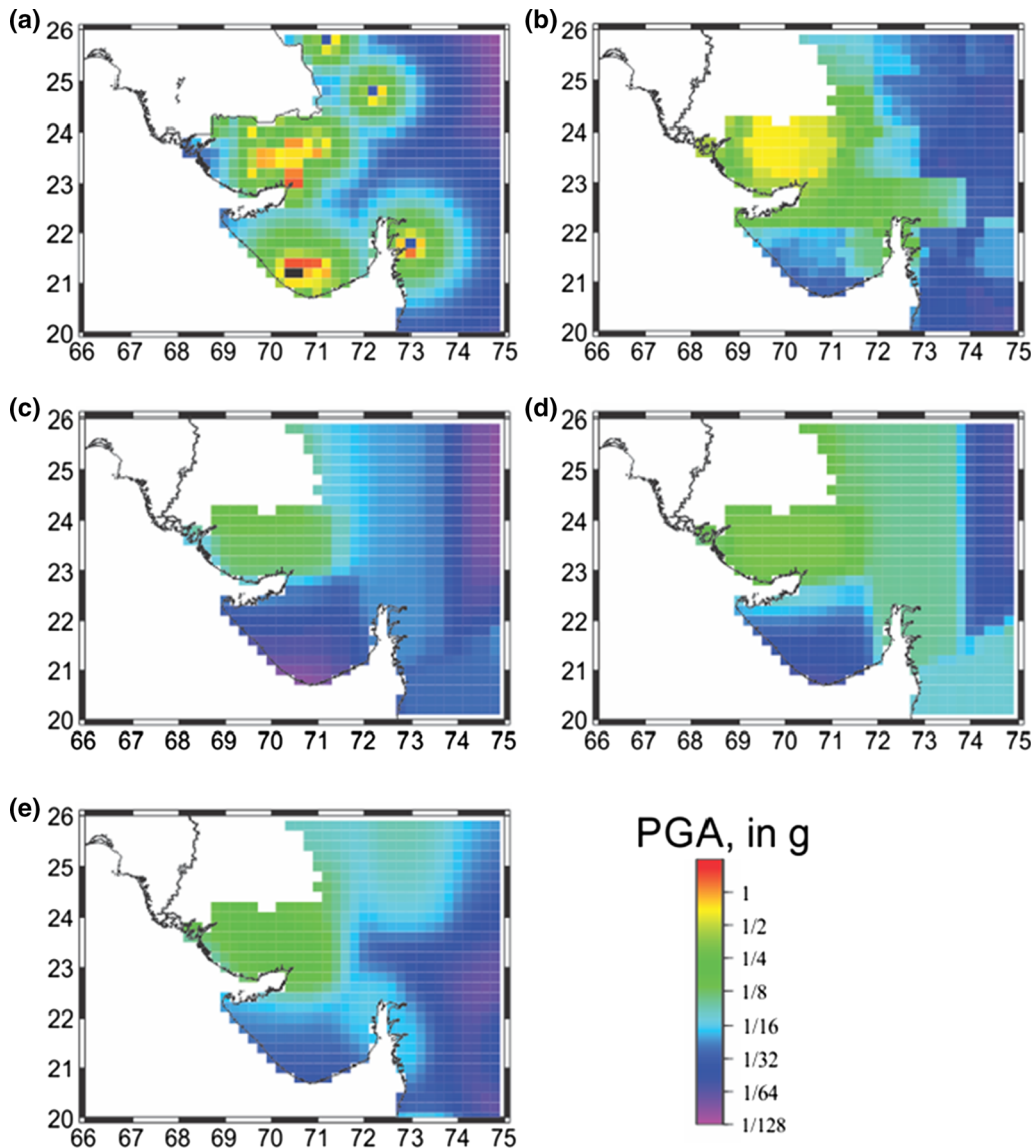

Figure 4
The five seismic hazard maps in terms of PGA (in g) **a** based on USLE approach, **b** DGA, **c** DGA10%, **d** DGA2%, **e** as given on the final GSHAP seismic hazard map

(2016) for 10 and 2% chance of exceedance in 50 years (Fig. 4c, d, correspondingly) and the *probabilistic* Global Seismic Hazard Assessment Program (GSHAP) map (Giardini et al. 1999; Shedlock et al. 2000) which provided the global distribution of maximum PGA with 10% chance of exceedance in 50 years (Fig. 4e). For the purposes of cross-comparison, all the five seismic hazard maps in Fig. 4 display seismic hazard in terms of peak ground acceleration (PGA) assessed for the same standard regular grid $0.2° \times 0.2°$ mesh (Magrin et al. 2016).

The difference between the hazards computed using USLE (Fig. 4a) and the other four methods is striking: it is the only one map predicting accelerations of about 1 g and above on both the northern and southern 1st rank lineaments outlining the Kathiawar Peninsula macro-block. Unlike the other four maps, the USLE one confirms the evidence of PGA above 1 g in the 2001 Bhuj earthquake and does not exclude such a ground shaking on the other side of/the Kathiawar Peninsula. It should be noted that the 2001 Bhuj earthquake was one of the first deadliest surprises for the probabilistic GSHAP PGA map (Giardini et al. 1999) with a huge underestimation of ground shaking, about 3 units of Modified Mercalli Intensity (Kossobokov and Nekrasova 2011). As mentioned above, tectonically, the Bombay Graben may possess enough energy accumulated in geologic time and subcontinent scale for producing a significant earthquake. It is also confirmed, although indirectly, with the results of computer modeling the dynamics of blocks-and-faults structures (Vorobieva et al. 2014) and pattern recognition of the earthquake-prone areas in the Gujarat Region (Gorshkov et al. 2015).

Figure 5 demonstrates the empirical probability distributions of the model PGA values in a Gujarat region provided by the five seismic hazard maps, specifically, USLE, DGA, DGA10%, DGA2%, and GSHAP (Fig. 4). It is notable that at the level of perceived strong ground shaking (MMI = 6, PGA = g/8) the DGA and USLE approaches agree on the proportion of the Gujarat territory at risk, although disagree on location of such hazardous areas and possibility of the violent and extreme shaking of more than 1 g. The other three maps, i.e., probabilistic GSHAP and DGA adjusted to a certain chance
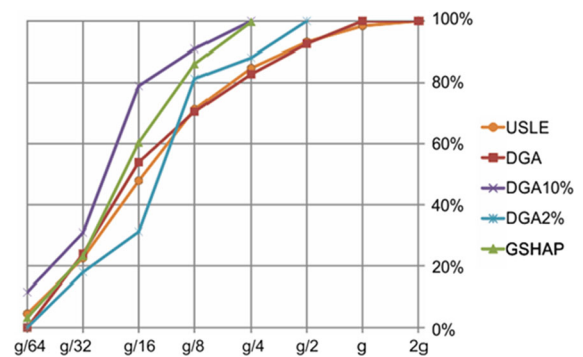

Figure 5
The empirical probability distributions of the PGA estimates on the five model hazard maps in Fig. 4

of exceedance in 50 years, appear to underestimate the hazardous areas in Gujarat by a factor of 2–4. At the extreme level of ground shaking, model underestimation reaches a factor of 8 for GSHAP and the most risky semi-probabilistic DGA10% approaches, which size appears in agreement with the real observations in the 2001 Bhuj earthquake.

Naturally, disagreement in hazard assessment transfer to evaluation of risks. Following (Parvez et al. 2014), let us consider the same four seismic risk estimates applied to the India's Census 2011 population data an object of risk. The first estimate in a cell g is based on the constant equal vulnerability of an individual, $R_i(g) = H(g) \cdot \int_g P$, where $\int_g P$ is the integral of the population density over the cell g, i.e., the number of individuals within the area of the cell g. The second risk estimate differentiates individual vulnerability in proportion to the population density at a given site, $R_{ii}(g) = H(g) \cdot \int_g P \cdot P$. This and the other two assumptions—$R_{iii}(g) = H(g) \cdot \int_g P \cdot P^2$ and $R_{iv}(g) = H(g) \cdot \int_g P \cdot P^3$—appear to be rather natural due to specifics of man-made environment in highly populated areas. As an illustration, the five model maps of $R_{iii}(g)$ in arbitrary units are given in Fig. 6. The empirical distributions of the four different risk values in Gujarat for each of the five seismic hazard assessment models are given in Fig. 7. As could be expected, the risks follow seismic hazard trends, so that the USLE approach provides most conservative estimations, while the GSHAP and DGA10% ones appear too optimistic, unless rather subjective probabilistic assumptions are brought into argument. Although at the level of average or median risk the

five models are rather comparable in evaluation, their differences at the extreme values differ by a factor from 10 to 10,000.

To avoid misleading counterproductive interpretations, we have to emphasize that *the risk estimates presented for the territory under study are given here for academic methodological purposes only*. They do not use complicated procedures that might be more adequate convolutions of hazard, objects and their vulnerability, and are used here to illustrate the general problem-oriented approach. The estimations addressing more realistic and practical kinds of seismic risks, not presented here, should involve experts in distribution of objects of risk of different vulnerability, i.e., specialists in earthquake engineering, social sciences, and economics.
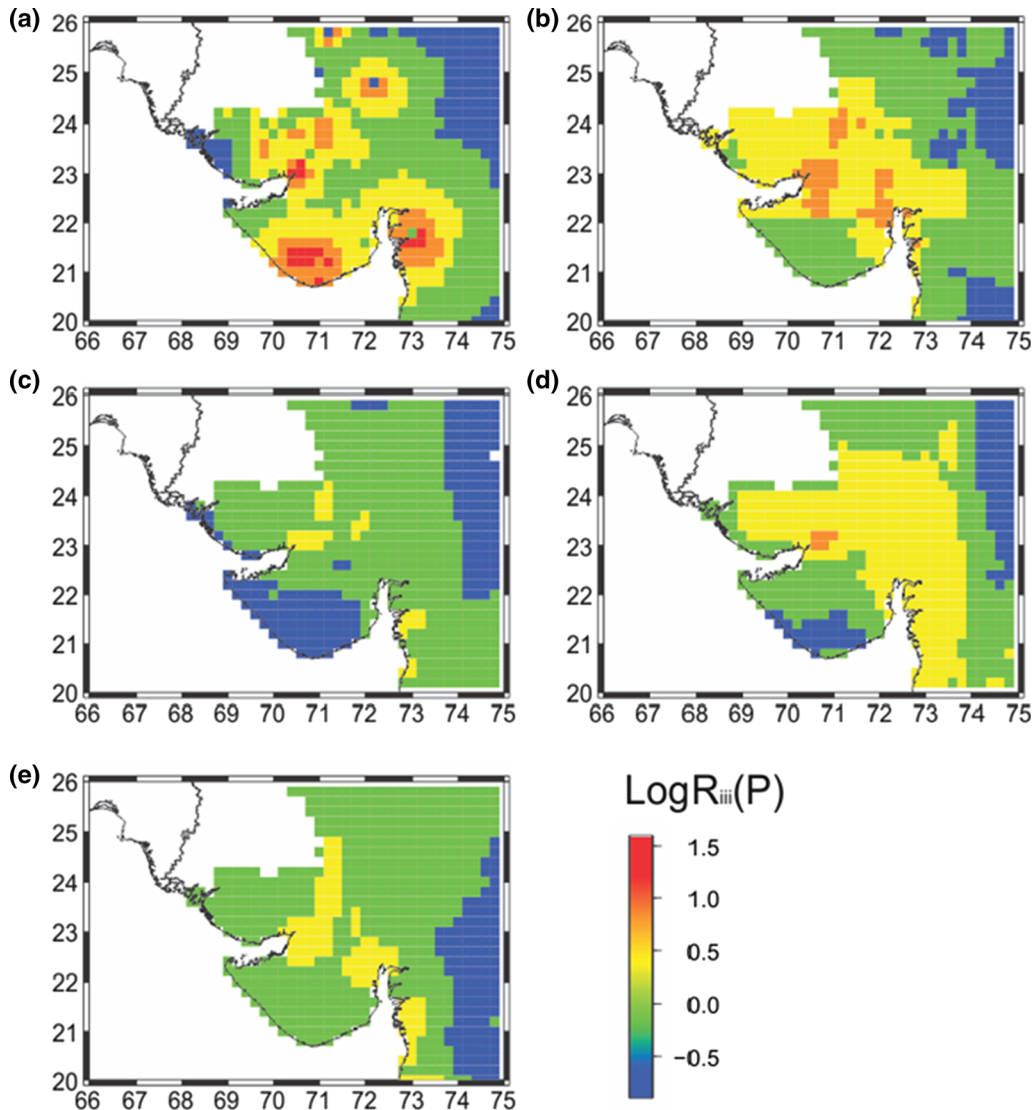

Figure 6
The maps of seismic risk $R_{iii}(g)$ for population of Gujarat region. Oversimplified convolutions, $R_{iii}(g) = H(g) \cdot \int_g P \cdot P^2$, of the India's Census 2011 population data with seismic hazard assessment $H(g)$ based on USLE (**a**), **b** DGA, **c** DGA10%, **d** DGA2%, **e** GSHAP approaches (seismic hazard maps in Fig. 4)
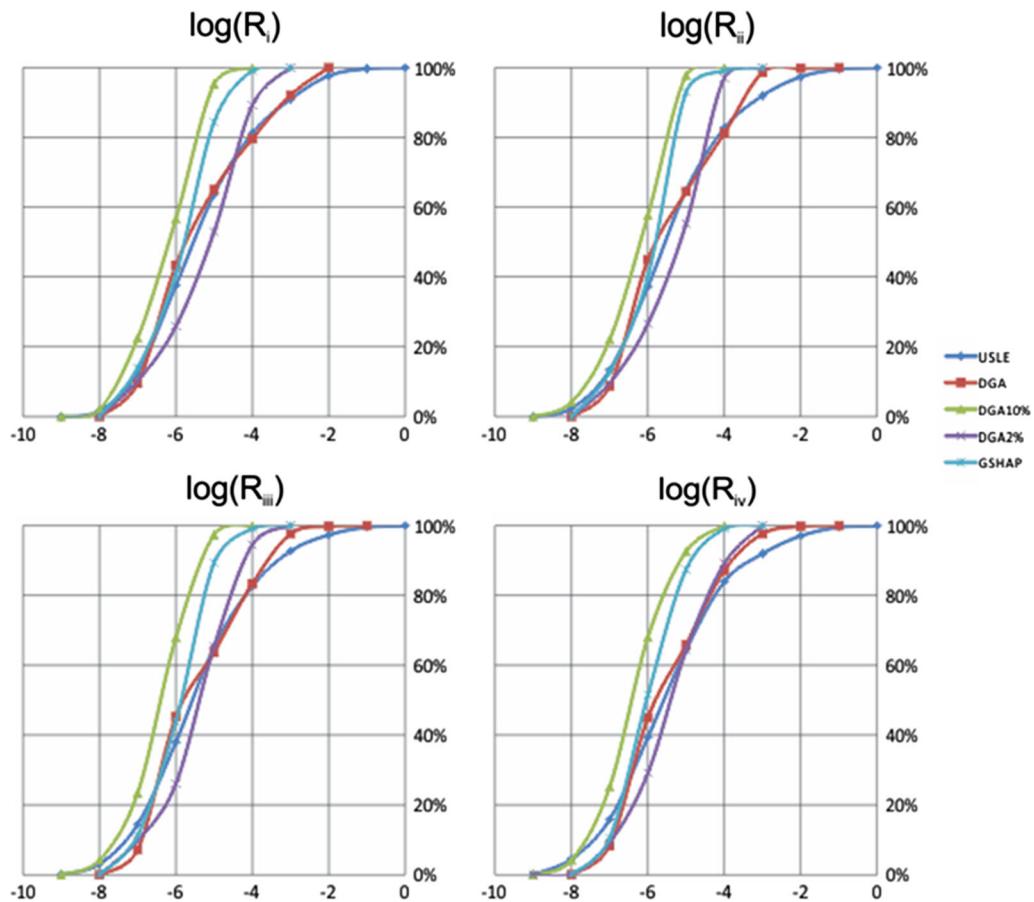
Figure 7
The empirical probability distributions of the four different risks in Gujarat region for the five seismic hazard models

4. Conclusion

Seismic hazard and risk assessments are rather uncertain nowadays. Our case study for the State of Gujarat, India discloses a possibility of much higher risks than those on the existing probabilistic seismic hazard maps when naturally fractal distribution of earthquake loci is taken into account along with tectonic evidence and pattern recognition arguments. First of all, it refers to the two areas to the North of continuation to the Arabian Sea of the Narmada-Son Lineament that crosses the entire Indian subcontinent; in particular, these are the areas to the North of Gimar Hills and Baroda Plane, where the USLE approach suggests a possibility of significant or even great earthquakes. Further investigation of the Kathiawar Peninsula tectonic structure and dynamics along with paleoseismological searches may help with reliable information for resolving the problem of seismic safety in the region.

REFERENCES

Bak, P., Christensen, K., Danon, L., & Scanlon, T. (2002). Unified scaling law for earthquakes. *Physical Review Letters, 88,* 178501–178504.

Bapat, A., Deshpande N. V., Das P. B., & Bhavnarayana, V. (1989). Pre-impoundment seismicity studies around Sardar Sarovar Site, CBIP 55, R&D Session.

Bendick, R., Bilham, R., Fielding, E., Gaur, V. K., Hough, S. E., Keir, G., et al. (2001). The 26 January "Republic Day" Earthquake, India. *Seismological Research Letters, 72*(3), 328–335.

Bhatia, S. C., Kumar R., Gupta H. K., (1999). A probabilistic seismic hazard map of India and adjoining regions. *Annales Geophysicae, 42*, 1153–1164.

Bhatia, B. C., Chetty, T. R. K., Rao, M. N., Gorshkov, A. I., Glazko, M. P., Rantsman, E.Ya., et al. (1994). Morphostructural zoning scheme of the Himalayan belt, fore deep and the Indian shield. Scale 1:5,000,00. Explanatory notes. NGRI, Hyderabad, India).

Chopra, S., Kumar, D., Rastogi, B. K., Choudhury, P., & Yadav, R. B. S. (2013). Estimation of site amplification functions in Gujarat region, India. *Natural Hazards, 65*(2), 1135–1155. doi:10.1007/s11069-012-0116-6.

Christensen, K., Danon, L., Scanlon, T., & Bak, P. (2002). Unified scaling law for earthquakes. *Proceedings of National Academy of Sciences, 99*(suppl 1), 2509–2513.

Davis, C., Keilis-Borok, V., Kossobokov, V., & Soloviev, A. (2012). Advance prediction of the March 11, 2011 Great East Japan Earthquake: A missed opportunity for disaster preparedness. *International Journal of Disaster Risk Reduction, 1,* 17–32. doi:10.1016/j.ijdrr.2012.03.001.

de Nardis, R., Fliipi, L., Costa, G., Suhadolc, P., Nicoletti, M., & Lavecchia, G. (2014). Strong motion recorded during the Emilia 2012 thrust earthquakes (Northern Italy): A comprehensive analysis. *Bull Earthquake Eng, 12,* 2117–2145.

GHDB. (1989). Global Hypocenters Data Base CD-ROM. NEIC/USGS, Denver, CO, 1989 and its updates through December 2015.

Giardini, D., Grünthal, K., Shedlock, P., & Zhang, P. (1999). The GSHAP global seismic hazard map. *Annali di Geofisica, 42*(6), 1225–1228.

Giardini, D., Grünthal, G., Shedlock, K. M., & Zhang, P. (2003). The GSHAP global seismic hazard map. In W. Lee, H. Kanamori, P. Jennings, & C. Kisslinger (Eds.), *International handbook of earthquake & engineering seismology. International geophysics series* (Vol. 81 B, pp. 1233–1239). Amsterdam: Academic Press.

Gorshkov, A., Gaudemer, Y., Mandal, P., & Novikova, O. (2015). Identification of earthquake-prone areas in some intraplate regions. 26th IUGG General Assembly, Prague, Czech Republic, June 22–July 2, 2015 Abstract: S07p-328.

Hough, S. E., Martin, S., Bilham, R., & Atkinson, G. M. (2002). The 26 January 2001, M 7.6 Bhuj, India, earthquake: observed and predicted ground motions. *Bulletin of the Seismological Society of America, 92,* 2061–2079.

Johnston, A. C., & Kanter, L. R. (1990). Earthquakes in stable continental crust. *Scientific American, 262,* 68–75.

Kayal, J. R. (2003). Seismic tomography structures of source areas of the two recent devastating earthquakes in Peninsular India. *Journal of the Virtual Explorer, 12,* 66–71.

Keilis-Borok, V. I., Kossobokov, V. G., & Mazhkenov, S. A. (1989). On similarity in spatial seismicity distribution. *Computational Seismology, 22,* 28–40. **(Moscow, Nauka)**.

Khattri, K. N., Rogers, A. M., Perkins, D. M., & Algermissen, S. T. (1984). A seismic hazard map of India and adjacent areas. *Tectonophysics, 108,* 93–134.

Klügel, J.-U. (2008). Seismic hazard analysis—Quo vadis? *Earth-Science Reviews, 88*(1), 1–32.

Kossobokov, V. G. (2005). Earthquake prediction: Principles, implementation, perspectives. In V. I. Keilis-Borok., A. A. Soloviev (Eds.), *Earthquake prediction and geodynamic processes. Part 1 (Computational seismology, Issue 36)*. Moscow: GEOS (**in Russian**).

Kossobokov, V. G., & Mazhkenov, S. A. (1994). On similarity in the spatial distribution of seismicity. In D. K. Chowdhury (Ed.), *Computational seismology and geodynamics/AGU* (Vol. 1, pp. 6–15). Washington: The Union.

Kossobokov, V., & Nekrasova, A. (2003). Generalized Gutenberg–Richter recurrence law. Geophysical Research Abstracts, 5, 2003. Abstracts of the Contributions of the EGS-AGU-EGU Joint Assembly, Nice, France, 06-11 April, (CD-ROM): EAE03-A-06597.

Kossobokov, V. G., & Nekrasova, A. K. (2007). Unified scaling law for earthquakes: Implications for seismic hazard and risk assessment. In: IUGG2007, July 2–13, 2007, Perugia, Italy. Abstracts, SS002-65.

Kossobokov, V. G., & Nekrasova, A. K. (2011). Recent testing of the Global Seismic Hazard Assessment Program (GSHAP) maps. The 1st Annual Meeting of the Strategic Chinese-Korean-Japanese Cooperative Program: Seismic Hazard Assessment for the Next Generation Map, Harbin, China, 25–30 November.

Kossobokov, V., & Nekrasova, A. (2012). Global seismic hazard assessment program maps are erroneous. *Seismic Instruments, 48*(2), 162–170. doi:10.3103/S0747923912020065.

Lavecchia, G., Ferrarini, F., Brozzetti, F., Nardis, R. D., Boncio, P., & Chiaraluce, L. (2012). From surface geology to aftershock analysis: Constraints on the geometry of the L'Aquila 2009 seismogenic fault system. *Italian Journal of Geosciences, 131*(3), 330–347.

Magrin, A. (2012). Multi-scale seismic hazard scenarios. PhD thesis, Univ. degli Studi di Trieste.

Magrin, A., Parvez, I. A., Vaccari, F., Peresan, A., Rastogi, B. K., Cozzini, S., et al. (2016). Neo-deterministic definition of seismic and tsunami hazard scenarios for the territory of Gujarat (India). In S. D'Amico (Ed.), *Earthquakes and their impact on society* (pp. 193–212). Springer Natural Hazards. doi:10.1007/978-3-319-21753-6_7.

Molchan, G., Kronrod, T., & Panza, G. F. (1997). Multiscale seismicity model for seismic risk. *Bulletin of the Seismological Society of America, 87,* 1220–1229.

Nekrasova, A. (2008). Unified Scaling Law for Earthquakes: Implications for seismic active word zones. (Ph. D thesis), M.V. Lomonosov Moscow State University, pp. 1–136 (**in Russian**).

Nekrasova, A., & Kossobokov, V. (2002). Generalizing the Gutenberg–Richter scaling law. EOS Trans AGU 83(47): NG62B-0958.

Nekrasova, A., & Kossobokov, V. (2003). Generalized Gutenberg–Richter recurrence law: Global map of parameters. Geophysical Research Abstracts, 5, 2003. Abstracts of the Contributions of the EGS-AGU-EGU Joint Assembly, Nice, France, 06–11 April, (CD-ROM): EAE03-A-03801.

Nekrasova, A., & Kossobokov, V. (2005a). Temporal variation of the seismic unified scaling law parameters. Geophysical Research Abstracts, 7, 2005. Abstracts of the Contributions of the EGU General Assembly 2005, Vienna, Austria, 24–29 April, (CD-ROM): EGU05-A-05840.

Nekrasova, A. K., & Kosobokov, V. G. (2005b). Temporal variations in the parameters of the Unified Scaling Law for

Earthquakes in the eastern part of Honshu Island (Japan). *Doklady Earth Sciences, 405,* 1352–1356.

Nekrasova, A., & Kossobokov, V. (2005c). Unified Scaling Law for Earthquakes: Mega-cities and urban agglomerations. Eos Trans. AGU, 86(52), Fall Meet. Suppl., Abstract S23A-0229.

Nekrasova, A., & Kossobokov, V. (2006). Unified scaling law for earthquakes in the Lake Baikal region. *Doklady Earth Sciences, 407A*(3), 484–485.

Nekrasova, A., Kossobokov, V., Aoudia, A., Perezan, A., & Panza, G. F. (2011). A multiscale application of the Unified Scaling Law for Earthquakes in the Central Mediterranean area and Alpine region. *Pure and Applied Geophysics, 168,* 297–327.

Nekrasova, A., Kossobokov, V., Parvez, I. A., & Tao, X. (2015). Seismic hazard and risk assessment based on the unified scaling law for earthquakes. *Acta Geodaetica et Geophysica, 50*(1), 21–37. doi:10.1007/s40328-014-0082-4. ISSN 2213-5812.

Okubo, P. G., & Aki, K. (1987). Fractal geometry in the San Andreas fault system. *Journal Geophysical Research, 92,* 345–355.

Panza, G. F., Romanelli, F., & Vaccari, F. (2001). Seismic wave propagation in laterally heterogeneous anelastic media: Theory and applications to seismic zonation. *Advances in Geophysics, 43,* 1–95.

Parvez, I. A., Gusev, A., Panza, G. F., & Petukhin, A. (2001). Preliminary determination of the interdependence among strong motion amplitude, earthquake magnitude and hypocentral distance for the Himalayan region. *Geophysical Journal International, 144,* 577–596.

Parvez, I. A., Nekrasova, A., & Kossobokov, V. (2014). Estimation of seismic hazard and risks for the Himalayas and surrounding regions based on Unified Scaling Law for Earthquakes. *Natural Hazards, 71*(1), 549–562. doi:10.1007/s11069-013-0926-1.

Parvez, I. A., Vaccari, Franco, & Panza, G. F. (2003). A deterministic seismic hazard map of India and adjacent areas. *Geophysical Journal International, 155,* 489–508.

Petersen, M. D., Rastogi, B. K., Schweig, G. E. S., Harmsen, S. C., & Gomberg, J. S. (2004). Sensitivity analysis of seismic hazard for the northwestern portion of the state of Gujarat, India. *Tectonophysics, 390,* 105–115.

Rantsman, E. Ya., Glasko, M. P., & Gorshkov, A. I. (1996). Hierarchy of the present-day block structure of the Indian shield and its orogenic framework. *Transactions (Doklady) of the Russian Academy of Sciences/Earth Science Sections, 349*(5), 839–845.

Rao, D. A., Ram Babu, H. V., & Sivakumar Sinha, G. D. J. (1992). Crustal structure associated with Gondwana graben across the Narmada-Son lineament in India: An inference from aeromagnetics. *Tectonophysics, 212*(1), 163–172.

Shedlock, K., Giardini, D., Grünthal, G., & Zhang, P. (2000). The GSHAP global seismic hazard map. *Seismological Research Letters, 71*(6), 679–686.

Shukla, J., & Choudhury, D. (2012). Seismic hazard and site-specific ground motion for typical ports of Gujarat. *Natural Hazards, 60*(2), 541–565.

Singh, S. K., Pacheco, J. F., Bansal, B. K., Perez-Campos, X., Dattatrayam, R. S., & Suresh, G. (2004). A source study of the Bhuj, India Earthquake of 26 January, 2001 (MW 7.6). *Bulletin of the Seismological Society of America, 94*(4), 1195–1206.

Stoppa, F., & Berti, C. (2013). Reducing seismic risk by understanding its cultural roots: Inference from an Italian case history. *Natural Sciences, 5*(8A1), 78–91.

Tripathi, J. N. (2006). Probabilistic assessment of earthquake recurrence in the January 26, 2001 earthquake region of Gujarat, India. *Journal of Seismology, 10,* 119–130.

Vorobieva, I., Mandal, P., & Gorshkov, A. (2014). Numerical modeling of seismicity and geodynamics of the Kachchh rift zone, Gujarat, India. *Tectonophysics, 634,* 31–43.

Wesnousky, S. G., Seeber, L., Rockwell, T. K., Thakur, V., Briggs, R., Kumar, S., et al. (2001). Eight days in Bhuj: Field report bearing on surface rupture and genesis of the 26 January 2001 earthquake in India. *Seismological Research Letters, 72,* 514–524. doi:10.1785/gssrl.72.5.514.

Wyss, M., Nekrasova, A., & Kossobokov, V. (2012). Errors in expected human losses due to incorrect seismic hazard estimates. *Natural Hazards, 62*(3), 927–935. doi:10.1007/s11069-012-0125-5.

Yadav, R. B. S., Tripathi, J. N., Rastogi, B. K., & Chopra, S. (2008). Probabilistic assessment of earthquake hazard in Gujarat and adjoining regions of India. *Pure and Applied Geophysics, 165,* 1813–1833.