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

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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 Kutch 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°×0.2° (i) in terms of design ground acceleration (DGA) based on the neo-deterministic approach, (ii) in terms of probabilistic exceedance of peak ground acceleration (PGA) by GSHAP, and (iii) 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 2011 census data, and a few model assumptions of vulnerability.

Methodology based on $\log N = A + B\cdot(M_0 - M) + C\cdot\log L$

A catalogue of earthquakes is used as initial input data source. A space-time-magnitude volume, $S \times T \times M$ is considered, where S is the territory, T is time interval from T_0 to T_1, and M is the magnitude range above M_0; the events with magnitude $m \geq M_0$ are reasonably complete in the catalogue since T_0. The input data are processed as follows:

1. The magnitude range M is subdivided into q adjacent intervals of length ΔM –

$$M_j = \{m : M_0 + (j-1)\,\Delta M \leq m < M_0 + j\,\Delta M\}, \quad j = 1,2,\ldots,q.$$

2. The entire area S is subdivided into a hierarchy of h levels. The 0-level corresponds to the entire S imbedded in a square of side length L_0. (To avoid double-counting at the borders, a square of side length L here is a set $\{(x, y) : x_1 \leq x < x_1 + L; y_1 \leq x < y_1 + L\}$.) In the two successive levels i and $i+1$ ($i = 0, 1, \ldots, h-1$) of hierarchy each square of side length L_i is split into the four equal squares of side length $L_{i+1} = L_i/2$. A square at the level i of this hierarchy can be denoted as $w_i(e)$ for any point e inside it and, at the same time, as Q^i_r where r is the index number of this square between 1 and 4^i.

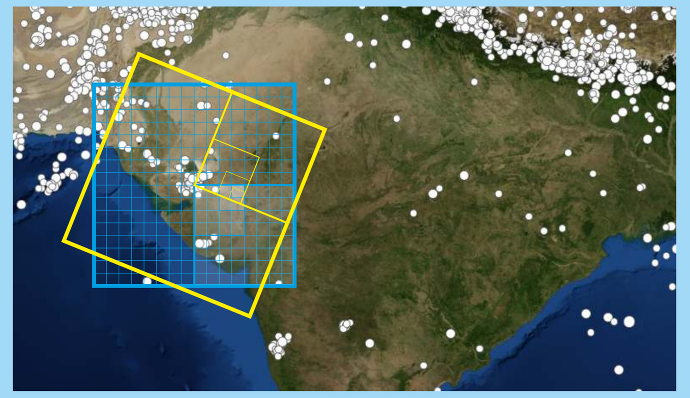
3. Using the earthquake catalog, for each one out of the q magnitude ranges and for each one out of the h levels of hierarchy, the following number N_{ji} is computed

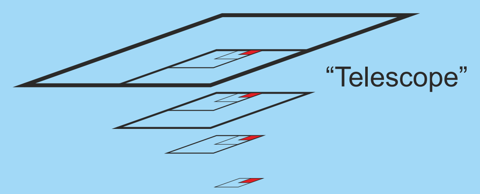
$$N_{ji} = [\,\sum(n_j(Q^i_r))^2\,] / N_j$$

where summation extends over all areas $\{Q^i_r\}$ at the i-th level of hierarchy; $n_j(Q^i_r)$ is the number of events from a magnitude range M_j in an area Q^i_r of linear size L_i; N_j is the total number of events from a magnitude range M_j.

It should be mentioned that this estimate of fractal dimension suggested in (Kossobokov and Mazhkenov 1988; 1994), although originally very close in motivation to estimation of the Hausdorff capacity dimension D_0 (Mandelbrot 1982), in essence, corresponds to the correlation dimension D_2 (Atmanspacher et al. 1988).

Usually, N_{ji} are normalized in time to 1 year and in space to an area of 1 degree of the Earth meridian in length.





4. Estimates of A, B, and C in (2) are derived from the set of linear algebraic equations $\log_{10} N_{ji} = A - B(M_j - M_0) + C\log L_i$ by the least squares method. Unlike many other recent applications (e.g., Bak et al. 2002) the method makes heuristic adjustments for heterogeneity of seismic distribution, as well as for consistency of the real data statistics in different magnitude ranges. Specifically, the equations that correspond to evidently incomplete samples of data due to extremely low recurrence rates of higher magnitude earthquakes in an area are excluded from computations. For this purpose a heuristic limitation requiring $\log_{10}(N_{j,i} / N_{j+1,i}) > const$ on transfer from the magnitude range M_j to M_{j+1} (where const is a free parameter of the SCE algorithm, usually set to 2) is used. Similar limitation - $\log_{10}(N_{j,i}/N_{j,i-1}) > const$ - is introduced for the transfer from $(i-1)$-th to i-th level of spatial hierarchy.

5. In addition to the original prototype algorithm (Kossobokov and Mazhkenov 1988), the steps 1-4 are applied many (usually 100) times with randomized box counting settings at each seismically active location (Nekrasova and Kossobokov 2002). The resulting series of multiple estimates of the three coefficients are used to determine the final average values of A, B, and C along with their standard errors σ_A, σ_B, and σ_C.

6. The USLE coefficients were used for estimation and mapping the expected maximum magnitude M_{max} (or its corresponding PGA value) with a 10% chance of exceedence in 50 years. Specifically, for each 0.25°×0.25° cell at seismic location on a regional map we calculate the expected numbers of events from magnitude ranges M_j in 50 years, i.e. $N50(M_j, 0.25°) = 50 \times N(M_j, 0.25°)$, and then find the maximum magnitude, M_{max}, with the expected number $N50(M_{max}, 0.25°) \geq 10\%$. Naturally, these are the estimates of traditional maximum magnitude with 10% chance of exceedence in 50 years.

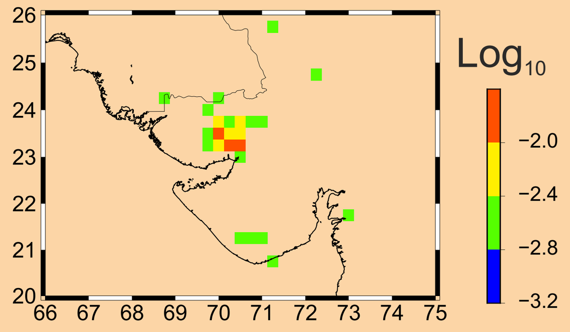
For each grid point we apply the empirical formula for acceleration produced by a source of M_{max} as inspired from (Parvez et al. 2001) –

$$Acc(M_{max}, D) = const \times g \times D\text{-}1.5 \times \exp(M_{max} - 5),$$

where D is the source-receiver distance on a 0.25°×0.25° grid, const = 6×4.8, g = 9.81 m/s² 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 km and 500 km, respectively.

Seismic data

We consider the territory of Gujarat region within 20–26°N and 66–75°E. The coefficients of USLE are evaluated by applying the SCE algorithm to about 150 normal depth seismic events with magnitude 4.8 or more from the 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°.



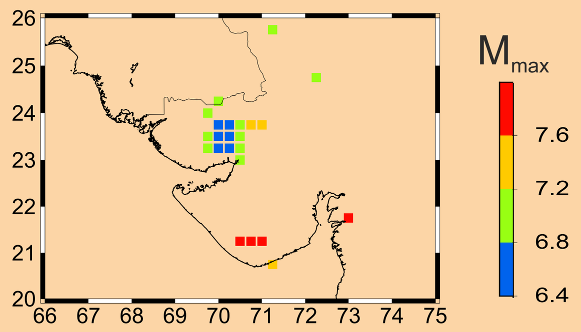
Logarithm of the empirical density distribution of seismic activity =

USLE coefficients at seismically active cells

We have obtained the reliable estimation of the USLE coefficients on the Gujarat region territory for the 23 cells. 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.

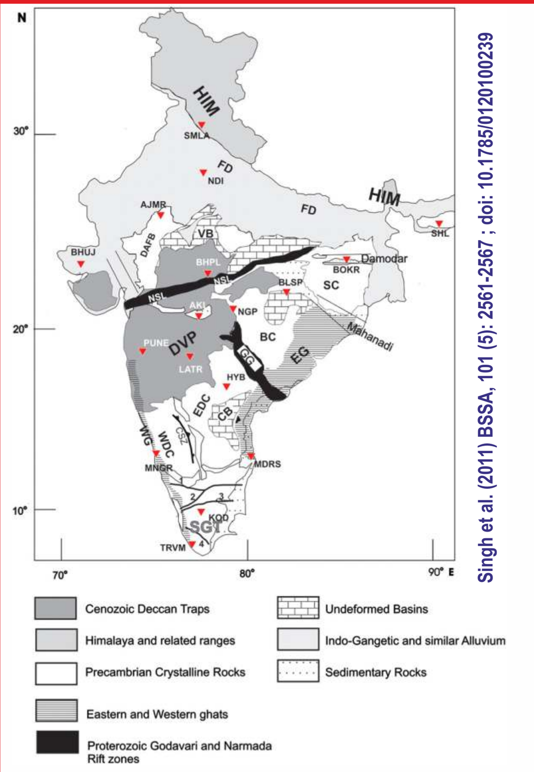
The coefficient B spreads from 0.52 to 0.65 which low values may be due to the great 2001 Bhuj earthquake and its aftershocks that dominate in the available catalog (about 35% of the total in the 600-km circle and 94% in the 100-km circle centered at epicenter of the great shock). The coefficient C ranges 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 Mw=4.9 and 5.1 on November 6, 2007 and Mw=5.1 on October 20, 2011.

Seismic hazard



The seismic hazard map in terms of M_{max} 10% chance in 50 years

The USLE coefficients were used for estimation and mapping the expected maximum magnitude M_{max} with a 10% chance of exceedence in 50 years. Specifically, for each 0.25°×0.25° cell at seismic location on a regional map we 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_{max}, with the expected number $N_{50}(M_{max}, 0.25°) \geq 10\%$. Naturally, these are the estimates of traditional maximum magnitude with 10% chance of exceedence in 50 years.



Singh et al. (2011) BSSA, 101 (5): 2561-2567 ; doi: 10.1785/0120100239

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.

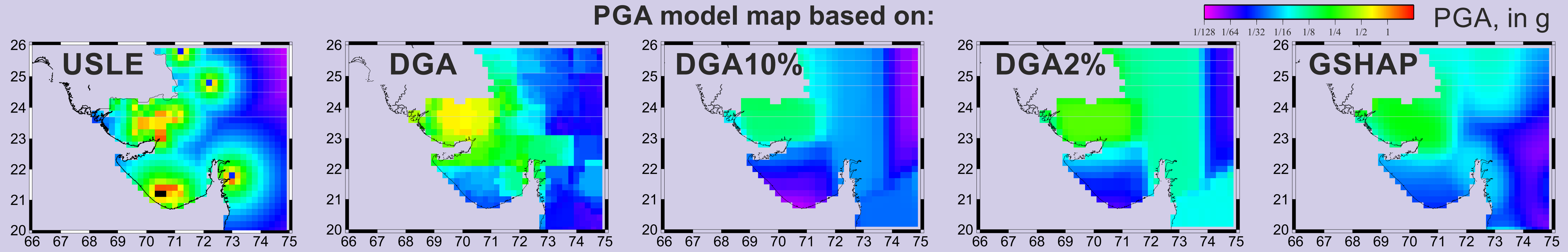
Seismic hazard model data

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

- the design ground acceleration (DGA) map
- the design PGA values adjusted to return period of 475 years corresponding to 10% chance of exceedence in 50 year (DGA10%)
- the design PGA values adjusted to return period of 2475 years corresponding to 2% chance of exceedence in 50 year (DGA 2%)
- 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

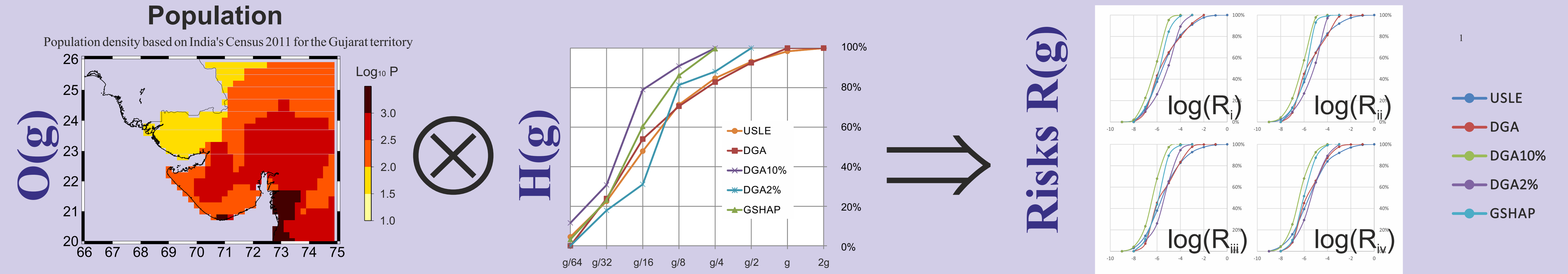
. The three design ground acceleration (DGA) maps are based on the neo-deterministic seismic hazard assessment, NDSHA (Panza et al., 2001)

PGA model map based on:

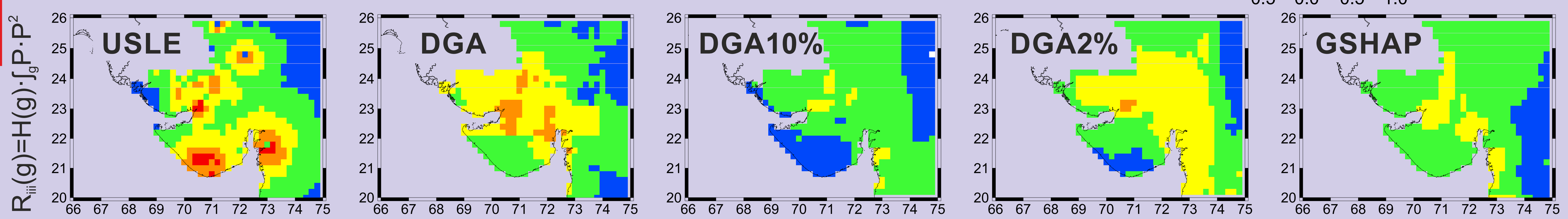


Seismic risk estimation

Any kind of risk R(g) estimates results from a convolution of the natural hazard at location g - H(g), with the exposed objects at risk at g - O(g) along with their vulnerability V(O).



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 argumen.



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.

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