

Advancing Seismic Hazard Assessment in India: Three Decades of Scientific Innovation and Impact

From Earthquake Catalogues and Ground Motion Models to AI-Driven Hazard Assessment and Resilient Infrastructure

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T.G. Sitharam
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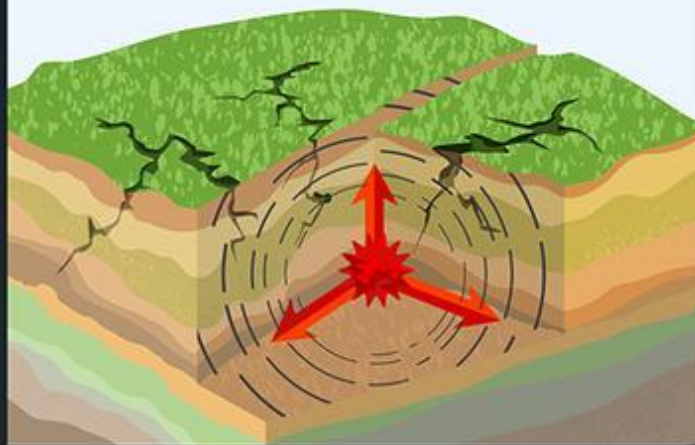
Preparing for Earthquakes: Lessons for India

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Earthquake Hazard Assessment

Sreevalsa Kolathayar
T.G. Sitharam

India and Adjacent Regions

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A BALKEMA BOOK

T. G. Sitharam · Naveen James
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Comprehensive Seismic Zonation Schemes for Regions at Different Scales

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Lecture Notes in Civil Engineering

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Springer Transactions in Civil
and Environmental Engineering

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Latest Developments in Geotechnical Earthquake Engineering and Soil Dynamics

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Lecture Notes in Civil Engineering

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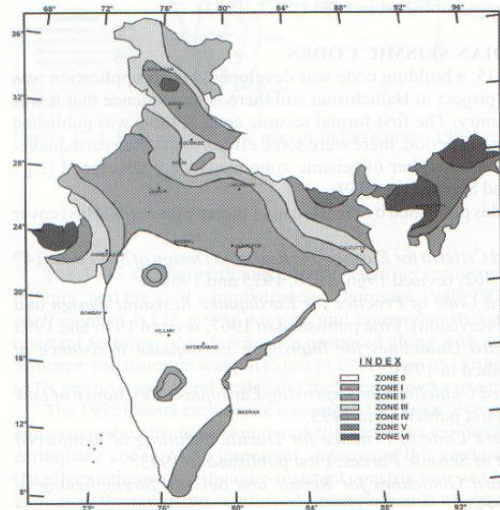
Seismic Hazards and Risk

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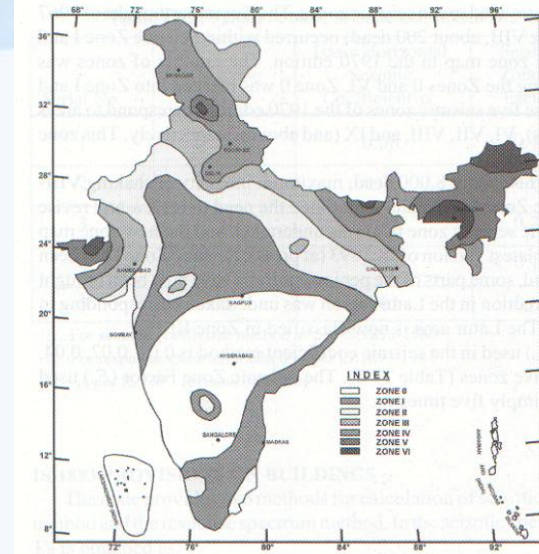
Development of Seismic Zonation Map (BIS-1893)

1962



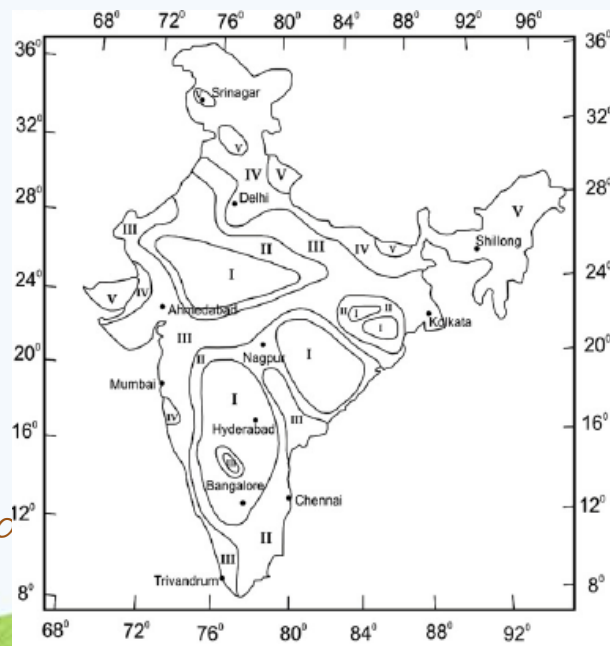
Based on EQ epicenters

1966



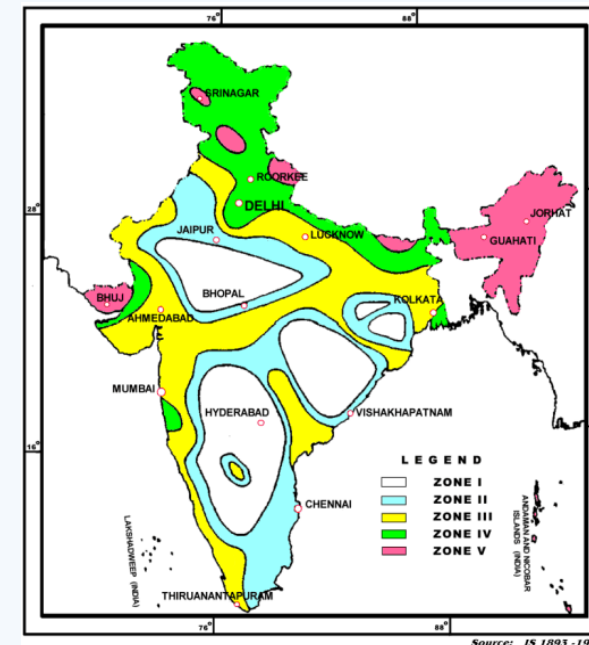
Geology and tectonic features

1970



After 1967 Koyana Earthquake.

1984



Past EQs and Regional tectonics.

Seismic Zonation of India

Sl. No	Place	Zone	Zone Factor (Z)	A _h
1	Gangtok	IV	0.24	0.06 W
2	Patna	IV	0.24	0.06 W
3	Jamnagar	IV	0.24	0.06 W
4	Ratnagiri	IV	0.24	0.06 W

$$A_h = \frac{\left(\frac{Z}{2}\right) \left(\frac{S_a}{g}\right)}{\left(\frac{R}{I}\right)}$$

✓ Why so much damages are happening in India/Asia?

where

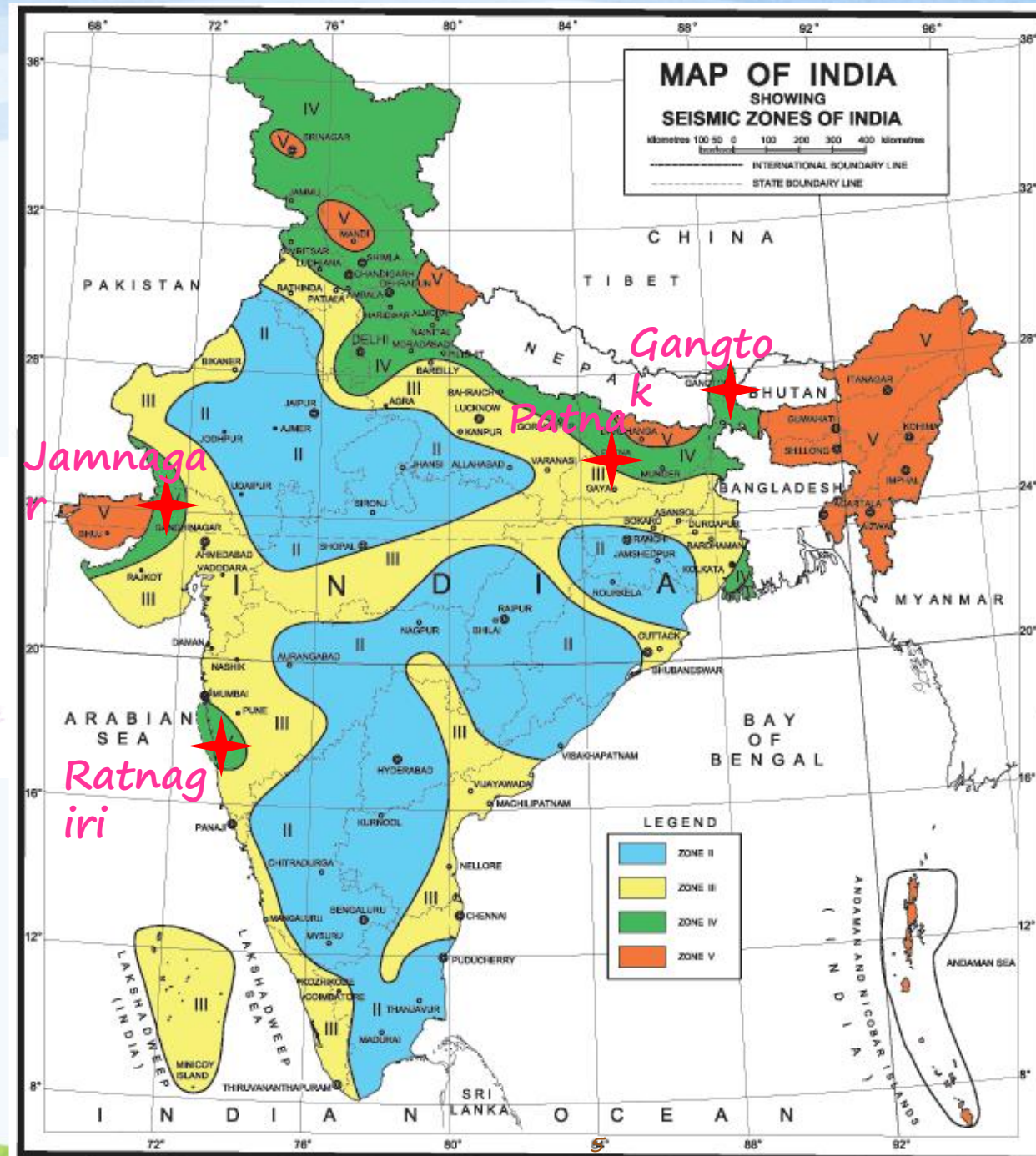
Z = zone factor (Table 3 IS1893:2016) ;

I = importance factor (Table 8 IS 1893:2016);

R = response reduction factor (Table 9 IS 1893:2016);

S_a/g = average acceleration coefficient for rock or soil sites as given in (Fig. 2. IS 1893:2016)

A_h is not changing with location even though seismicity, soil and hazards are completely different



Earthquakes & Damages

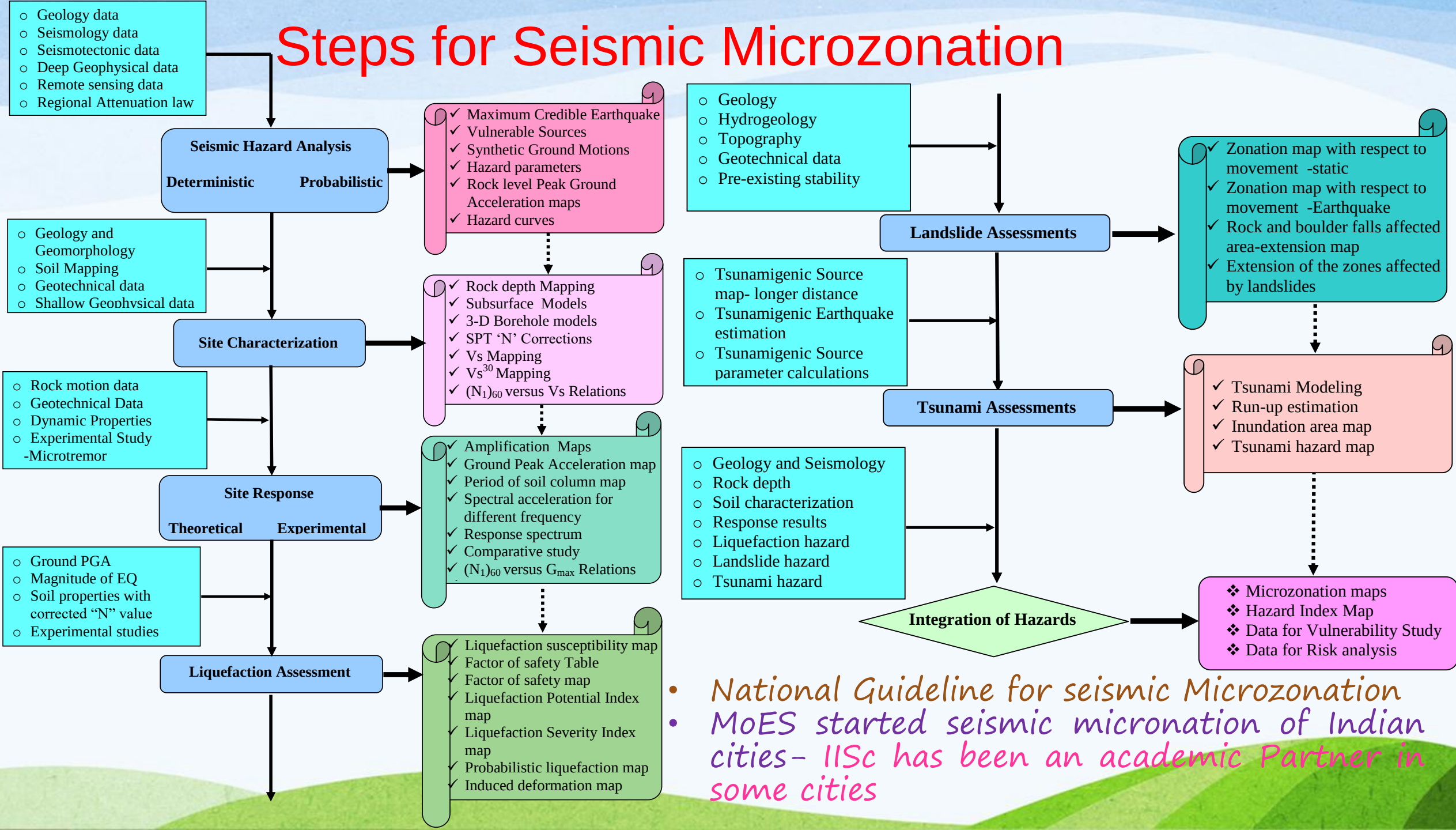


Different
type of
seismic
hazard for
Moderate
magnitudes



Prof Anbazhagan IISc Talk on 23-06-2022

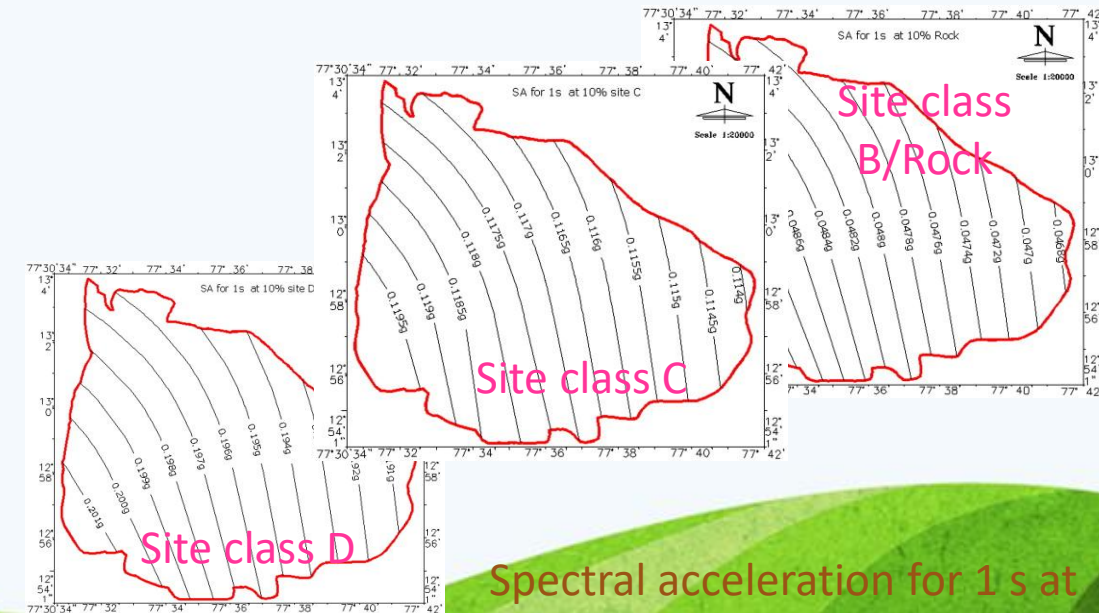
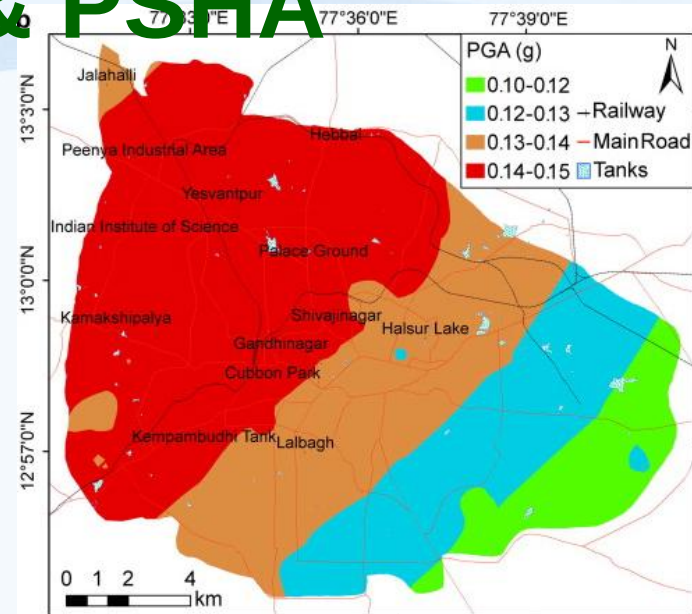
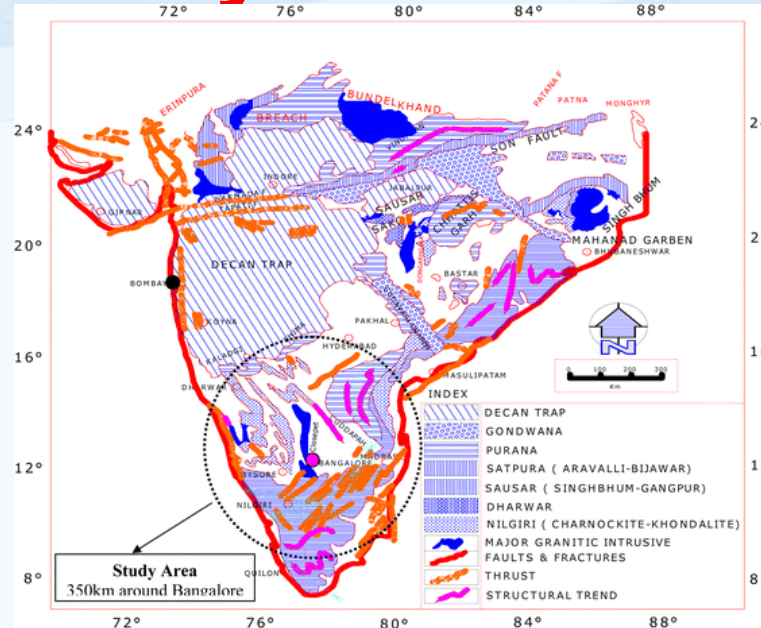
Steps for Seismic Microzonation



- National Guideline for seismic Microzonation
- MoES started seismic micronation of Indian cities- IISc has been an academic Partner in some cities

Seismic Hazard Analysis : DSHA & PSHA

- Use of Remote Sensing and Microseismic Data
- SHA estimation at every borehole hard rock depth
- PSHA estimation at bedrock and soil surface

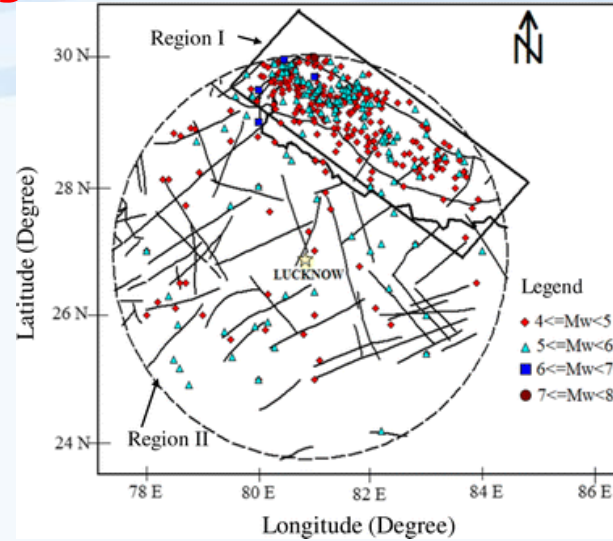
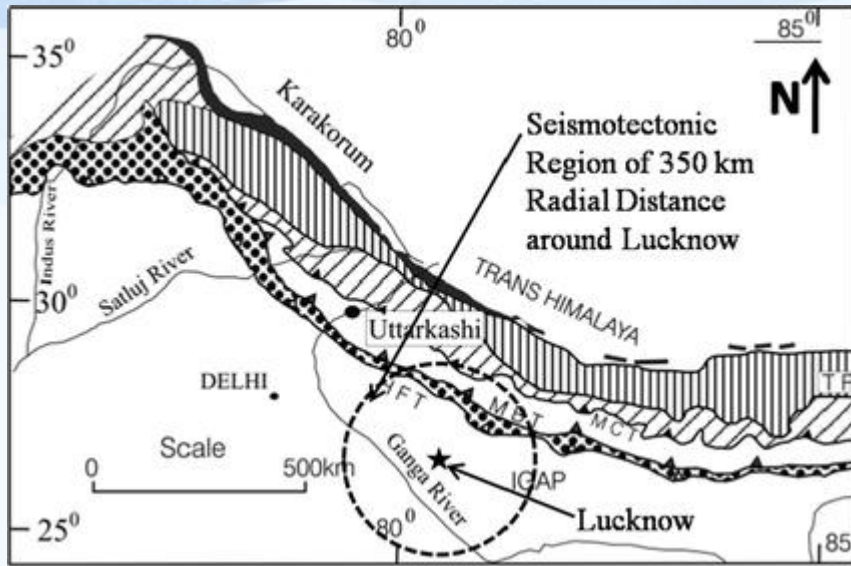


Sitharam, T. G., Anbazhagan, P. and Ganesha Raj, K., (2006).. "Use of remote sensing and seismotectonic parameters for seismic hazard analysis of Bangalore", Nat. Hazards Earth Syst. Sci., 6: 927-939. Dol: <https://doi.org/10.5194/nhess-6-927-2006>

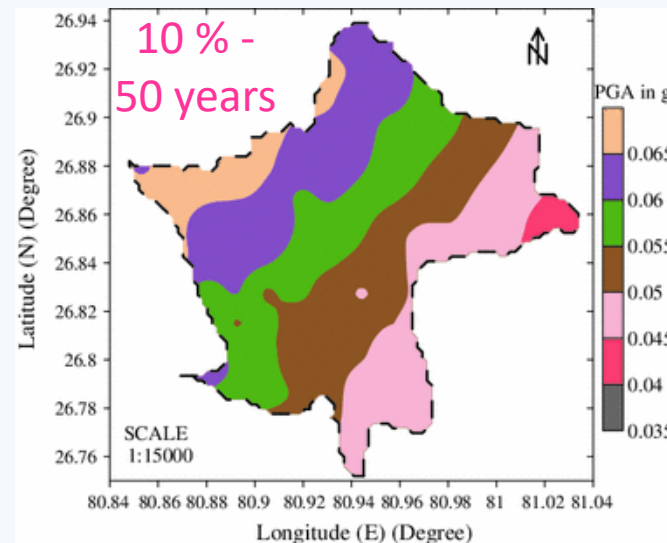
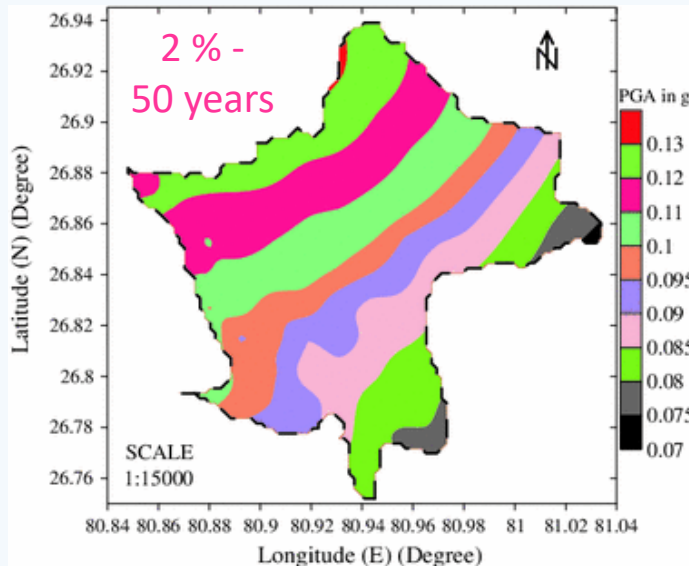
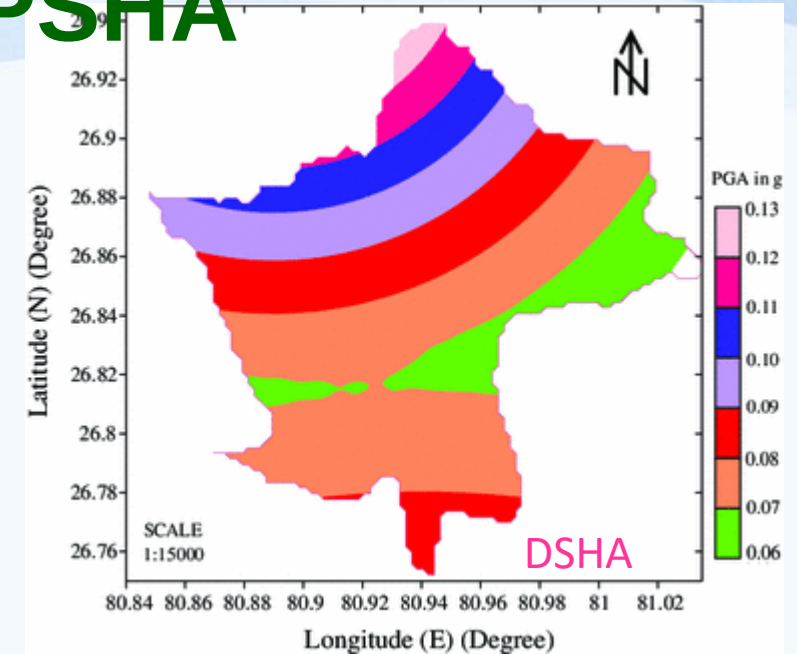
Anbazhagan P., Vinod, J. S. and Sitharam, T. G. (2009). "Probabilistic seismic hazard Analysis for Bangalore", Natural Hazards, 48:145-166. Dol: <https://doi.org/10.1007/s11069-008-9253-3>

Anbazhagan P., Sitharam, T.G., and Vipin, K.S. (2009). "Site classification and estimation of surface level seismic hazard using geophysical data and probabilistic approach", Journal of Applied Geophysics, 68 (2), 219-230. Dol: <https://doi.org/10.1016/j.jappgeo.2008.11.001>

Seismic Hazard Analysis : DSHA & PSHA



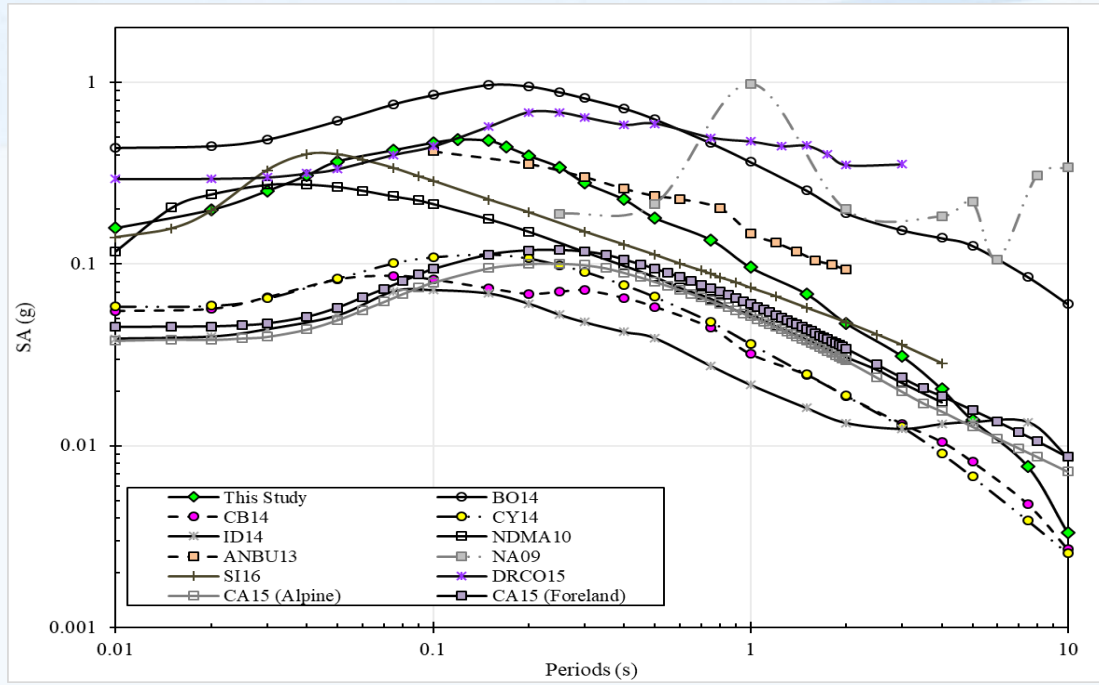
Seismotectonic map for Lucknow



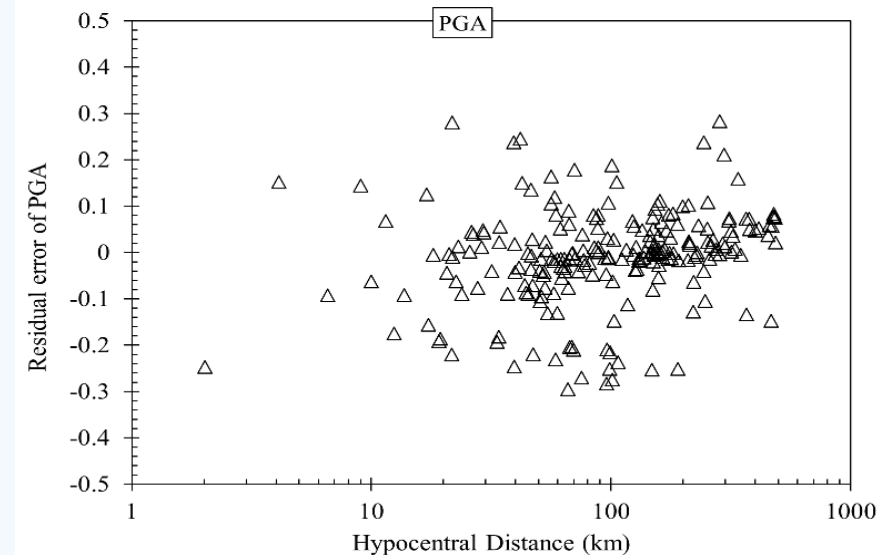
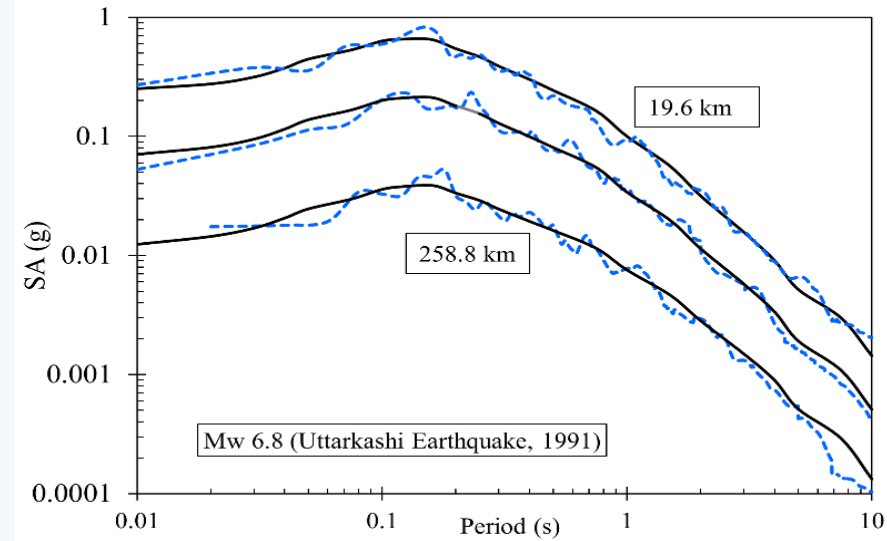
- Accounted highly active source with frequent events and other regions with less active & events separately.
- Hazard values estimated using GMPEs developed for Magnitude & distance required for the study area

Prediction Equations GM functional Form

$$\ln Y = a_1 + a_2(M - 6) + a_3(9 - M)^2 + a_4 \ln R + a_m \ln R (M - 6) + a_7 R + \sigma$$

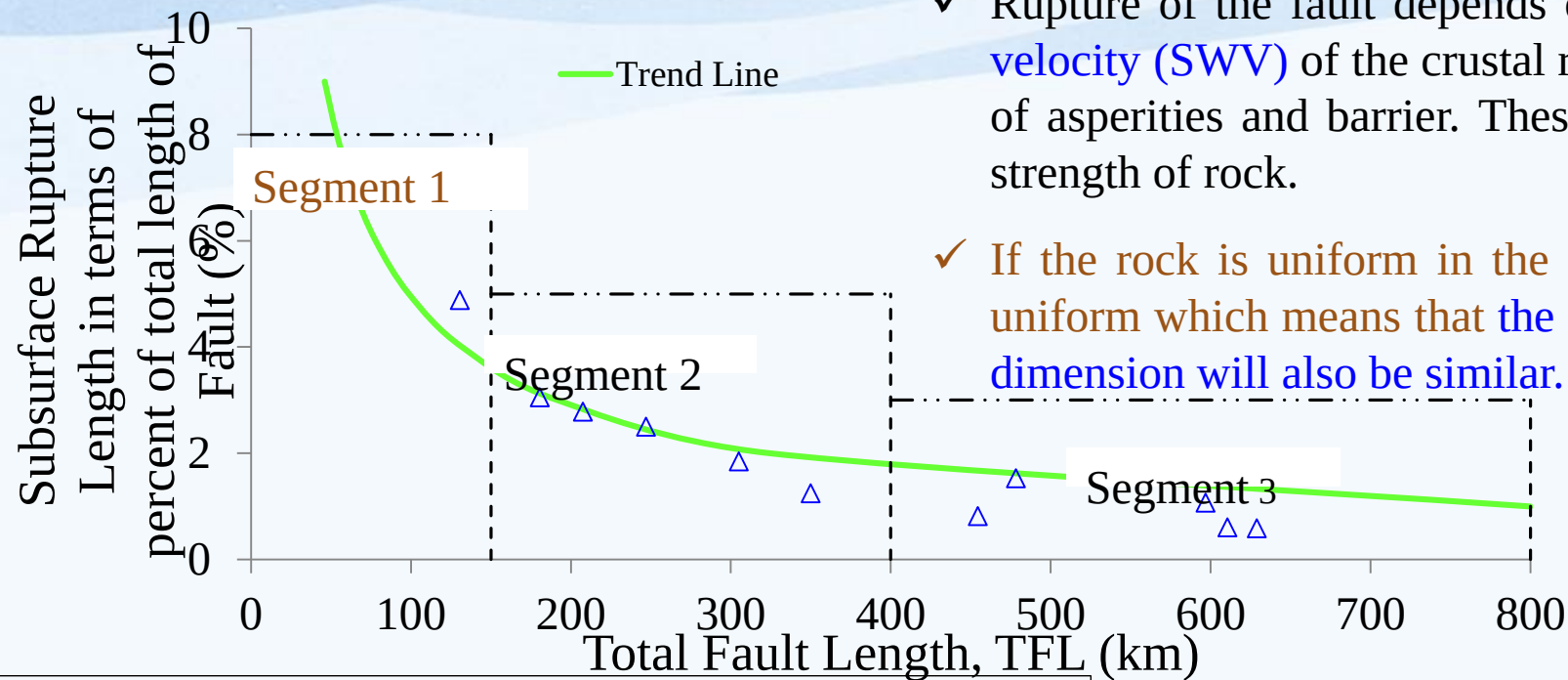


New GMPE with exiting GMPEs widely used in hazard analysis of HR for the major Magnitude of 8.7 (maximum reported 1950 Assam–Tibet earthquake) for rock level



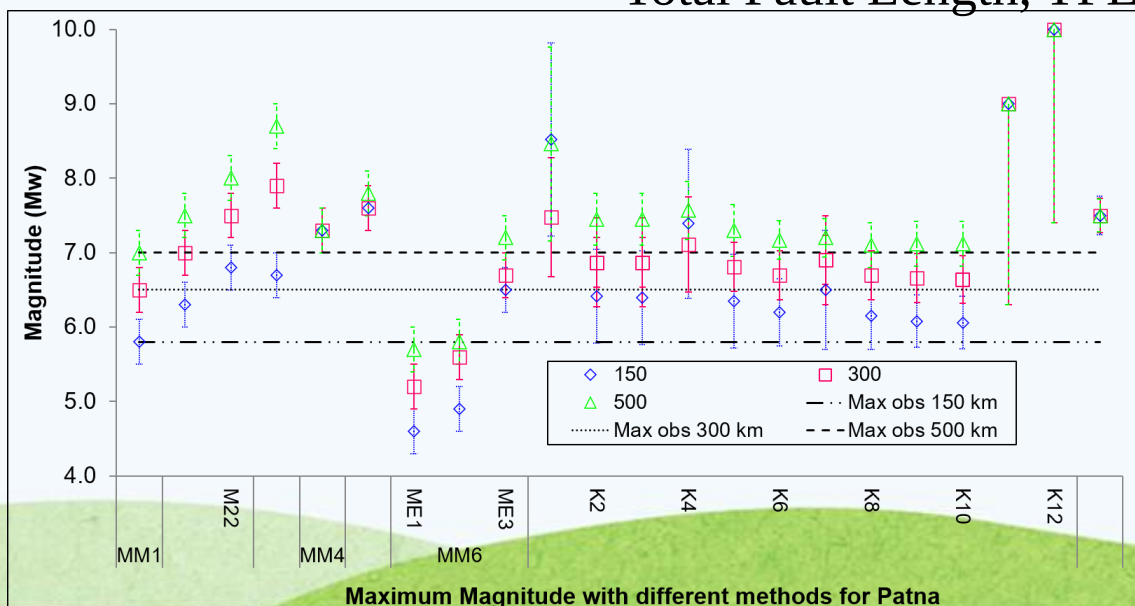
1. Determination of GMPE functional form for an active region with limited strong motion data: Application to the Himalayan region, **Journal of Seismology**, 22(1):161-185; DOI: <https://doi.org/10.1007/s10950-017-9698-5>
2. Regional seismological model parameter estimation and development of GMPE model for the active region of Himalaya" **Soil Dynamics and Earthquake Engineering**, 126, 105825. DOI: <https://doi.org/10.1016/j.soildyn.2019.105825>
3. "Relationship Between Intensity and Recorded Ground Motion and Spectral Parameters for the Himalayan Region", **Bulletin of the Seismological Society of America**, Vol. 106, No. 4, pp. 1672-1689, doi: 10.1785/0120150342.

$M_{\max}$ by Regional Rupture Characteristic



✓ Rupture of the fault depends on source parameters: density and shear wave velocity (SWV) of the crustal rock at rupture and other controlling parameters of asperities and barrier. These parameters are indirectly represented by the strength of rock.

✓ If the rock is uniform in the region then the nature of rupture will be also uniform which means that the average rupture dimension with respect to total dimension will also be similar.



"Maximum Magnitude Estimation Considering the Regional Rupture Character", *Journal of Seismology*, 19:695-719. DOI 10.1007/s10950-015-9488-x

Determine the maximum magnitude observed and TFL for each seismic source

Estimate the RLD using Wells and Coppersmith (1994) equation

$$\log(RLD) = -2.44 + 0.59M_w$$

Determine the segmented PFR based on the different TFL bins and trend observed for worst case

Based on the segmented TFL, RLD is increased corresponds to each seismic source

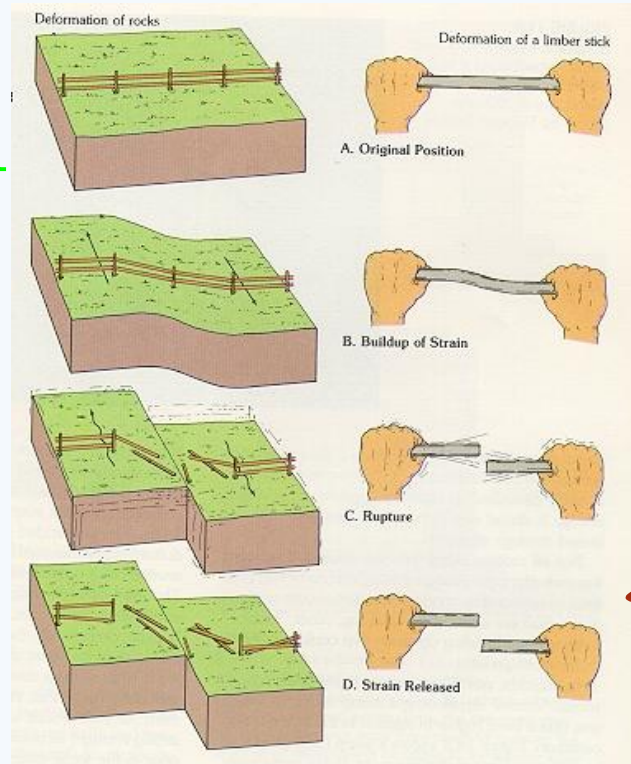
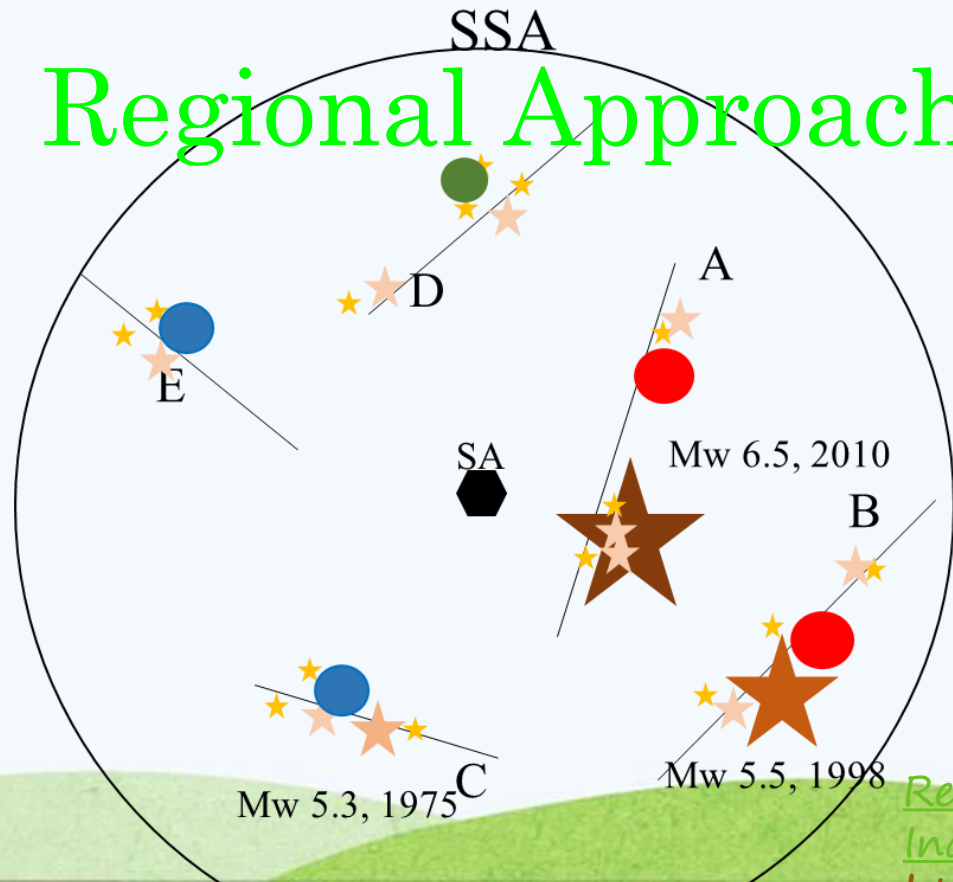
Using the new RLD estimate the maximum magnitude for each seismic source using Wells and Coppersmith (1994) equation

$$M_w = 4.38 + 1.49 \log(RLD)$$

Location of future earthquakes

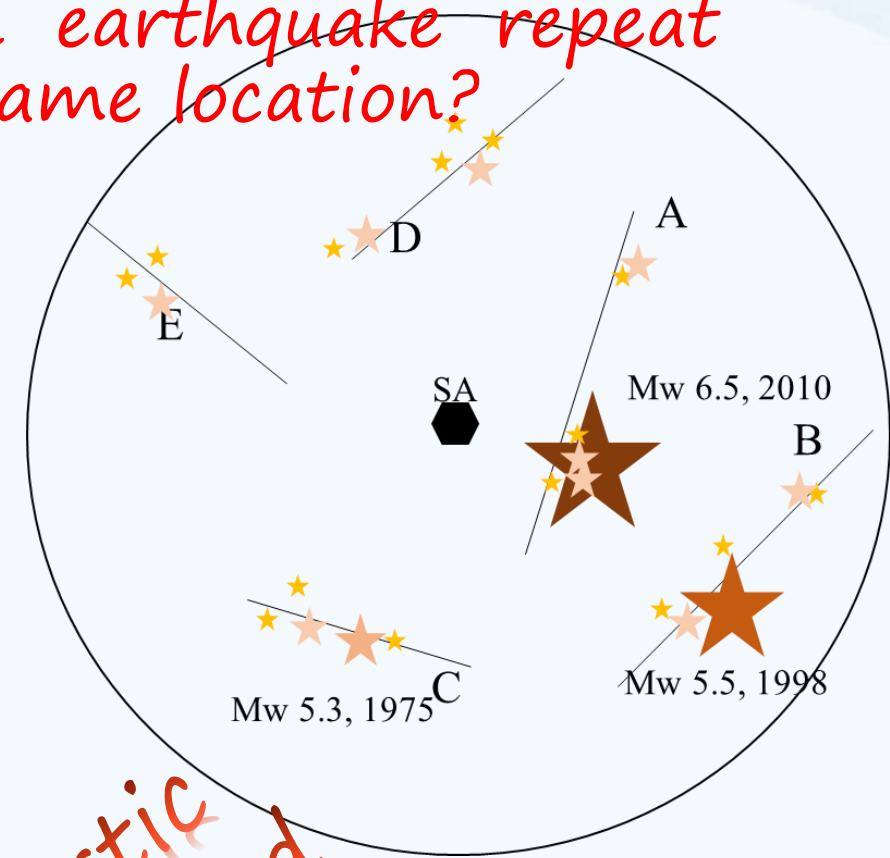
- Identification of probable potential future earthquake source locations in SSA by taking account of damaging earthquakes and strain released.

Regional Approach



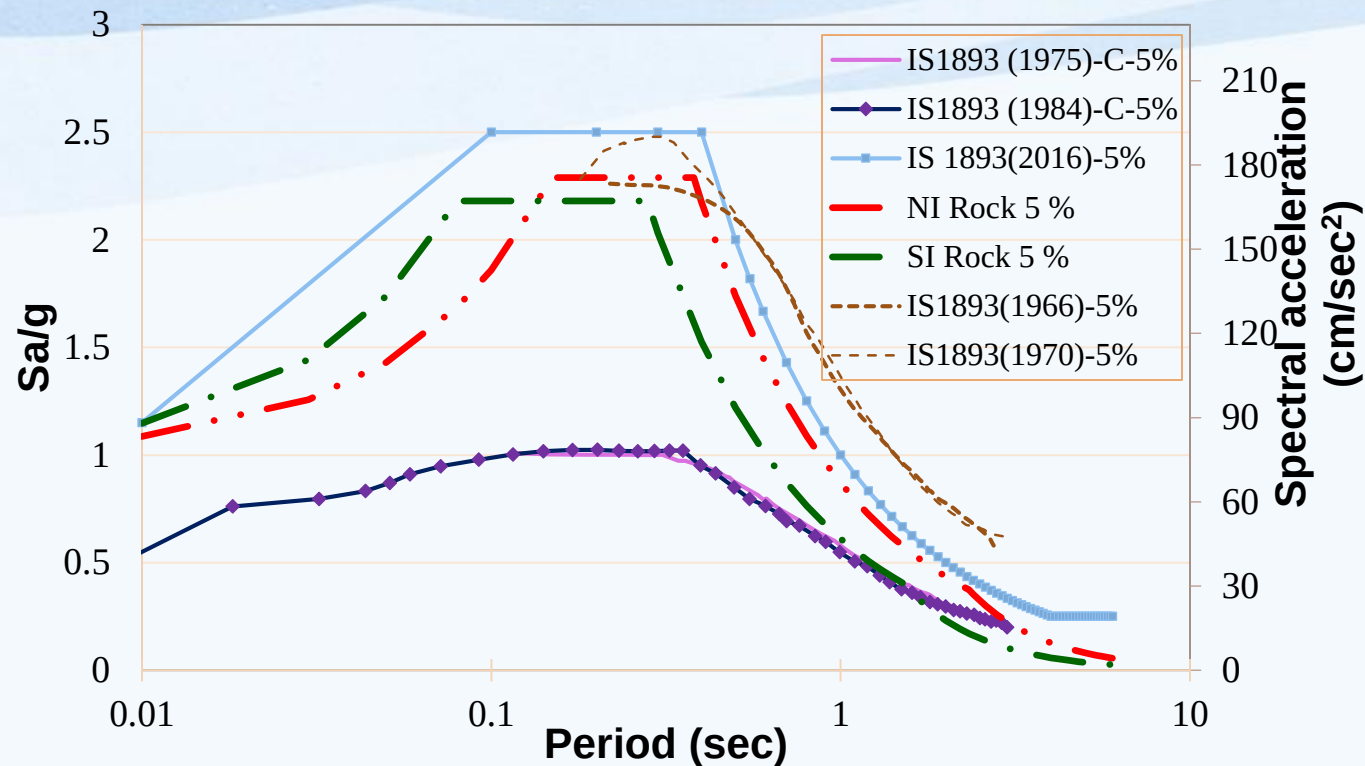
Conventional

- Can an earthquake repeat in the same location?



Elastic Rebound theory

Region Specific Design spectrum



Comparison of New design spectra with existing BIS:1893 Spectra at Bedrock

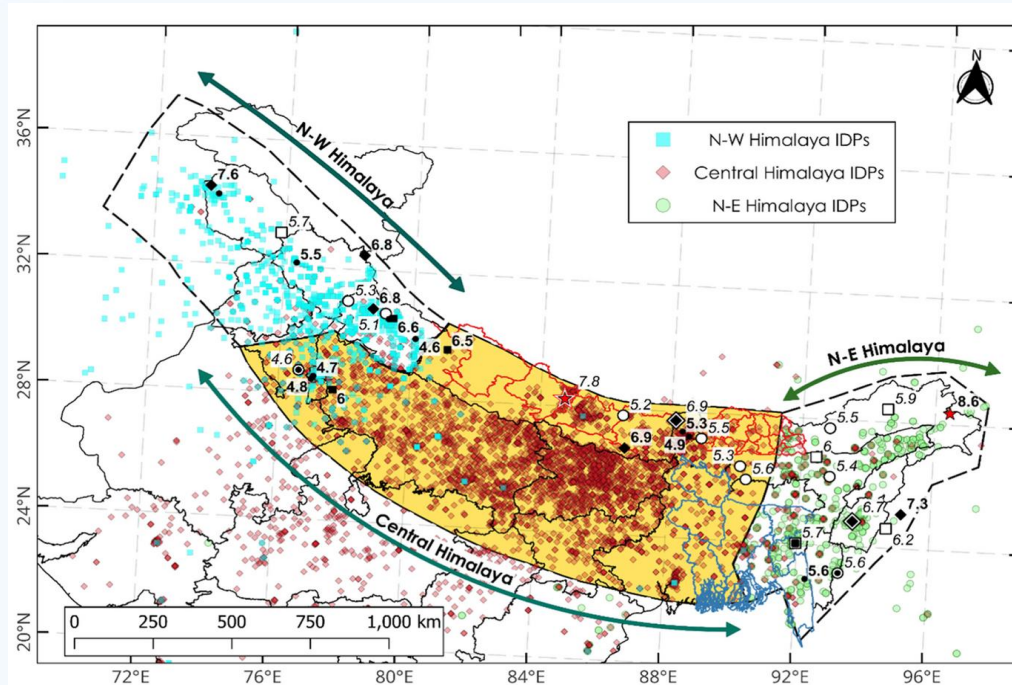
- ❖ IS1893 initial version of code was taken from the design spectrum arrived based on western recorded earthquake data & repeatedly reused in all revisions of IS1893 without developing a new spectrum based on Indian recorded data
- ❖ IS code design spectrum closely matched with Euro code rather than Indian data derived design spectrum

Parameters	North India (Interplate)	South India (Intraplate)
T_B	0.15	0.08
T_C	0.38	0.28
T_D / T_Y	2.33	1.52
S	1.00	1.00
β	2.29	2.18

- ✓ These parameters were also different from South and North India due to variations in seismotectonic characters.
- ✓ Presently followed seismic zonation map & design spectrum given in IS1893 (2016) are not from the regional studies and need regional-based hazard and design spectrum for different parts of India

Intensity and Duration Prediction models for India

- ❖ First robust Intensity Prediction Equations (IPEs) for the Himalayas and its sub-regions were developed using data of traditional surveys and online sources) separately for assessing the risk potential of future earthquakes.

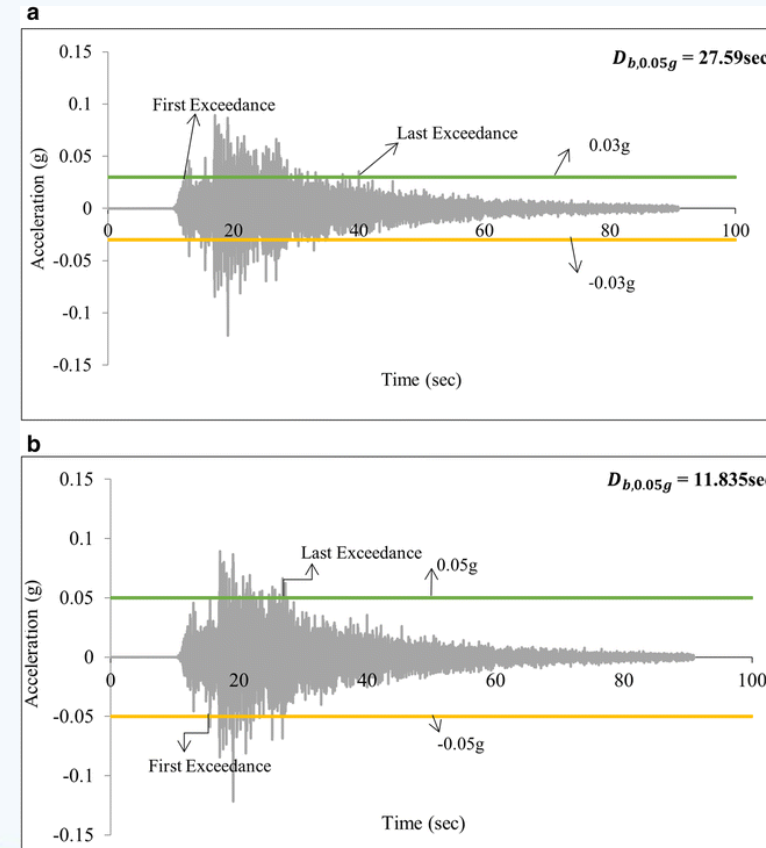


Himalayan earthquake event epicentre
locations with their respective occurrence
year from **TRAD** (in bold) and **DYFI** (in italics)
datasets

Anbazhagan P and Harish T (2025) "Next-Generation Earthquake Intensity and Magnitude Prediction Equations for Himalayan Region" ISET Journal of Earthquake Technology, Paper No. 597, Vol. 62, No. 2, June 2025, pp. 113-127. DoI: <https://doi.org/10.63898/EWMG7978>

Anbazhagan P, and H Thakur(2024)"Intensity Prediction Equations for Himalaya and its sub-regions based on data from traditional sources and USGS's Did You Feel It? (DYFI)" Journal of Seismology, 28:707-734.DoI: <https://doi.org/10.1007/s10950-024-10214-7>

Anbazhagan P and Kunal Motwani (2023)"Ground motion duration predictive models applicable for the Himalayan region" Journal of Earth System Science, 132:112, DoI:<https://doi.org/10.1007/s12040-023-02120-2>
Anbazhagan P. M. et.al (2017). "Empirical models for the prediction of ground motion duration for intraplate earthquakes", Journal of Seismology DOI:10.1007/s10950-017-9648-2 Vol.21 (4), 1001-1021.

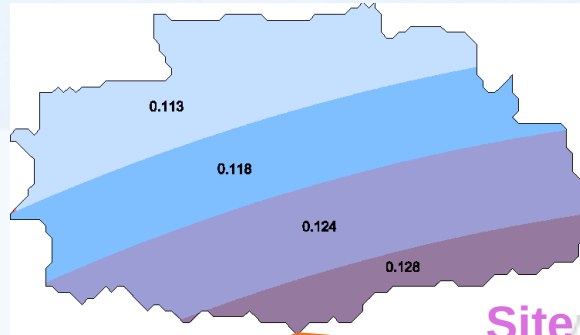


- ✓ First Duration Prediction model for Stable Region with data from Indian recorded earthquake data.
- ❖ Pioneer research on duration predictive model development using Indian recorded data

Seismic Geohazards studies

Rock PGA

SHA

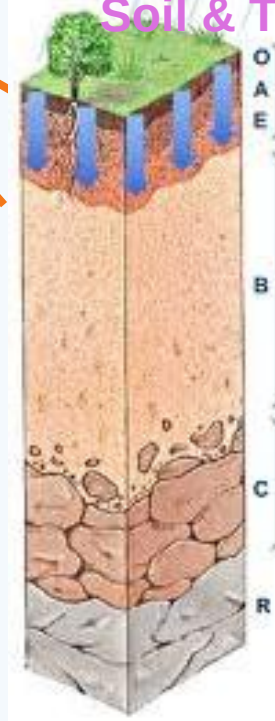


- Bedrock Level Design Spectrum
- Zonation Maps at bedrock Level

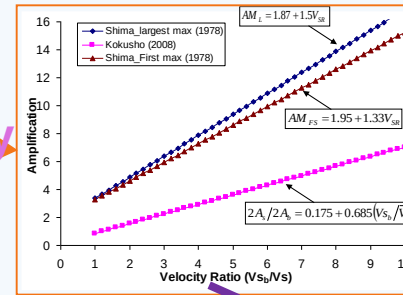
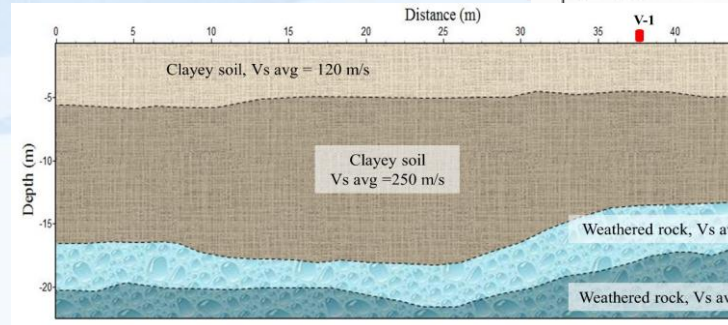
Site Characterization

- ❖ Applicability & Validation of method & Model
- ❖ Soil stiffness (V_s & γ)
- ❖ Thickness
- ❖ Comparison, Correlation & Relation
- ❖ Soil behaviour dynamic model

Site Effects Soil & Topography



Induced effects



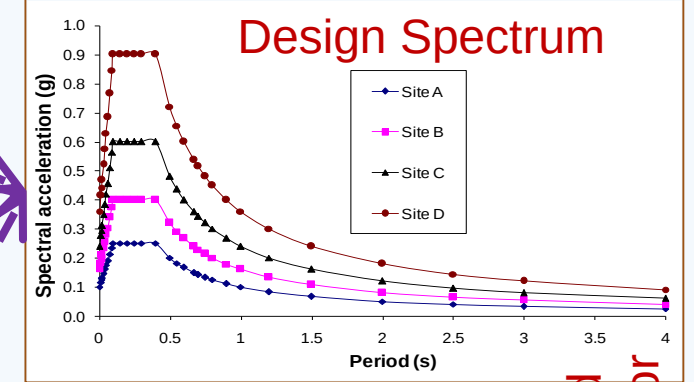
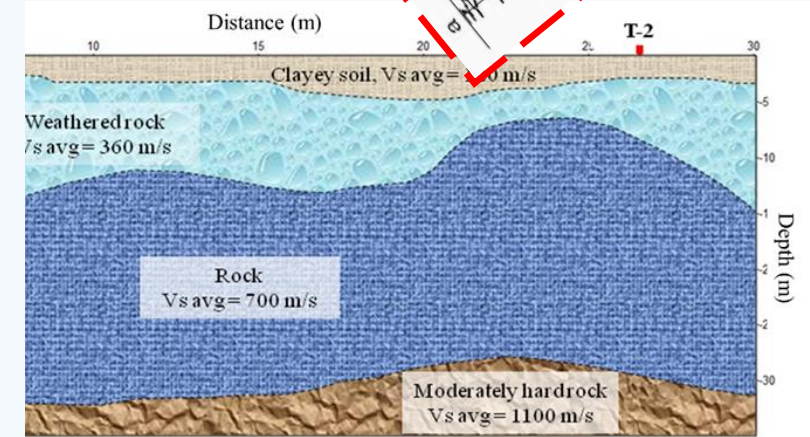
Amplification factor



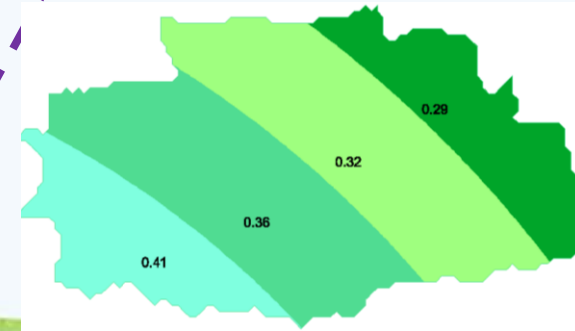
Liquefaction



Landslide

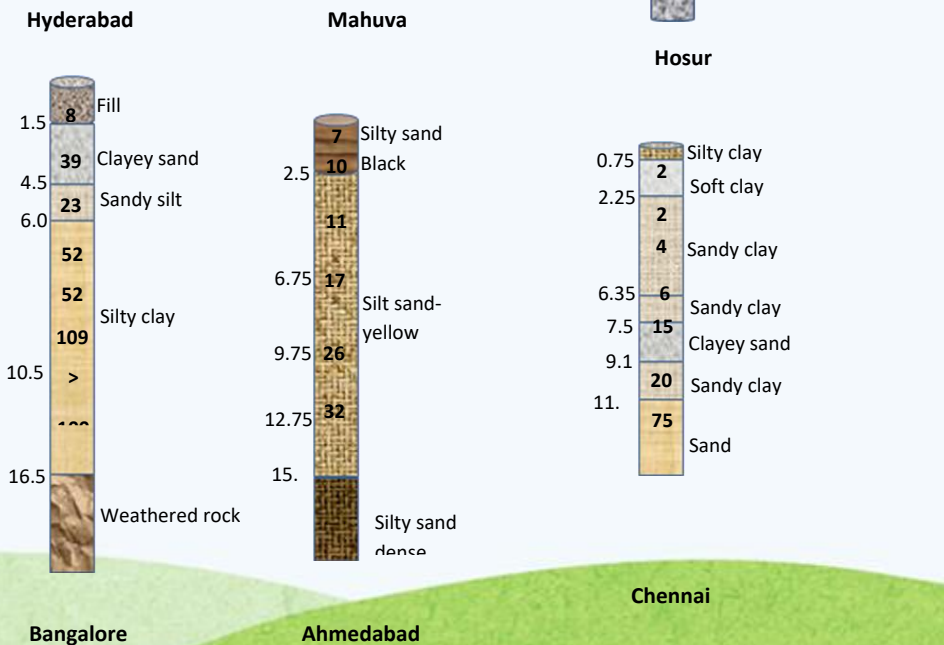
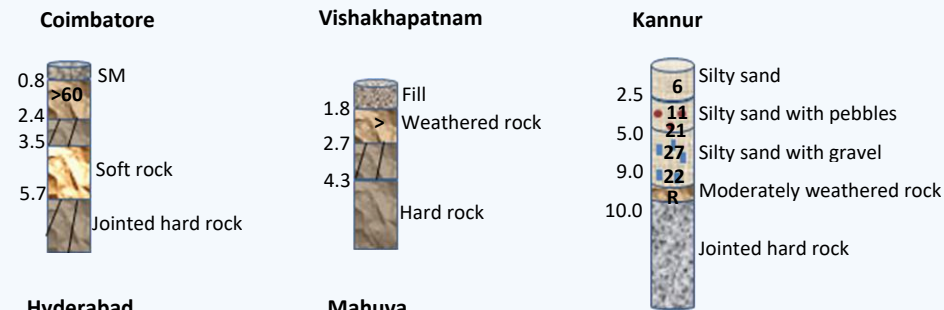
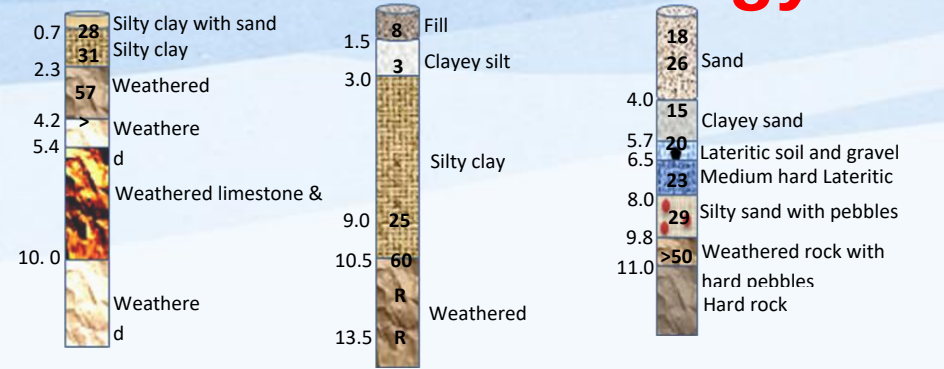


Design Spectrum

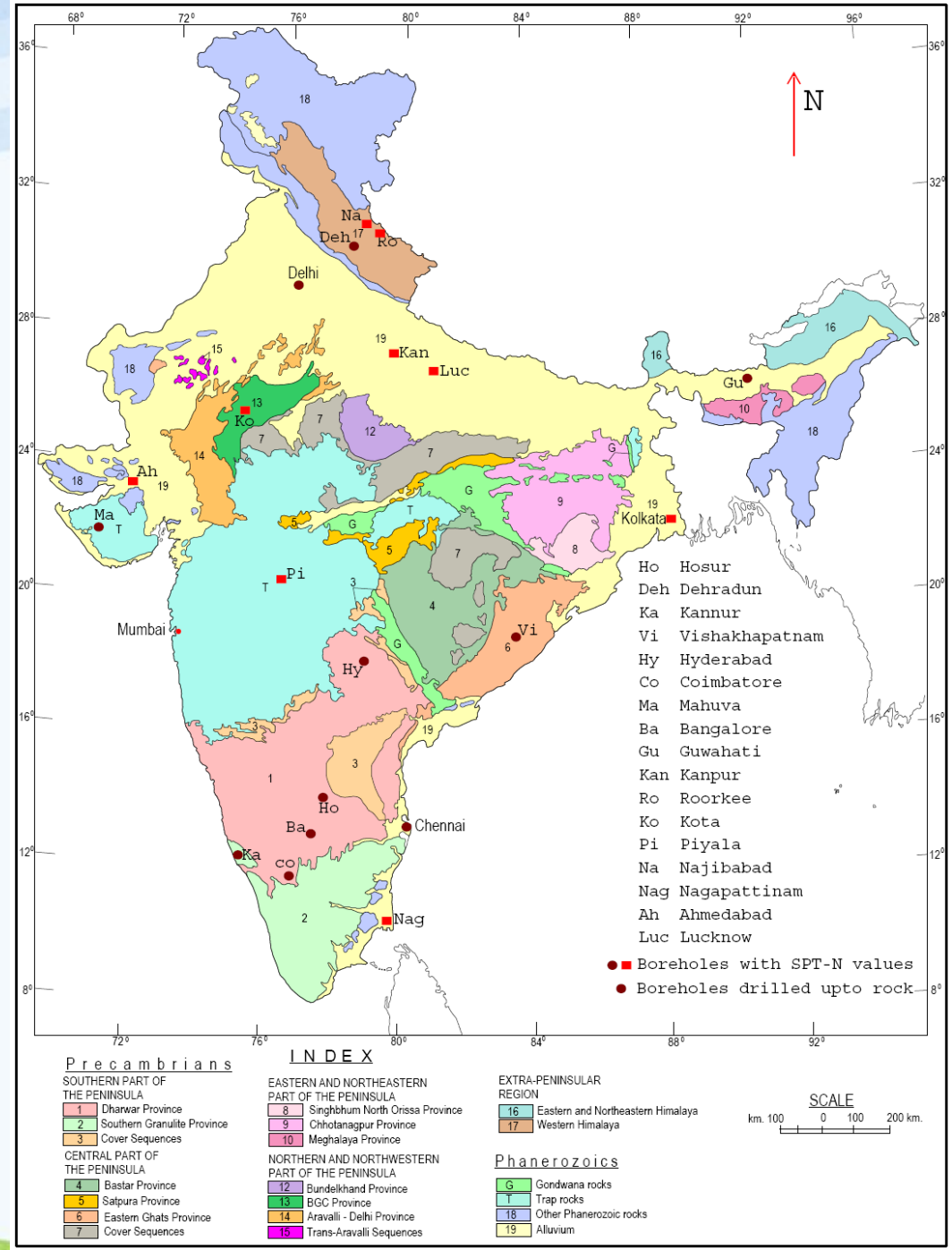


Zonation for/to
Surface Hazard
or Liquefaction or
Landslide

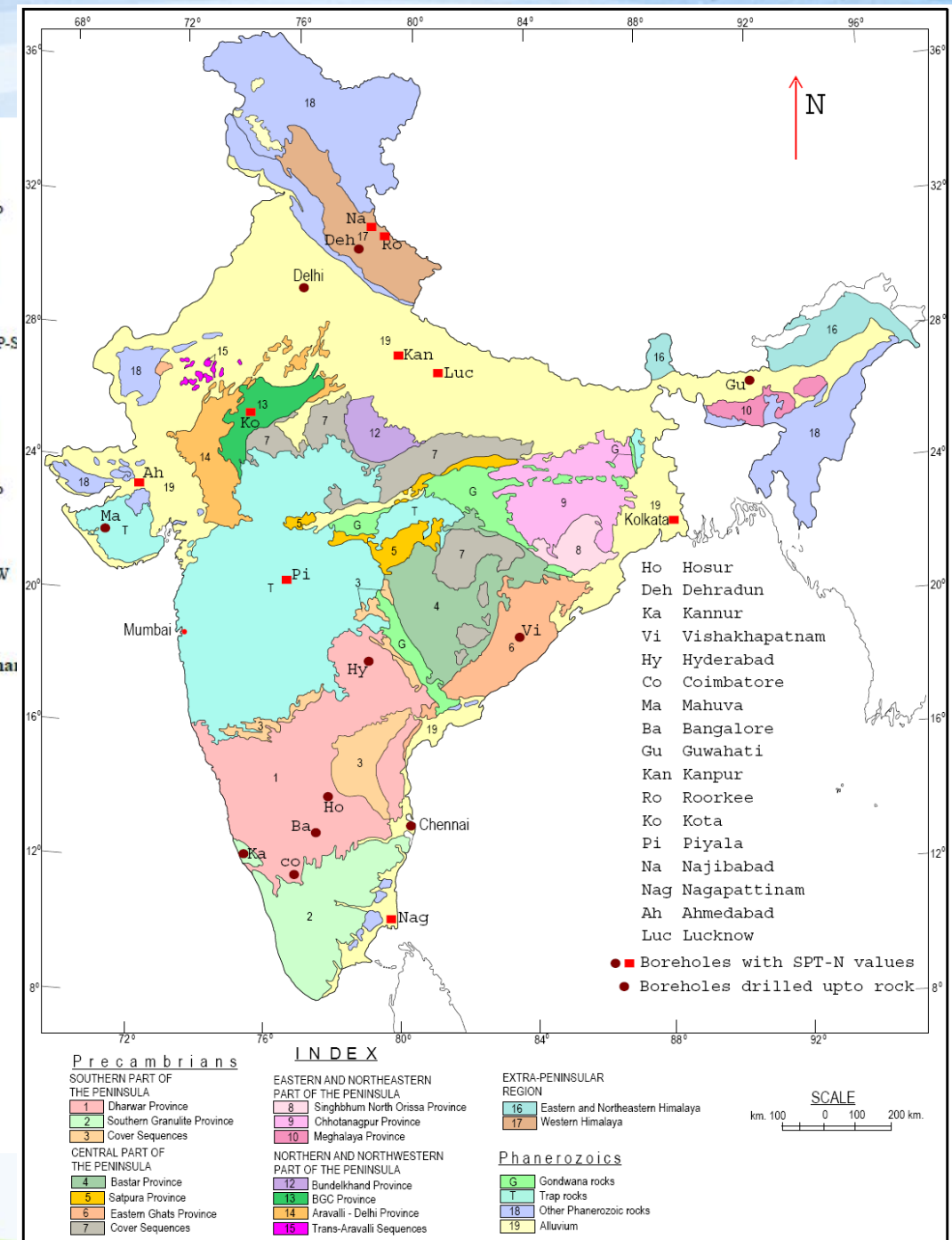
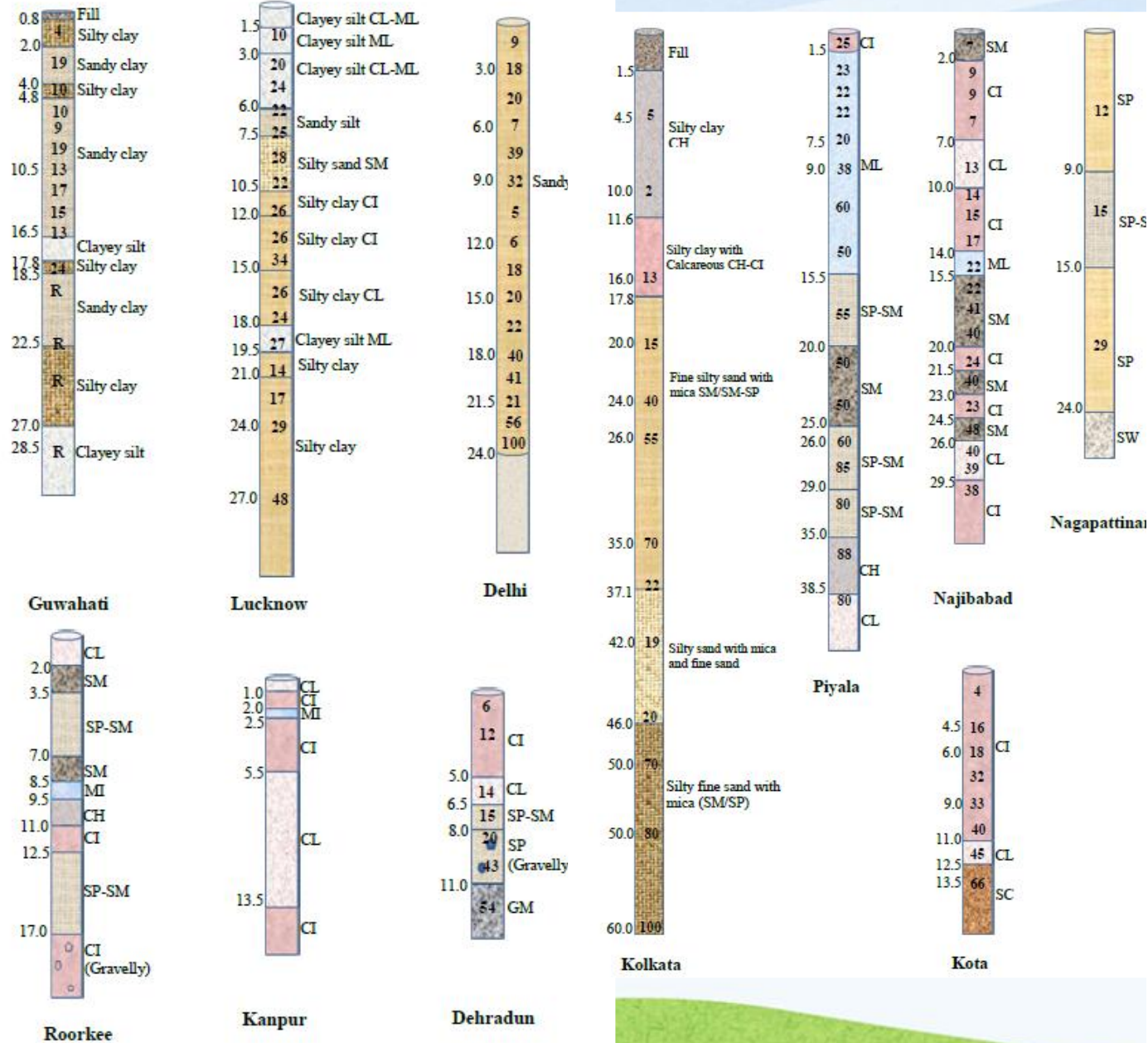
Indian Soil and Geology -South



"Provisions for Geotechnical Aspects and Soil Classification in Indian Seismic Design Code IS-1893", Disaster Advances, Vol. 7(3), 72-89.



Indian Soil and Geology -North

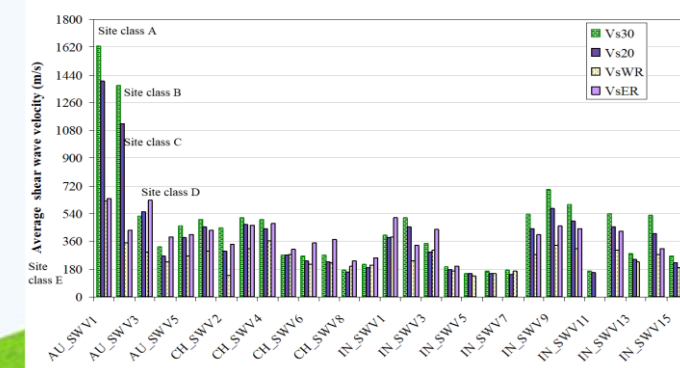
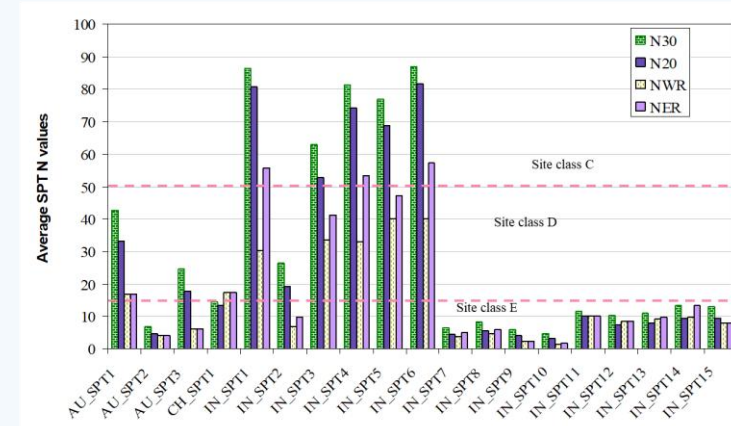
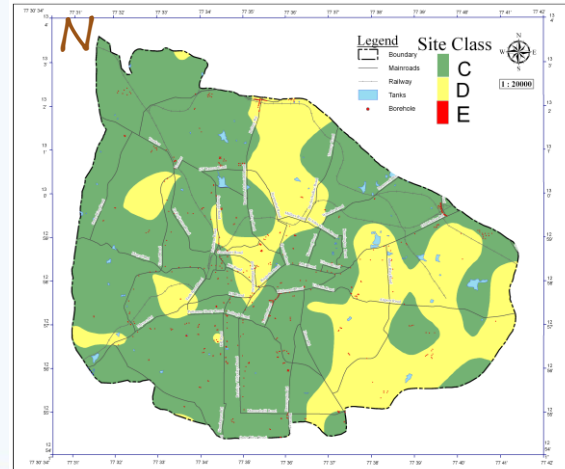
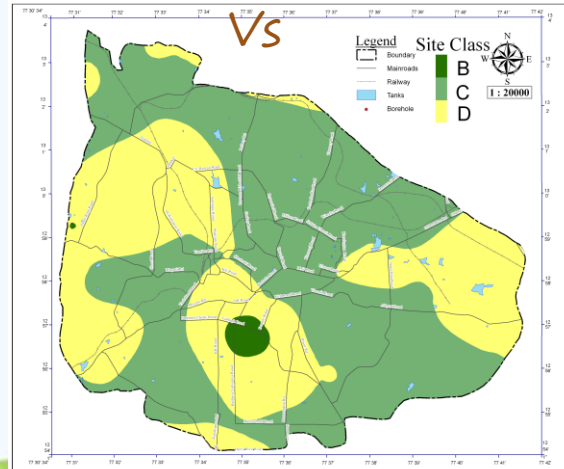
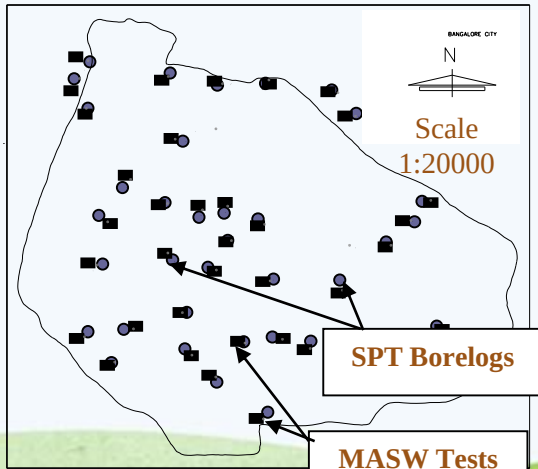
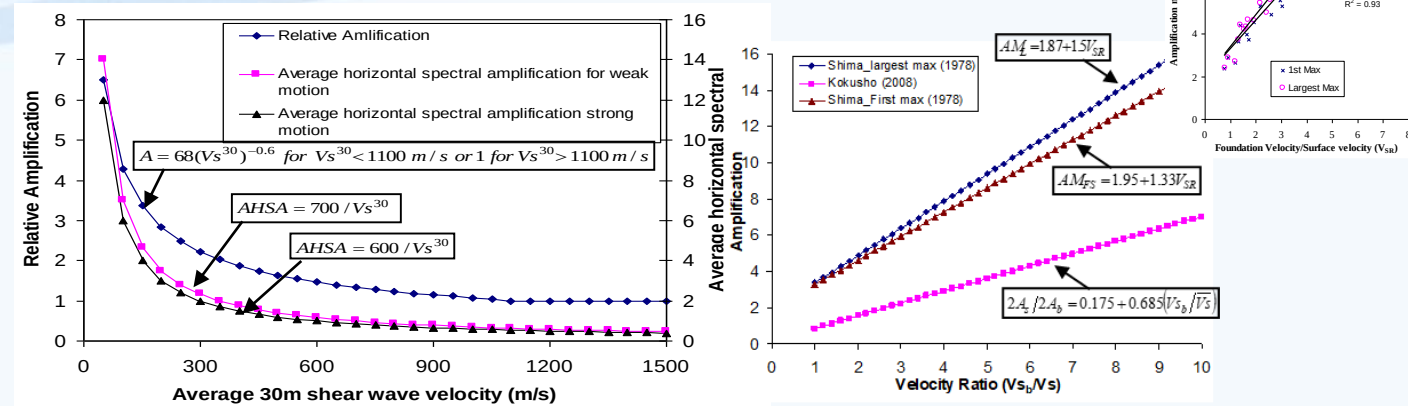


Seismic Site Classification

$$N_{30} \text{ or } V_{s30} = \frac{30 = \sum_{i=1}^n d_i}{\sum_{i=1}^n \left(\frac{d_i}{N_i \text{ or } V_{s_i}} \right)}$$

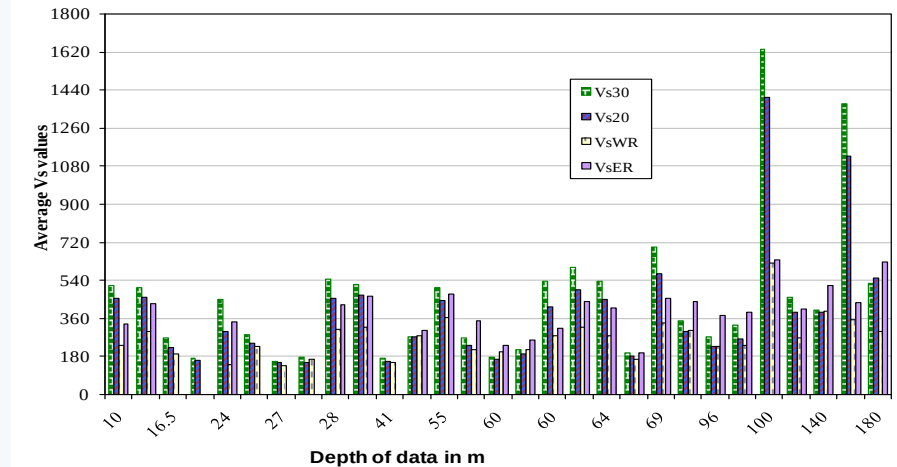
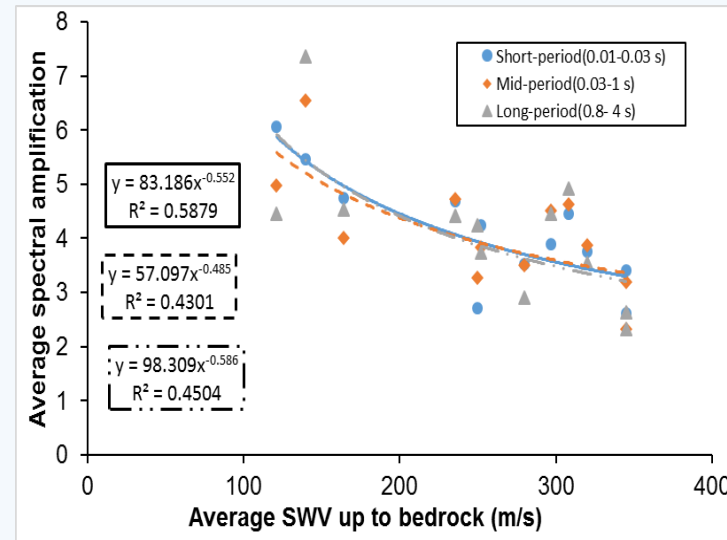
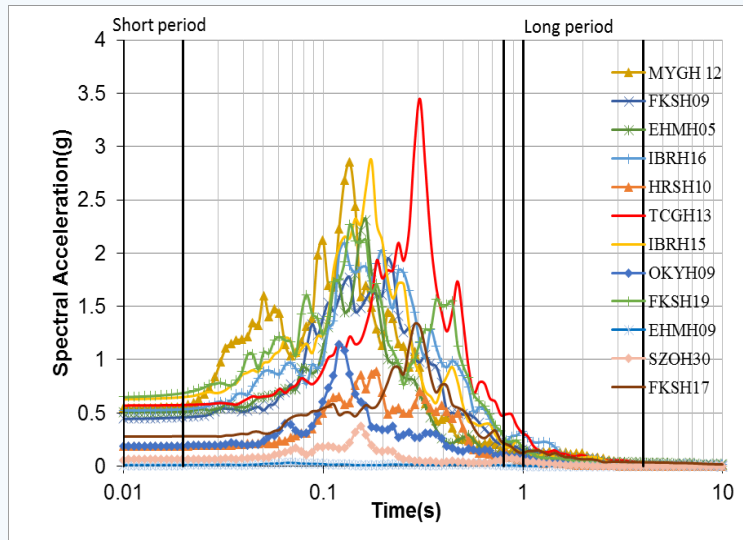
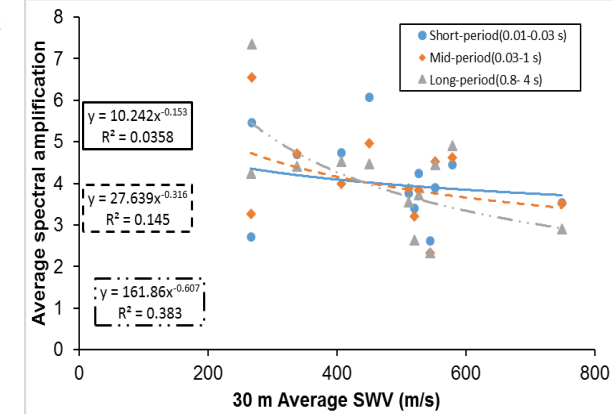
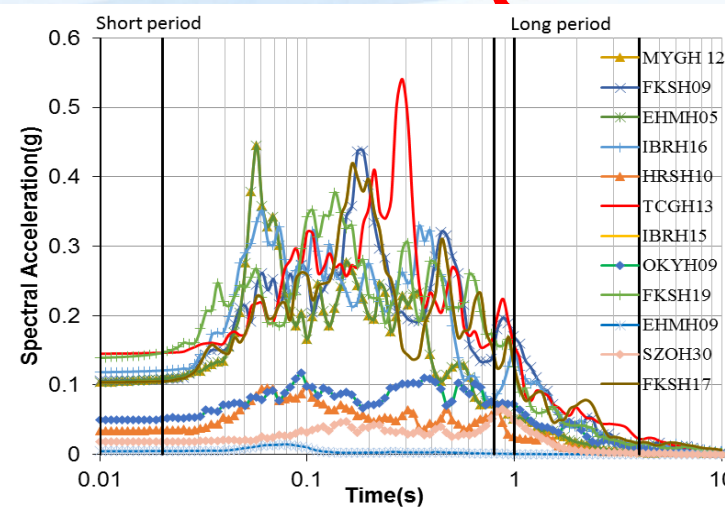
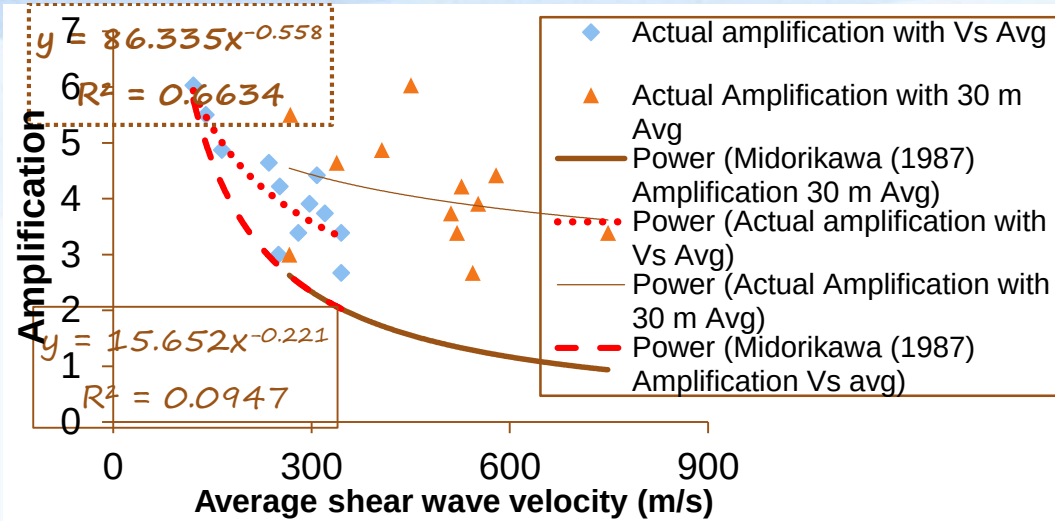
d_i and V_{s_i}/N_i denote the thickness (in meters) and corresponding shear wave velocity/standard penetration resistance (not to exceed 100 blows/0.3 m as directly measured in the field without corrections) of the i^{th} formation or layer, respectively, in a total of n layers in the top 30 m.

- ❖ SPT N values are directly or converted as Vs using JRA correlation was used
- ❖ Vs values are measured predominantly using MASW and no validation



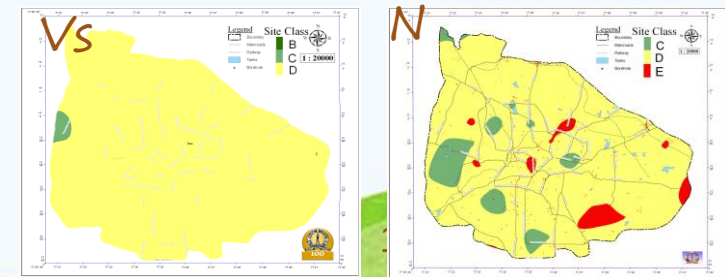
Site Classification based on 30 m

30 m Model works? – Recorded EQ data from Japan

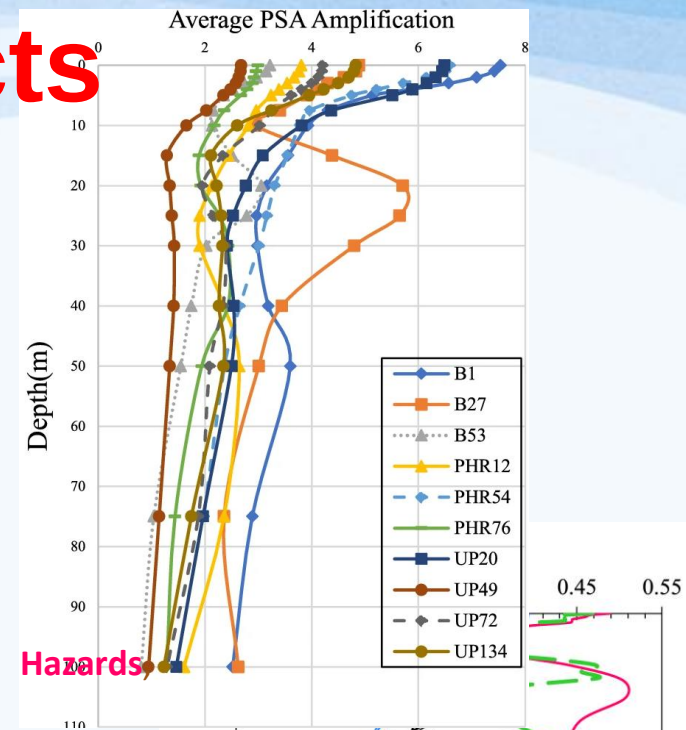
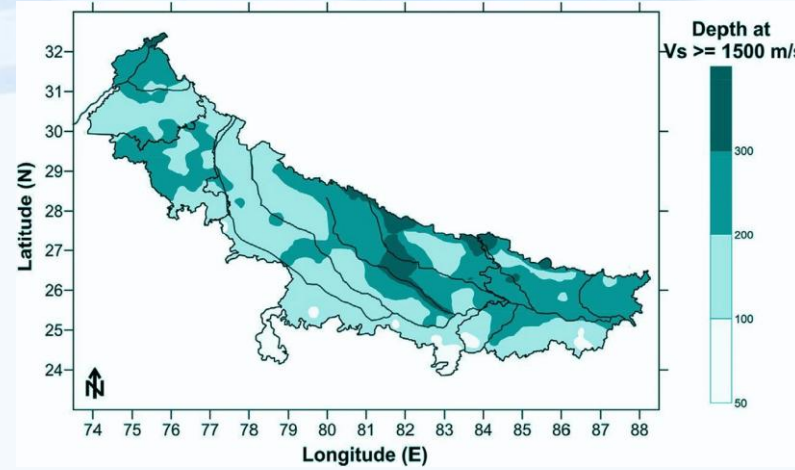
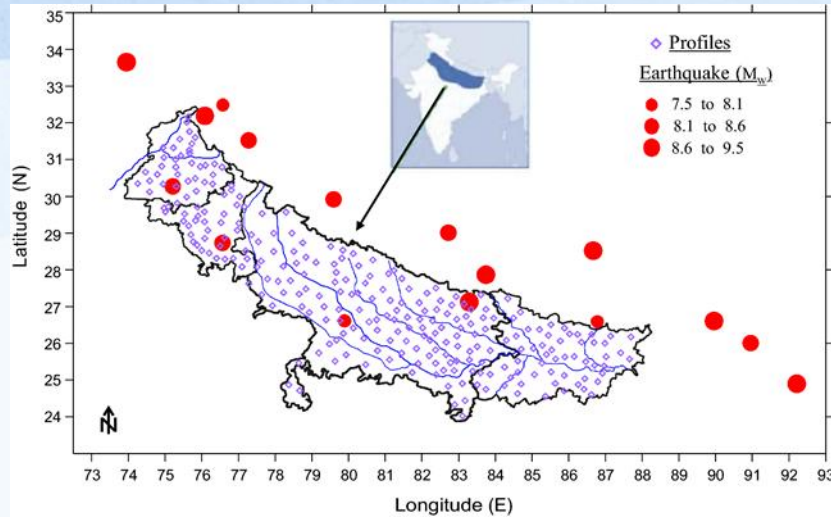


"Seismic Site Classification and Amplification of Shallow bedrock sites", Plos One, 13(12): e0208226. DOI: <https://doi.org/10.1371/journal.pone.0208226>.

Site Classification based on Soil Thickness

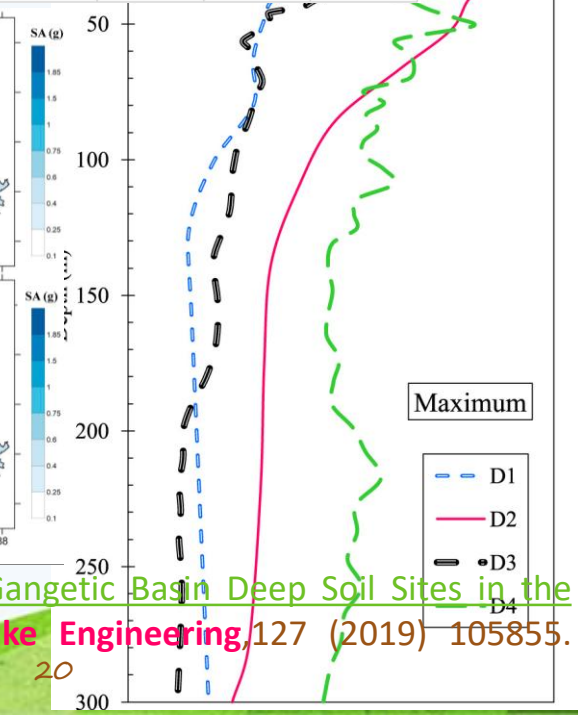
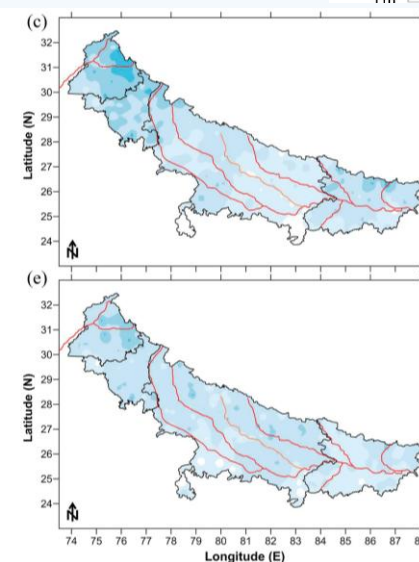
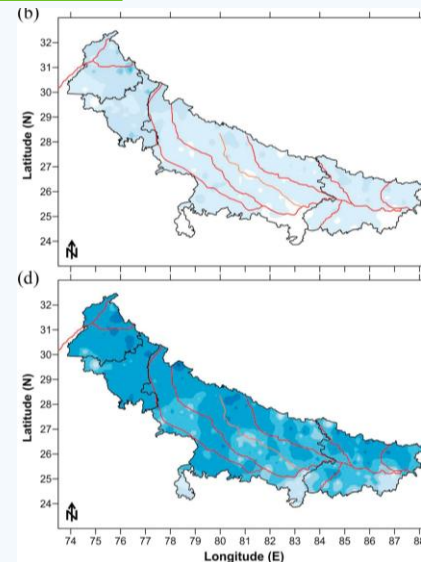
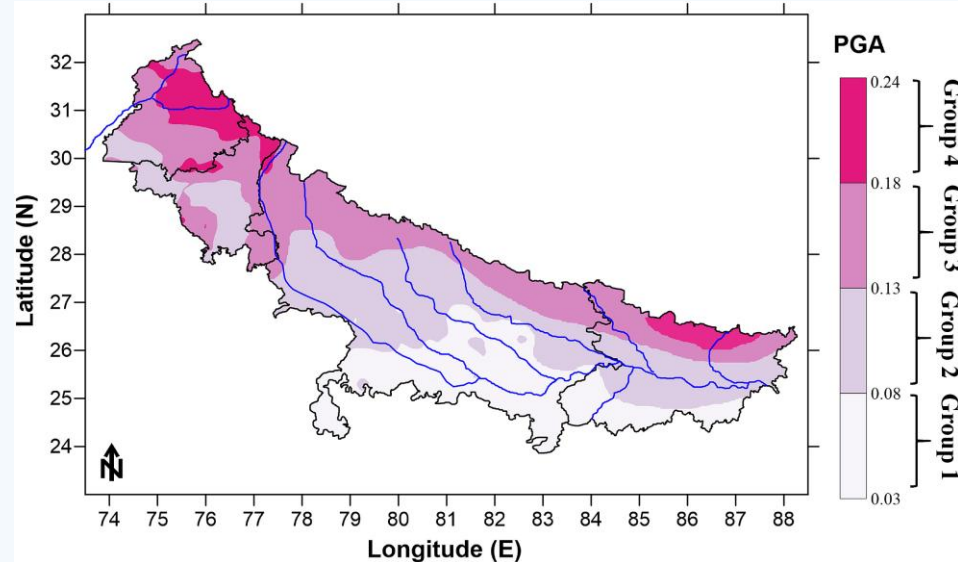


Future Seismic Hazards & Site Effects



Prediction of different depth amplifications of deep soil sites for potential scenario earthquakes" **Natural Hazards**

DOI:107:1935-1963.DOI: <https://doi.org/10.1007/s11069-021-04670-4>



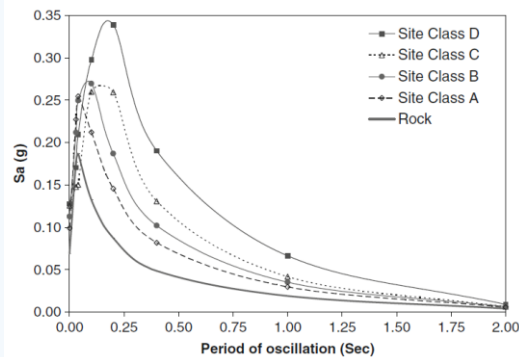
"Detailed seismic hazard, disaggregation and sensitivity analysis for Indo Gangetic basin" **Pure and Applied Geophysics**, DOI:<https://doi.org/10.1007/s00024-021-02762-7>

"Comprehensive Amplification Estimation of the Indo Gangetic Basin Deep Soil Sites in the Seismically Active Area" **Soil Dynamics and Earthquake Engineering**, 127 (2019) 105855. DOI:<https://doi.org/10.1016/j.soildyn.2019.105855>

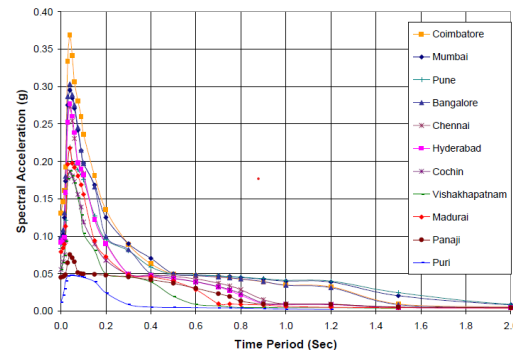
Development of Probabilistic Seismic Hazard Analysis Framework

Macro-Scale Regional Seismic Hazard Modeling

- **First Probabilistic Framework:** Established the first fully probabilistic hazard analysis (PSHA) framework for Peninsular India.
- **In-House Engine:** Developed custom computational models integrating complex source geometry, propagation paths, and GMPEs into probabilistic framework.
- **Spatial Seismicity Variability:** Quantified high-resolution spatial variability of completeness magnitudes and Gutenberg-Richter b-values.
- **Risk Engineering:** Generated uniform hazard response curves and Peak Ground Acceleration (PGA) values over varying return periods.



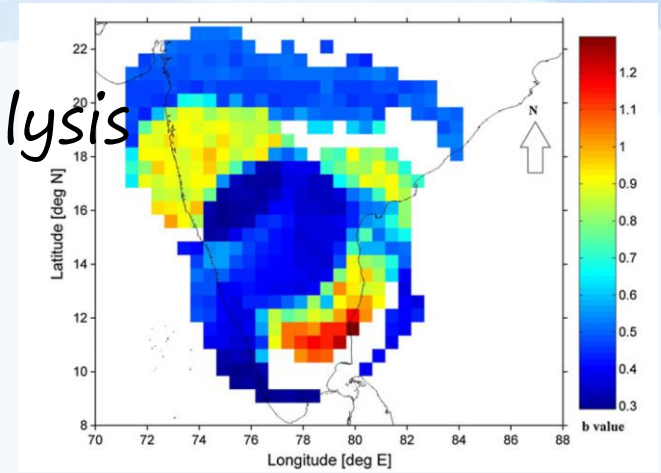
Response spectra for different site conditions



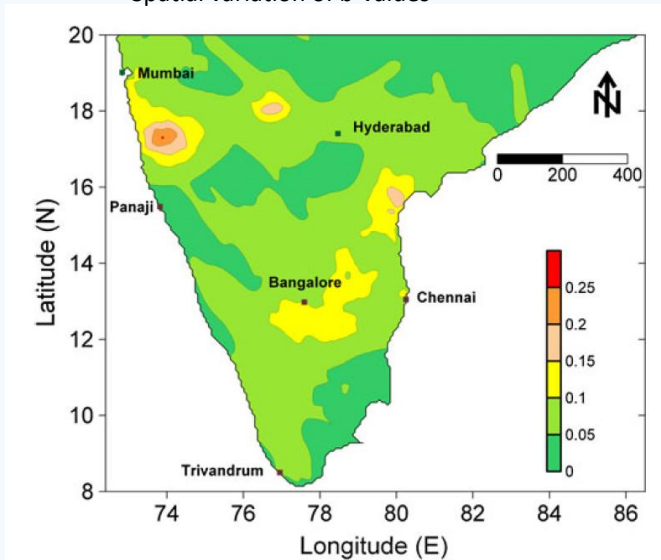
Response spectra for different cities

to national level studies.

Source:
Vipin et al. (2009),
Vipin and Sitharam (2011)



Spatial variation of b-values

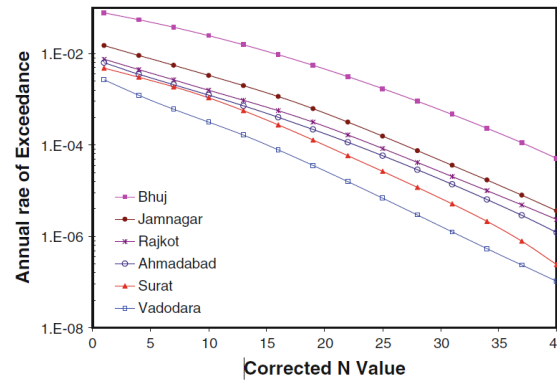


PGA values : 10% PE in 50 years

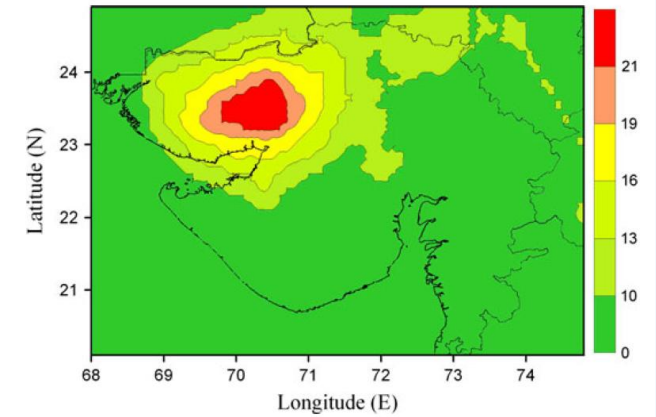
Outcome: Established a robust probabilistic foundation for seismic hazard assessment.

Modelling of Earthquake-Induced Ground and Infrastructure Response

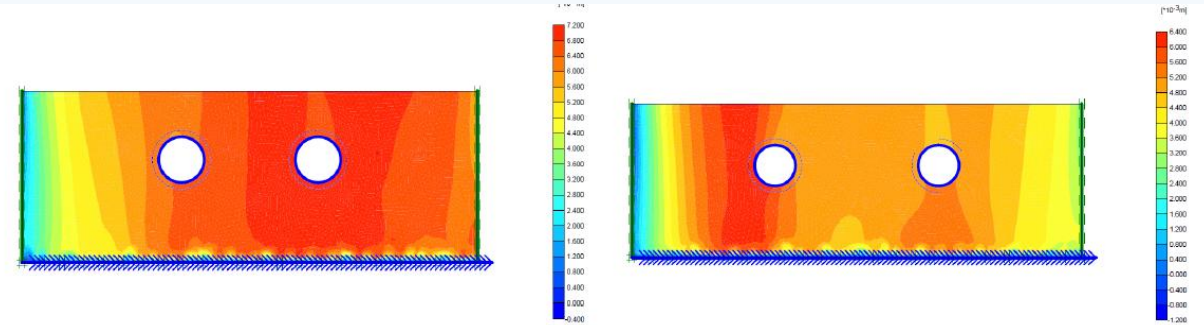
- **Probabilistic Triggering:** Built a novel methodology to evaluate liquefaction triggering parameters considering local soil profile and probability of an earthquake.
- **Site Variability Parameters:** Integrated ground motion uncertainty and geotechnical variability into continuous probability functions.
- **Regional Target Mapping:** Developed high-resolution probabilistic liquefaction potential models for seismically active regions in Gujarat.
- **Engineering Utility:** Designed probability of exceedance curves against corrected SPT N-values.
- **Seismic Response of Tunnels:** Evaluated the dynamic interaction of twin tunnels under seismic loading to identify optimum tunnel spacing and minimize settlement and vibration.



Liquefaction hazard curve



Corrected N values required to prevent liquefaction : 475 year return period



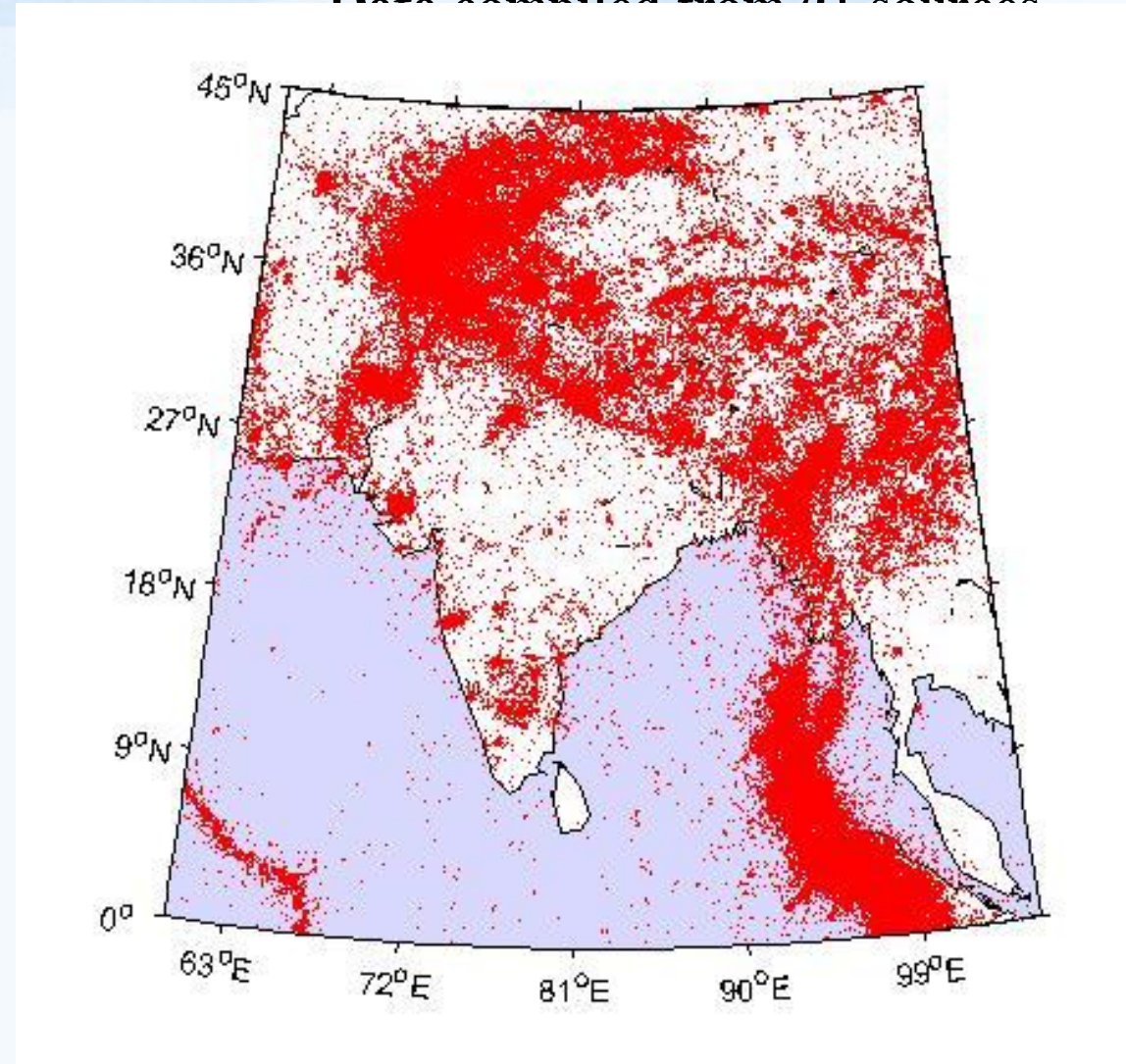
Seismic response of Twin tunnels

Selected Publications

- Vipin et al. (2009)
- Vipin et al. (2012)
- Vipin and Sitharam (2012)

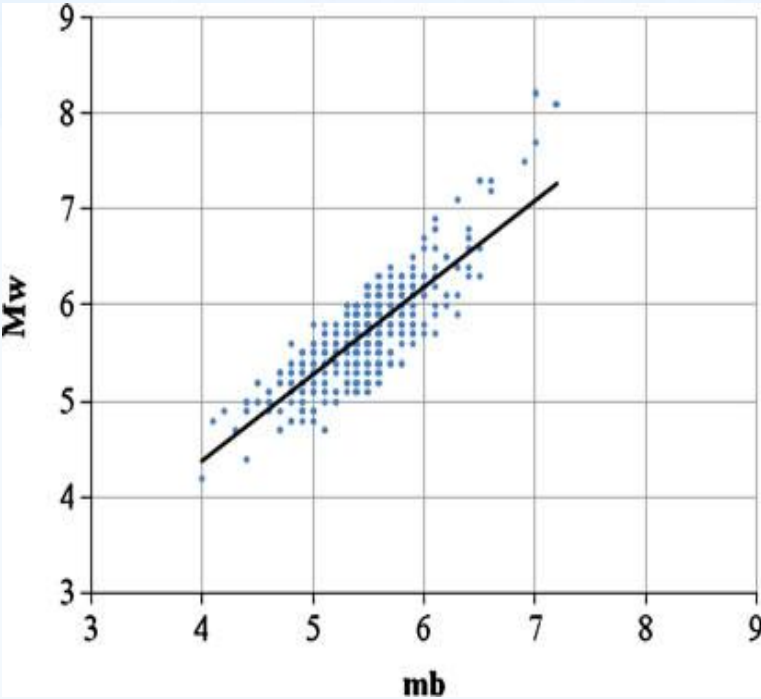
Spatial distribution of the epicenters of earthquake events for the period from 250BC to 2010AD

Data compiled from 21 sources



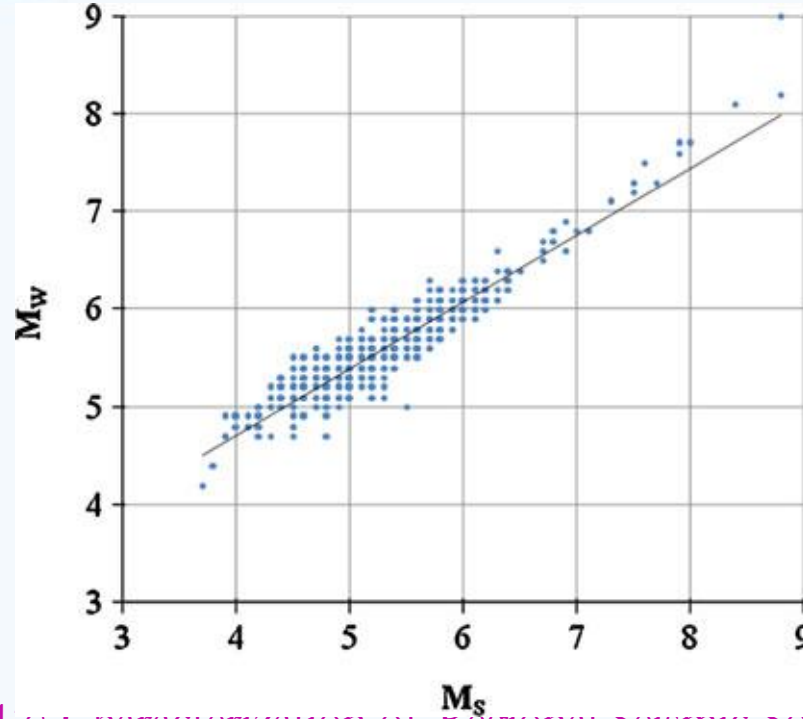
23 NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA
Kolathayar et al. (2012). Spatial variation of seismicity parameters across India and adjoining areas.
Natural Hazards (Springer) 60 (3), 1365-1379.

Region Specific Magnitude Conversion Relations



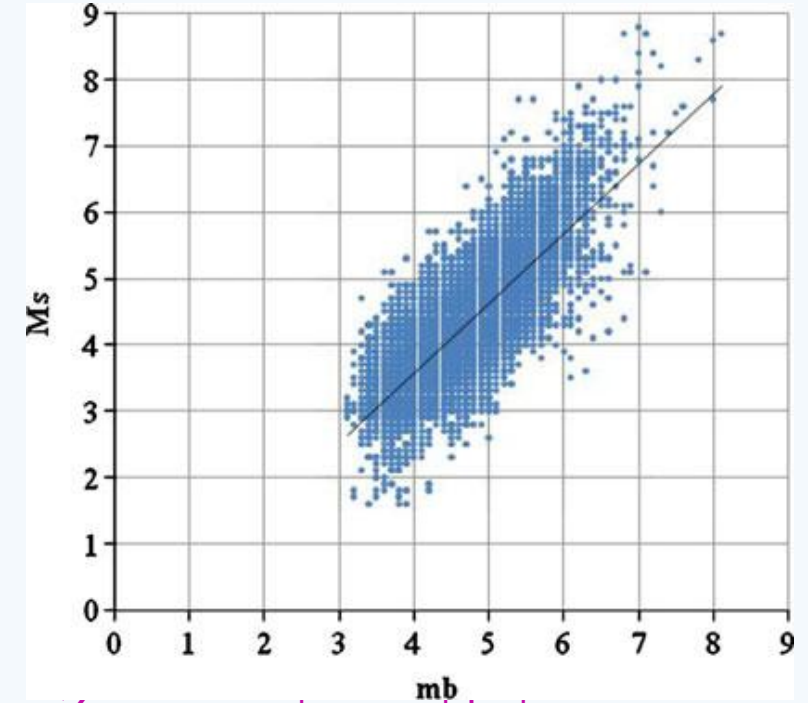
$$M_w = 1.08(\pm 0.0152)m_b - 0.325(\pm 0.081)$$

$R^2 = 0.732, n = 1,850$



$$M_w = 0.681(\pm 0.010)M_s + 1.993(\pm 0.053)$$

$R^2 = 0.893, n = 1,254$

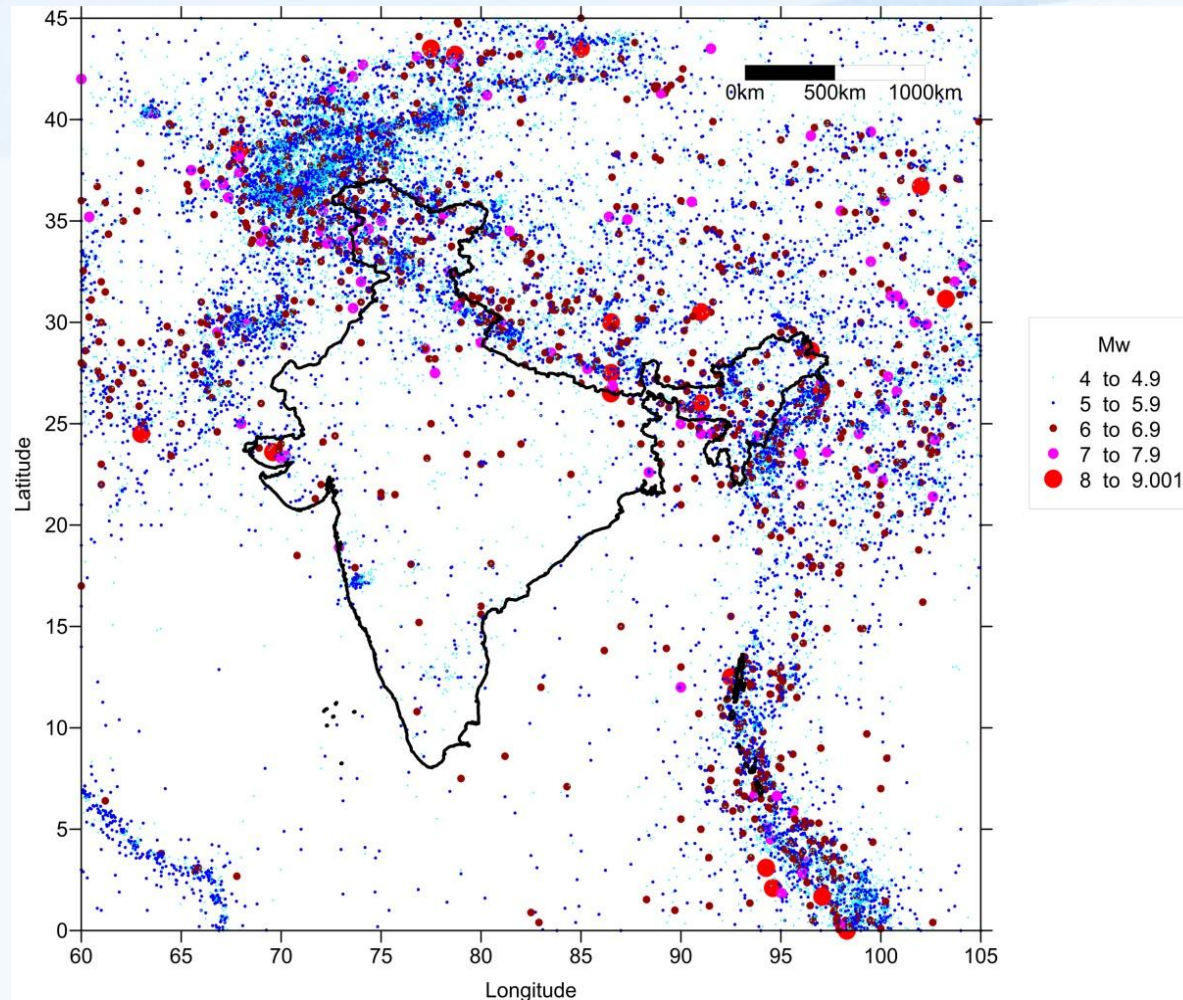


$$M_s = 1.057(\pm 0.006)m_b - 0.649(\pm 0.028)$$

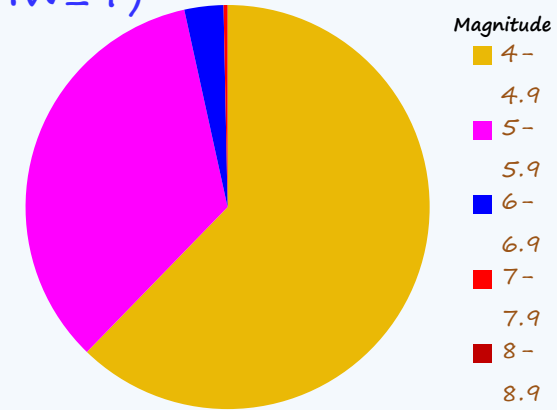
$R^2 = 0.659, n = 16,734$

Kolthavar S and Sitharam T.G (2014) Characterization of Regional seismic source Zones in and around India. *Seismological Research Letters* (Seismological Society of America) 85(1) 77-85.

Distribution of Earthquake events in and around India



Map generated with
27146 independent
Earthquake events
(M_w ≥ 4)



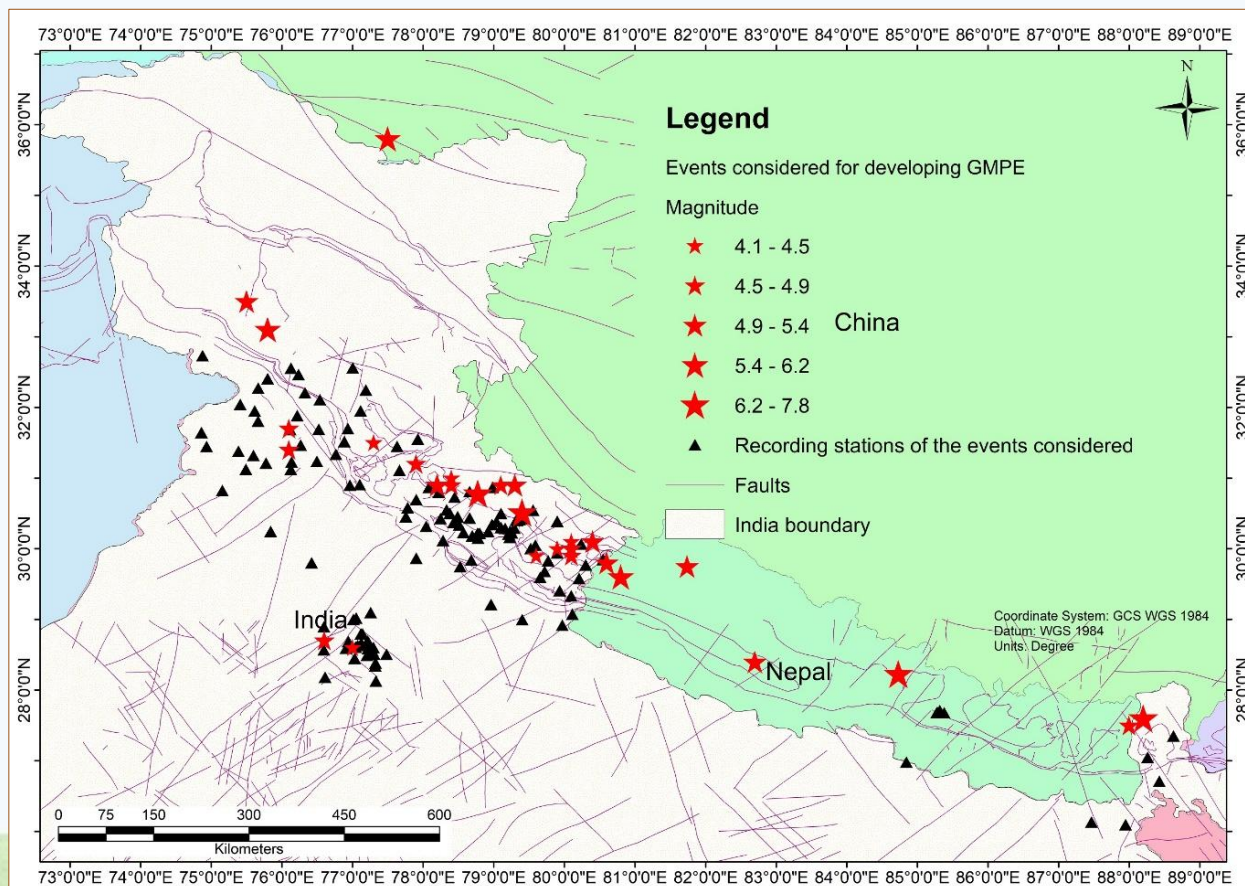
Magnitude (M _w)	No. of events
4 - 4.9	16079
5 - 5.9	9879
6 - 6.9	1036
7 - 7.9	129
8 - 9	22

Kolathayar S and Sridharan T G (2012) Characterization of Regional Seismic Source Zones in and around India. **Seismological Research Letters** (Seismological Society of America) 83(1) 77-85. (IF: 3.78)

Ground motion Attenuation

National Strong Motion Instrumentation Network of India

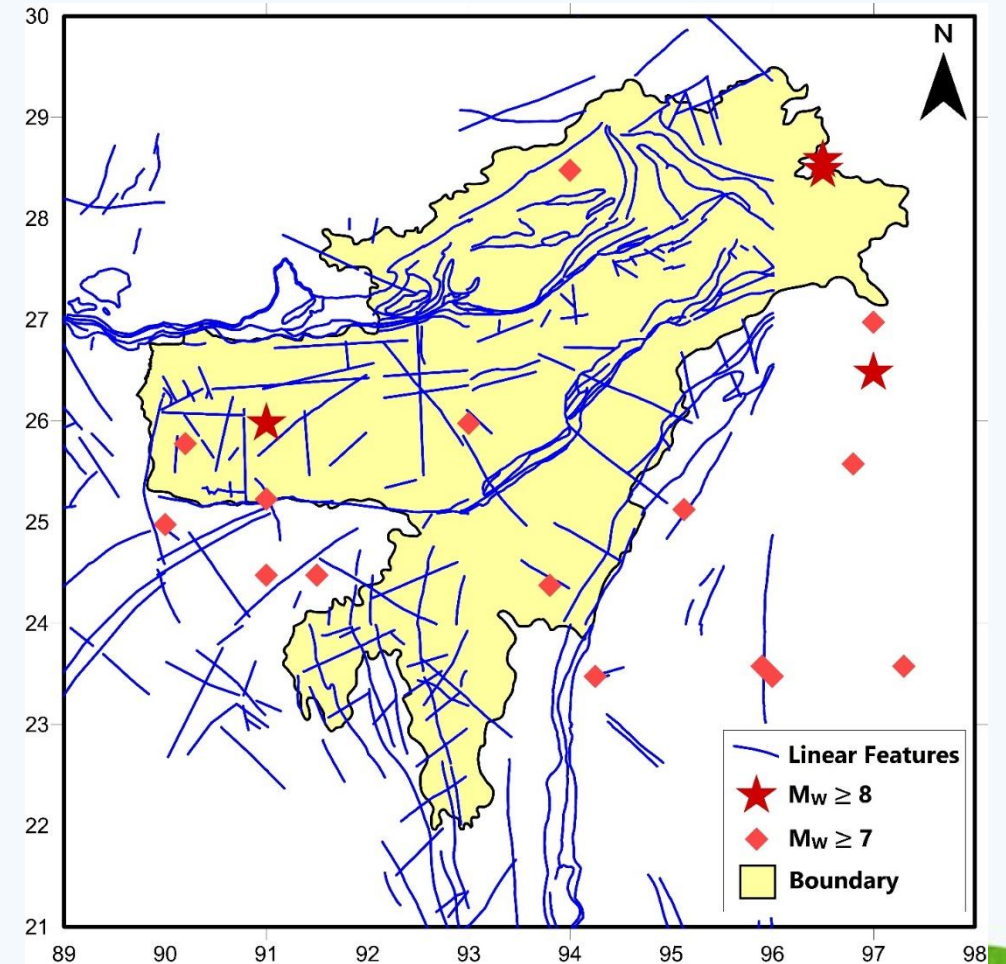
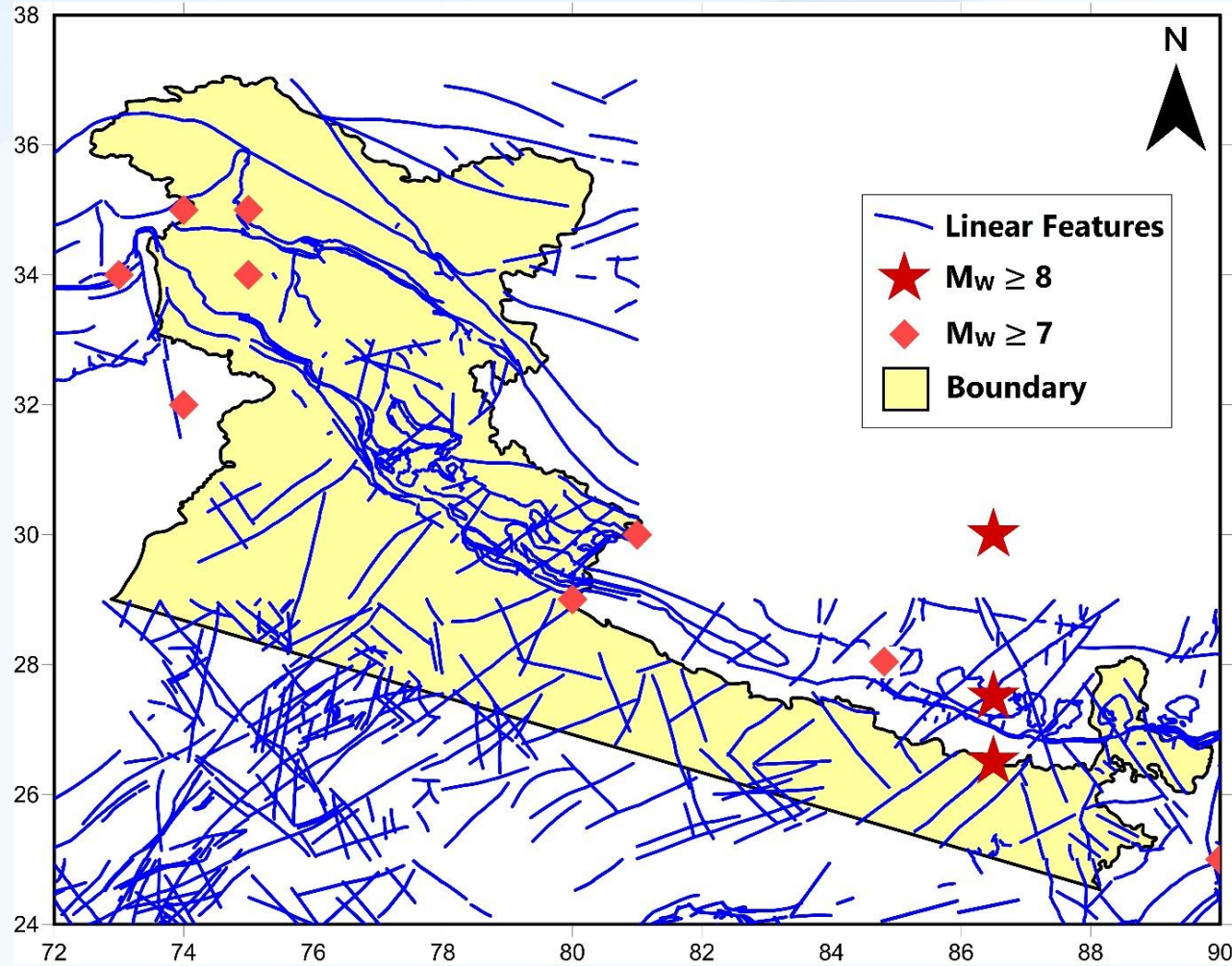
IIT Roorkee, between 1985 and 1991 deployed 135 analog strong motion accelerographs in the Himalayas forming three strong motion arrays: UP array, Kangra array and Shillong array. Later a total of 280 digital seismographs covering the Northern and Central Himalayas, NE Himalayas and the Delhi region.



- Seismotectonic map of the Himalayas showing seismic sources, recording stations and events considered

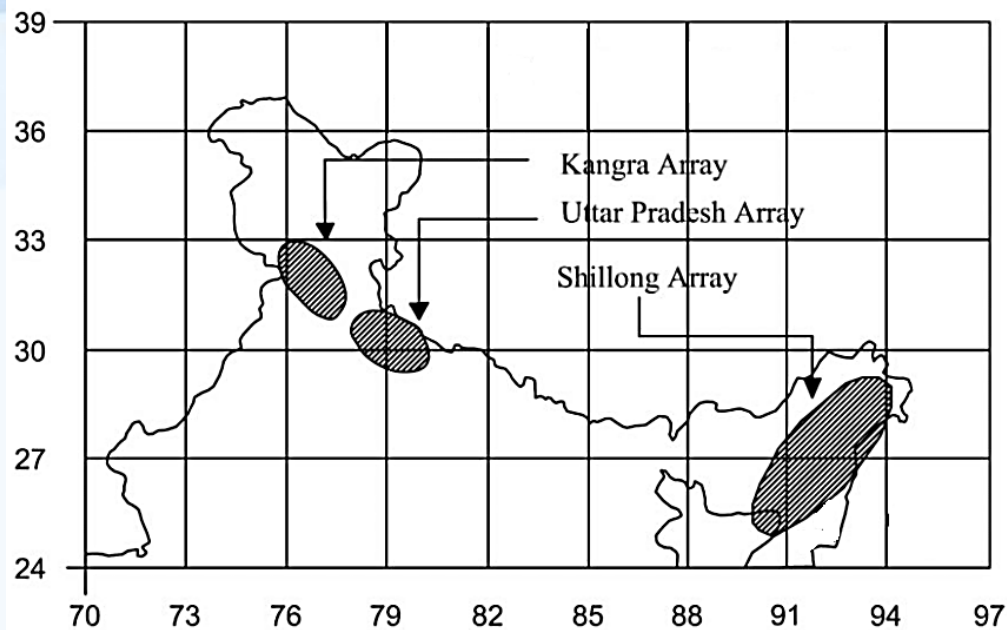
Data Sources: PESMOS, CESMD, COSMOS

Study Area



Study area of NCH and NEH showing identified faults and events above magnitude 7 in the region

of India



Map showing the strong motion arrays (Sharma, 2005)

IITR deployed 298 digital seismographs covering the Northern and Central Himalayas, North-East Himalayas and the Southern alluvial plains and the Delhi region (Kumar et al. 2012; Mittal et al. 2012).

Map showing the location of instruments along the Himalayan belt (Kumar et al., 2012)

INDIAN NATIONAL STRONG MOTION INSTRUMENTATION NETWORK

SPONSORED BY : MINISTRY OF EARTH SCIENCES



Development of GMPE for North Himalayas

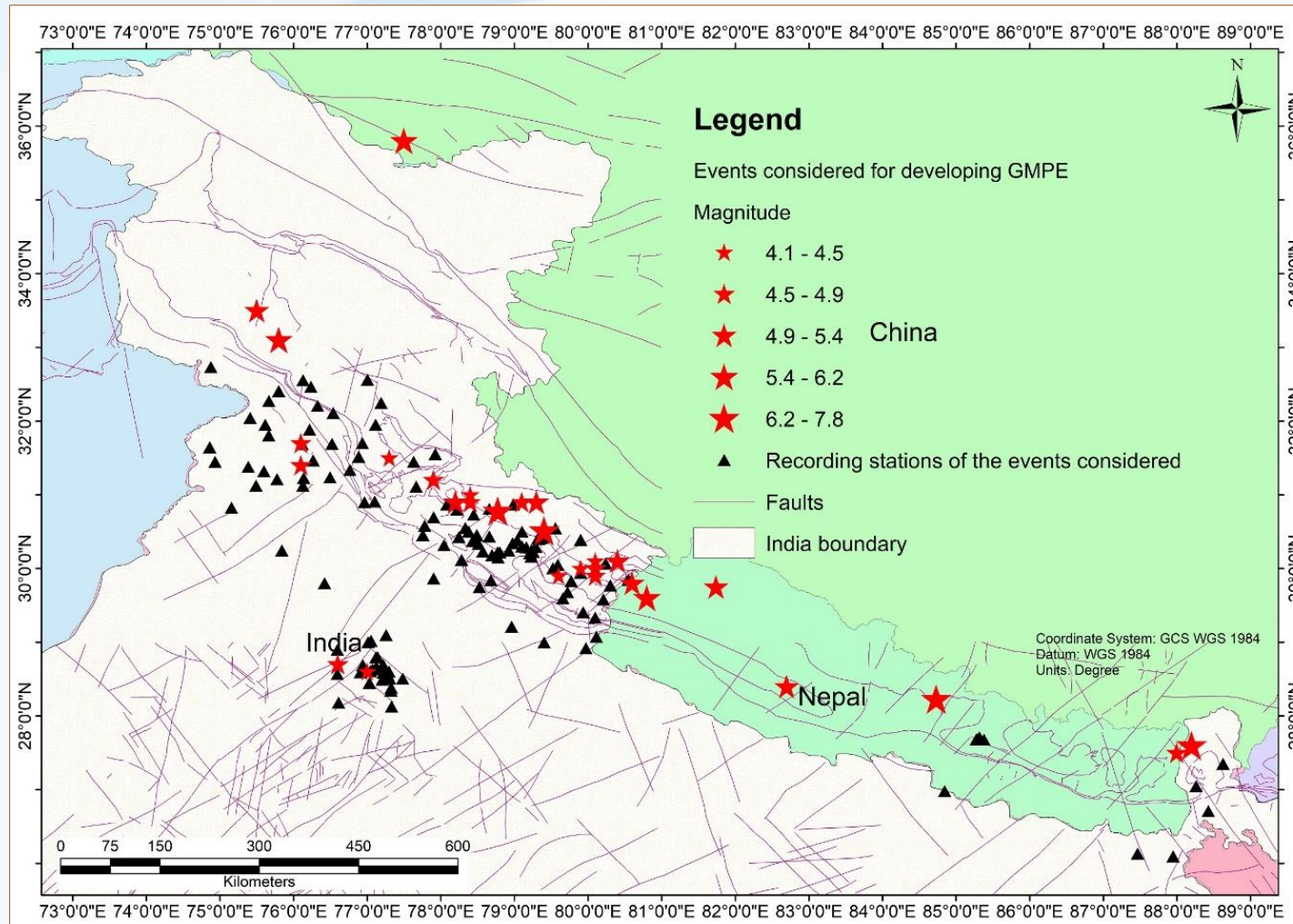
- General form of ground motion attenuation relations:

$$\log Y = f_1(M) + f_2(r, E) + f_3(r, M, E) + f_4(F) + \varepsilon$$

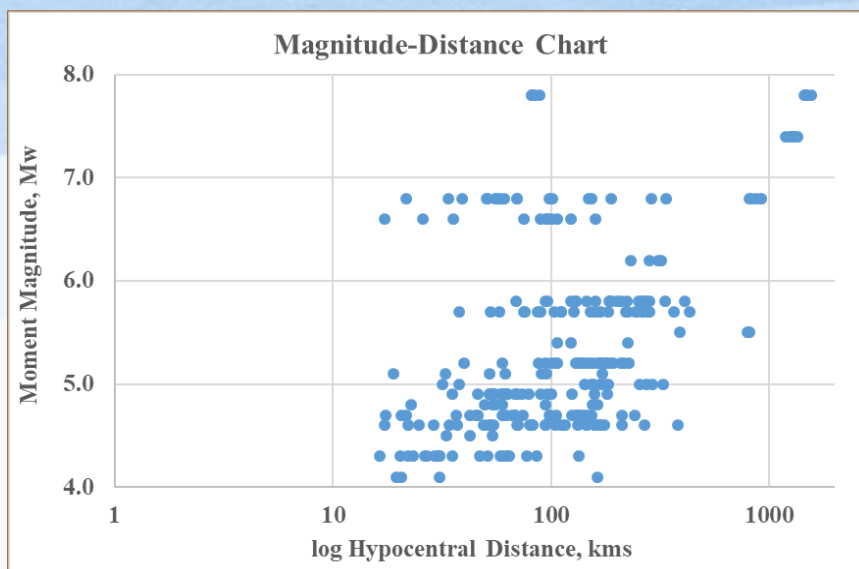
- The regression model preferred for the analysis here is the Campbell (1981) model that includes $f_1(M)$, $f_3(r, M, E)$, and $f_4(F)$, but excluding the tectonic term (Abrahamson and Litehiser, 1989).
- The non-linear regression model thus assumed for developing the attenuation relation is as follows (Sharma 1998, Anbazhagan 2013, Arjun Kumar 2017);

$$\log Y = c_1 + c_2 M - b \log (X + e^{c_3 M}) + \varepsilon$$

Seismotectonic map of NCH showing seismic sources, recording stations and events considered

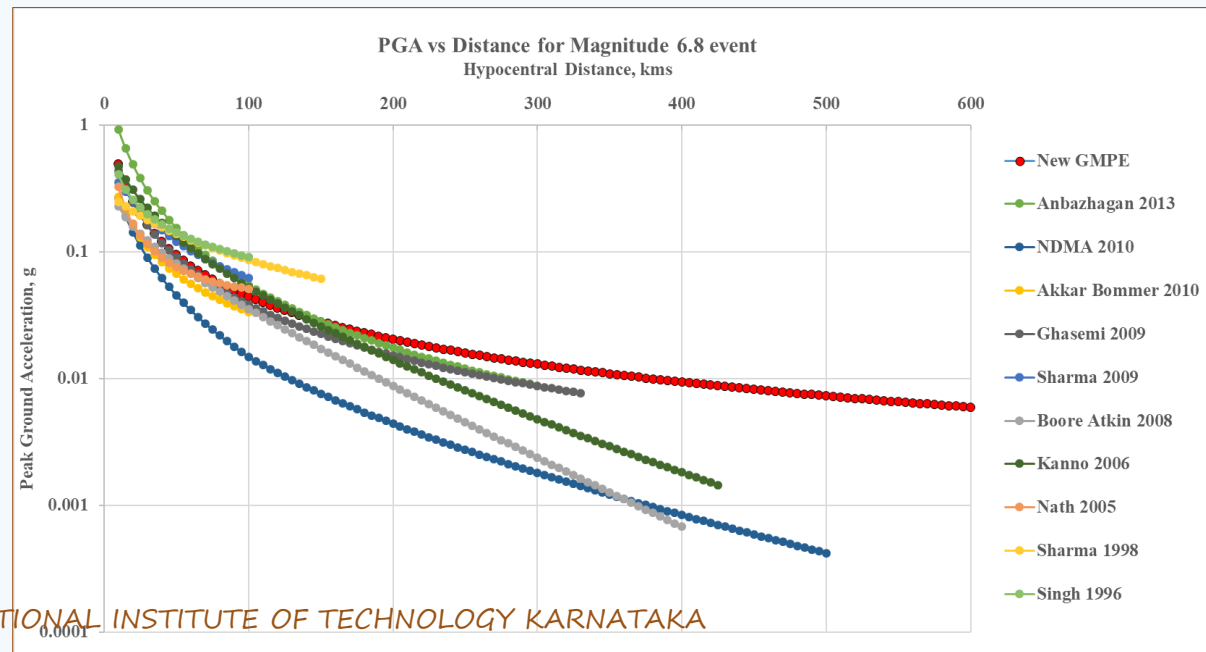


A total of 33 earthquake events, with a total of 278 data entries, ranging from moment magnitude of 4.1 to 7.8 and hypocentral distance 16km to 1560km was available

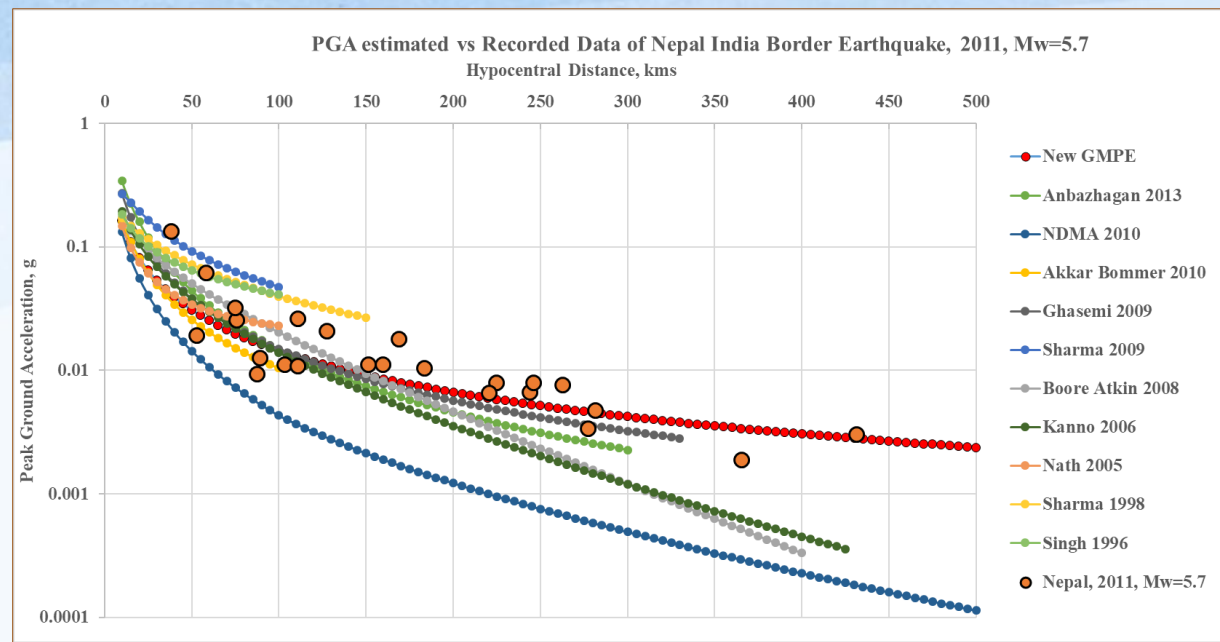


Decay parameter = 1.13, using which regression parameters $c_1 = -2.097$, $c_2 = 0.443$ and $c_3 = 0.110$ and a standard error of 0.549 was estimated (Ramkrishnan et al., 2019*).

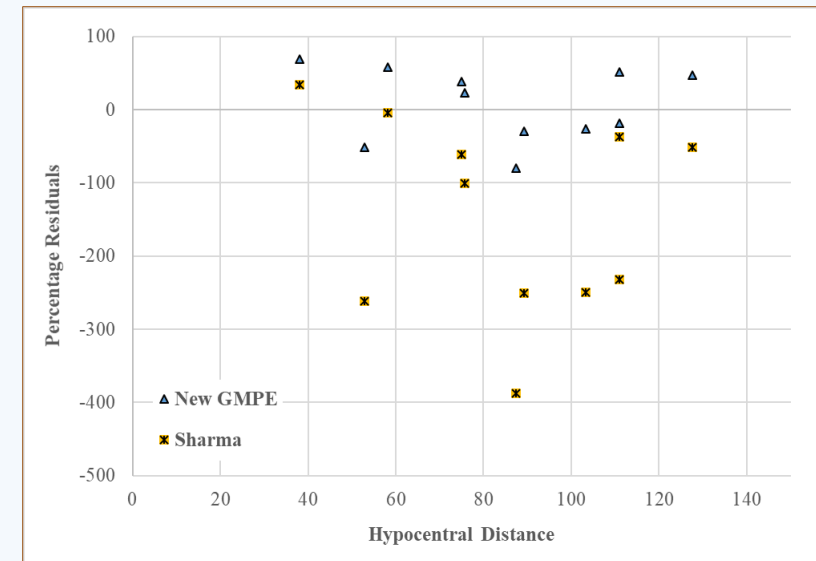
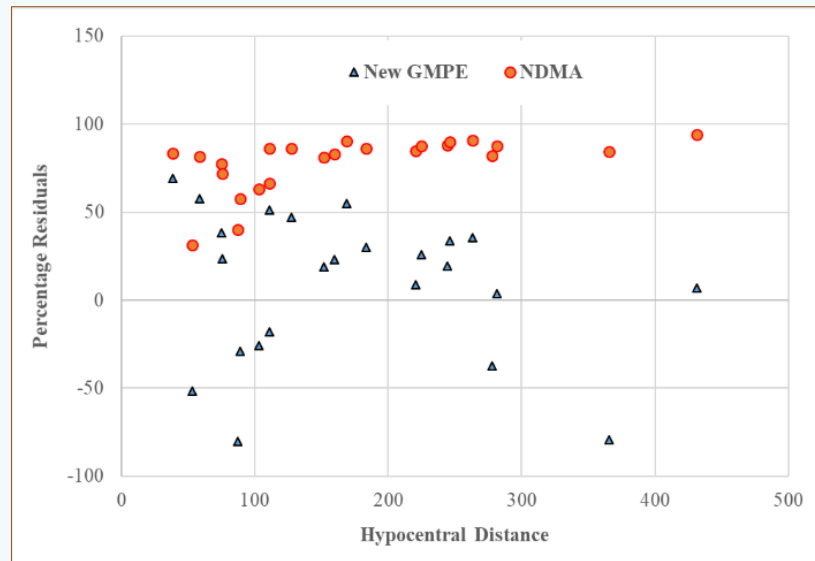
$$\log Y = -2.097 + 0.443M - 1.13 \log (X + e^{0.110M}) \pm 0.549$$



PGA predicted using previous GMPEs and new GMPE vs Hypocentral distance

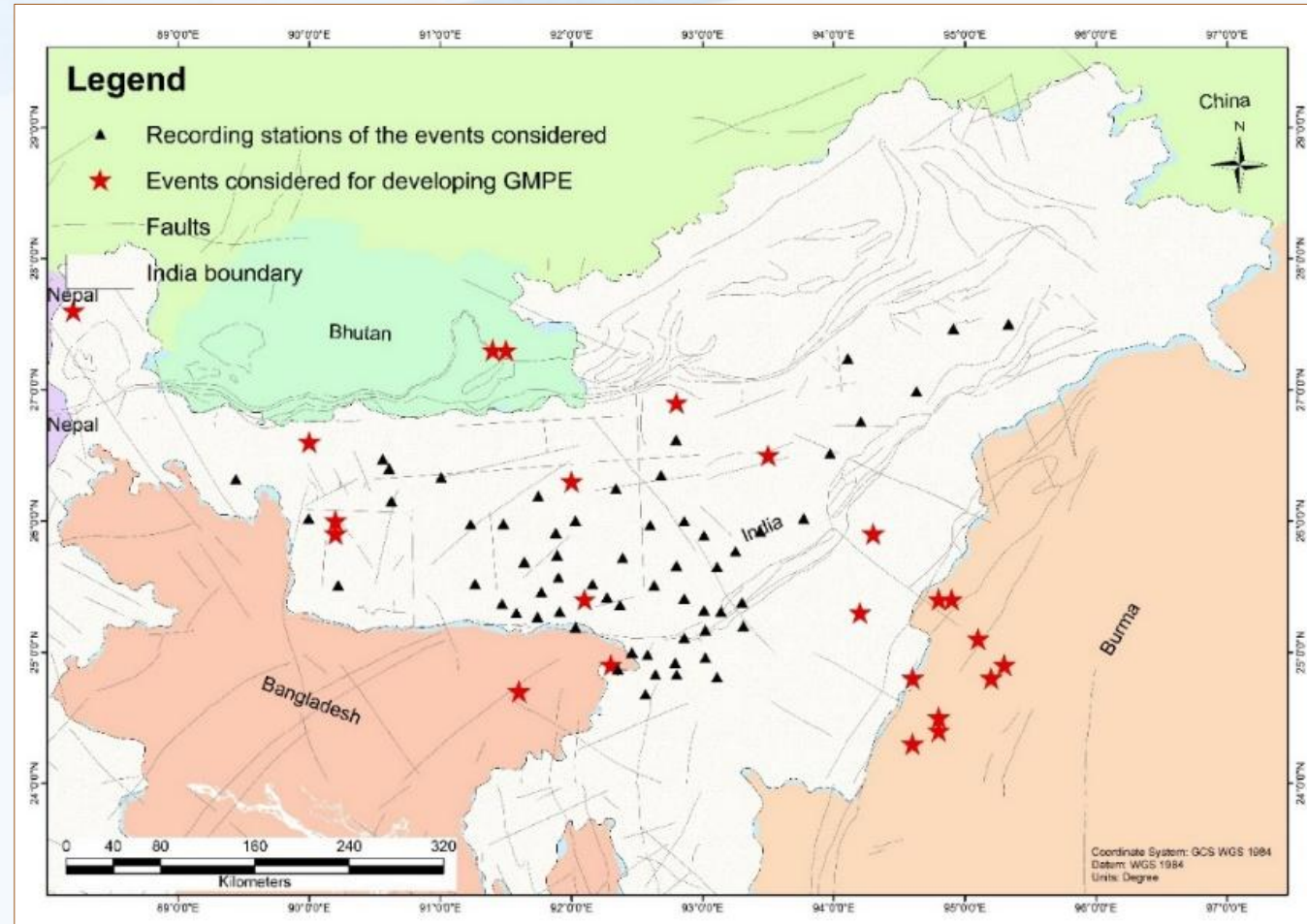


Original recorded data of Nepal-India border earthquake of Apr 4, 2011, vs PGA, predicted using new GMPE and previous GMPEs



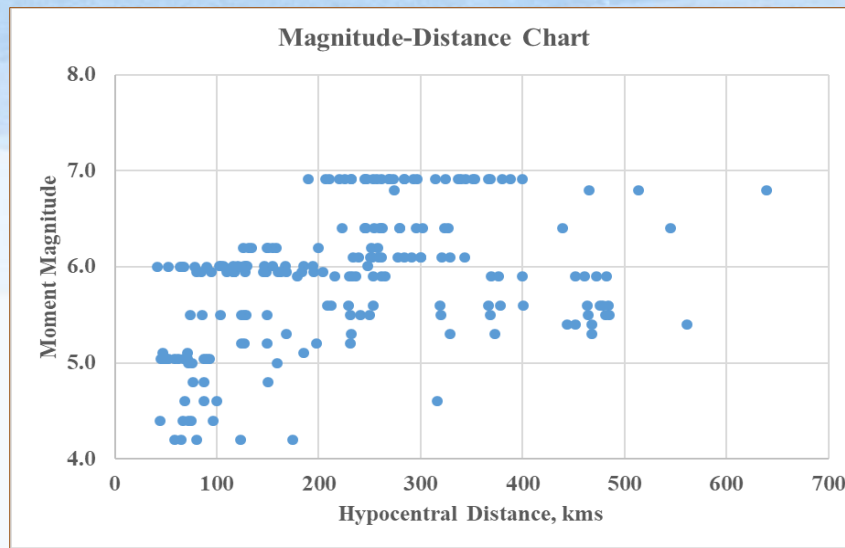
32 NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA
The plot of residual percentage between actual and predicted PGA (left) residual percentages of PGA predicted using new GMPE and NDMA (2010) (right) residual percentages of PGA predicted using new GMPE and Sharma (1998)

Seismotectonic map of NEH showing seismic sources, recording stations and events considered



A total of 25 earthquake events, with a total of 210 data entries, ranging from moment magnitude of 4.2 to 6.9 and hypocentral distance 42km to 640km was consolidated (Ramkrishnan et al., 2018*).

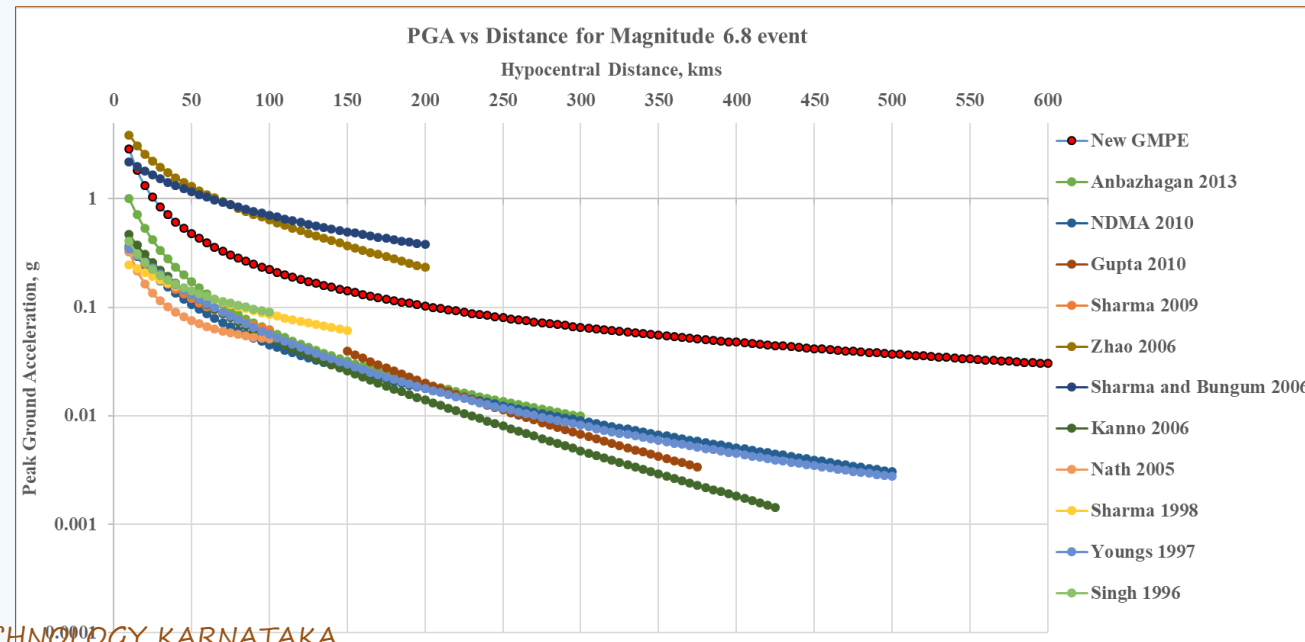
* Ramkrishnan R., S. Kolathayar, T. G. Sitharam (2018), "New Attenuation Relations for the North East Himalayas", 16th Symposium on Earthquake Engineering, ISET, IIT Roorkee, Dec 2018. (Published)

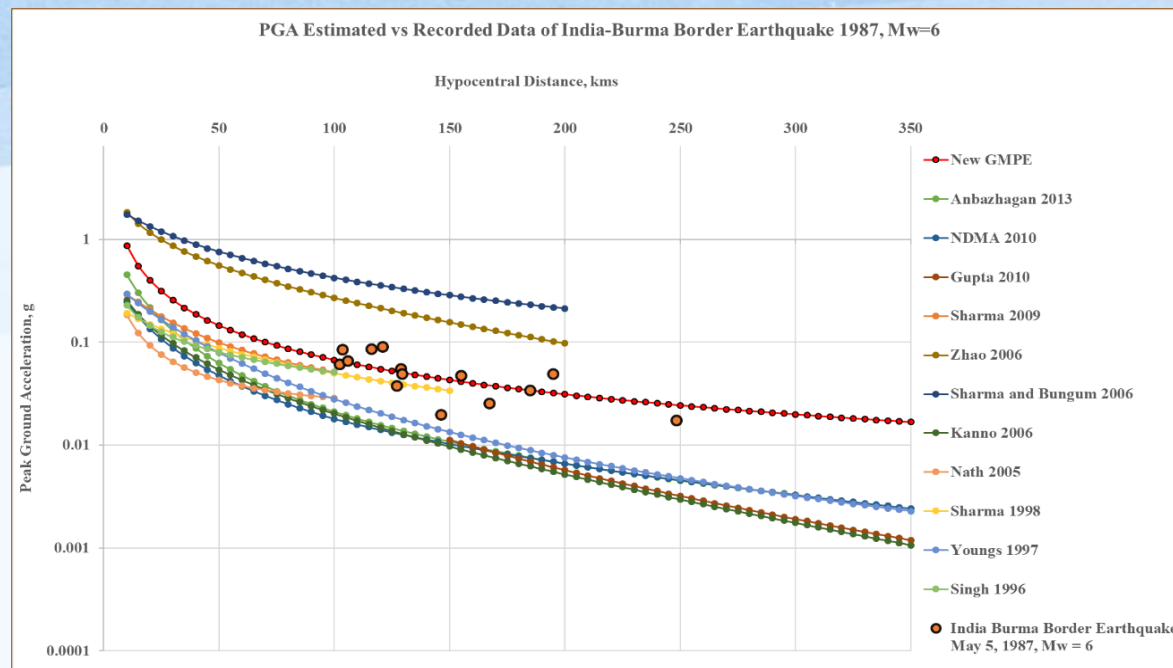


Decay parameter = 1.11, using which regression parameters as $c_1 = -2.415$, $c_2 = 0.577$ and $c_3 = -1.057$ and a standard error of 0.480 was estimated (Ramkrishnan et al., 2020*).

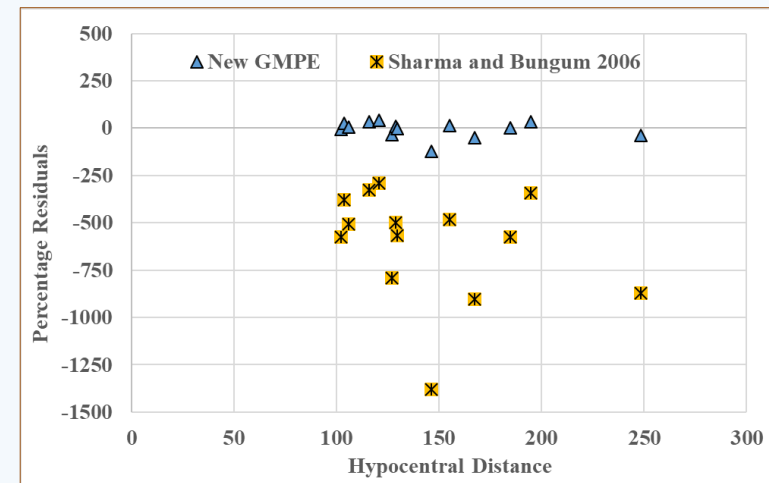
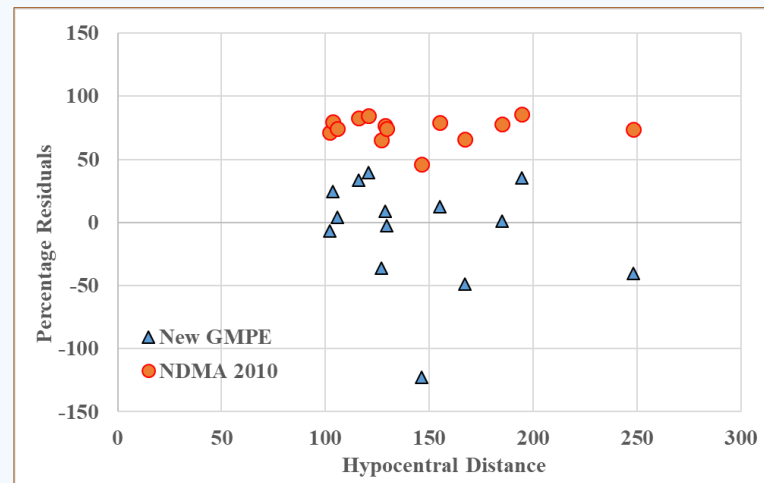
$$\log Y = -2.415 + 0.577M - 1.11 \log (X + e^{-1.057M}) \pm 0.480$$

PGA predicted using previous GMPEs and new GMPE vs Hypocentral distance





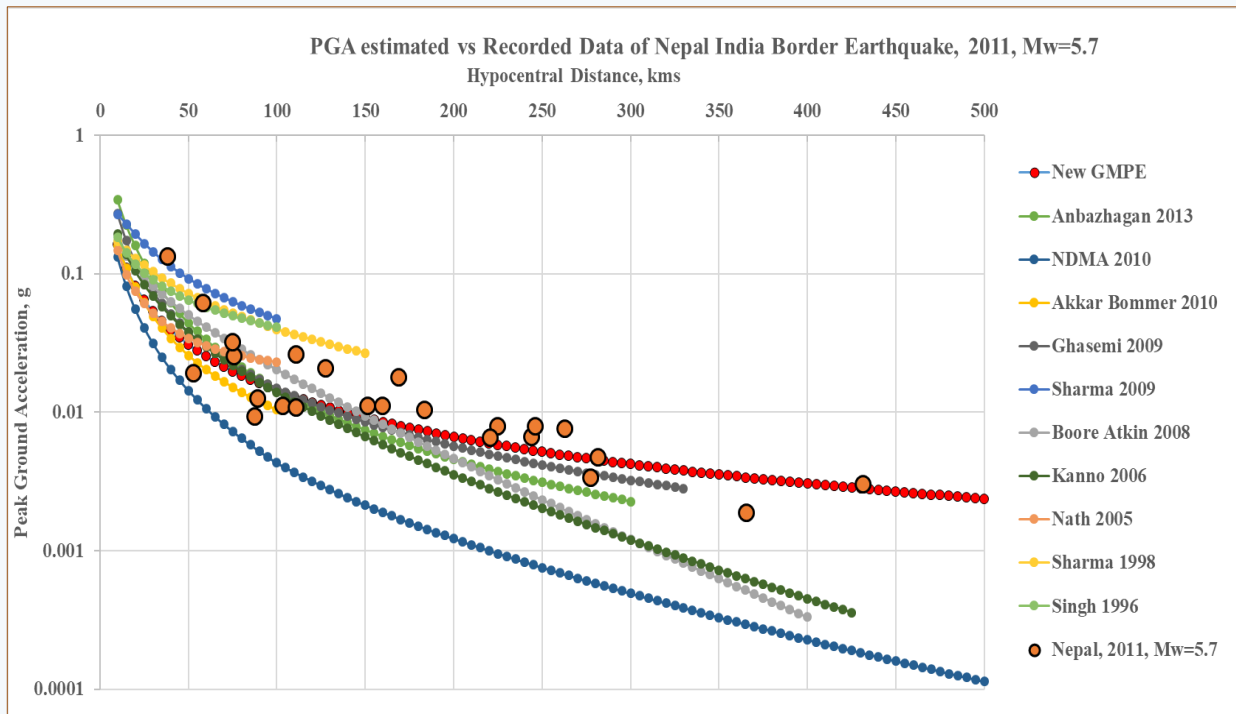
Original recorded data of India-Burma Border earthquake of May 5, 1987, vs PGA, predicted using new GMPE and previous GMPEs



The plot of residual percentage between actual and predicted PGA (left) residual percentages of PGA predicted using new GMPE and NDMA (2010) (right) residual percentages of PGA predicted using new GMPE and Sharma and Bungum (2006)

Development of GMPE for Himalayas and NE

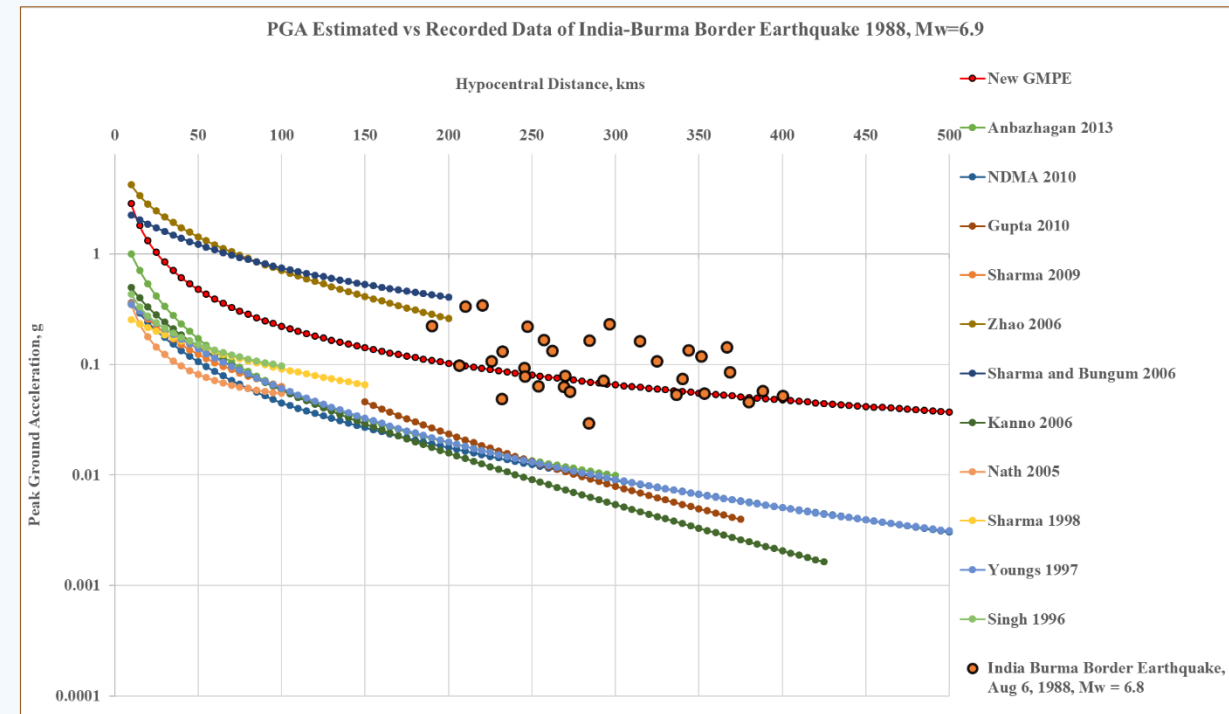
- GMPE for North and Central Himalayas: $\log Y = -2.097 + 0.443M - 1.13 \log (X + e^{0.110M}) \pm 0.549$
- GMPE for North East Himalayas: $\log Y = -2.415 + 0.577M - 1.11 \log (X + e^{-1.057M}) \pm 0.480$



Original recorded data of Nepal-India border earthquake of Apr 4, 2011, vs PGA predicted using new GMPE and previous GMPEs

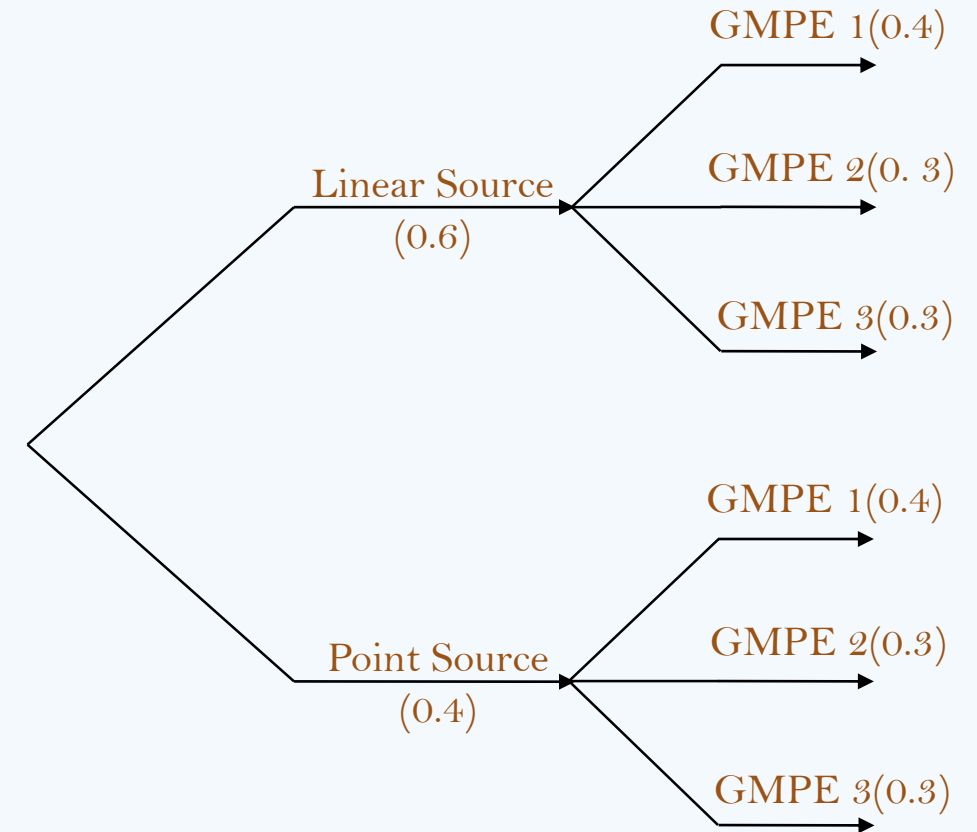
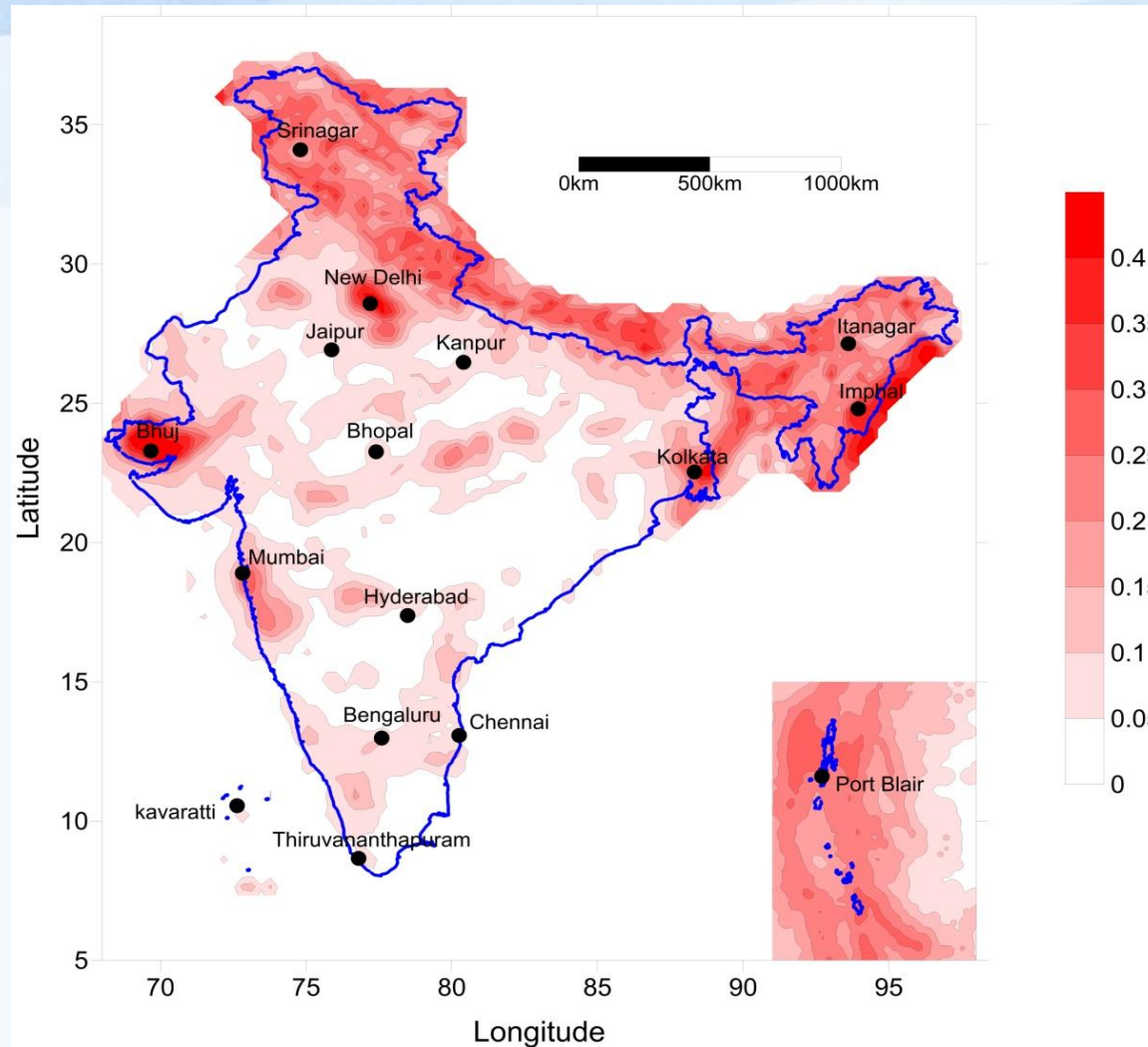
36

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Original recorded data of Sonipat earthquake of Sep 7, 2011, vs PGA predicted using new GMPE and previous GMPEs.

Deterministic Seismic Hazard Assessment



Logic Tree Framework

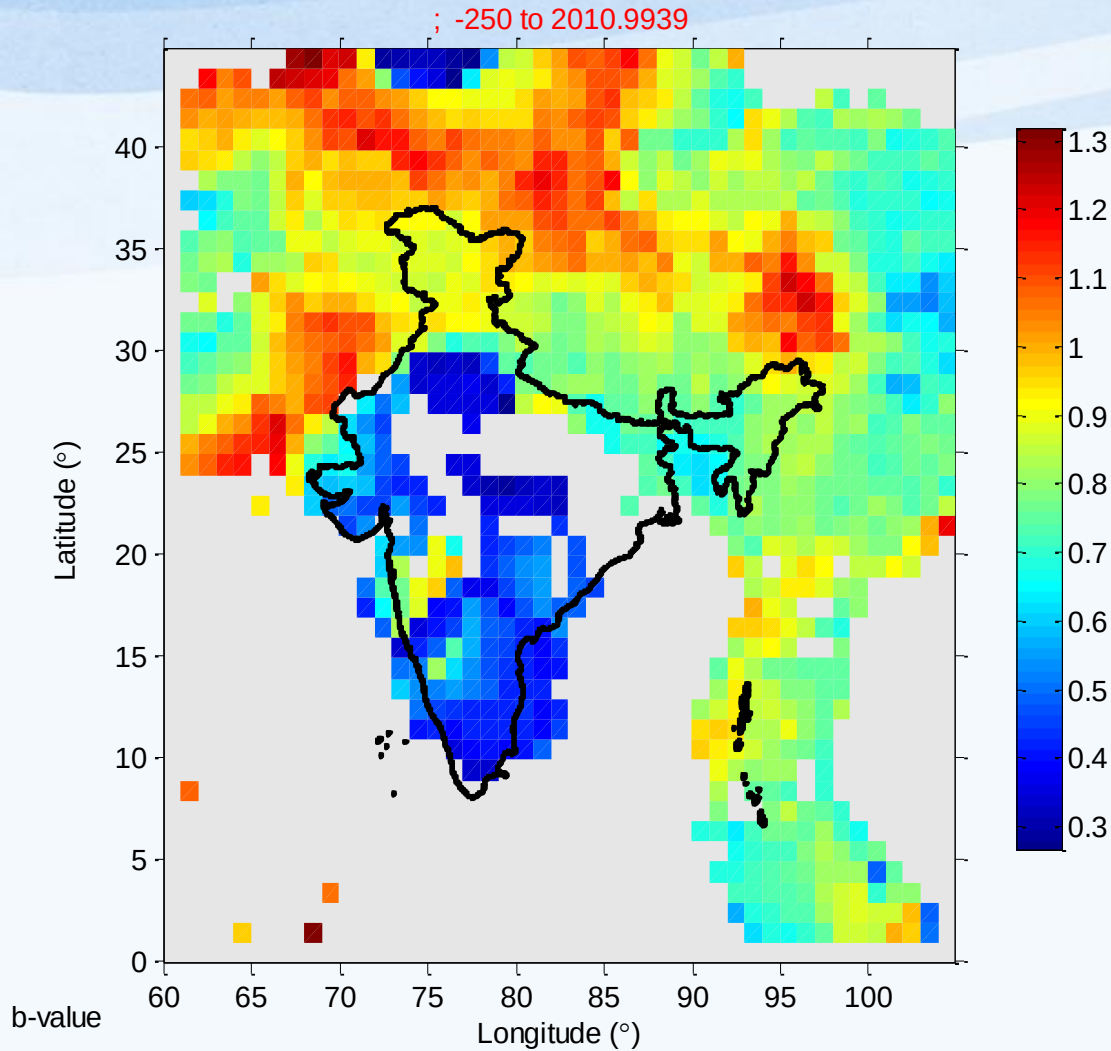
Spatial variation of PGA (g) value from DSHA

37

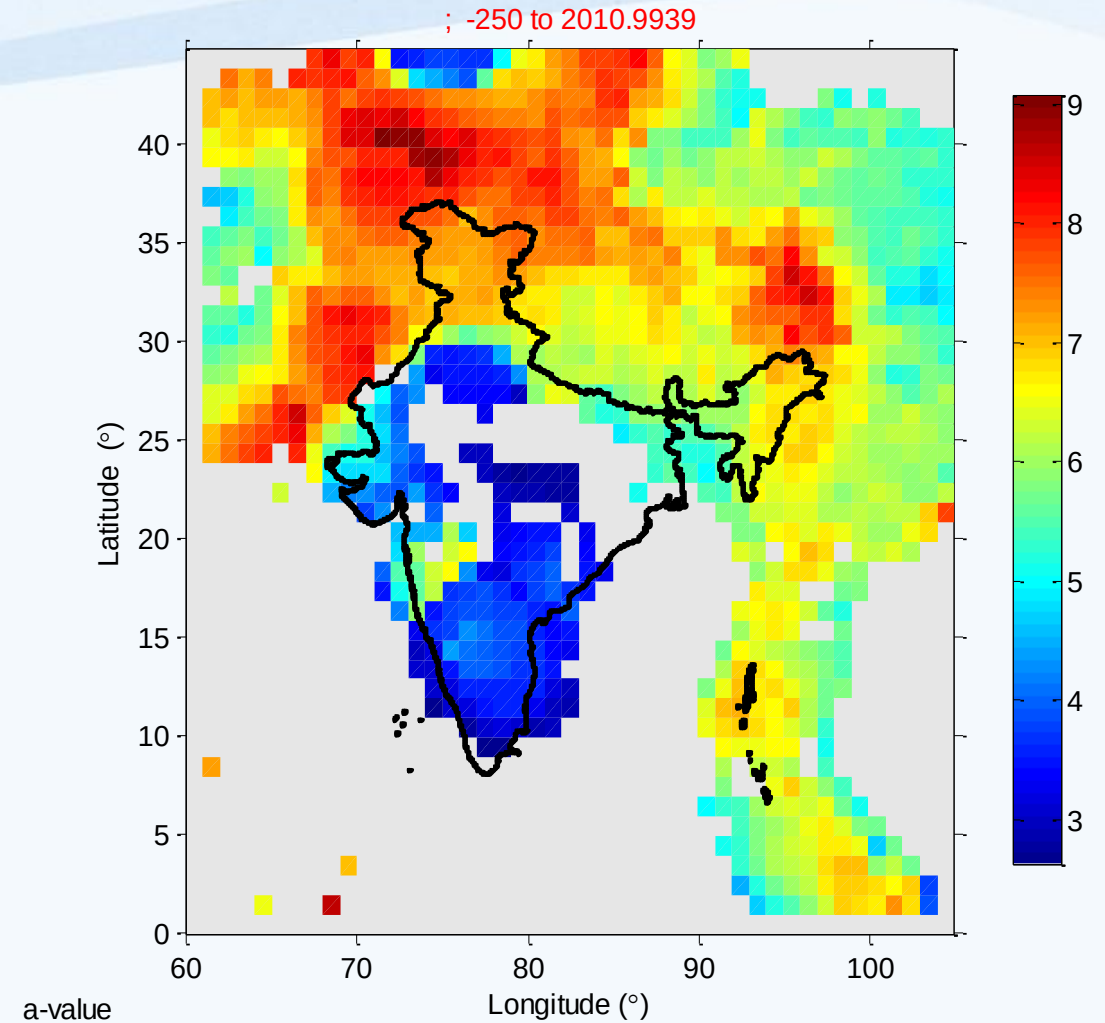
NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA

Kolathayar et al. (2012) Deterministic Seismic Hazard Macrozonation of India. *Journal of Earth System Sciences* (Springer) 121(5). 1351–1364. Citations: 124

Seismicity analysis

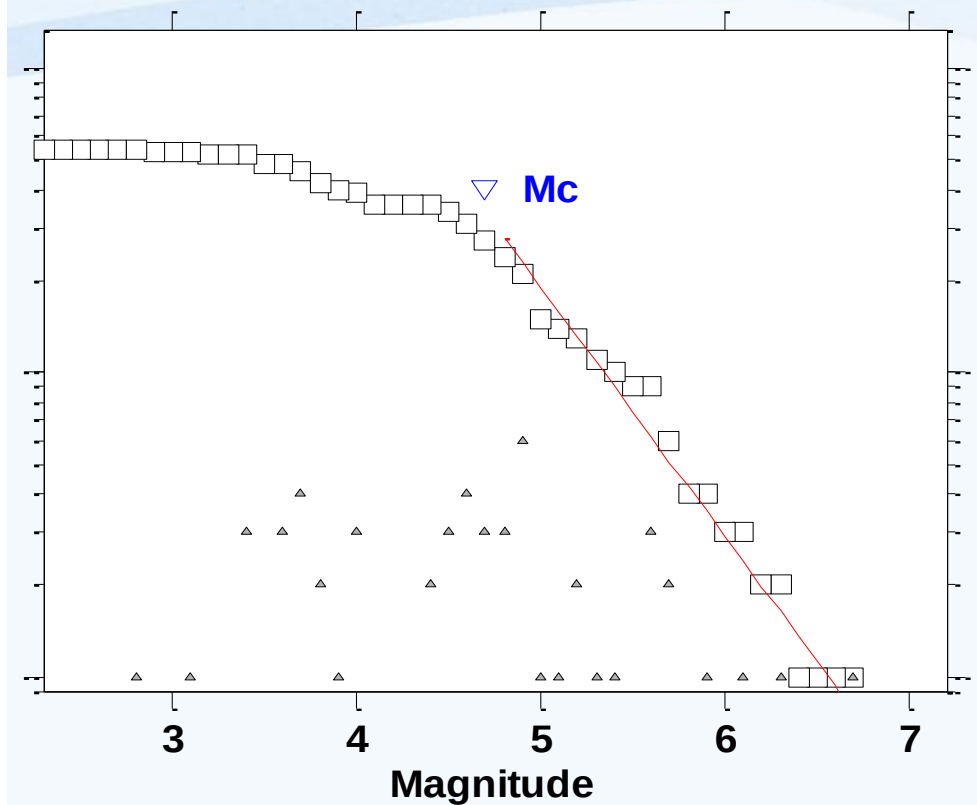
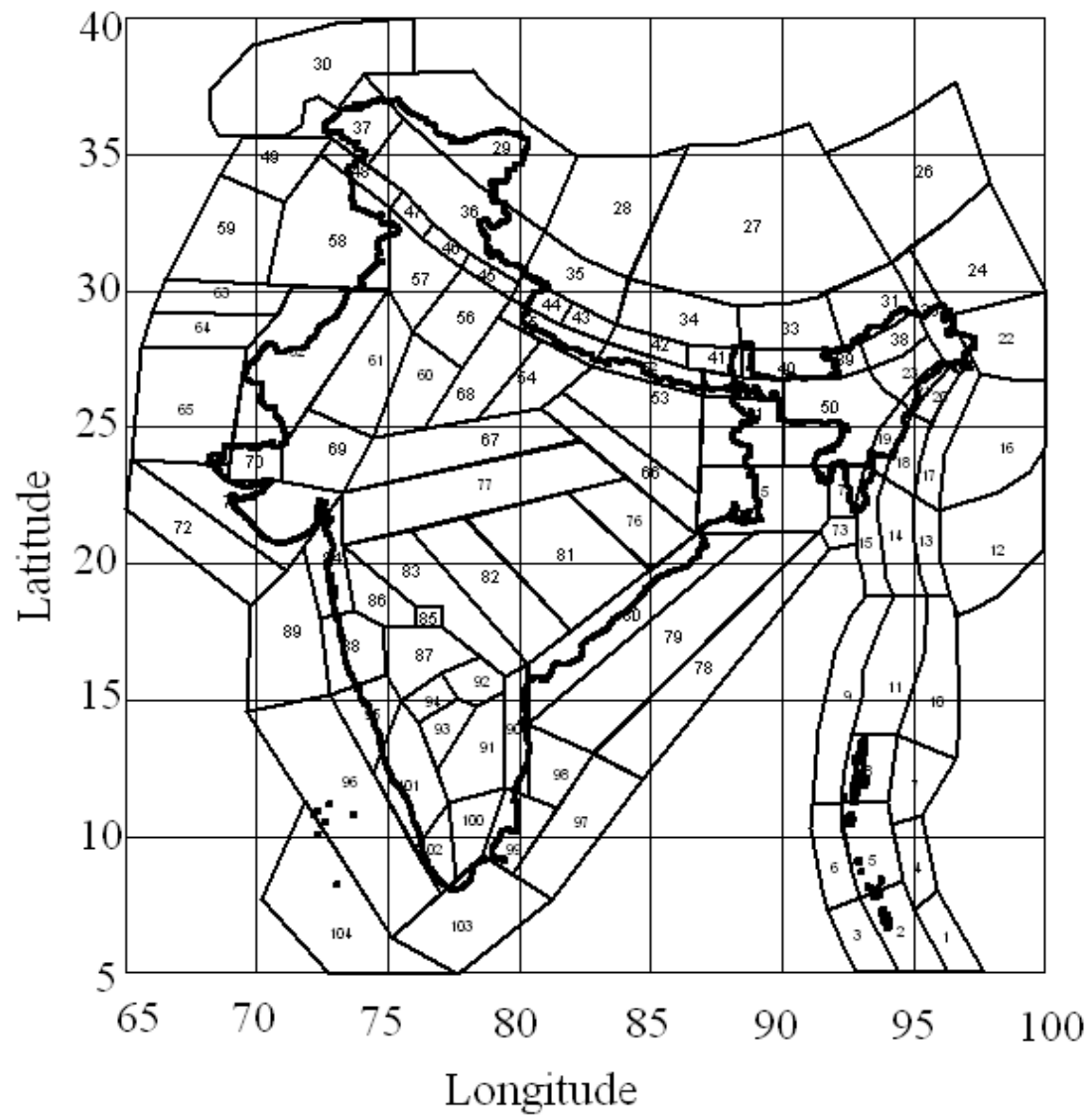


Spatial variation of b value from declustered catalog



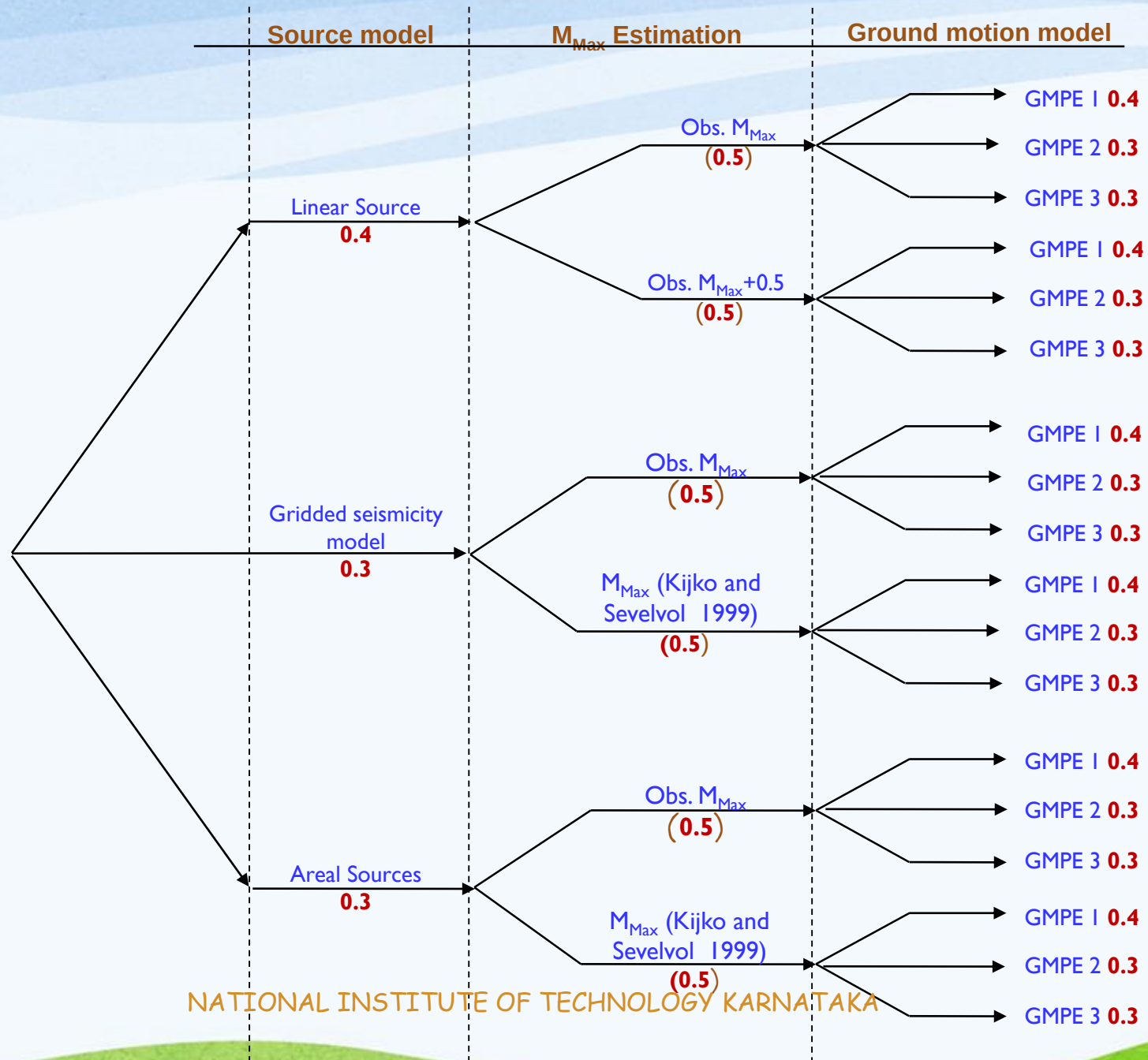
Spatial variation of a value from declustered catalog

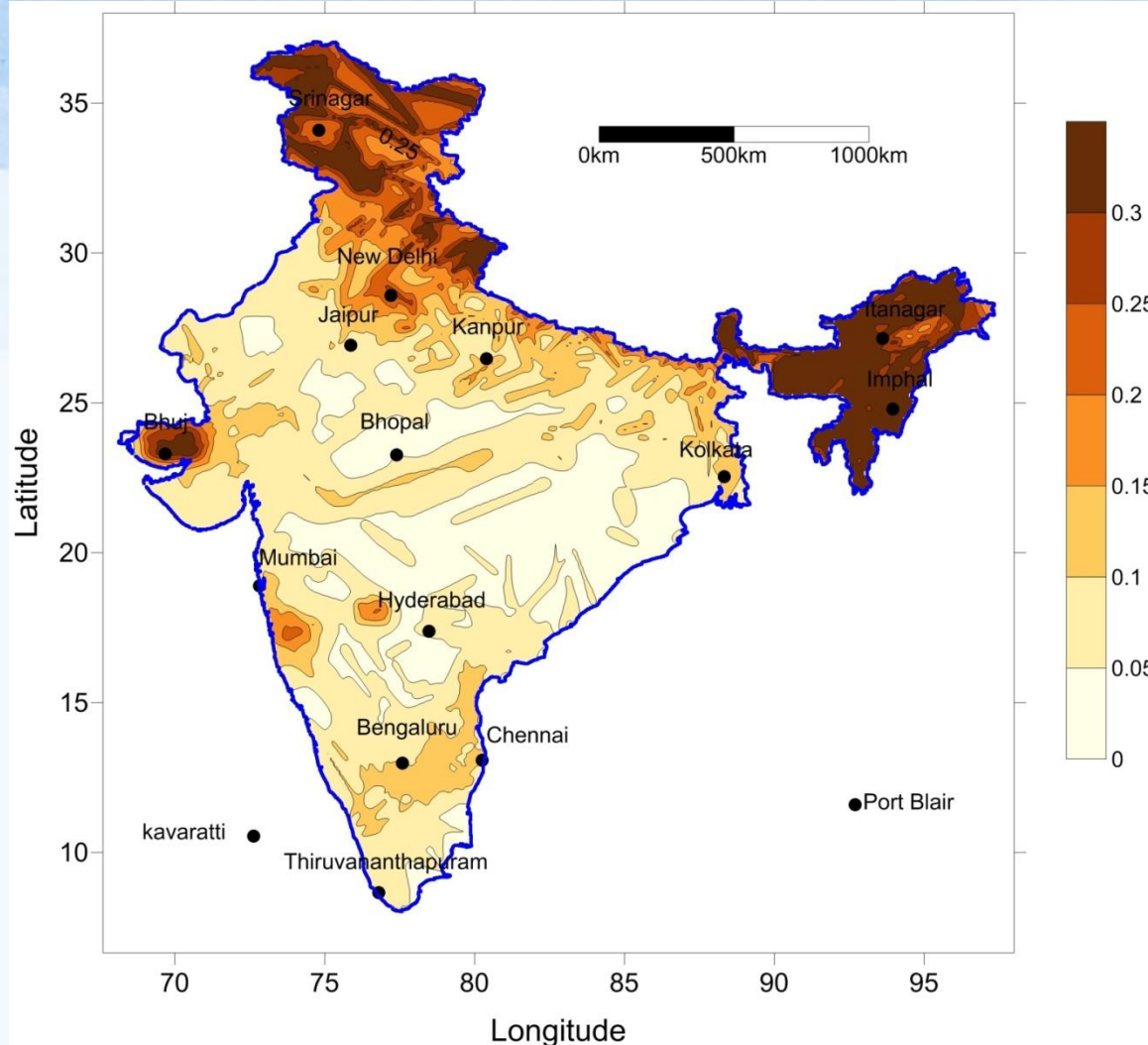
³⁸ Kolathayar et al. (2012). NATIONAL INSTITUTE OF TECHNOLOGY, KARNATAKA
Spatial variation of seismicity parameters across India and adjoining areas. **Natural Hazards**
(Springer) 60 (3), 1365-1379.



Maximum Likelihood Estimate, Uncertainties by bootstrapping
 a value = 0.82 ± 0.27 , a value = 5.38 , a value (annual) = 3.58
 Magnitude of Completeness = 4.7 ± 0.42

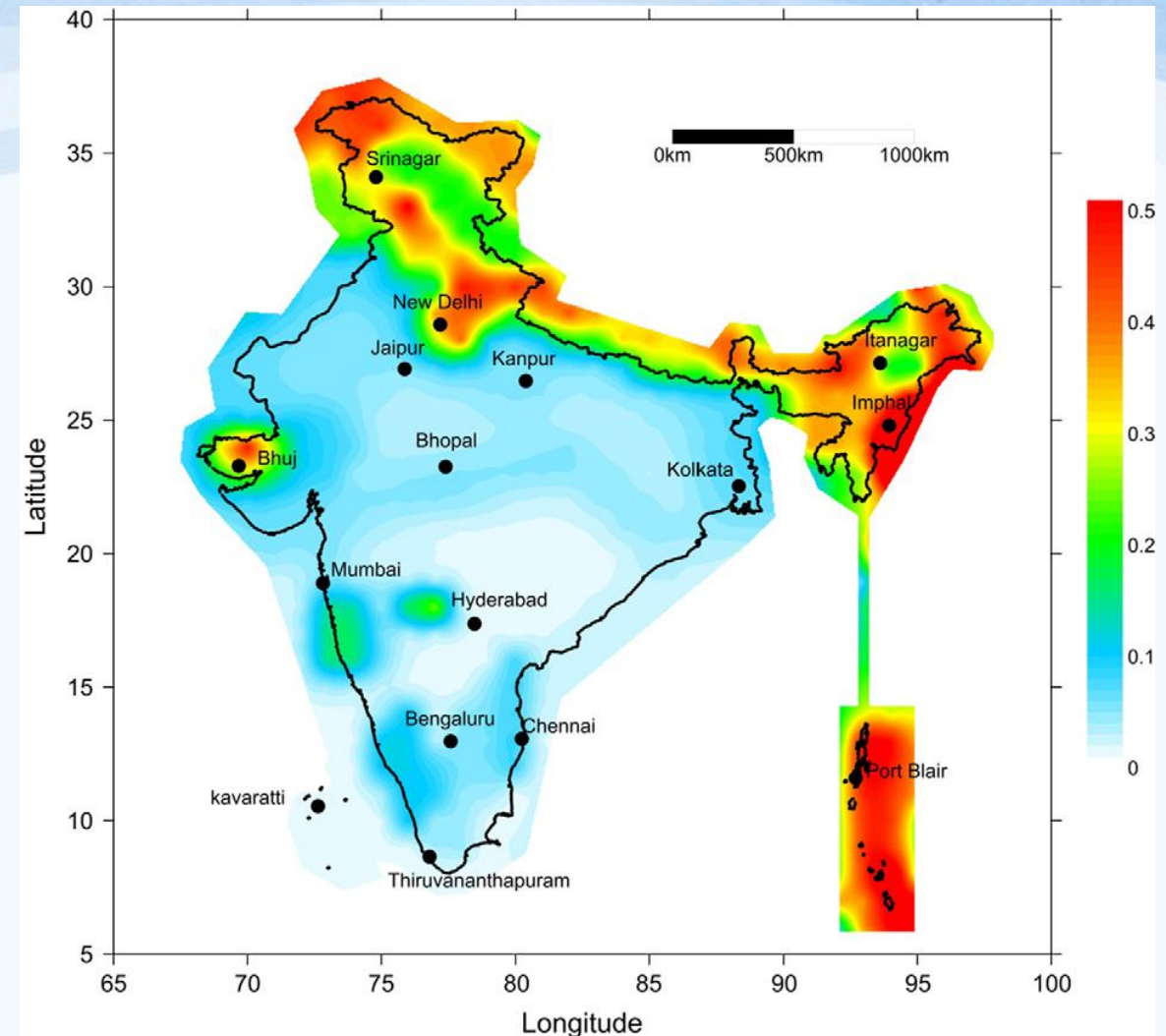
Frequency Magnitude Distribution for
Source zone 1





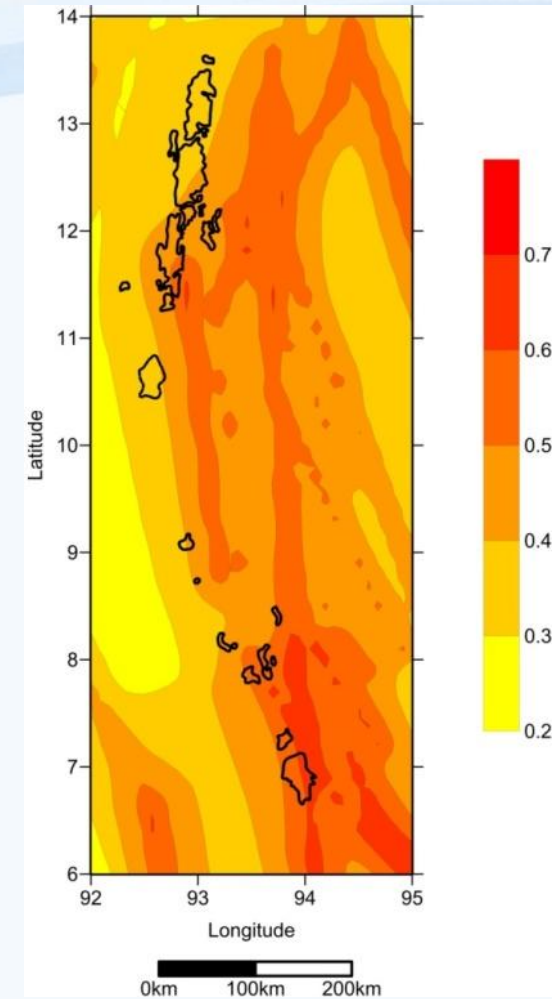
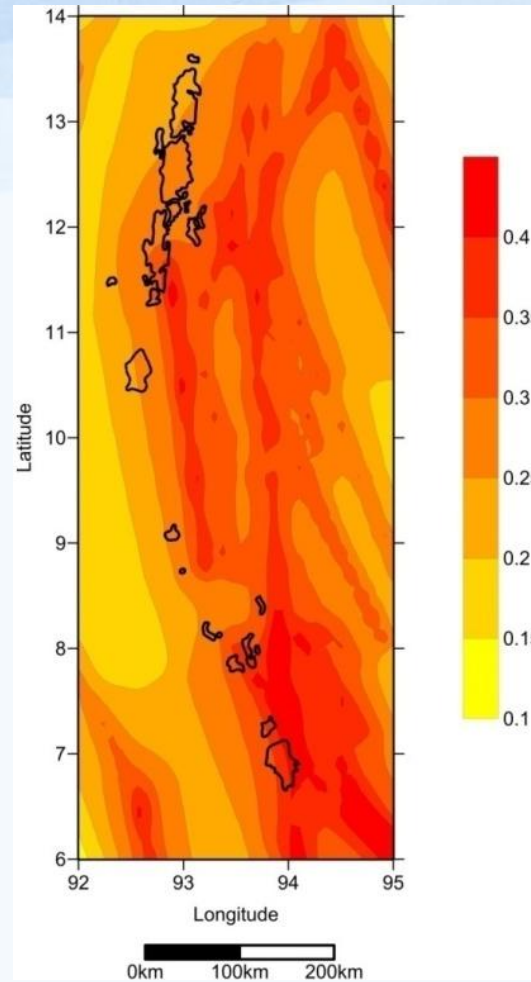
PGA values (g) for 475 years return period (Logic Tree)

Kolathayar S & Sitharam TG. Earthquake Hazard Assessment. ISBN 978-1-138-30923-4, CRC Press Balkema, Taylor & Francis Group, London, 2018.



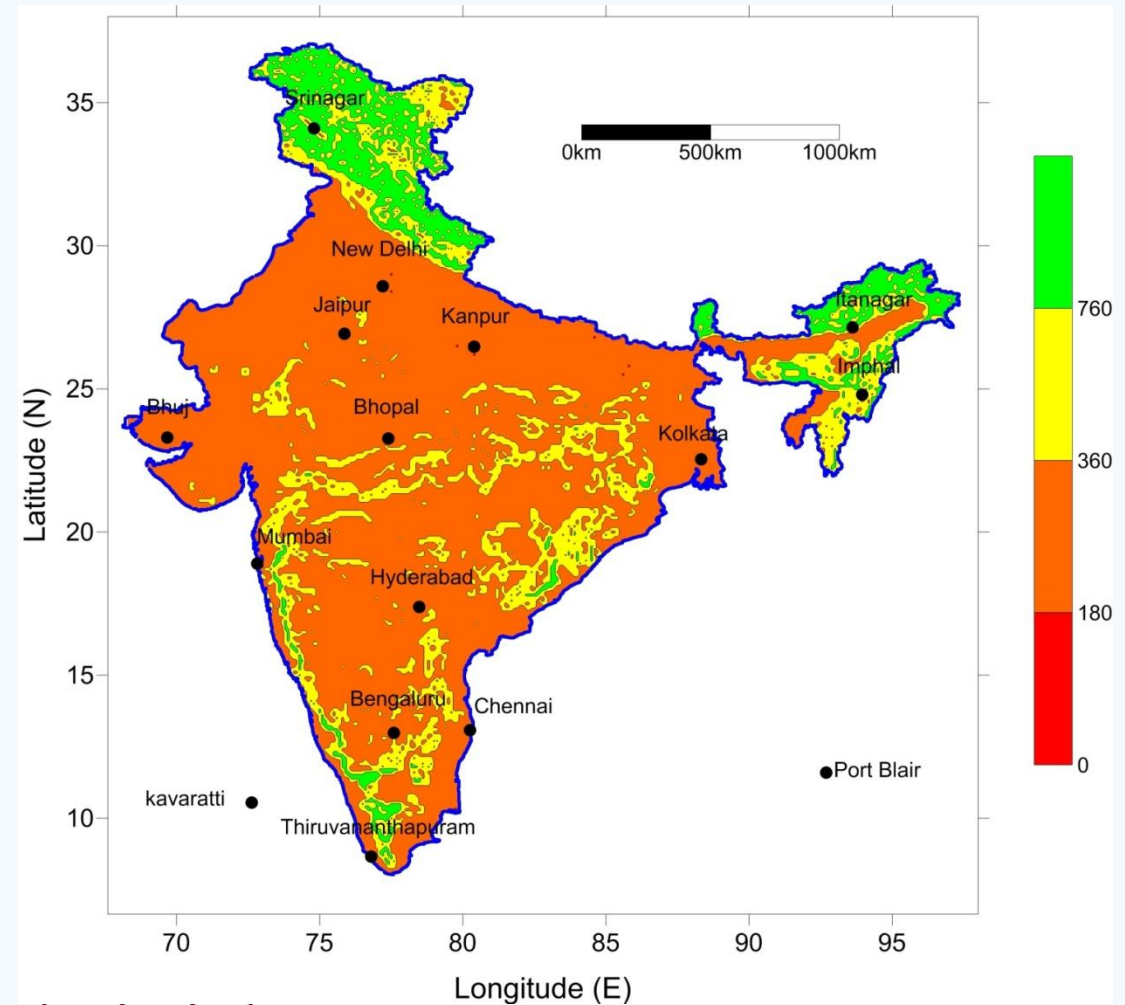
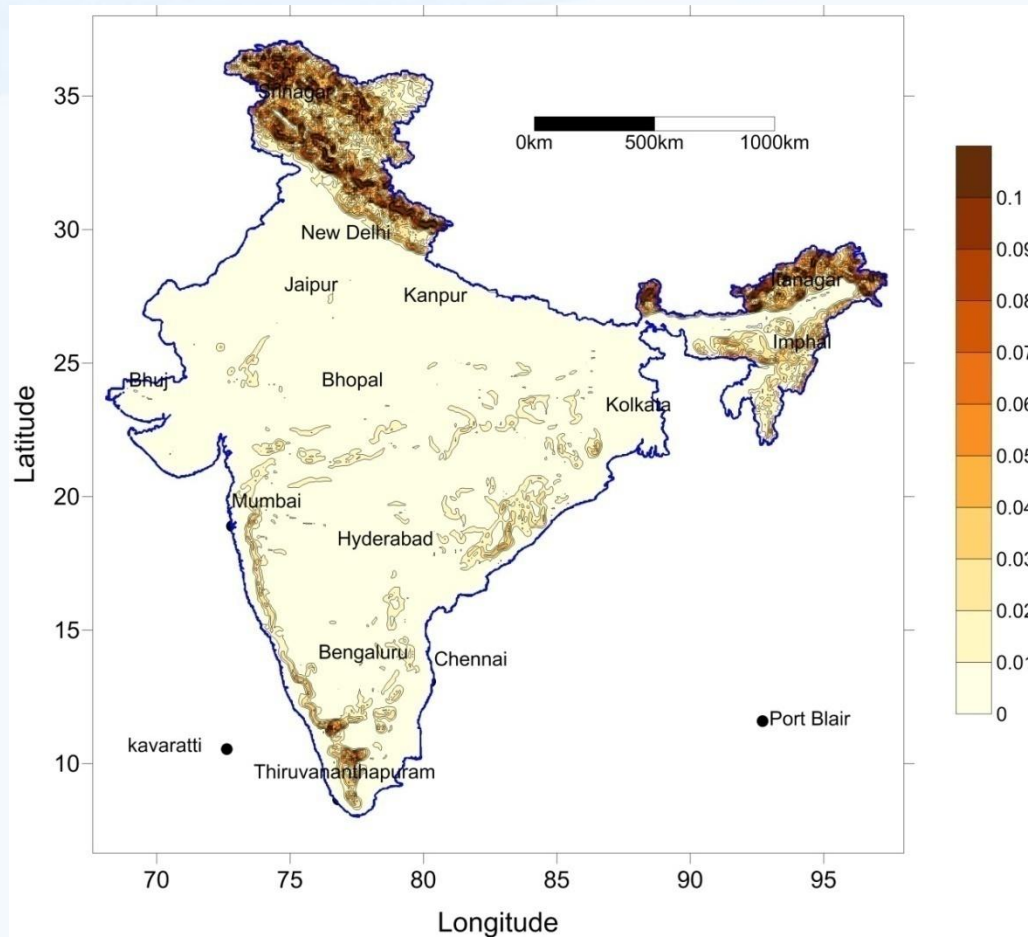
PGA values (g) for 475 years return period (Areal source)

Sitharam T G and Kolathayar S (2013) Seismic Hazard Analysis of India using Areal Sources. **Journal of Asian Earth Sciences Elsevier (2013) 62: 647-653. (IF: 3.515)**



Spatial variation of PGA value (g) in Andaman & Nicobar regions
corresponding to a return period of 475 years and 2475 years

Topographic gradient as a proxy for site characteristics



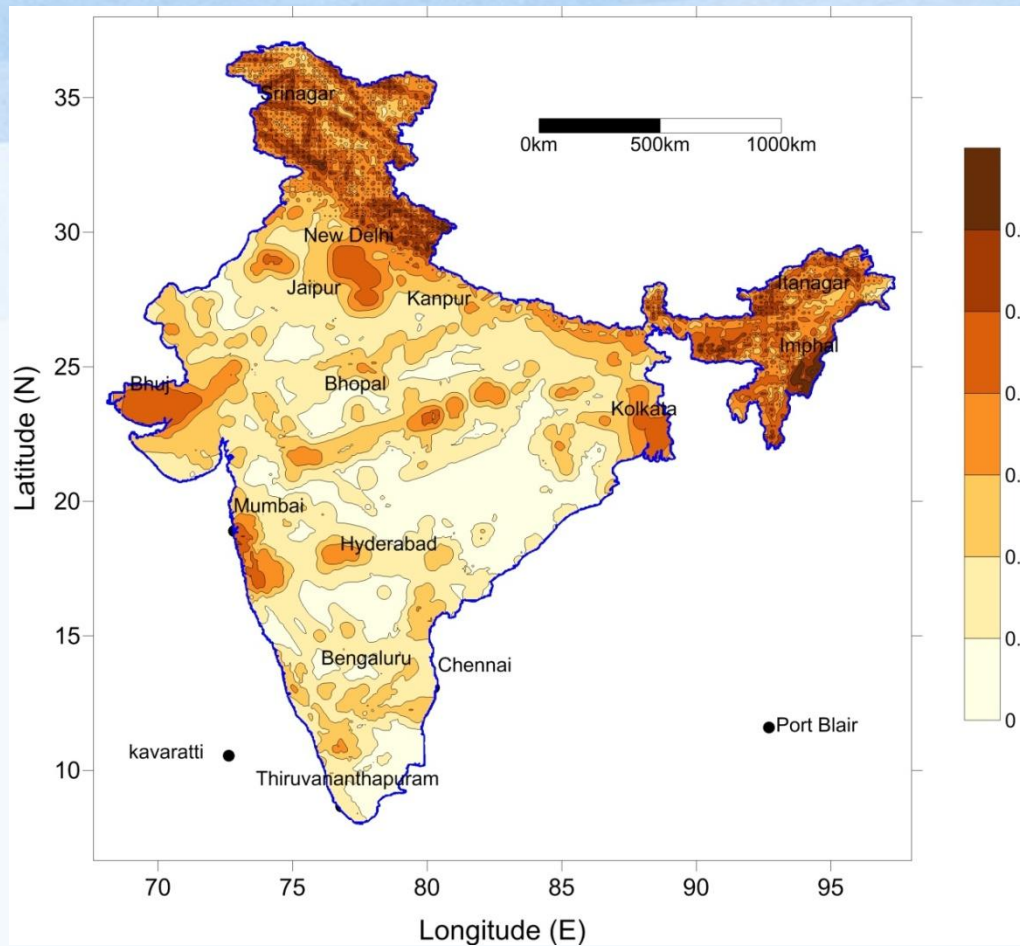
Contour map showing the spatial variation of slope value (m/m)

43

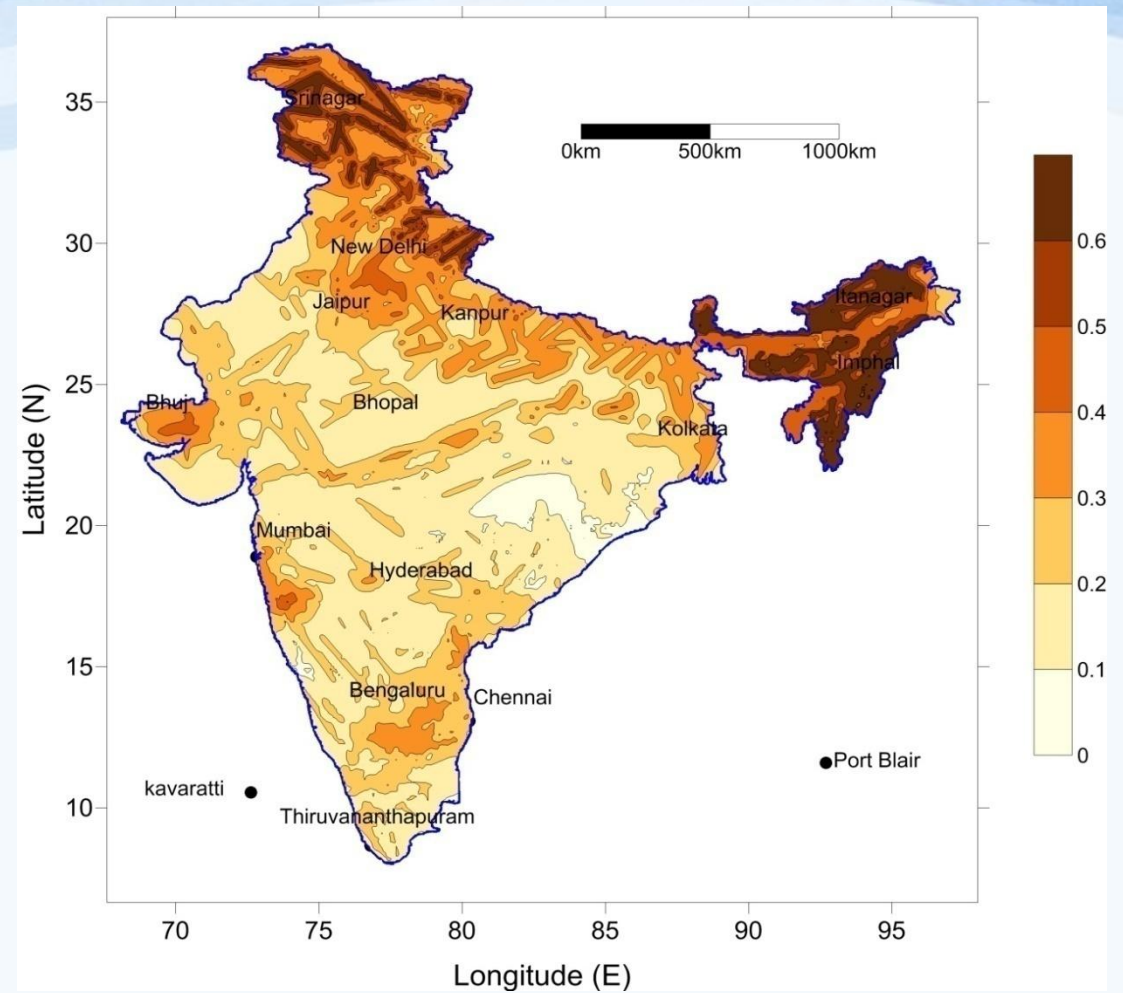
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VS30 (m/s) contour map derived from the slope values

T.G. Sitharam, S. Kolathayar, and N. James (2015) In **Geoscience Frontiers** (2015), Volume 6, Issue 6, Pages 847–859, (IF: 4.28)



Surface level PGA value (g) (DSHA)



Surface level PGA value (g) (PSHA) for a return period of 475

44 Sreeyalsa Kolathayar & Sitharam TG. Earthquake Hazard Assessment. ISBN 978-1-138-30923-4,
 NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA
 CRC Press Balkema, Taylor & Francis Group, London, 2018.

Seismic Hazard Analysis for Lucknow

- Two methods to perform the seismic hazard analysis
 - Deterministic seismic hazard analysis
 - Probabilistic seismic hazard analysis
- Seismotectonic region up to 350 km radial distance around Lucknow centre considering MBT and MCT.
- Past event details collected from different resources;
 - SEISAT (2000)
 - United States Geological Survey (USGS)
 - Indian Meteorological Survey (IMD)
 - Northern California Earthquake Data Centre (NCEDC)
 - National Earthquake Information Centre (NEIC)
- A total of 1831 earthquakes within 350 km from Lucknow centre.
- Collected earthquakes converted to moment magnitude (M_w) using Scordilis (2006)

$$M_w = 0.67 (\pm 0.05) M_s + 2.07 (\pm 0.03) \quad \text{for } 3.0 \leq M_s \leq 6.1$$

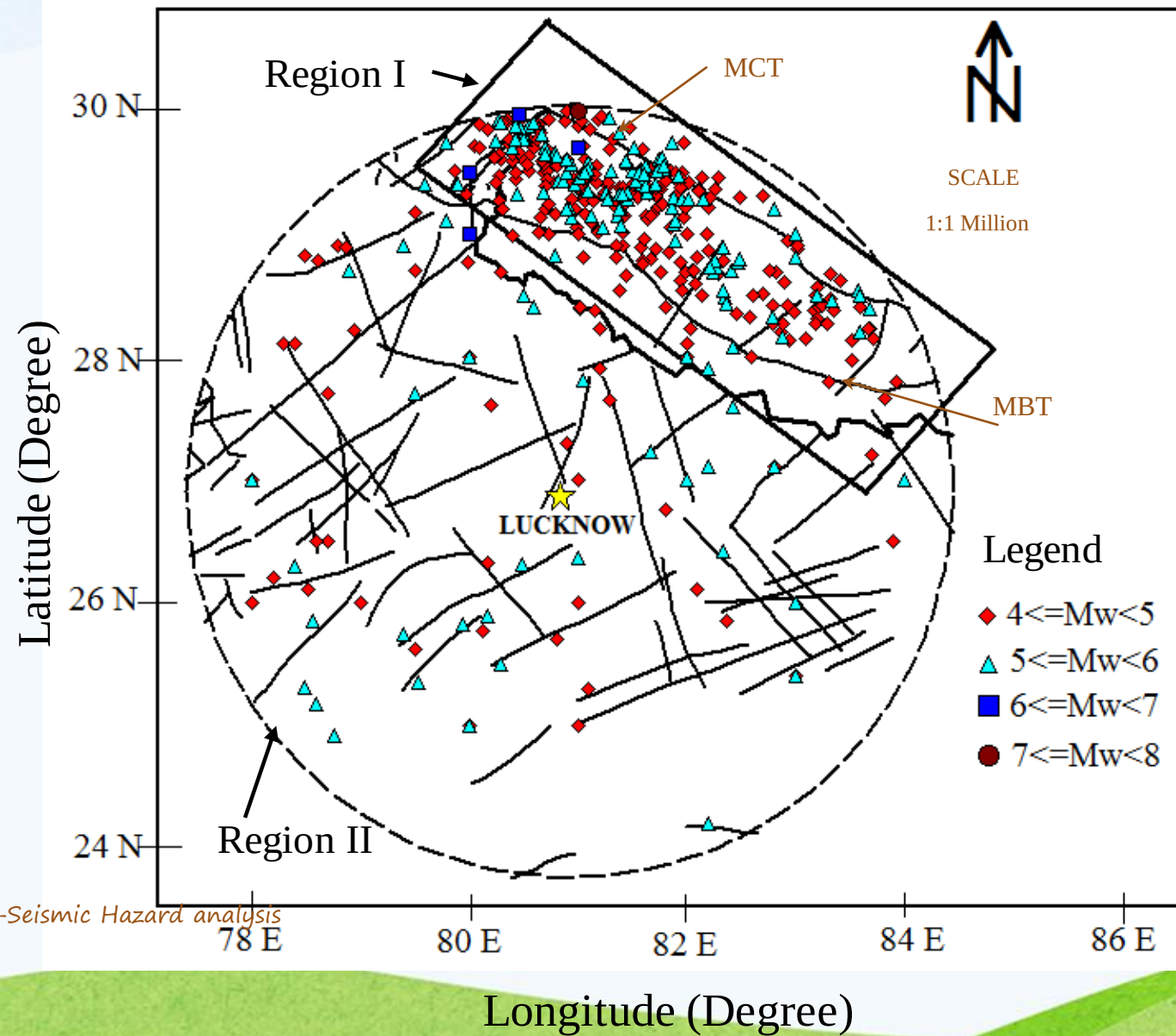
$$M_w = 0.99 (\pm 0.02) M_s + 0.08 (\pm 0.13) \quad \text{for } 3.0 \leq M_s \leq 6.1$$

TGS 2026-Seismic Hazard analysis

$$M_w = 0.85 (\pm 0.04) m_b + 1.03 (\pm 0.23) \quad \text{for } 3.5 \leq m_b \leq 6.2$$

Ref: Kumar et al. (2013)

Seismotectonic map

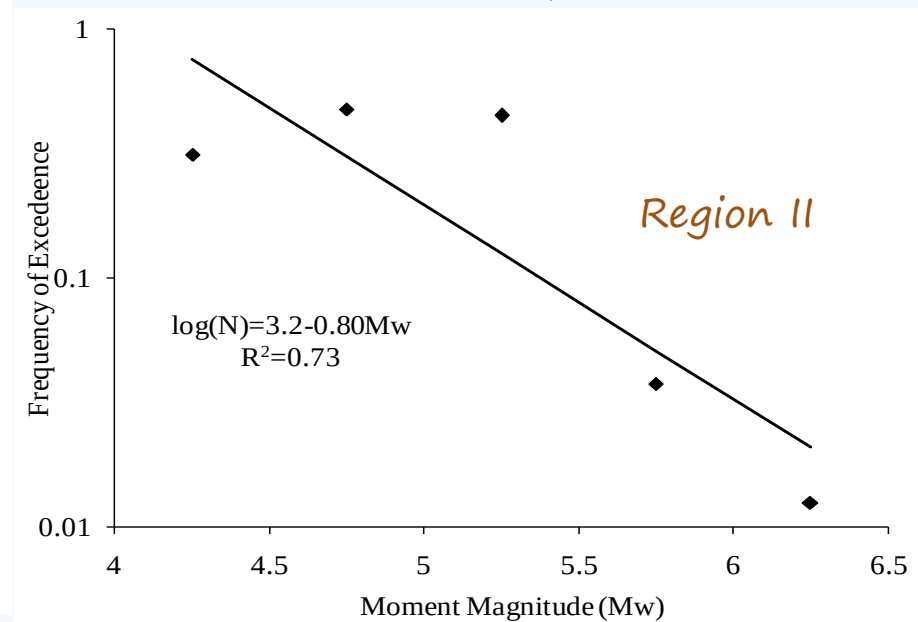
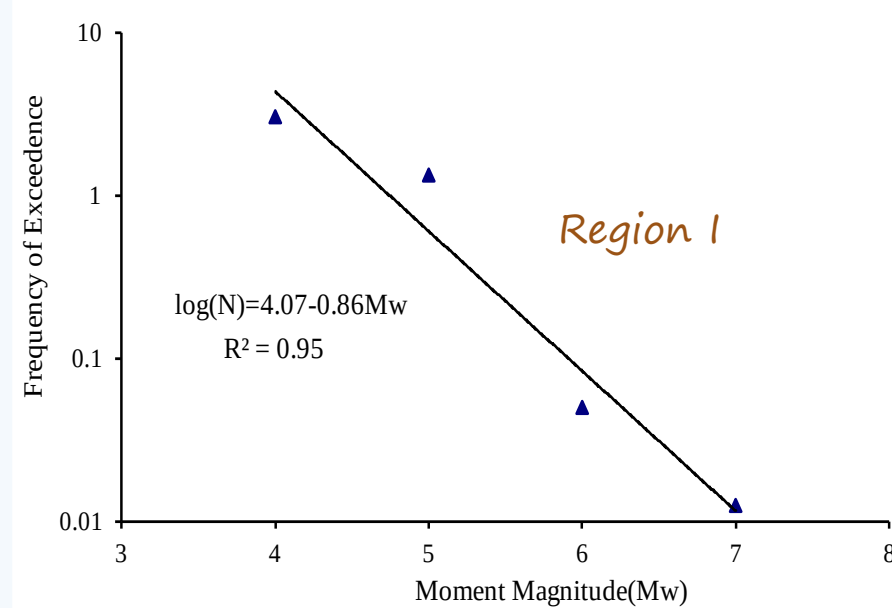


TGS 2026-Seismic Hazard analysis

Ref: Kumar et al. (2013)

q-k Recurrence Relation

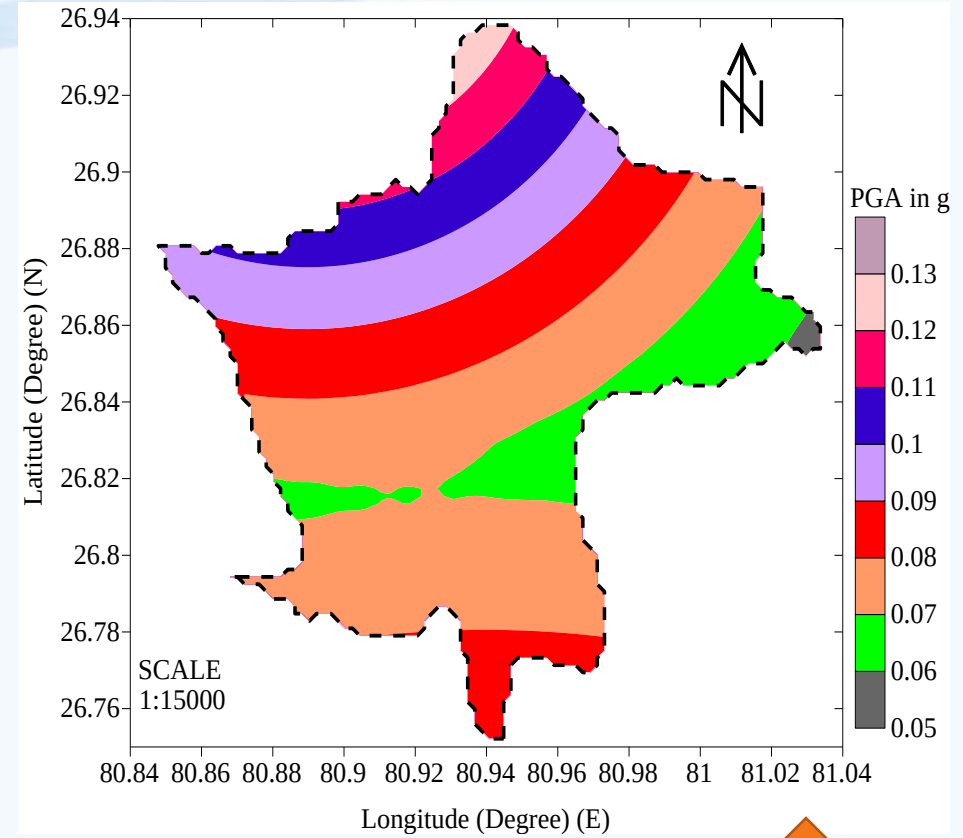
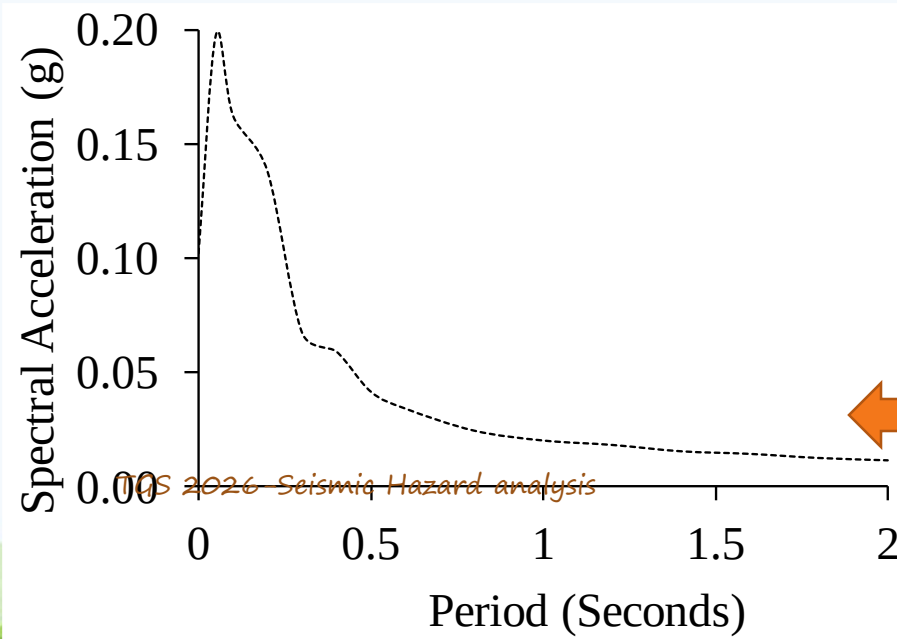
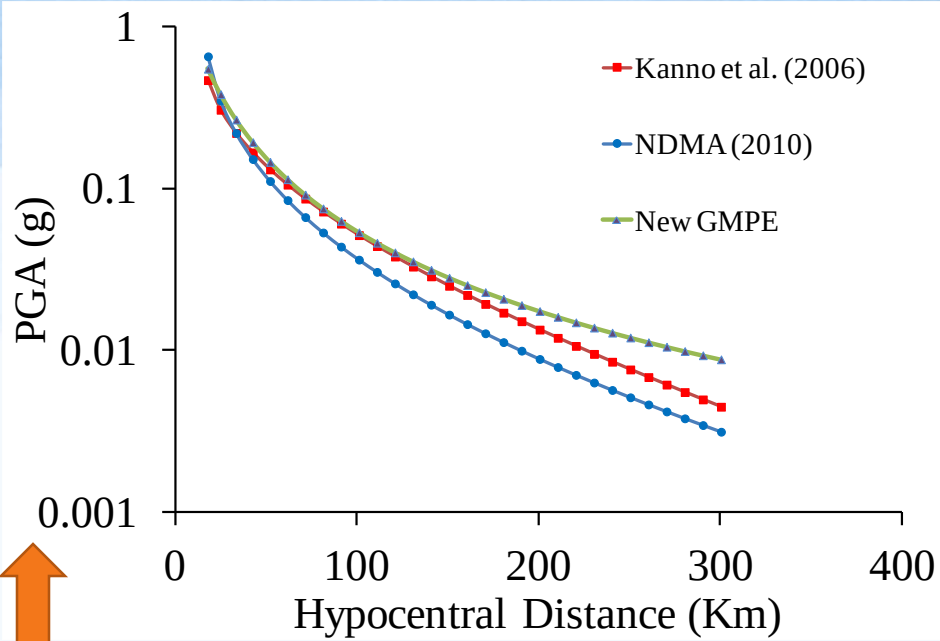
- Using the complete data set for both the regions, the seismic parameters have been estimated separately.
- b values for Region I and II found are 0.86 and 0.90 respectively.



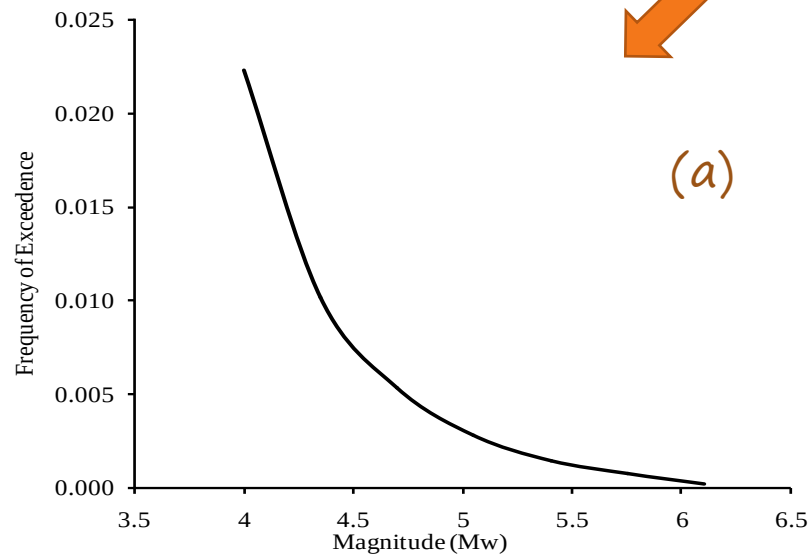
Region I	Region II
0.86 (present study)	0.90 (present study)
0.73 (NDMA, 2010)	0.81 (NDMA, 2010)
1.0 (Sreevalsa et al., 2012)	0.85 (Sreevalsa et al., 2012)
0.80 Mahajan (2009)	-
0.65 (Kumar, 2012)	-

TGS 2026-Seismic Hazard Analysis

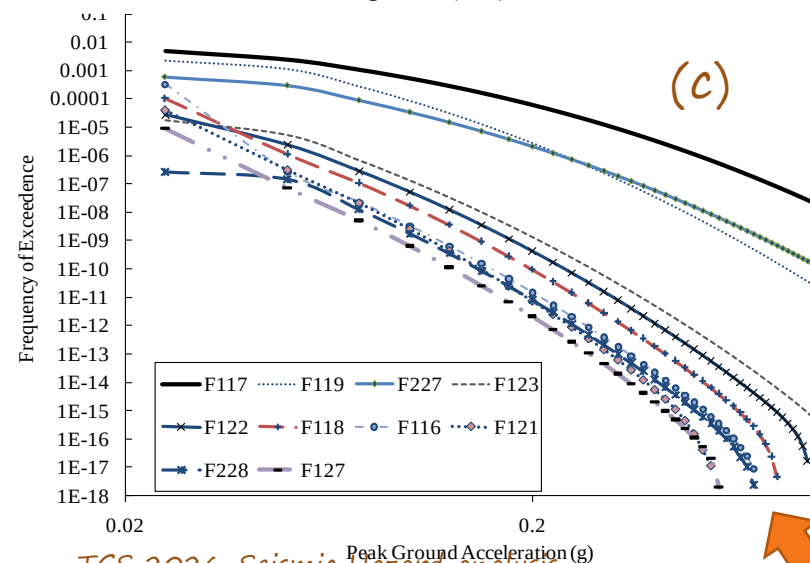
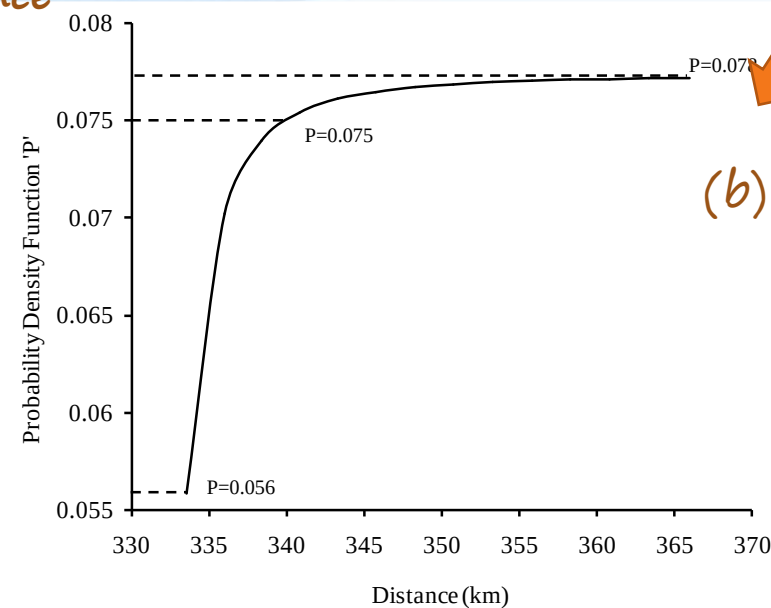
Ref: Kumar et al. (2013)



Magnitude exceedence probability

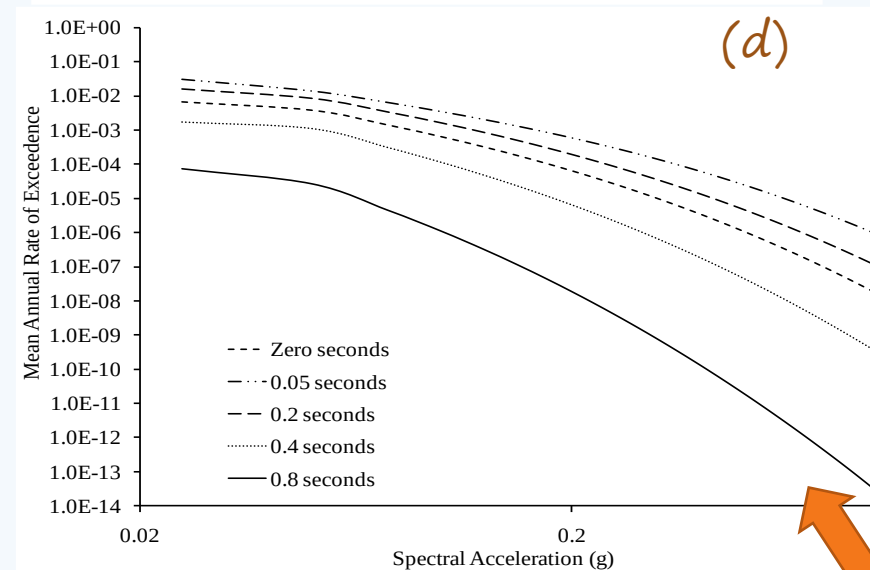


Probability density function for hypocentral distance



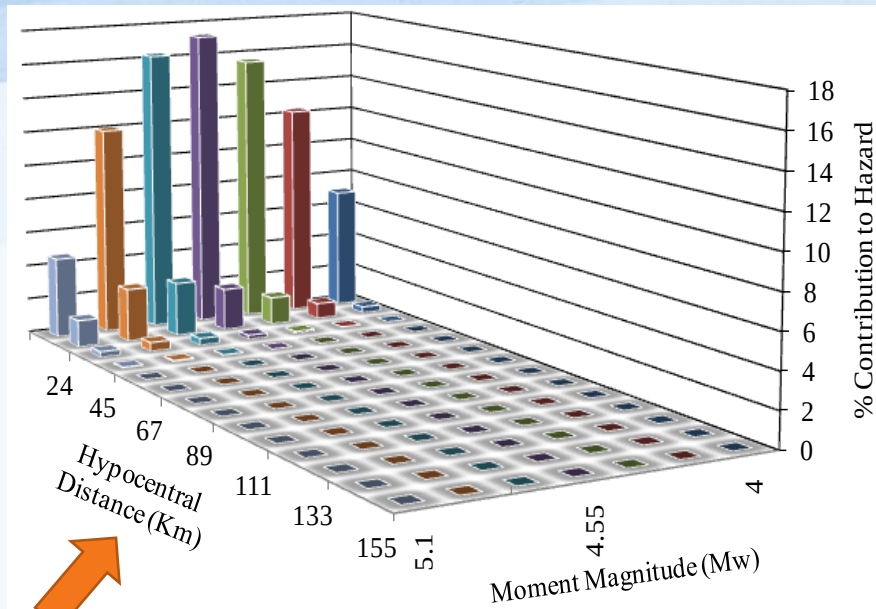
TGS 2026-Seismic Hazard analysis

Hazard curves for Ten most contributing sources at Lucknow city centre for zero

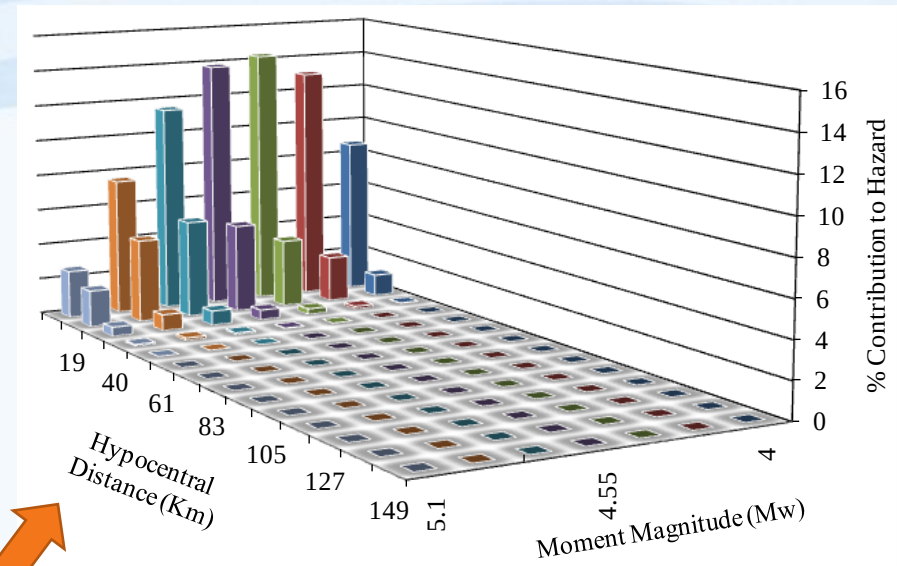


Hazard curves for different periods at Lucknow city centre

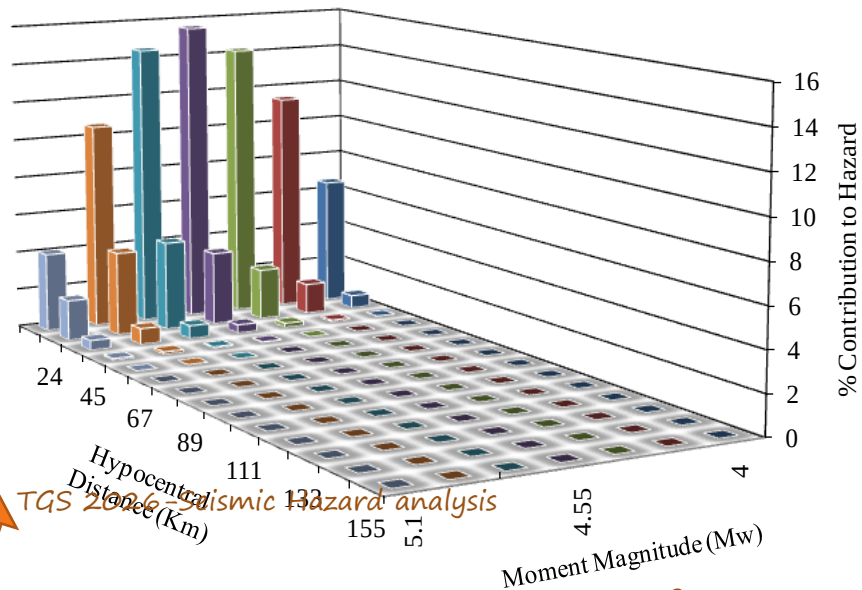
Ref: Kumar et al. (2013)



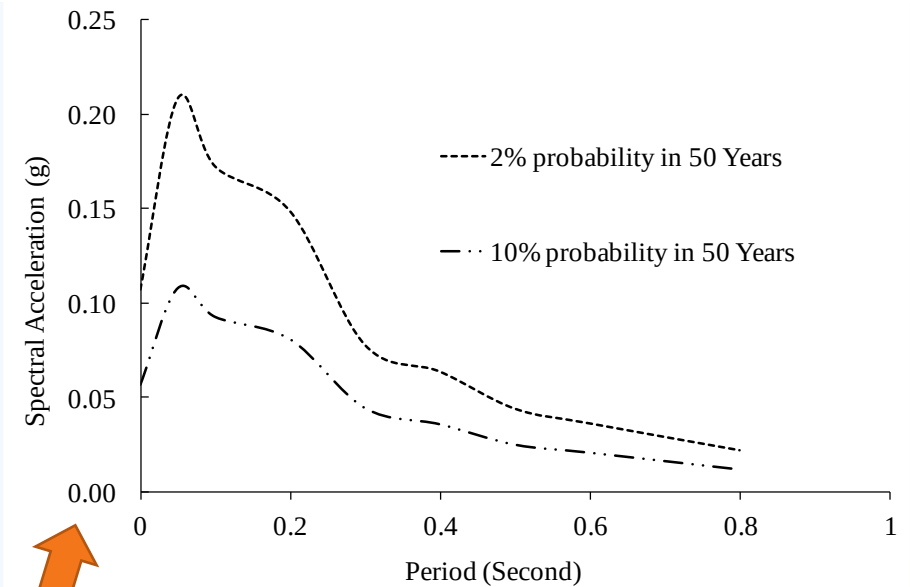
F117 at Lucknow city centre



F117 in the northern part of Lucknow

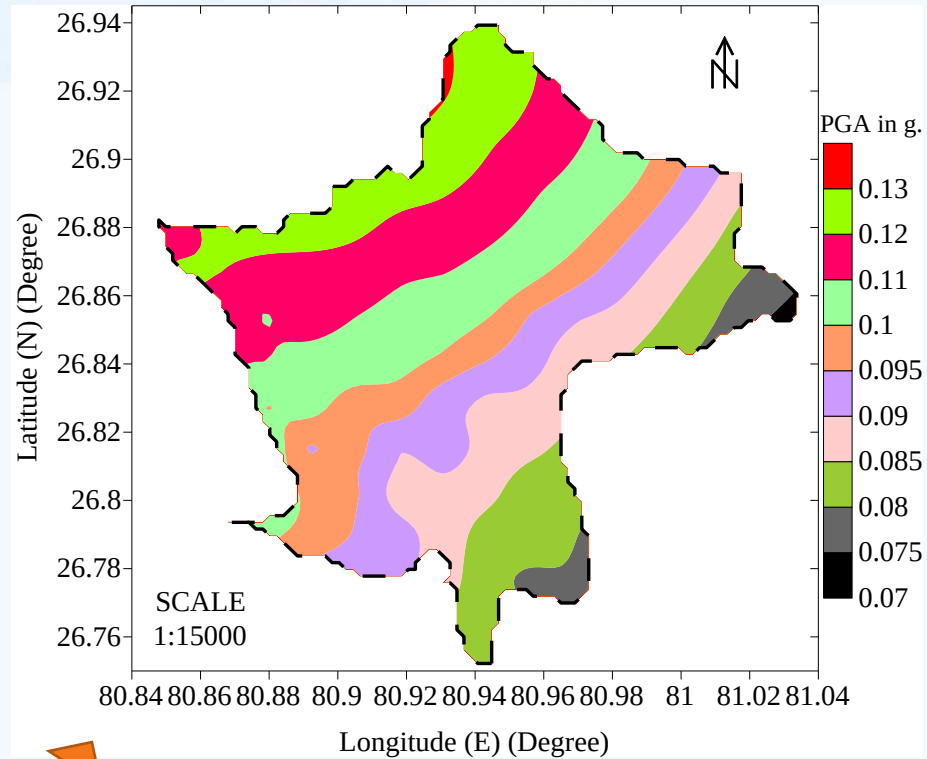


F117 in the western part of Lucknow

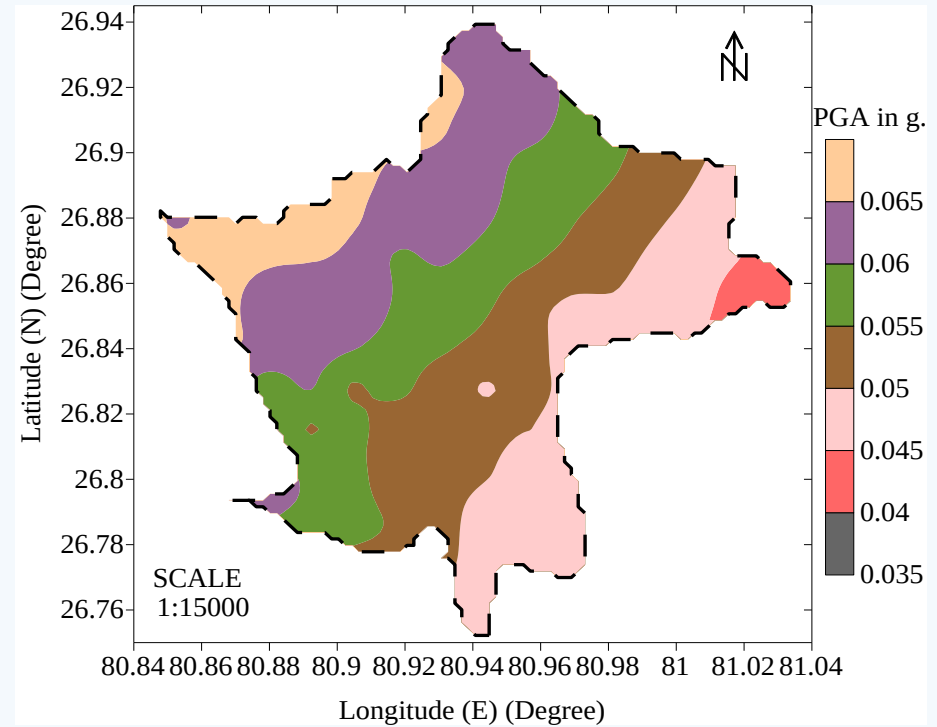


Uniform hazard spectra (UHS) at Lucknow city centre

PSHA maps for Lucknow



PSHA for 2 % probability of exceedence in 50 years



PSHA for 10 % probability of exceedence in 50 years



Importance of identification of source zones in seismic hazard analysis

Introduction

- To reduce the economic and life losses during an EQ:

- Earthquake resistant design is most important.



Based on the seismic design parameters obtained from seismic hazard analysis.

- Two types of seismic hazard analysis (commonly):

- Deterministic

- Probabilistic



Most popular

- Fundamental step in Probabilistic seismic hazard analysis:

- Delineation of seismic source zones.

- Seismic source zones are the areas that:

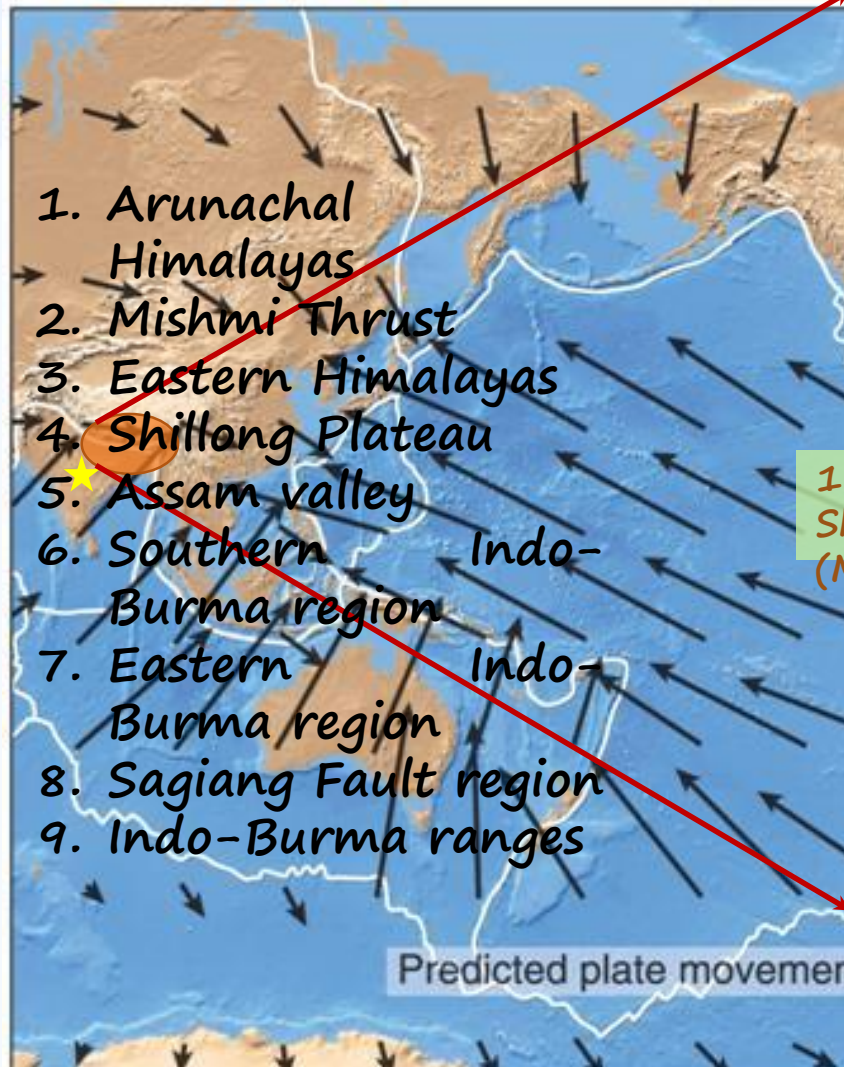
- Share common seismological, tectonic, and geologic attributes.

- Can be described by a unique magnitude-frequency relation.

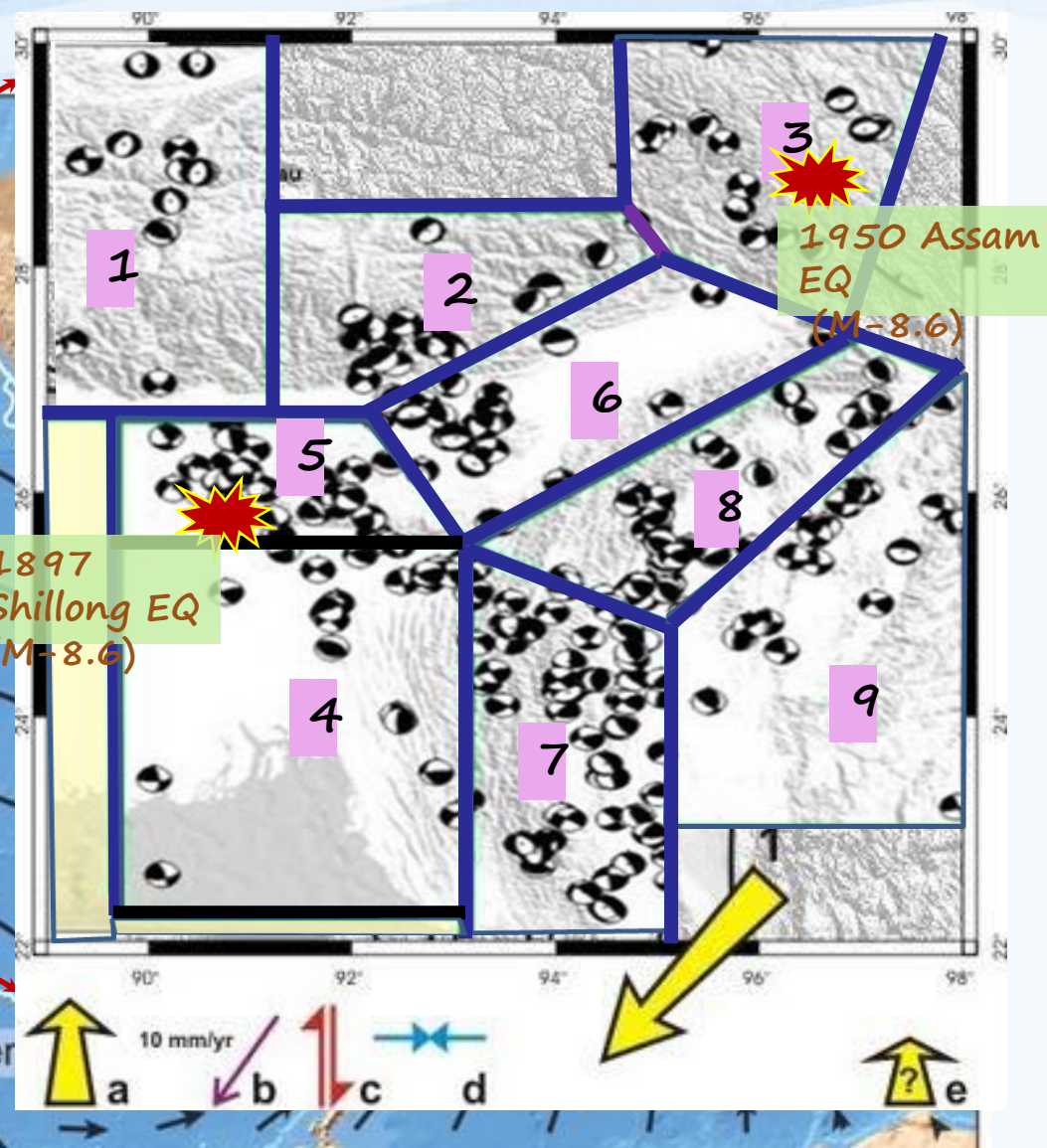
TGS 2026 - Seismic Hazard analysis

Types of seismic source zone

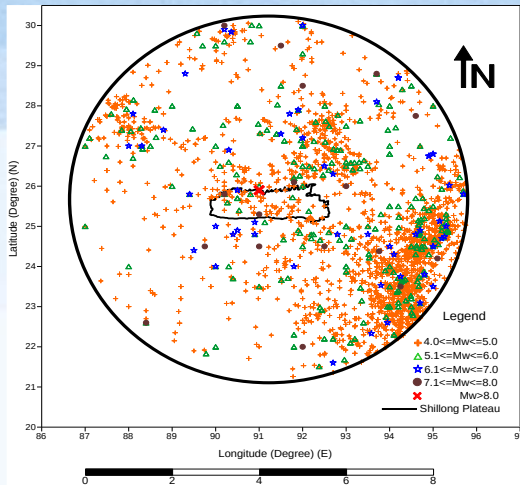
- Four types of seismic source zones (Thenhaus, 1986 and Araya and Der Kiureghian, 1988):
 - Seismotectonic zone
 - Casual relationship between faults and earthquakes established within the zones.
 - Process of mechanism and generation of earthquake can be studied.
 - Paleoseismic zone
 - Have an important Quaternary-Holocene structural history.
 - Have possibility of seismic activity in future.
 - Lack seismic history
 - Seismogenic zone
 - Lacks the development of a clear history relating the contemporary seismic activity to a geologic structure/faults.
 - Capable of generating earthquakes anywhere in the zone.
 - Seismicity zone
 - Based on spatial distribution of seismic history.
 - No fault information is utilized.



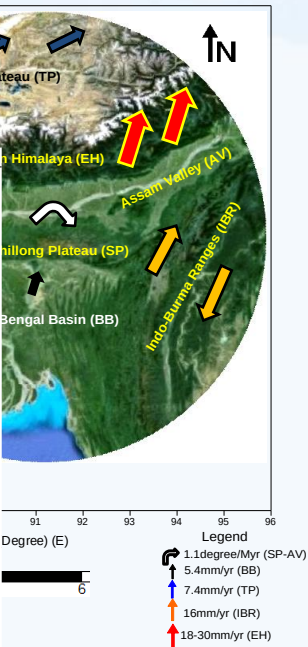
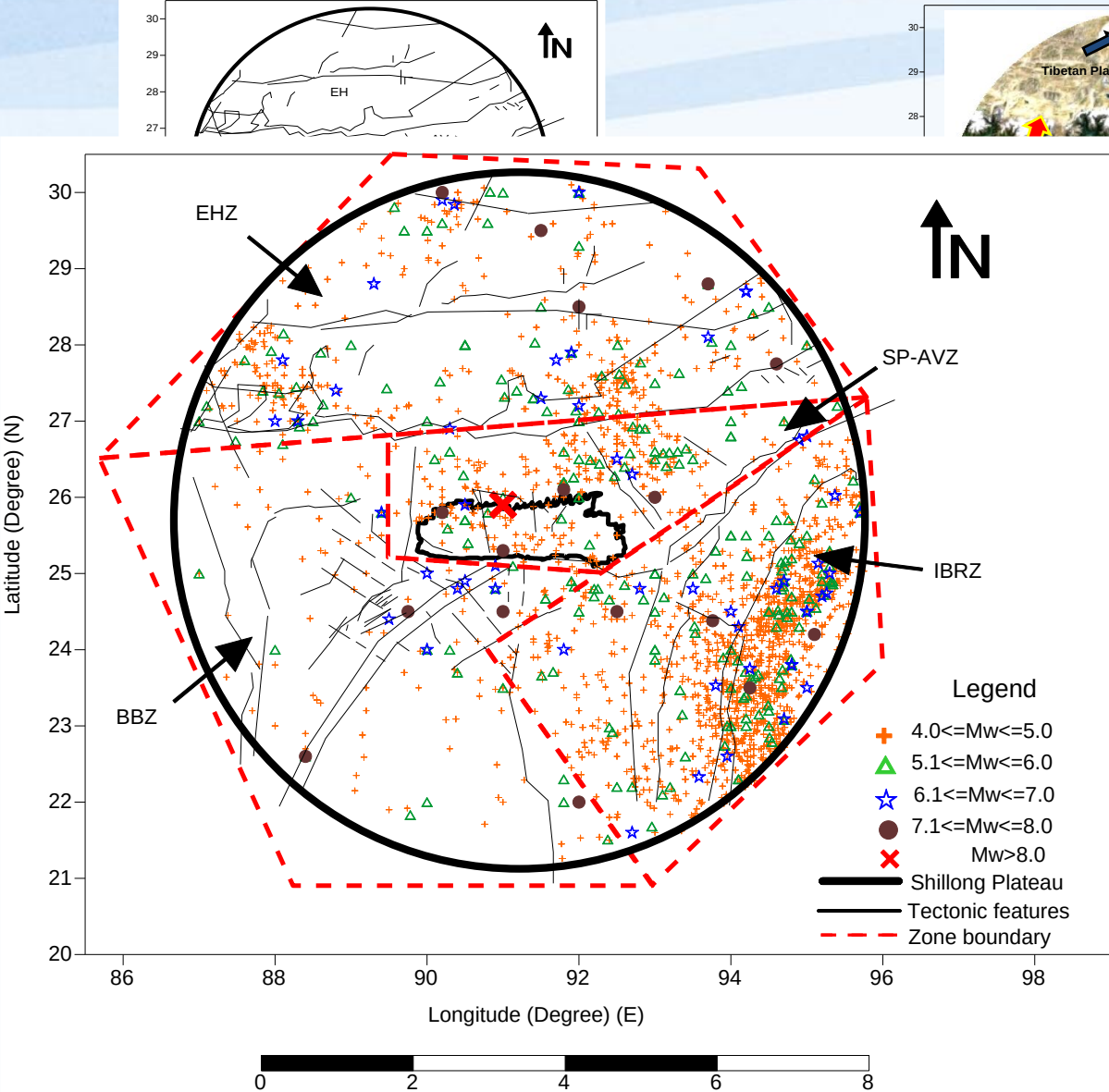
TGS 2026-Seismic Hazard analysis



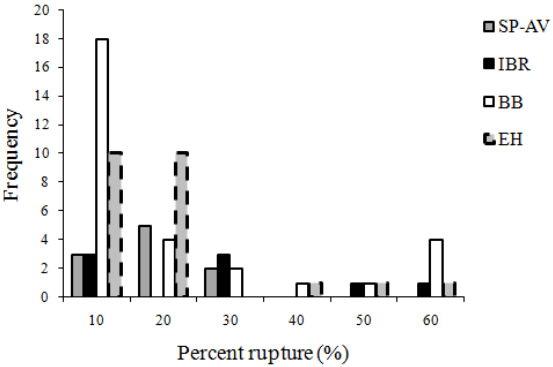
After Angelier and Baruah (2009)



Past EQs within 500km radial distance



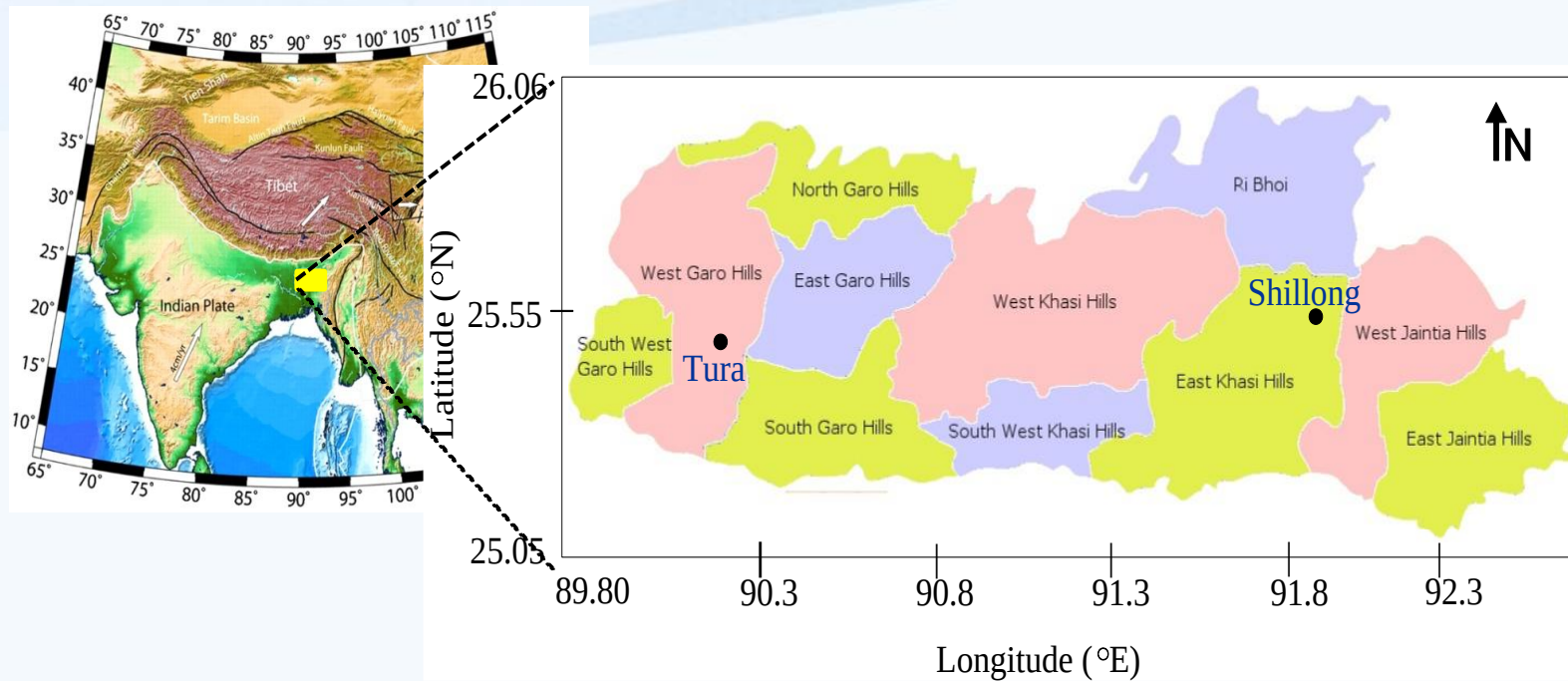
movement within tectonic region



Rupture characteristics across the seismotectonic province

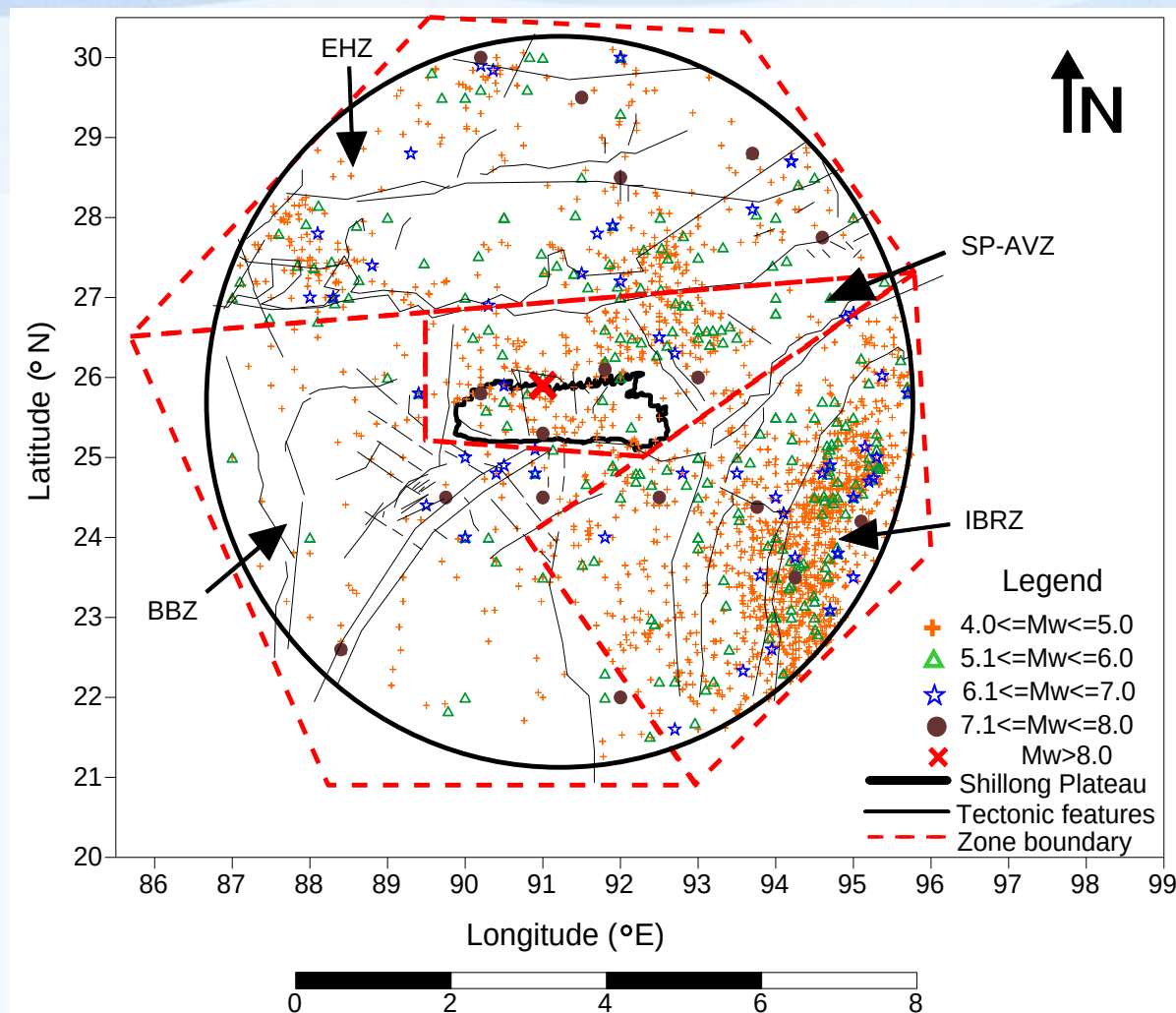
Ref: Baro and Kumar (2017)

Effect of the size of study area of weights of GMPEs



Study area of Meghalaya

TQS 2026-Seismic Hazard analysis



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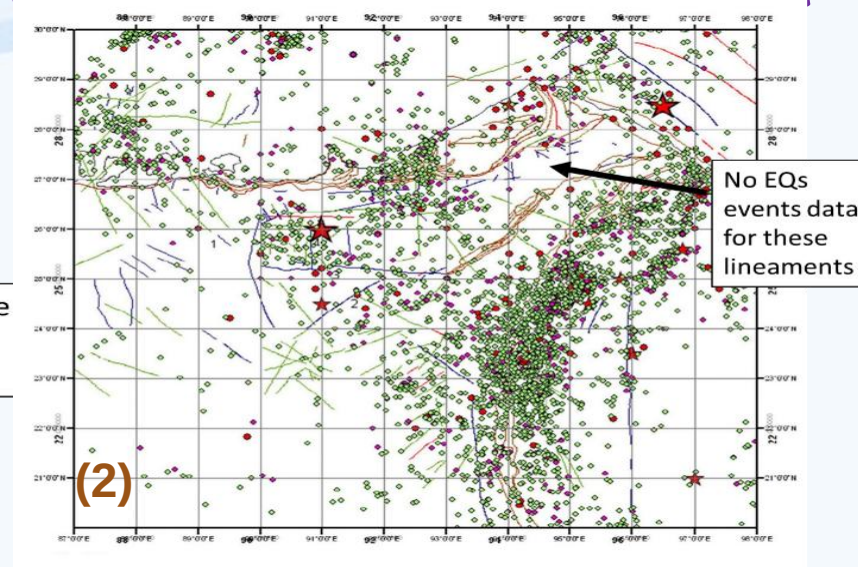
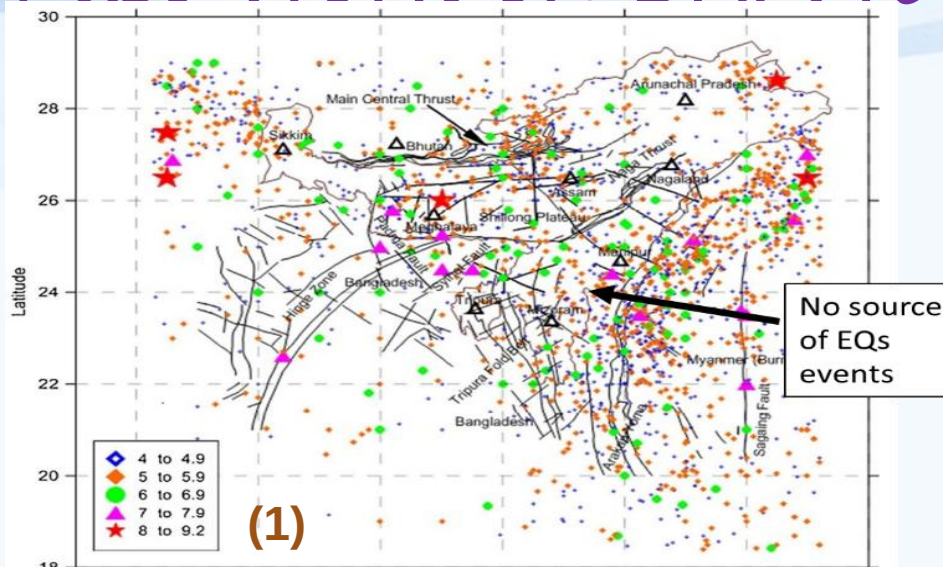
For Shillong City					
Zone	GMPEs	LLH values	DSI values	Rank	Weights
SP-AVZ	Toro (2002)	2.51	7.03	2	0.41
	Kanno et al (2006)	3.50	-46.06	4	-
	NDMA (2010)	1.98	55.02	1	0.59
	Anbazhagan et al. (2013)	2.86	-15.98	3	-
IBRZ	Toro (2002)	19.09	116.91	1	1
	Kanno et al (2006)	22.08	-72.74	4	-
	NDMA (2010)	20.70	-28.81	3	-
	Anbazhagan et al. (2013)	20.45	-15.35	2	-
BBZ	Toro (2002)	8.74	16.86	2	0.33
	Kanno et al (2006)	10.20	-57.68	4	-
	NDMA (2010)	8.89	5.00	3	0.29
	Anbazhagan et al. (2013)	8.52	35.81	1	0.38

For Tura					
Zone	GMPEs	LLH values	DSI values	Rank	Weights
SP-AVZ	Toro (2002)	2.82	-26.45	3	-
	Kanno et al (2006)	4.19	-71.58	4	-
	NDMA (2010)	2.80	-25.12	2	-
	Anbazhagan et al. (2013)	1.22	123.16	1	1
IBRZ	Toro (2002)	6.13	11.56	2	0.31
	Kanno et al (2006)	7.66	-61.46	4	-
	NDMA (2010)	6.26	1.83	3	0.28
	Anbazhagan et al. (2013)	5.72	48.06	1	0.41
BBZ	Toro (2002)	8.37	20.47	1	0.35
	Kanno et al (2006)	9.52	-45.71	4	-
	NDMA (2010)	8.38	19.63	2	0.35
	Anbazhagan et al. (2013)	8.56	5.60	3	0.31

Past Work on SHA for different parts of NE India

Studied by	EQ catalogue duration	Data completeness	4 ≤ Mw < 5	5 ≤ Mw < 6	6 ≤ Mw < 7	7 ≤ Mw < 8	8 ≤ Mw
<i>Sharma and Malik (2006)</i> (NE India)	1762-2001 AD (1220 events)	Not performed					
<i>Kanth et al. (2009)</i> (Imphal)	1869 Cachar EQ, 8.1Mw in Indo-Burma	No catalogue					
<i>Pallav et al. (2012)</i> (Manipur)	825-2009 AD (2774 events)	yes	1959–2009	1909–2009	1809–2009	1609–2009	Couldn't find
<i>Sitharam and Sil (2014)</i> (Tripura Mizoram)	1731-2011 AD (3251)	yes	1962-2011	1957-2011	1919-2011	1905-2011	1831-2011
Das et al. (2016) (NE India)	1897-2010 AD (2674)	yes	4.6–5.0 Mw (1960–2010)	5.1–5.5 Mw (1950–2010)	5.6–6.0 Mw (1920–2010)	Mw≥6.0 (1890–2010)	
Baro et al. (2018) (Shillong Plateau)	1411-2015 AD (2359)	yes	1975-2015	1915-2015	1895-2015	1855-2015	Couldn't find
Bahuguna and Sil (2018) (Assam)	1762-2015 AD (2882)	Yes	1971-2015	1961-2015	1921-2015	1881-2015	1811-2015

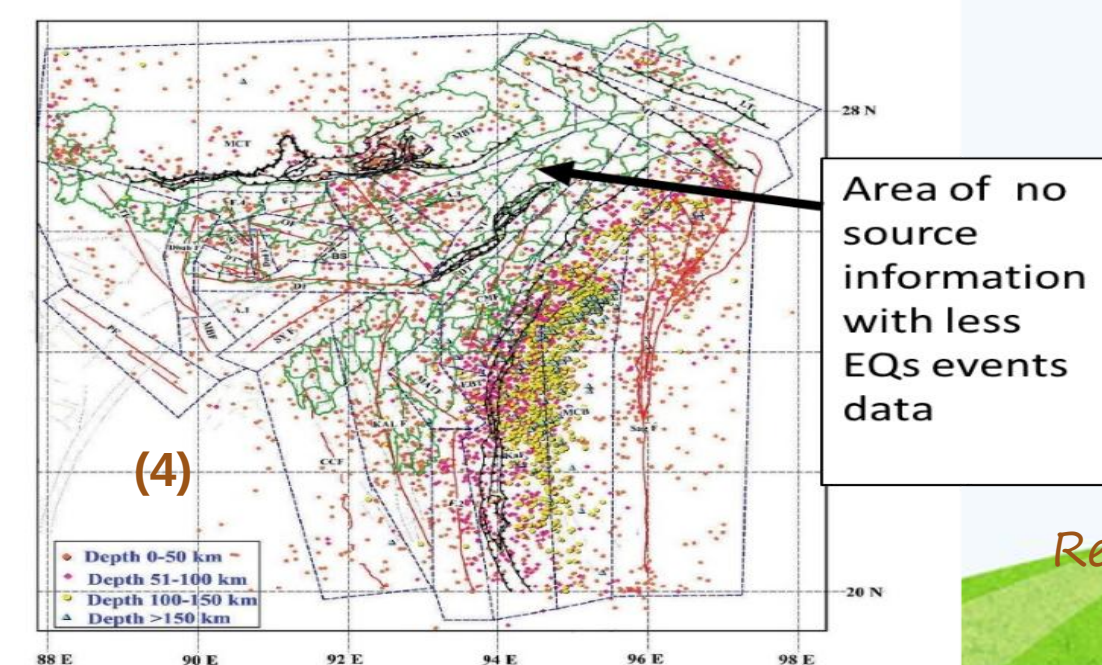
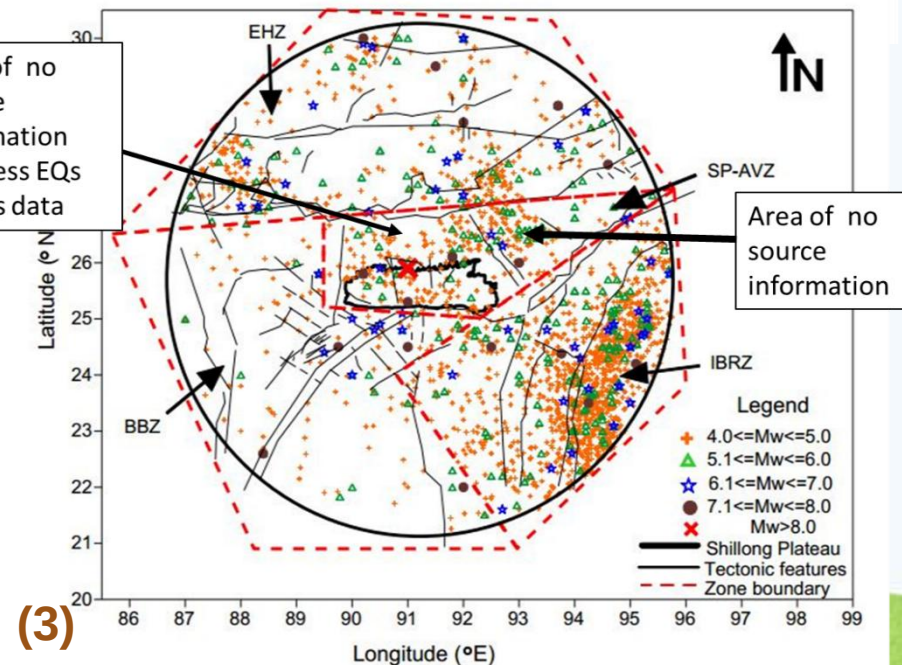
Past Work on SHA for different parts of NE India



— EQ Source

Figure:3 Seismotectonic map of the past researchers

1. Sitharam and Sil (2014)
2. Das et al. (2016)
3. Baro et al. (2018)
4. Bahuguna and Sil (2018)



Ref: Borah et al., (2018)

Data Collection

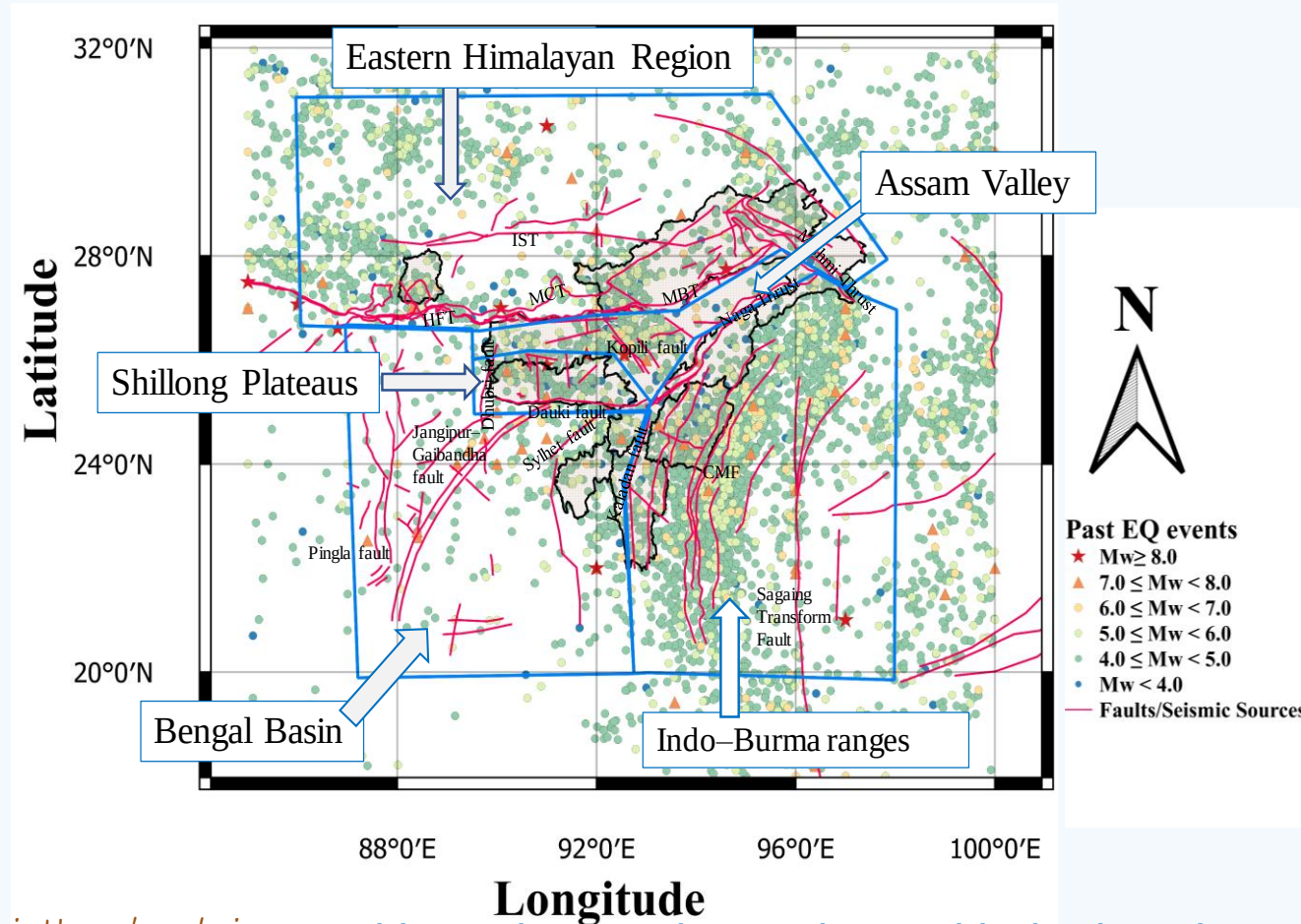
Past EQ data

- Sources: USGS, IMD, ISC NDMA (2010), NCS

- Magnitude
- Location
- Time of occurrence

Fault information

Sources: Bhukosh, past literature



TGS: 2026 Seismic Hazard analysis

Figure.4 Past EQs occurred in and around NEI along with the locations of faults

Methodology (Zonation based on EQ locations)

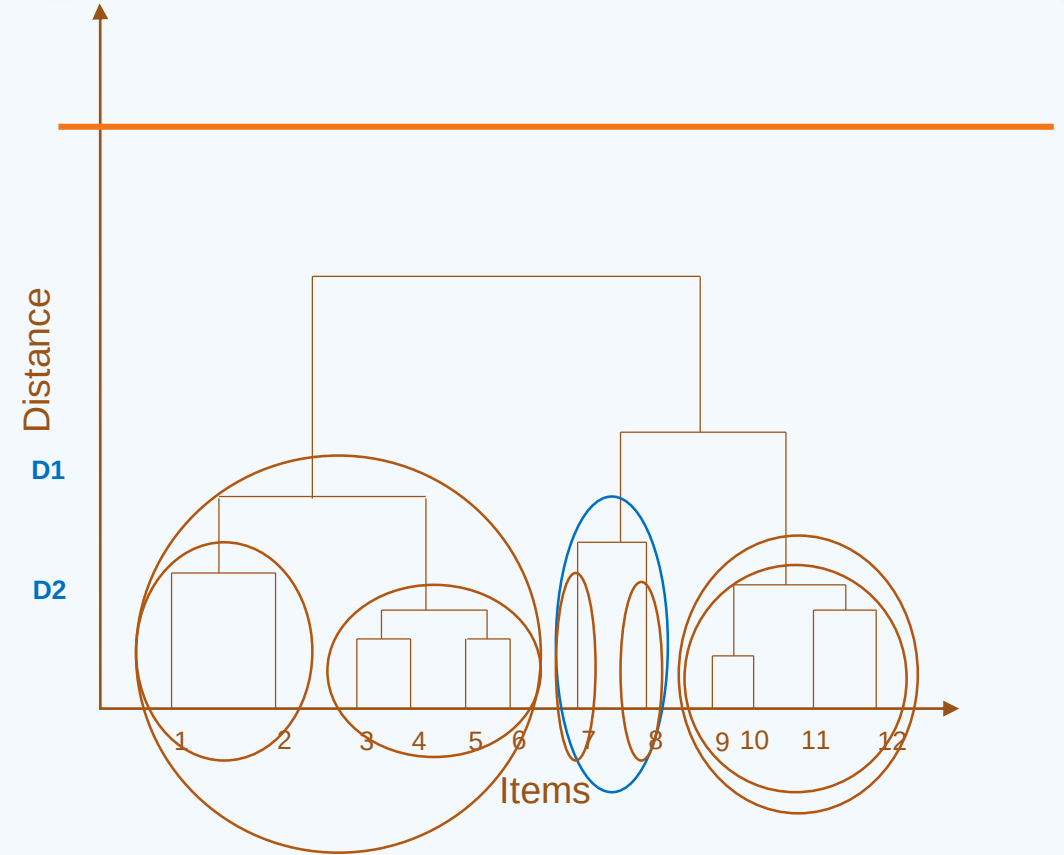
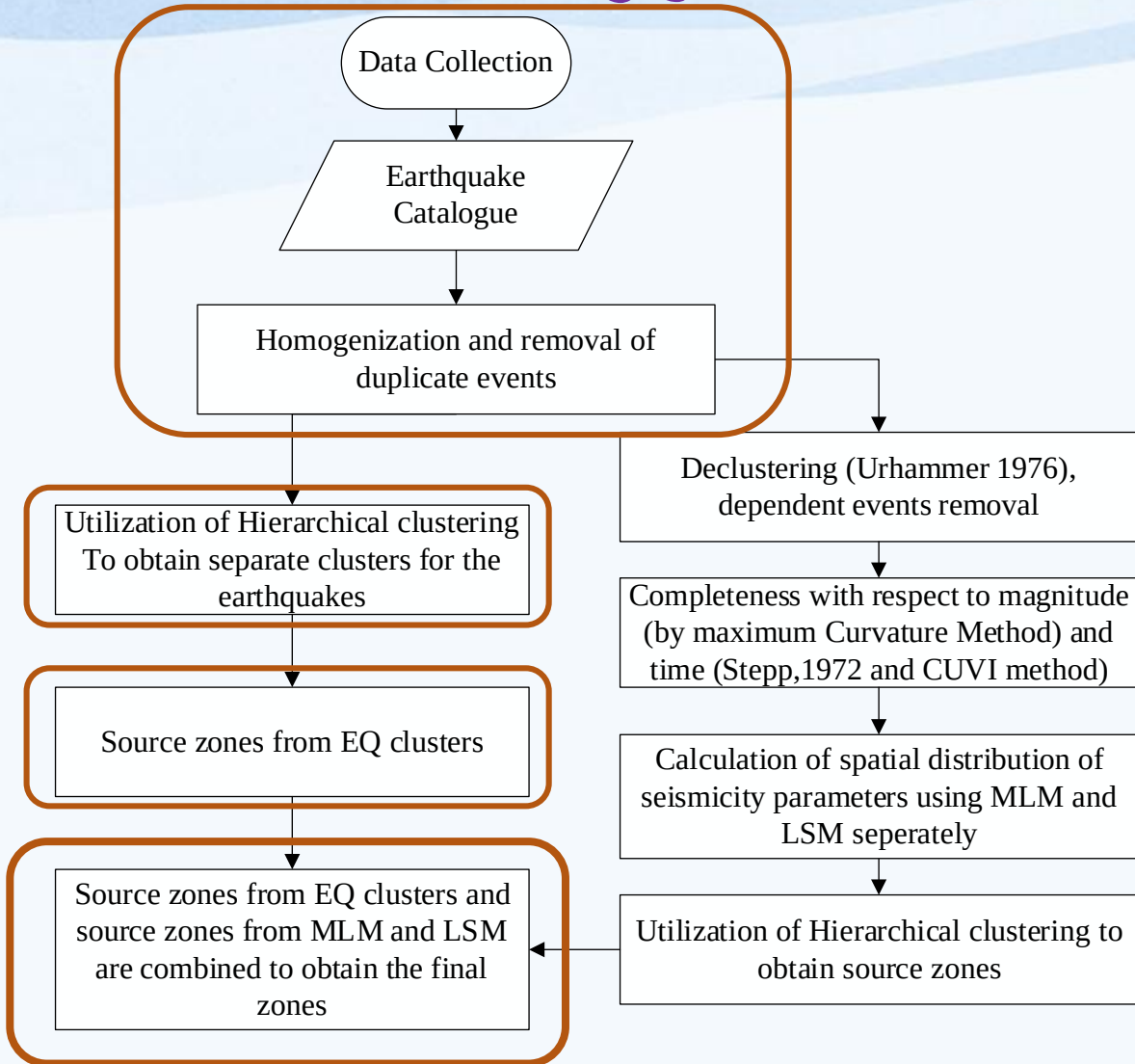


Figure:12 Hierarchical clustering

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Ref: Borah et al., (2021)

Source zones from clustering of EQ locations

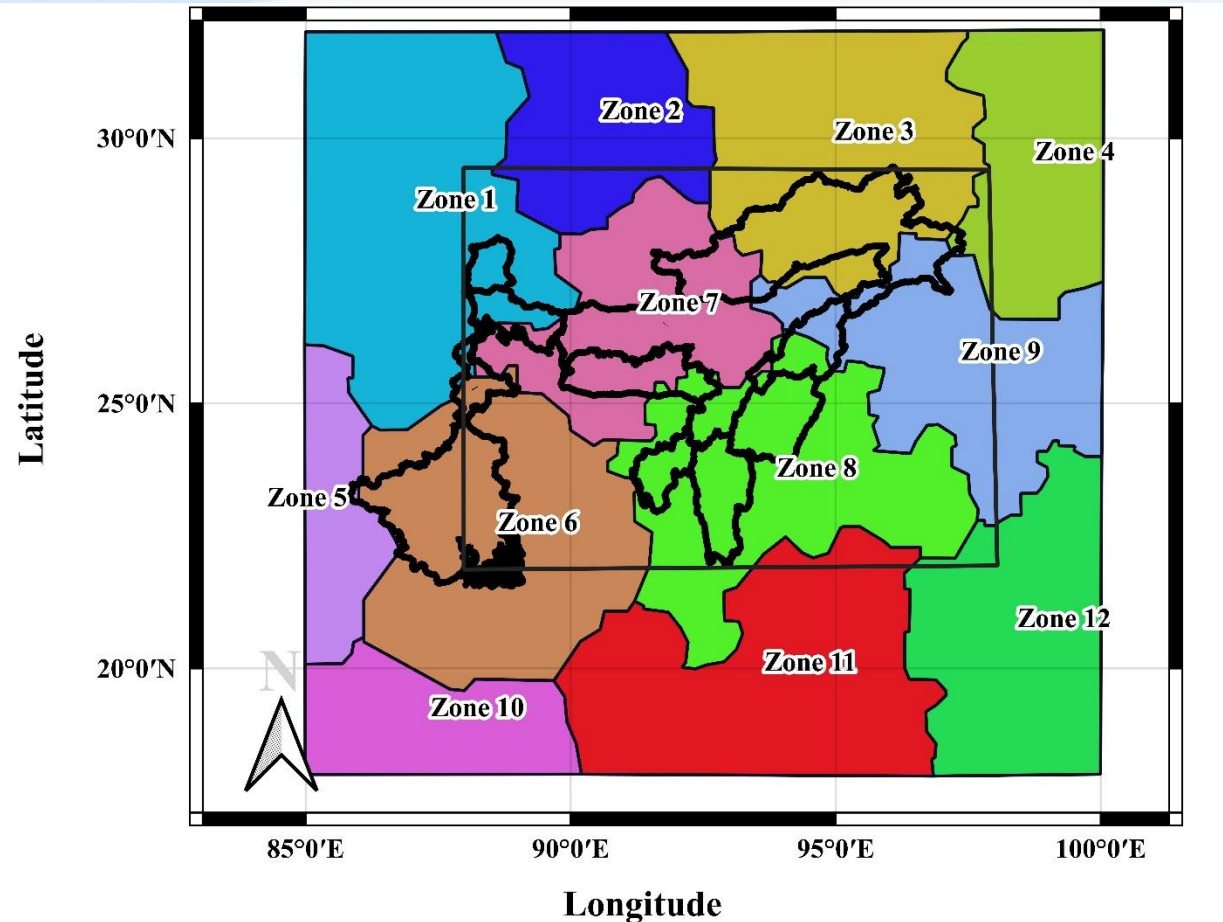
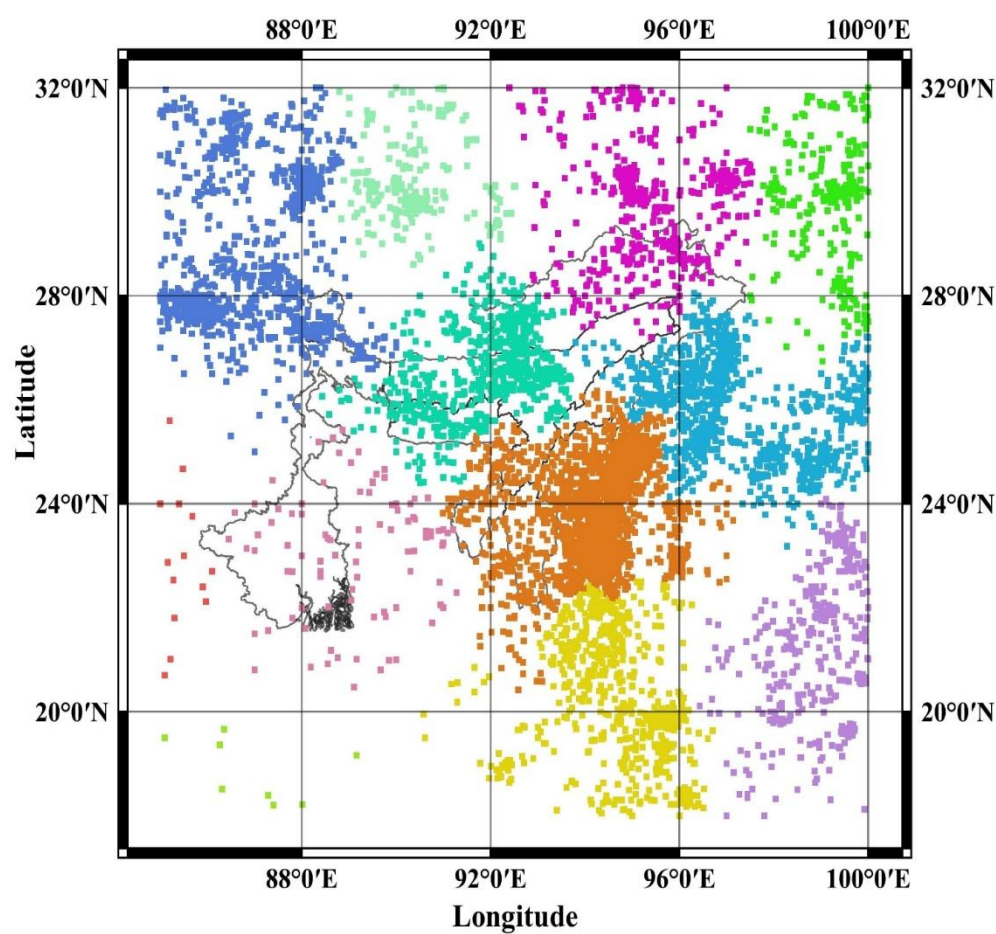


Figure:13(a) Hierarchical clustering of past EQs

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Figure:13(b) Source zonation based on of past EQs location

Ref: Borah et al., (2021)

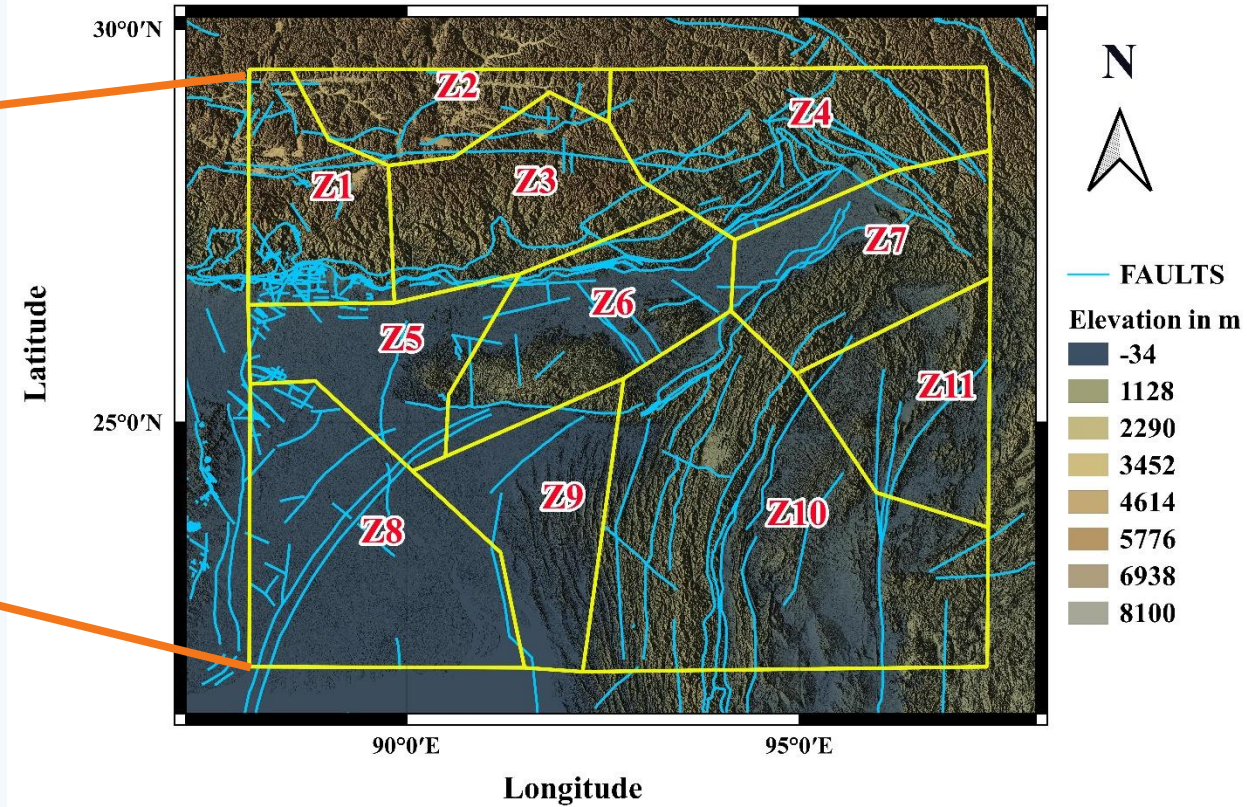
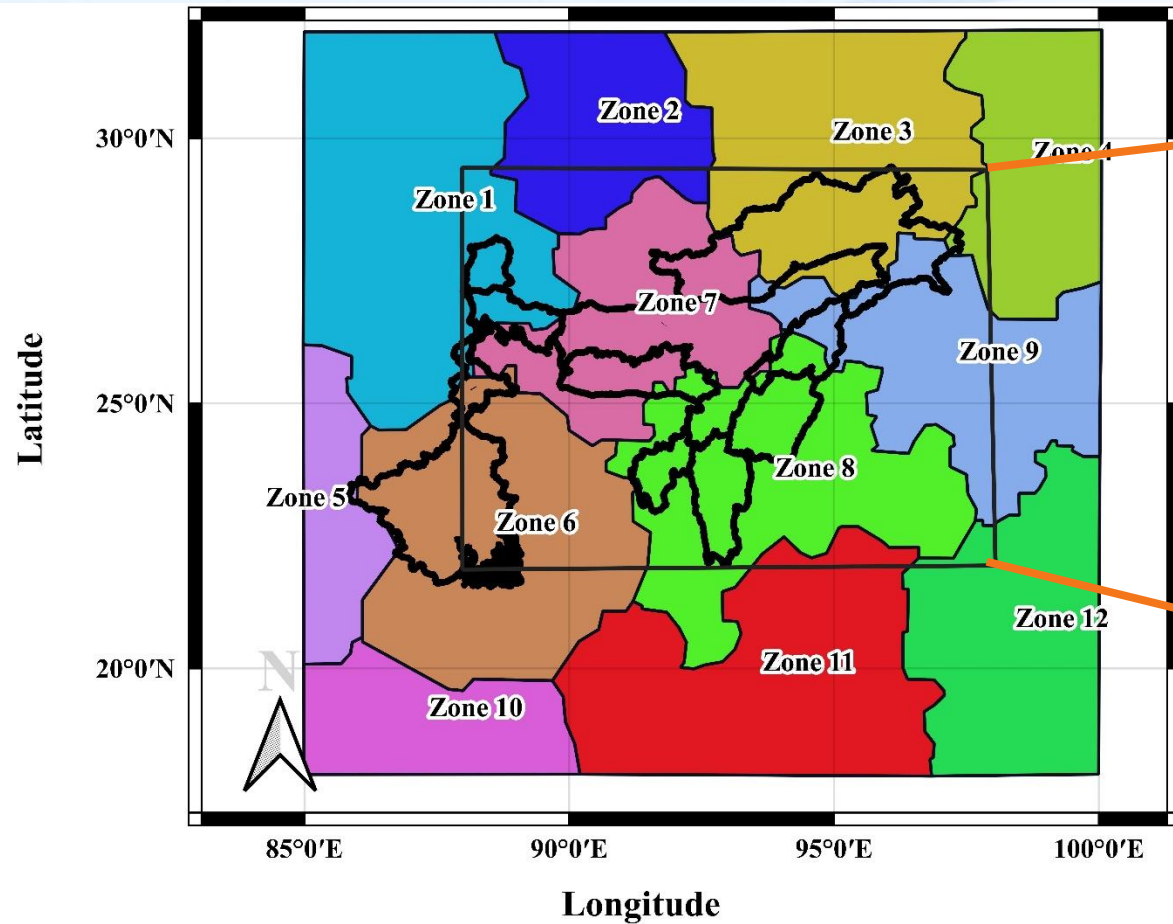
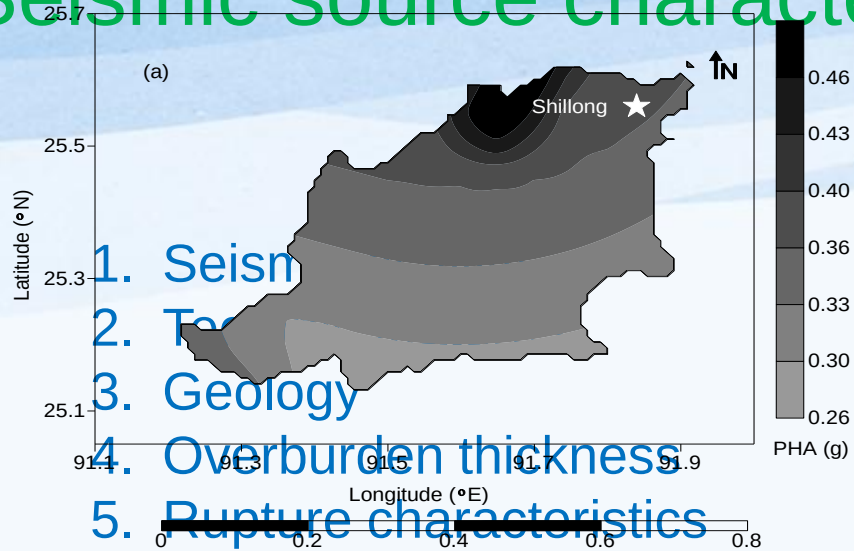


Figure:20 Source zonation based on of past EQs location and distribution of seismicity parameters

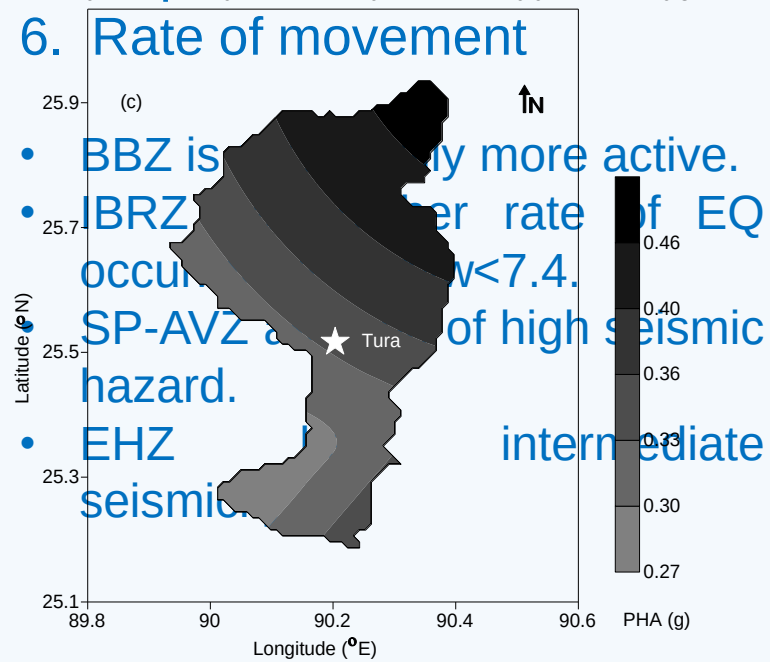
TGS 2026-Seismic Hazard analysis

Ref: Borah et al., (2021)

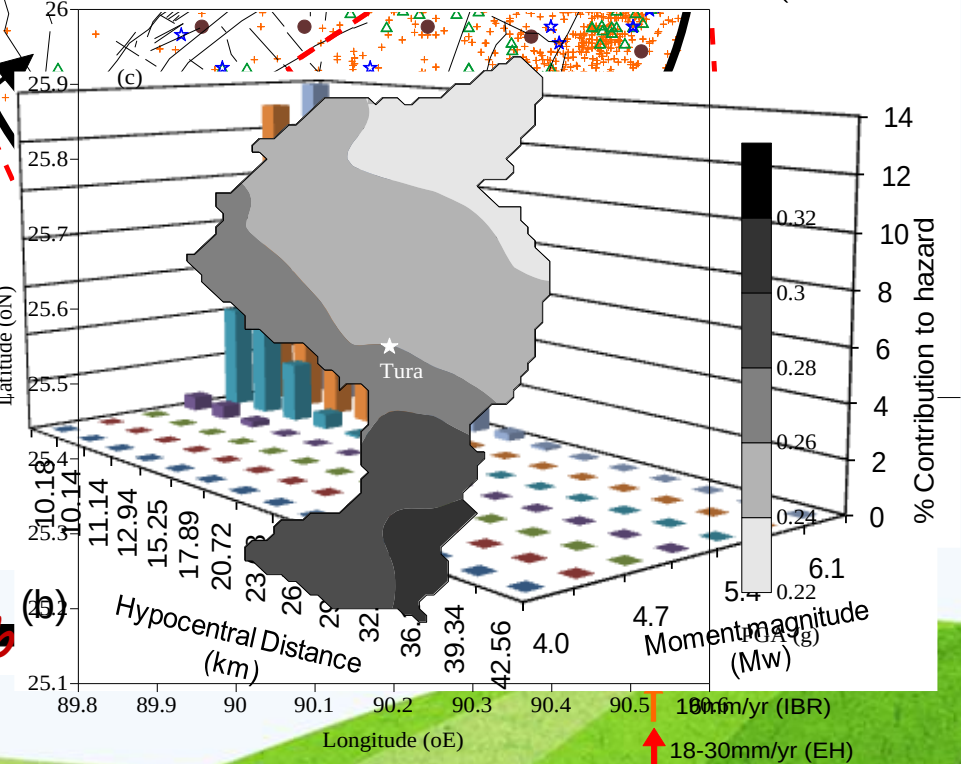
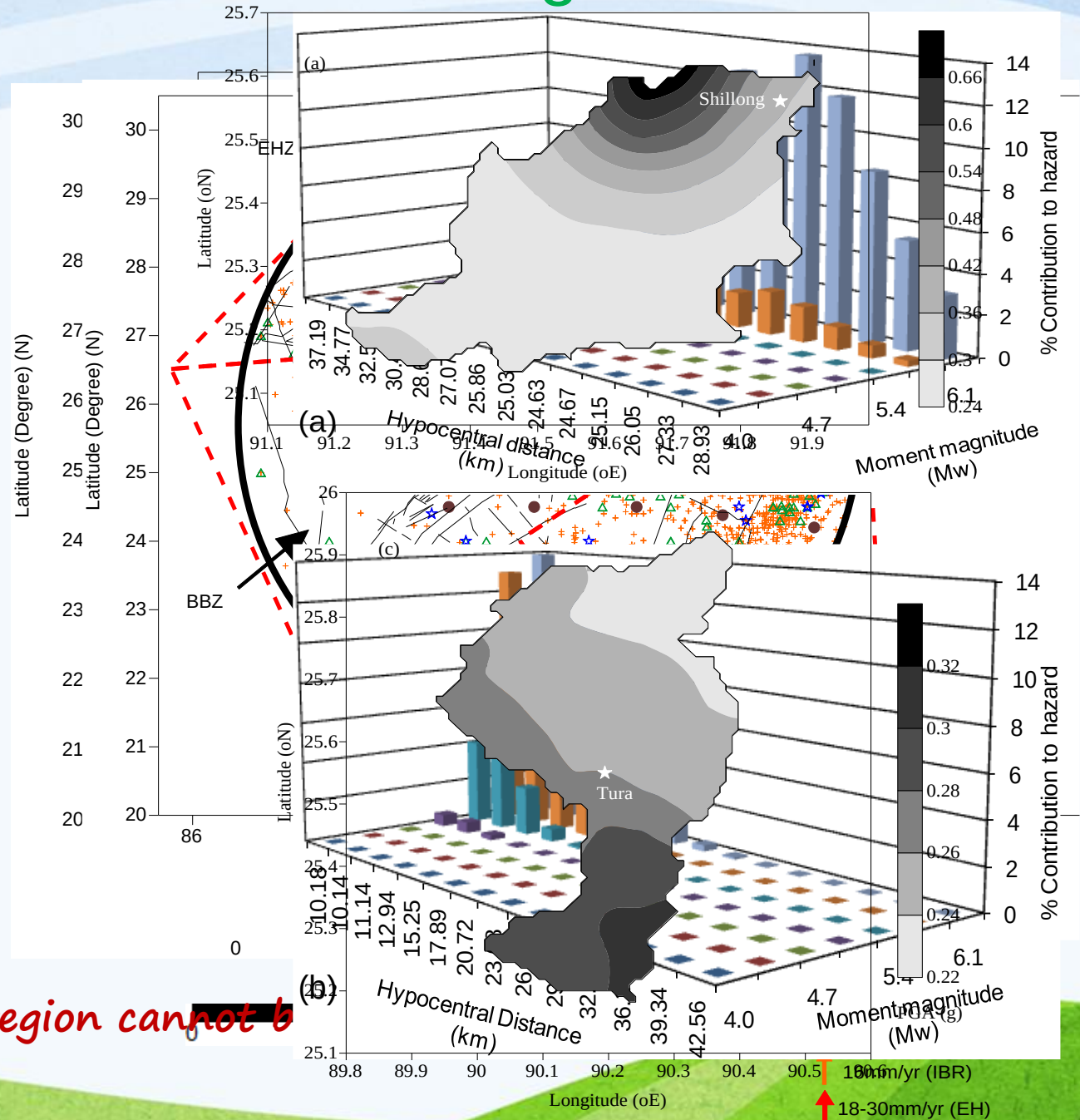
Seismic source characterization of the Shillong Plateau



1. Seism
2. Tect
3. Geology
4. Overburden thickness
5. Rupture characteristics
6. Rate of movement



- BBZ is highly more active.
- IBRZ has higher rate of EQ occurrence $M < 7.4$.
- SP-AVZ and Tura are of high seismic hazard.
- EHZ is of intermediate seismic hazard.

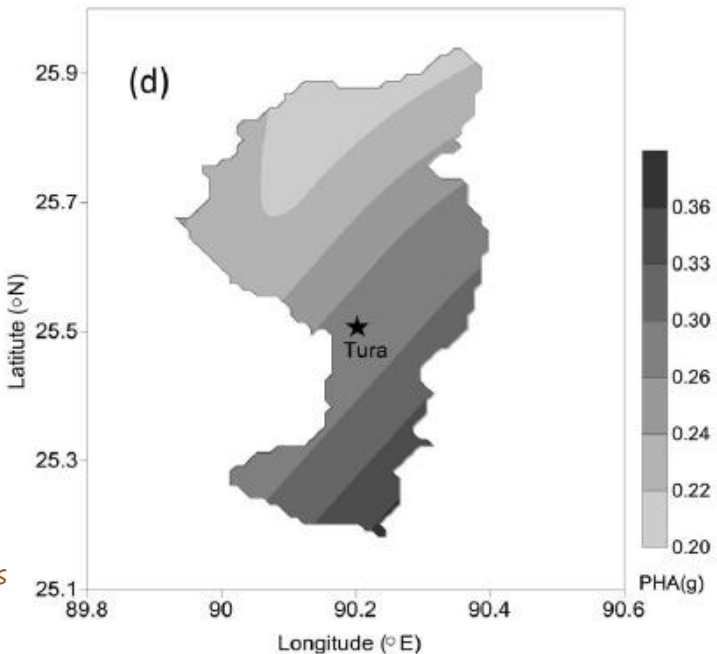
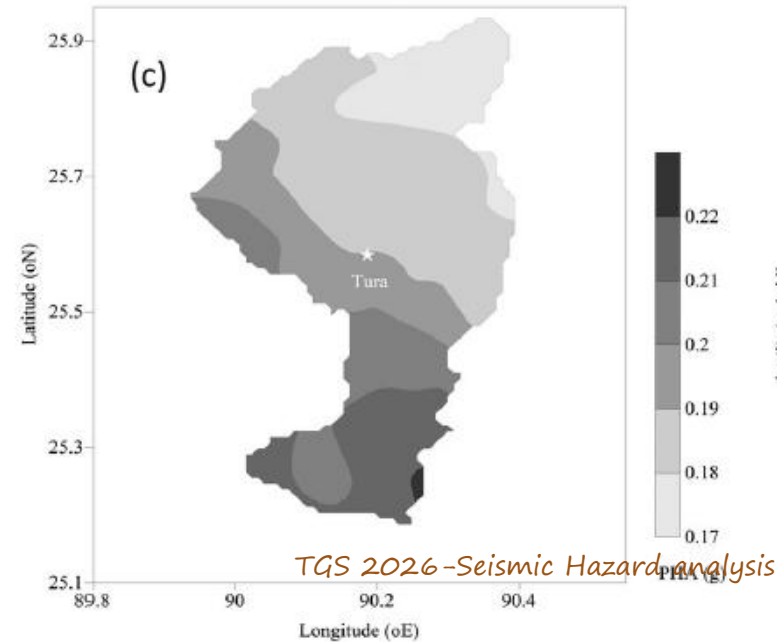
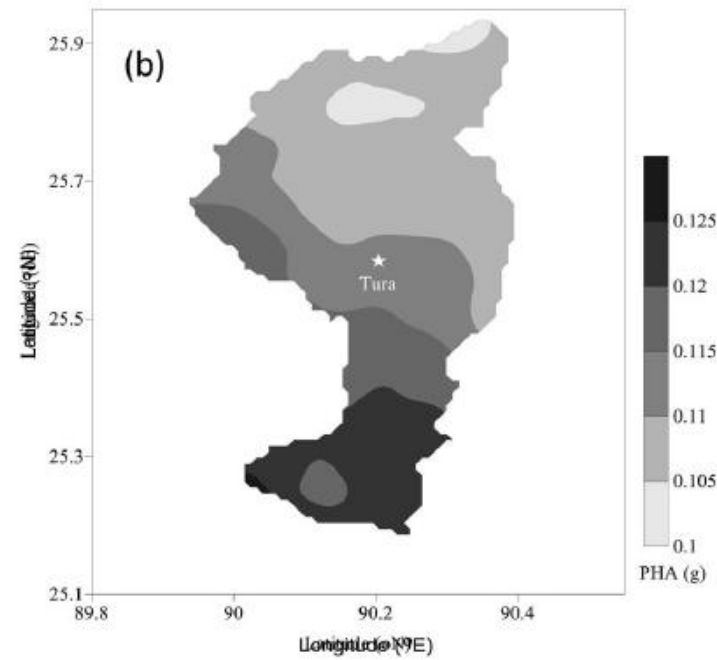
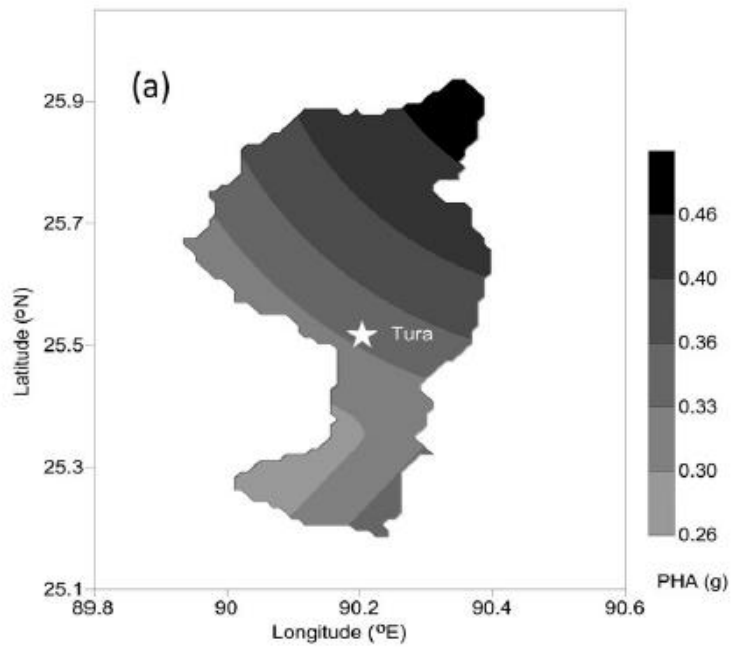


Seismic hazard of entire region cannot be selected GMPEs

Ref: Baro and Kumar (2017)

TGS 2016 - Seismic Hazard analysis

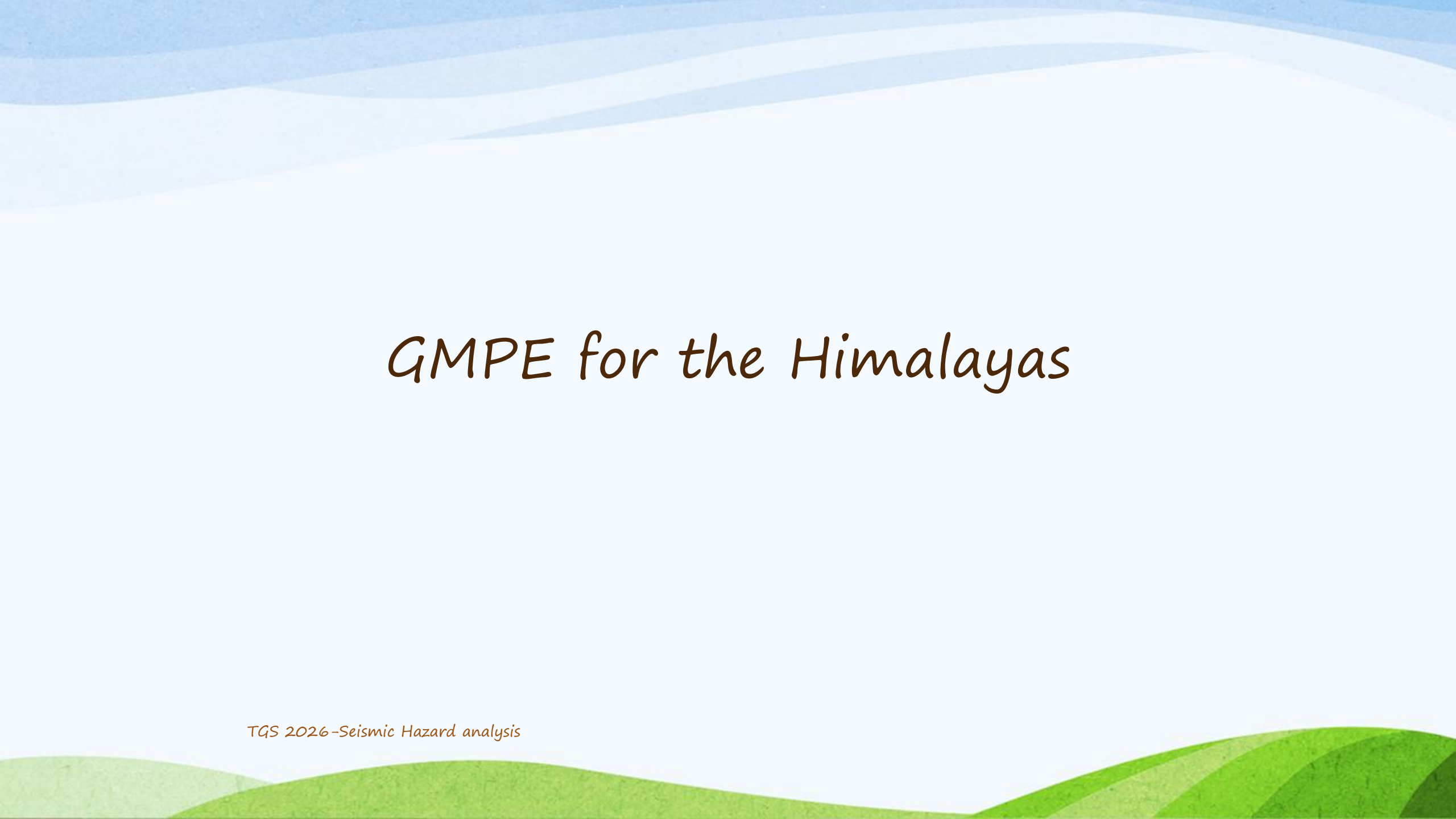
100mm/yr (IBR)
18-30mm/yr (EH)



Hazard maps for the West Garo hills: (a) DSH assessment map, (b) PSH assessment map for 10% probability of exceedance; (c) PSH assessment map for 2% probability of exceedance; (d) DSH assessment map with no contribution of the Oldham fault.

*Ref: Baro et al.,
(2021)*

TGS 2026-Seismic Hazard analysis



GMPE for the Himalayas

TQS 2026-Seismic Hazard analysis

Ref: Anbazhagan et al. (2013)

the site.

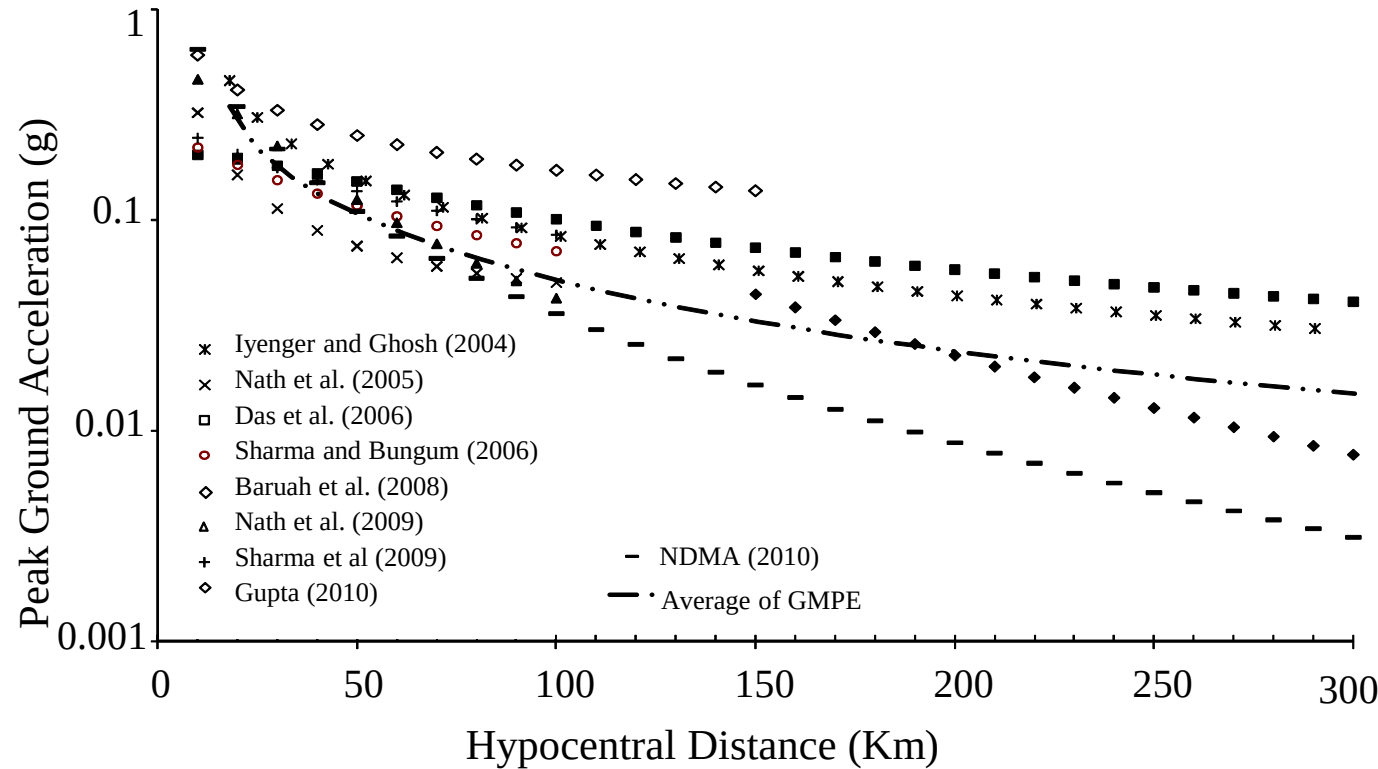
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Gro
(GM)

- Empirical
- Such equation the GMPE us
- Due to limite
- Existing GMF for.



No.	Reference	Database	(Mw)	Distance (Km)
1.	Singh <i>et al.</i> (1996)	Recorded data 5 earthquakes	5.7-7.2	≤ 400
2.	Sharma (1998)	66 recorded data from 6 earthquakes	5.5-6.8	≤ 150
3.	Nath <i>et al.</i> (2005)	80 recorded data and 25 simulated events	3-8.5	≤ 100
4.	Das <i>et al.</i> (2006)	261 recorded data from 6 earthquakes	5.5-7.2	≤ 300
5.	Sharma and Bungum (2006)	Combined dataset -14 Indian recorded events & and 9 from Europe	4.6-7.8	≤ 200
6.	Baruah <i>et al.</i> (2009)	82 recorded earthquakes at 8 broadband stations	2.5-5.0	≤ 145
7.	Nath <i>et al.</i> (2009)	Simulated ground motions	4.8-8.1	≤ 100
8.	Combined dataset consisting of recorded earthquakes from India and 10 recorded earthquakes from Zegros region	Combined dataset (Hazard analysis)	5.2-6.9	≤ 400
9.	Gupta (2010)	56 recorded data from 3 events	6.3-7.2	≤ 375
10.	NDMA (2010)	1600 Simulated ground motions	4-8.5	≤ 500

- Need of a new GMPE for Himalayan region covering wide range of magnitudes and hypocentral distance.

Earthquakes considered for GMPE

Ref: Anbazhagan et al. (2013)

Sl. No	List Earthquake (EQ)	Latitude (N)	Longitude (E)	(Mw)	Strike (°)	Dip (°)	Focal depth (km)	Source of Fault Plane Solution
1	1897 Shillong EQ	26	91	8.1	292	40	35	Nath et al. (2009)
2	1905 Kangra EQ	32.50	76.60	7.8	322	55	18	Singh, (1987)
3	1934 Bihar-Nepal EQ	26.60	86.80	8.0	280	30	14.8	Nath et al. (2009)
4	1950 Assam EQ	28.38	96.68	8.7	333	57.5	35	Nath et al. (2009)
5	1986 NE India EQ	25.42	92.08	5.4	253	20	43	Singh, (1987)
6	1986 Dharmasala EQ	32.18	76.29	5.4	299	19	7	CMT Harvard
7	1987 India-Burma EQ	25.27	94.20	5.9	34	32	50	Singh, (1987)
8	1988 India-Bangladesh EQ	24.64	91.51	6.0	110	28	15	Singh, (1987)
9	1988 Manipur EQ	25.15	95.13	7.1	284	45	90	Nath et al. (2009)
10	1991 Uttarkashi EQ	30.75	78.86	6.8	317	11	15	CMT Harvard
11	1991 Chamoli EQ	30.75	78.86	6.8	317	11	15	CMT Harvard
12	2005 Kashmir EQ	33.08	74.79	7.6	285	10	10	Raghukanth (2008a)
13	2005 Sikkim EQ	27.25	88.55	6.7	285	10	10	CMT Harvard

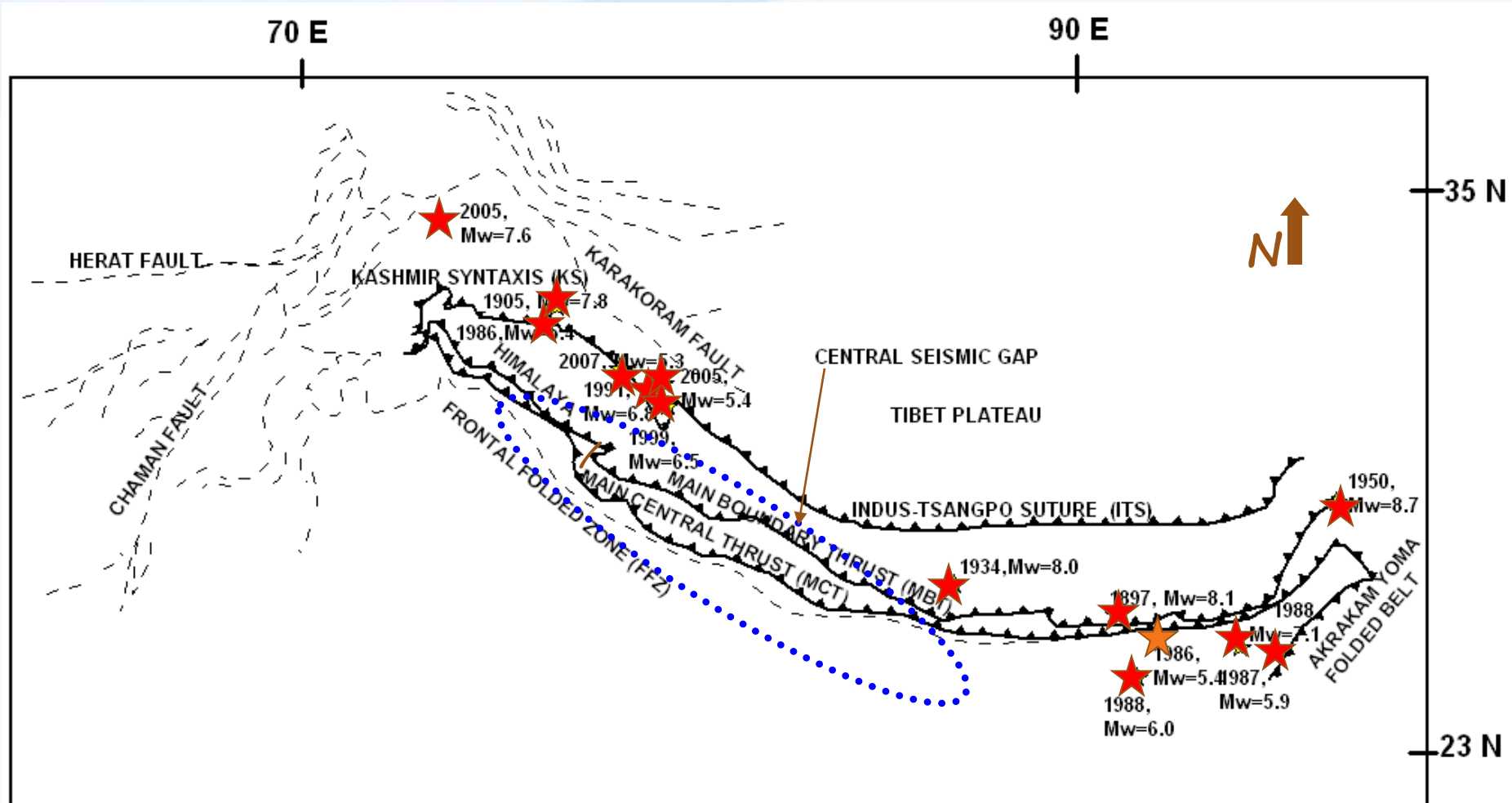
Validation of Seismic Hazard analysis

2008 Pithoragarh

Earthquake
Magnitude
2011 India-Nepal
2011 Sikkim

Magnitude
4.3
5.7
6.8

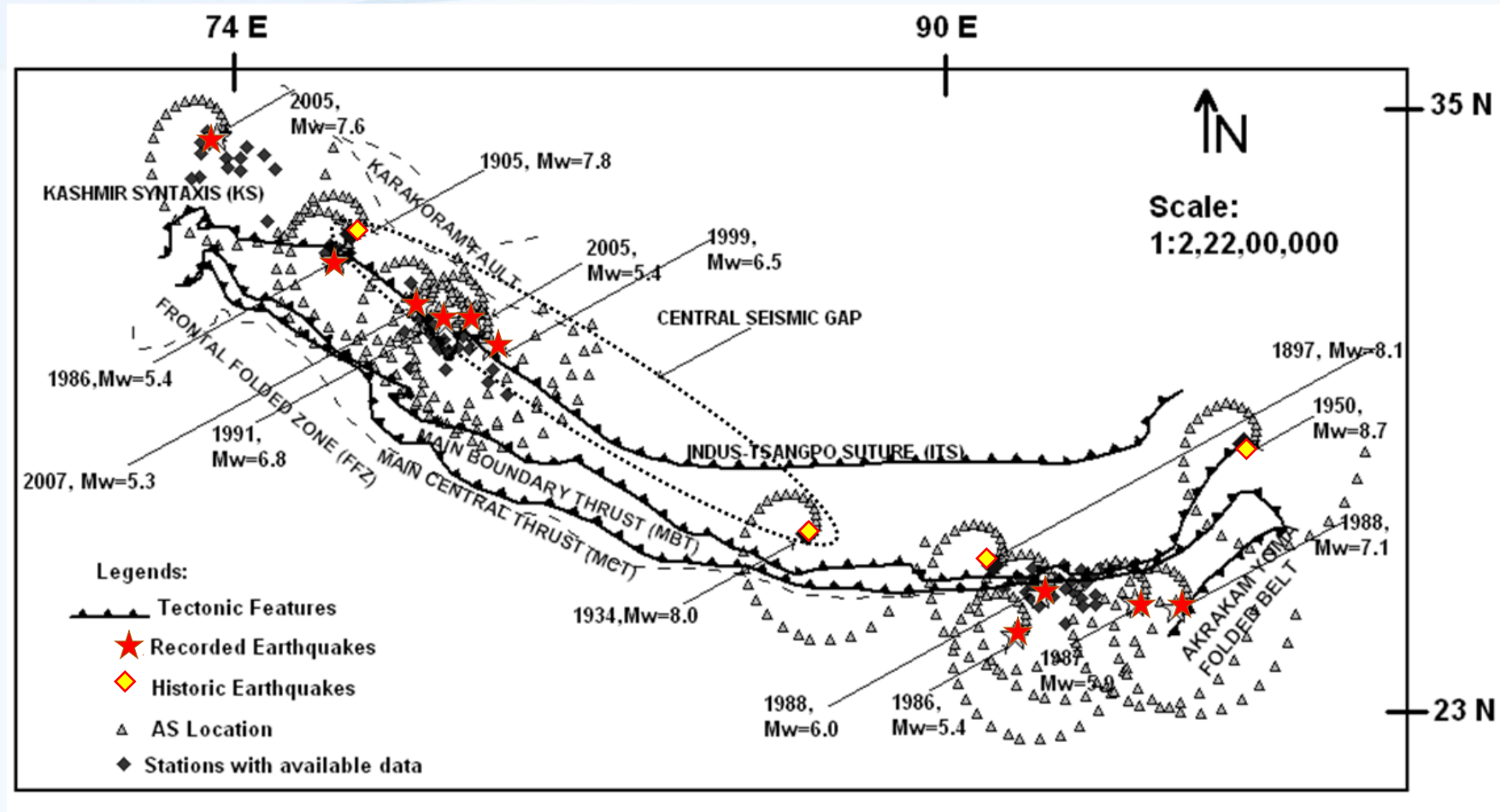
EARTHQUAKES CONSIDERED FOR GMPE



TQS 2026-Seismic Hazard analysis

Ref: Anbazhagan et al.
(2013)

Earthquakes considered for GMPE



TQS 2026-Seismic Hazard analysis

Ref: Anbazhagan et al.
(2013)

Regression analysis

- In total 420 (14x 30) synthetic ground motions generated.
- Combined database have been analyzed using two step regression procedure by Fukushima and Tanaka (1990)
- Used by Sharma(1998), Sharma and Bungum (2006), Fukushima and Tanaka (1990).
- General form of GMPE for Himalayan region is given below and adopted by Singh *et al.*, (1996); Sharma (1998); NDMA, (2010); Sharma and Bungum (2006);

$$\log (y)=c_1+c_2 M-b \log (R+\exp (c_3 M))+\sigma$$

where, y is the Spectral acceleration in g , b, c_1, c_2 and c_3 are the regression coefficients. R and M are the hypocentral distance (km) and the moment magnitude respectively. σ is the standard error term in the above equation

TGS 2026-Seismic Hazard analysis

Ref: Anbazhagan *et al.*
(2013)

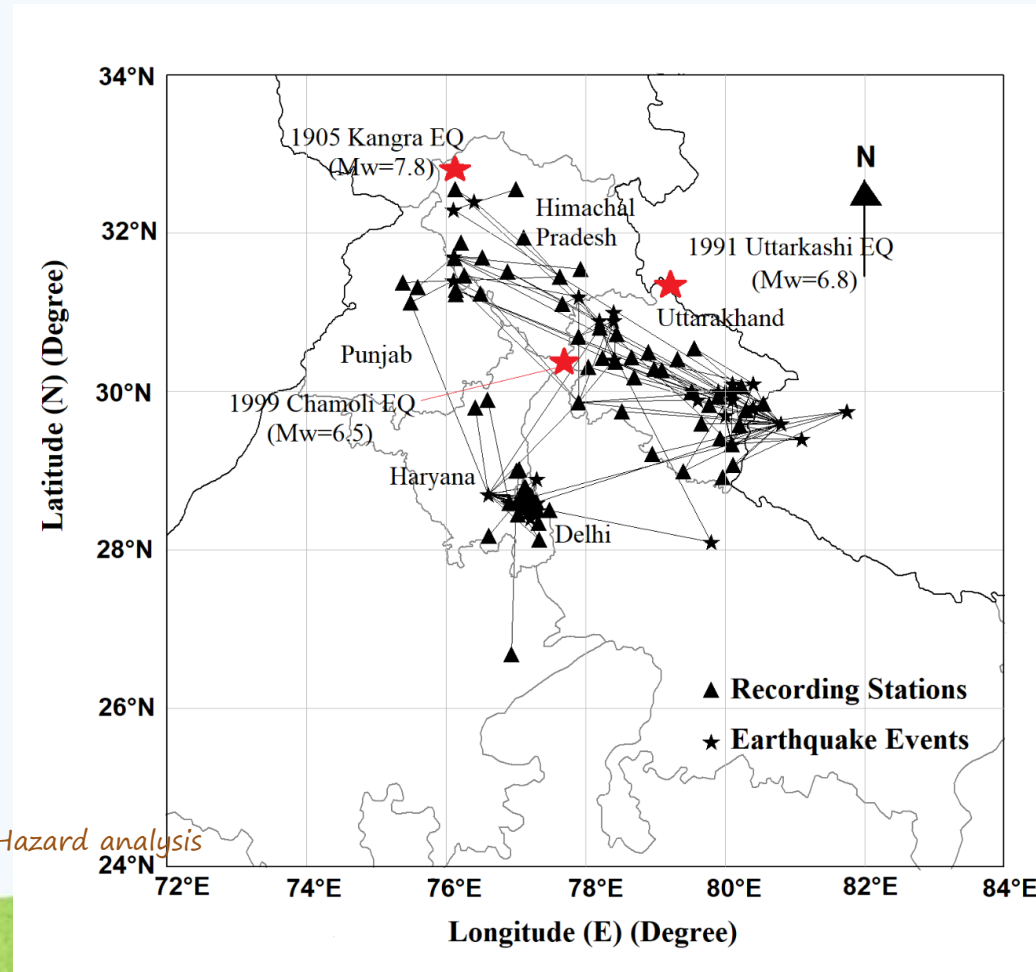


GMPE for North India

TQS 2026-Seismic Hazard analysis

Dataset considered for inversion

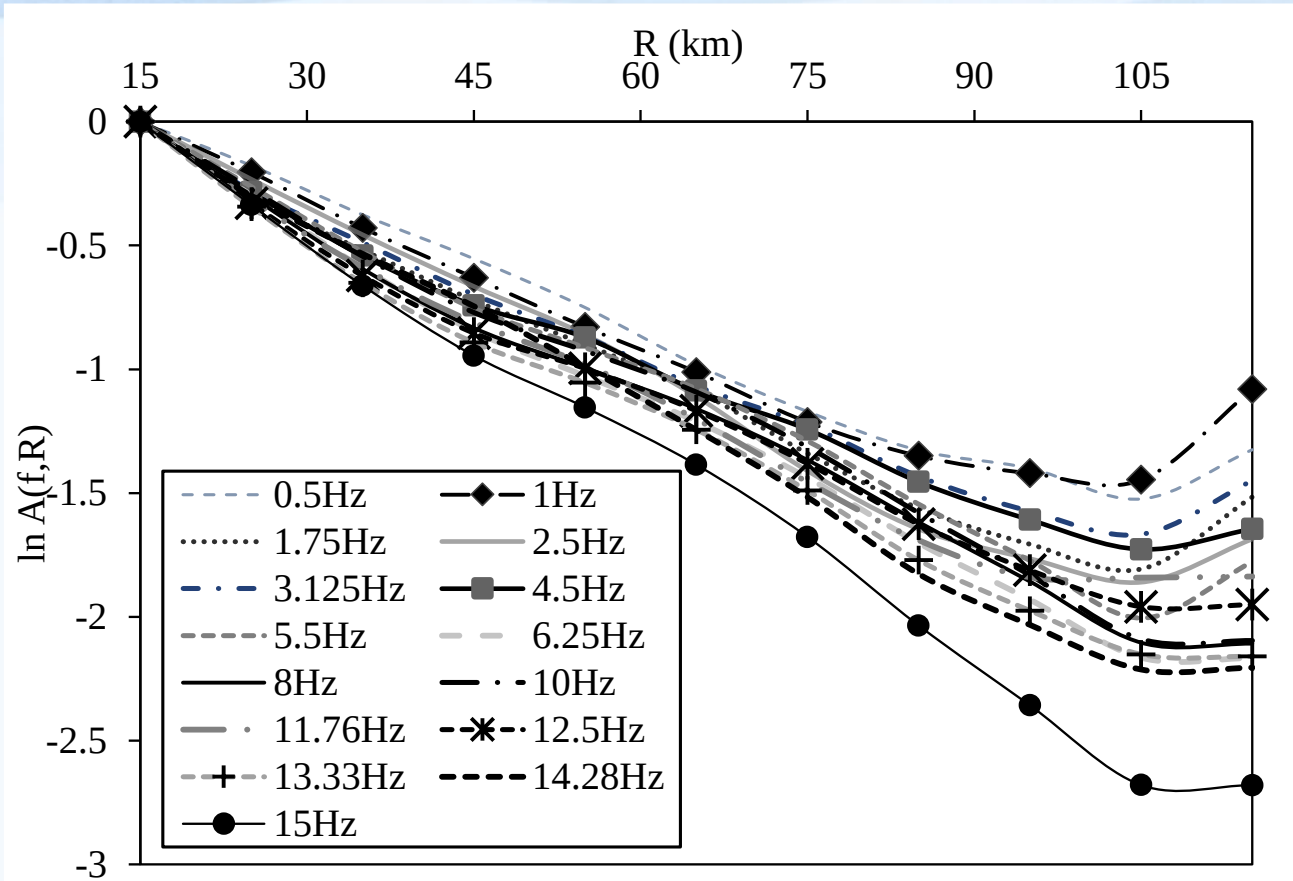
- Those earthquakes which are recorded in at least two recording stations within which at least one recording station is located within hypocentral distance equal to or less than the reference distance



Ref: Harinarayan and Kumar
(2020)

TGS 2026-Seismic Hazard analysis

Spectral attenuation with distance



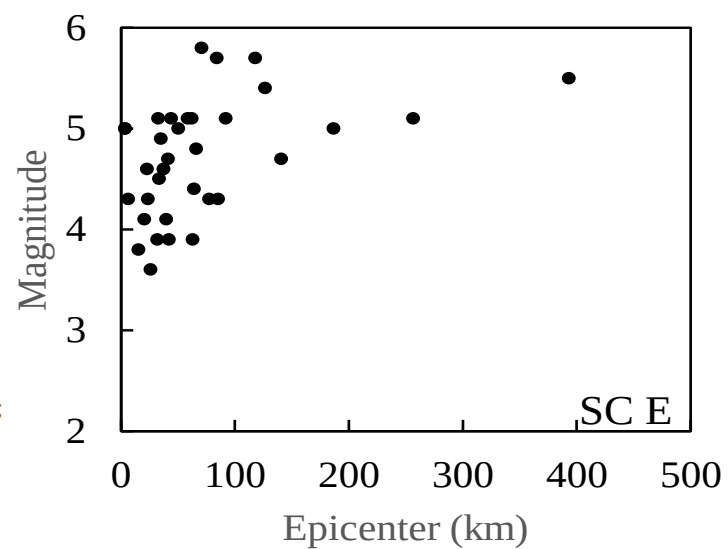
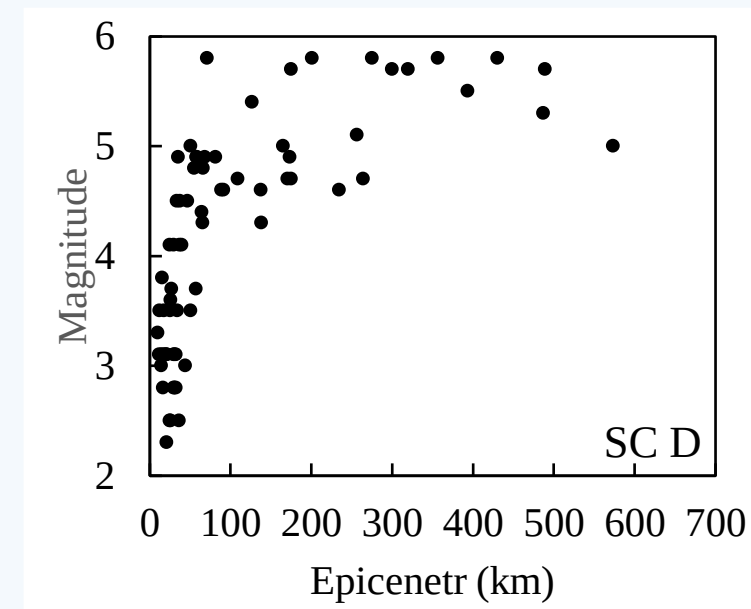
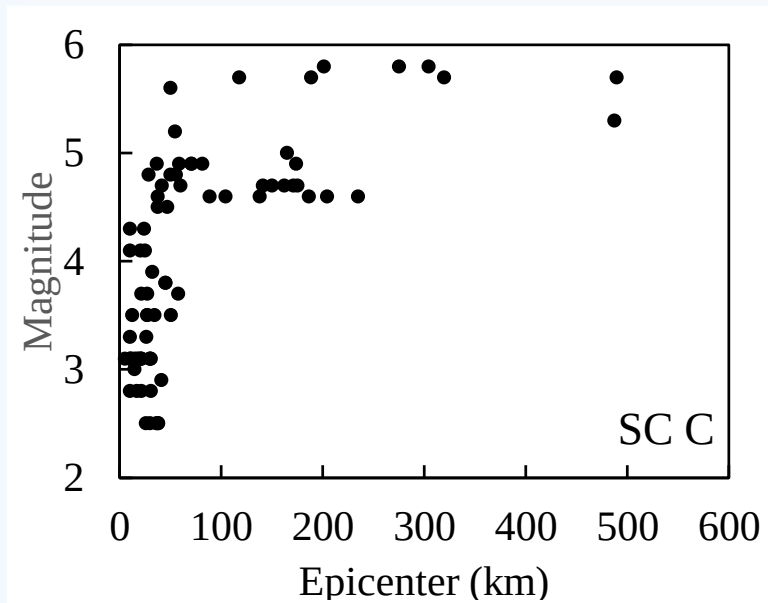
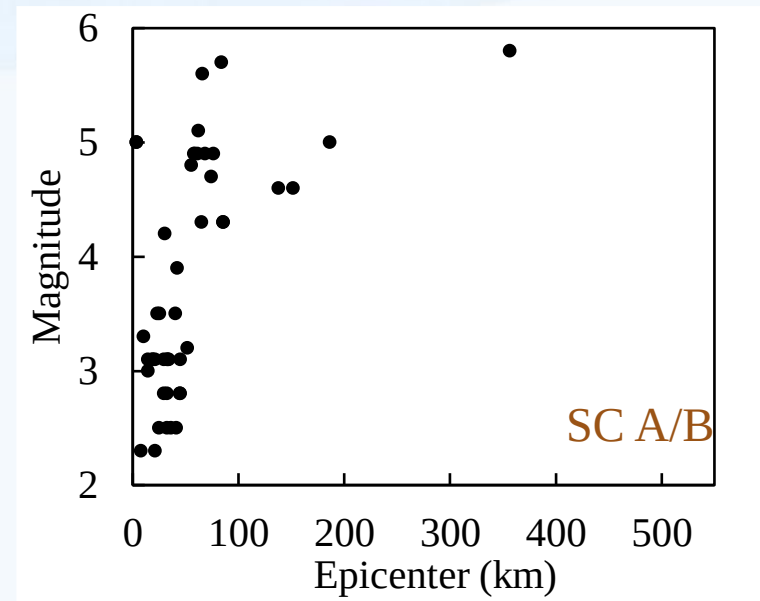
- Attenuation curves exhibit decay with hypocentre distance up to 105km
- Beyond 105km a kink is observed.
- A similar trend in the attenuation curves is reported for the Umbria Marche (Bindi et al. 2004) and Japan regions respectively (Oth et al.2011)
- Oth et al. (2011) attributed that behaviour to the combined effect of reflected or refracted wave arrivals from **Moho**

Ref: Harinarayan and Kumar
(2020)

Determination of GMPE

TQS 2026-Seismic Hazard analysis

Strong Motion Dataset



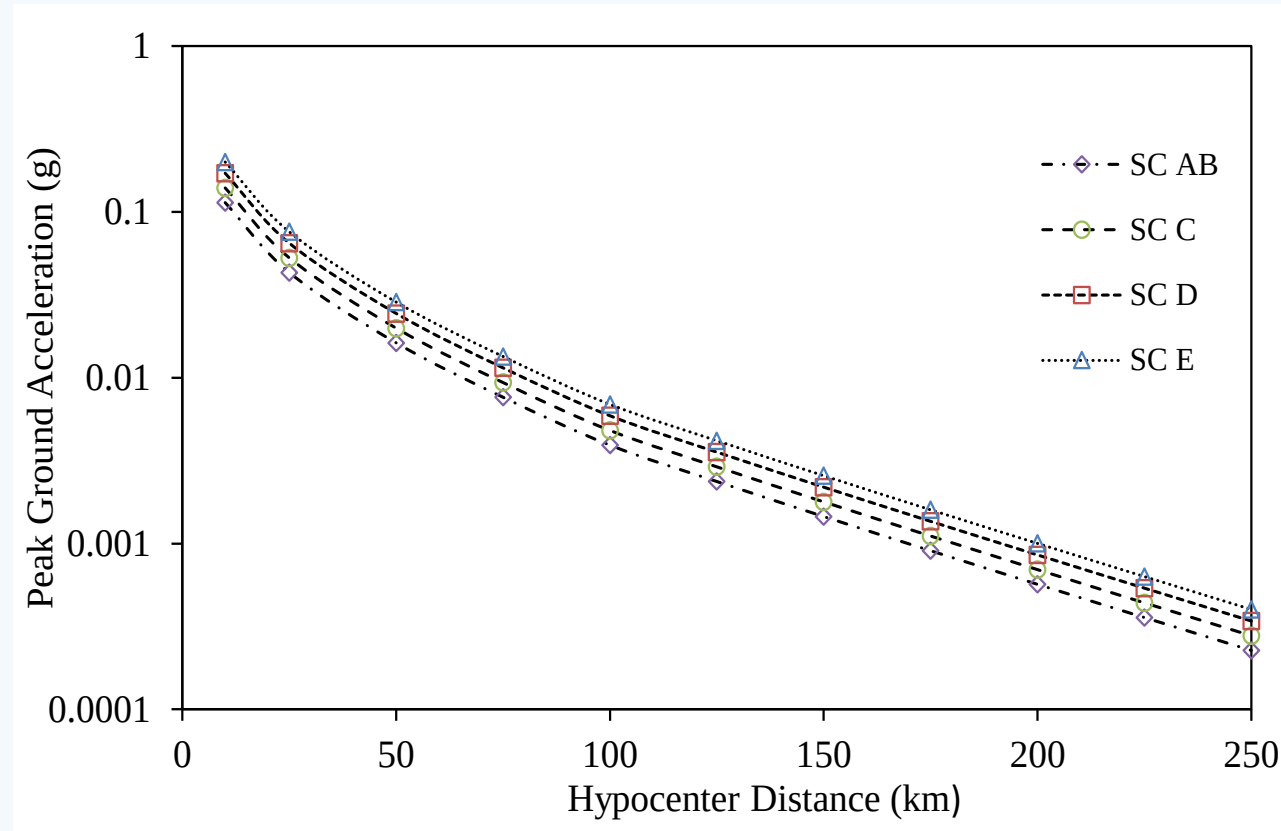
TQS 2026-Seismic Hazard analysis

Details of earthquakes considered for study with source parameters

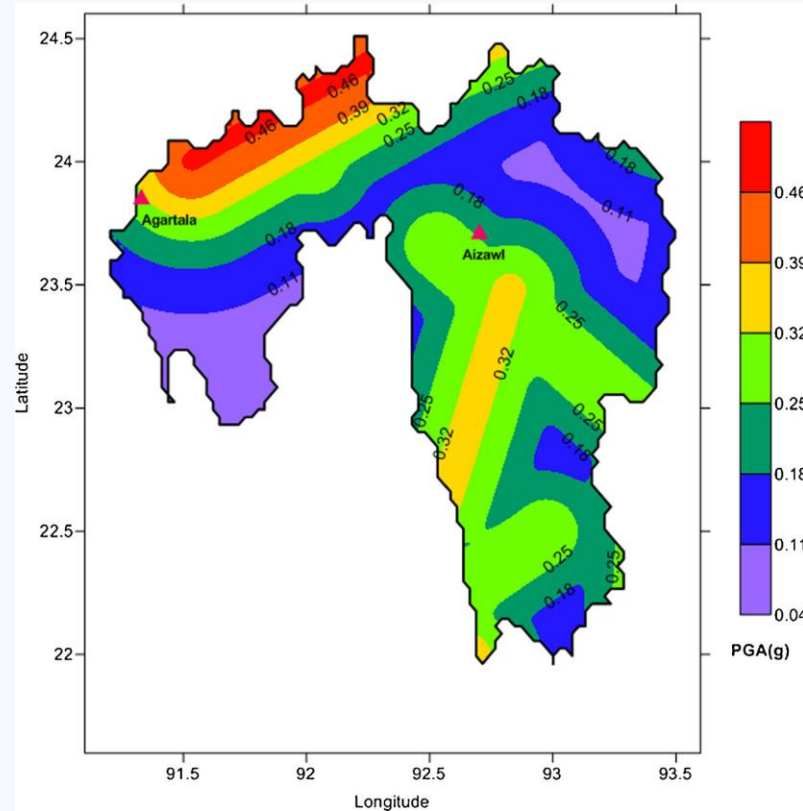
Si No.	Date	Lat. (°) (N)	Lon. (°) (E)	Depth (Km)	Magnitude	Stress drop (MPa)	Strike (°)	Dip (°)	Source of Fault plane solution
	(dd-mm-yyyy)								
	(hh:mm)								
1	25-02-09	30.556	79.331	2	3.5	1.67*	319	16	Prasad et al. 2017
2	03-05-10	30.4	78.4	8	3.7	3.07*	235	39	Prasad et al. 2017
3	28-05-10	31.2	77.9	43	4.8	6.59*	317	59	Prasad et al. 2017
4	09-02-2011	30.9	78.2	10	5	3.68*	306	80	Prasad et al. 2017
5	20-06-11	30.535	79.292	11.5	4.7	6.56*	306	80	Prasad et al. 2017
6	23-07-07	30.915	78.305	11.4	5	2.1*	262	3	Prasad et al. 2017
7	10-07-10	29.9	79.6	10	4.1	6.47*	169	29	Prasad et al. 2017
8	04-04-2011	29.6	80.8	10	5.7	14.53*	307	48	Kumar and Khandelwal, (2015)
9	22-07-2007	28.6	77	20.3	4.3	0.26*	262	3	Prasad et al. 2022
10	19-10-91	30.78	78.774	15	6.8	7.7**	317	14	CMT Harvard
11	28-03-99	30.408	79.416	15	6.5	6.6**	280	7	CMT Harvard
12	8-10_2005	34.493	73.629	26	7.6	11.3***	333	39	CMT Harvard
13	25-04-15	28.147	84.708	15	7.8	7.5\$	295	11	Galetzka et al. (2015)
14	05-03-2012	28.7	76.6	14	4.9	1.7*	250	33	Prasad et al. 2017
15	04-09-2008	30.1	80.4	10	5.1	0.89*	255	87	Prasad et al. 2017
*Present Study; **Chopra et al. (2012); ***Singh et al. (2006); \$Raghucharan and Somala, (2017)									

TQS 2026-Seismic Hazard analysis

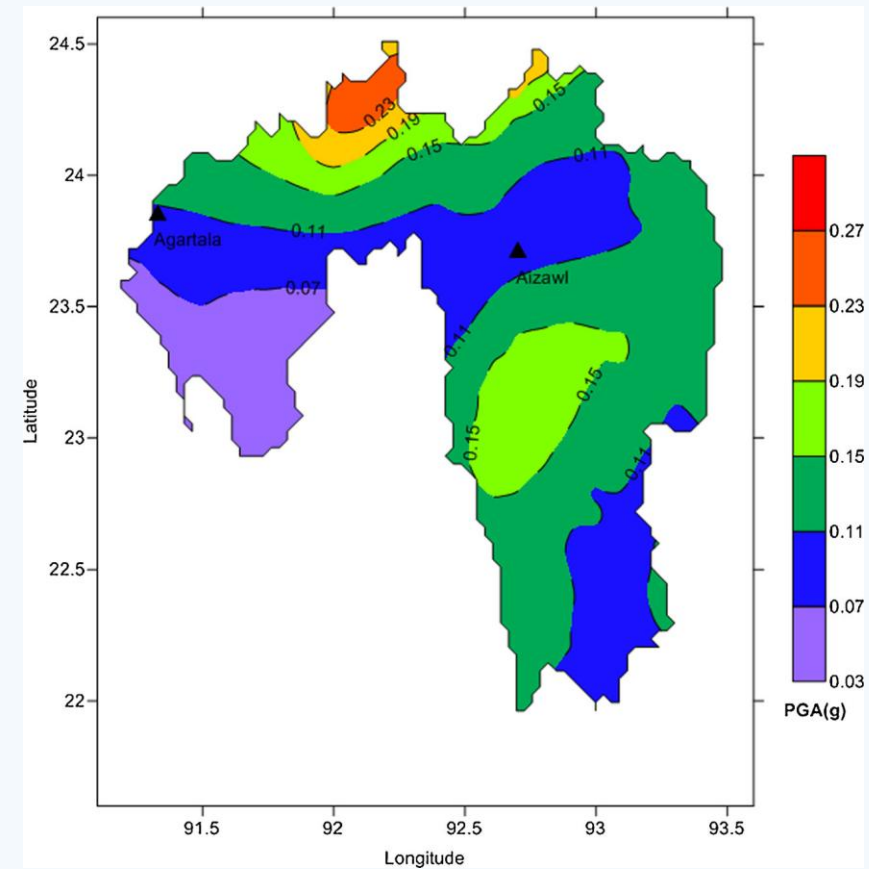
Proposed GMPE for Magnitude 5.7 for different hypocentre distance



Comprehensive seismic hazard assessment of Tripura and Mizoram states

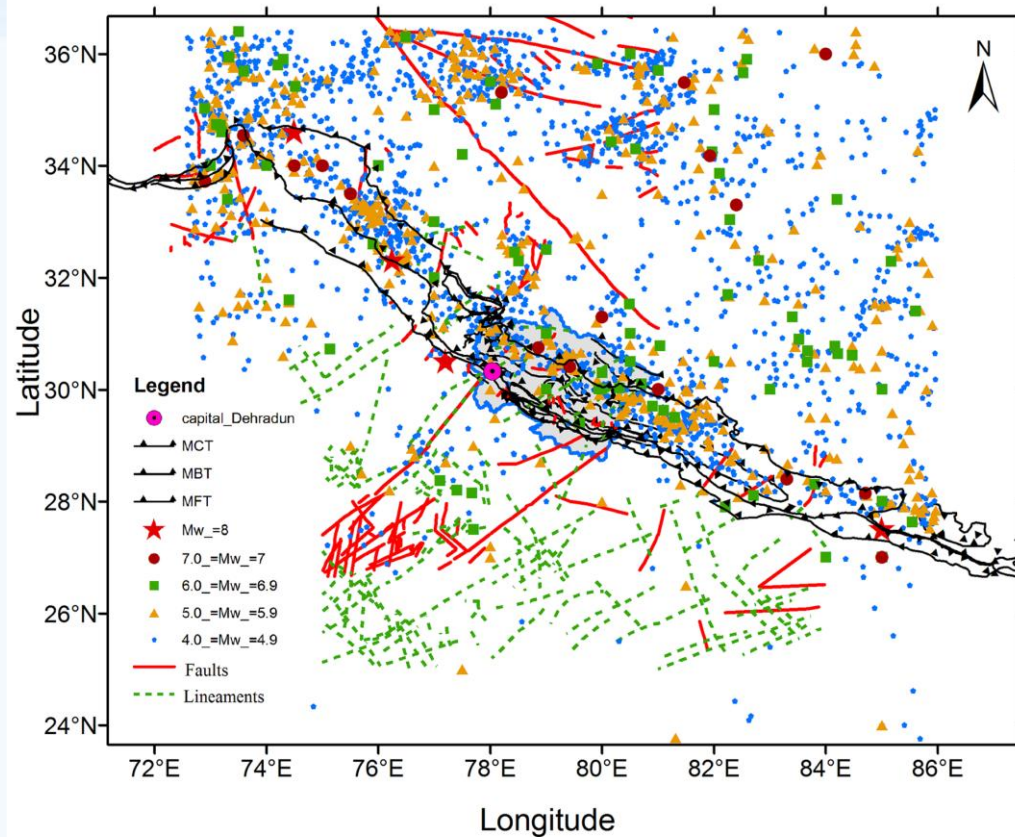


PGA map of Tripura and Mizoram states based on DSHA

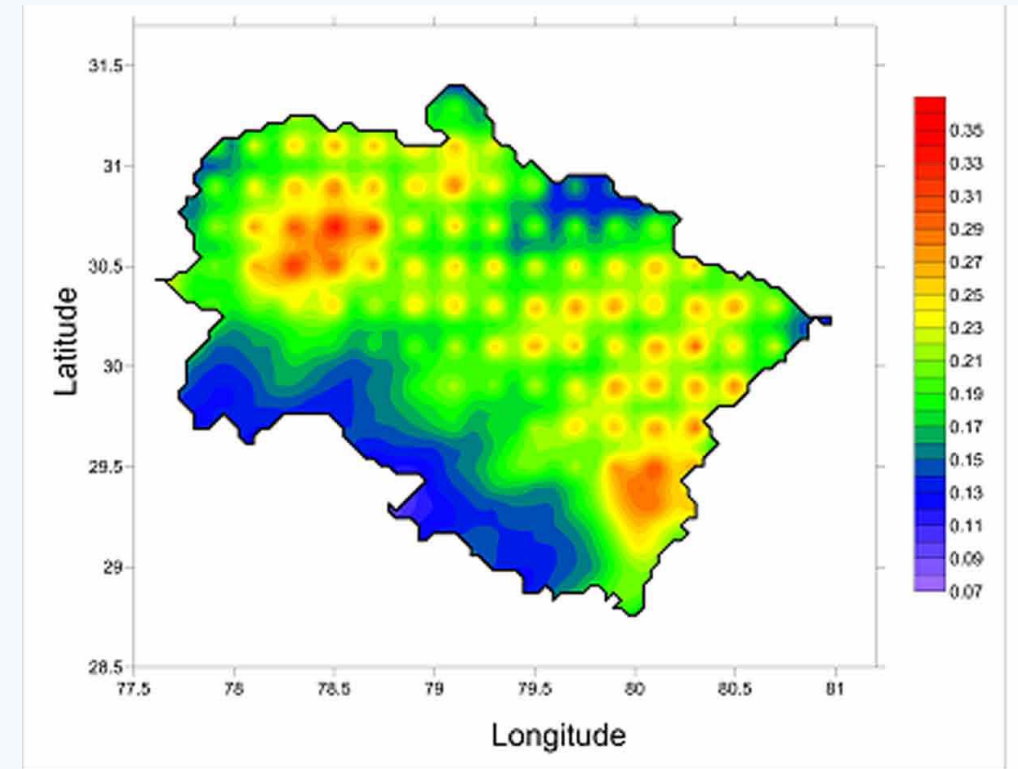


Spatial variation of PGA at rock level for 10% probability of exceedance in 50 years.

A Revisit to Seismic Hazard at Uttarakhand



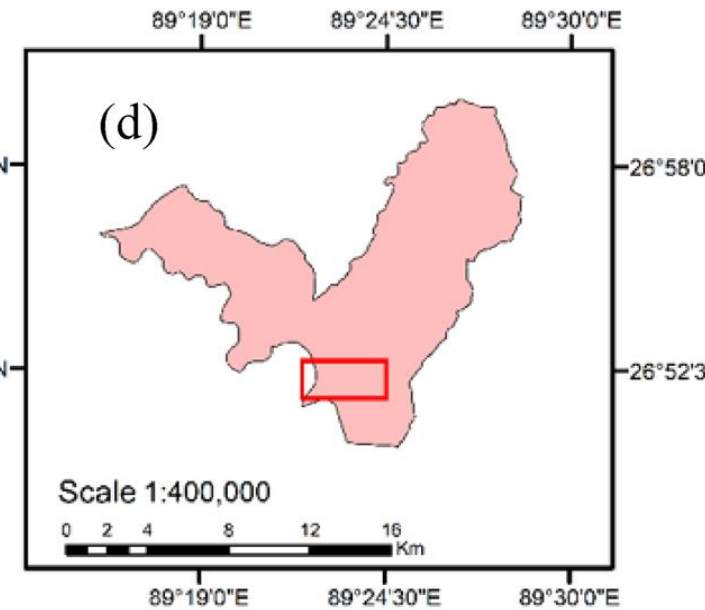
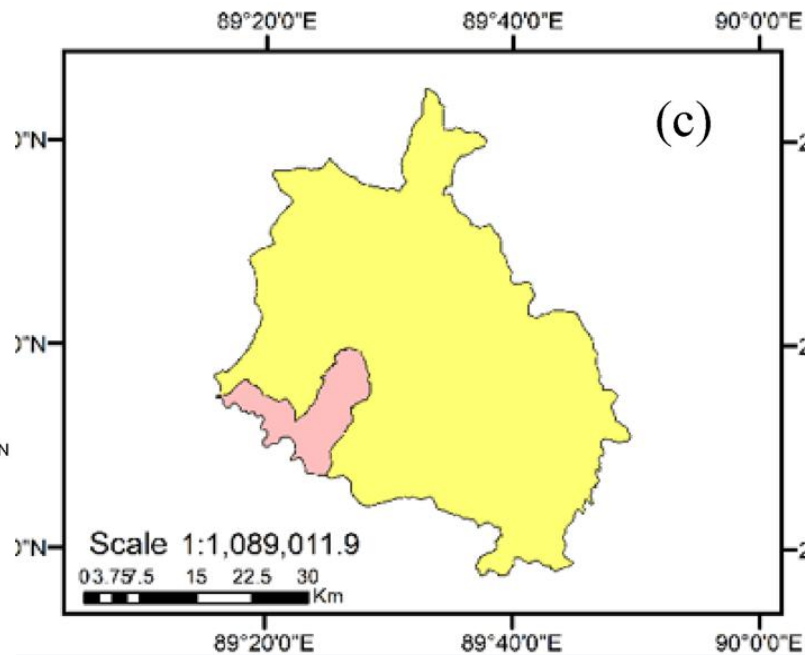
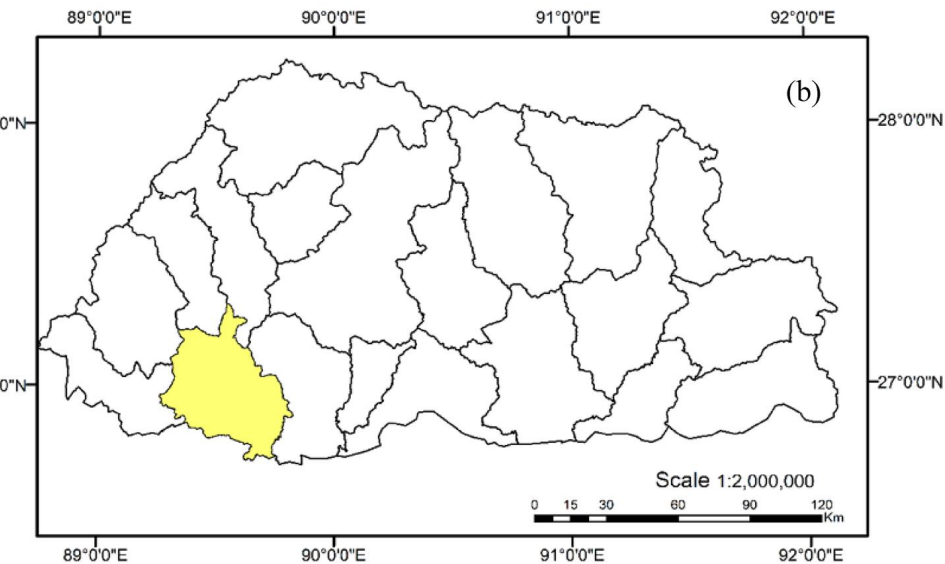
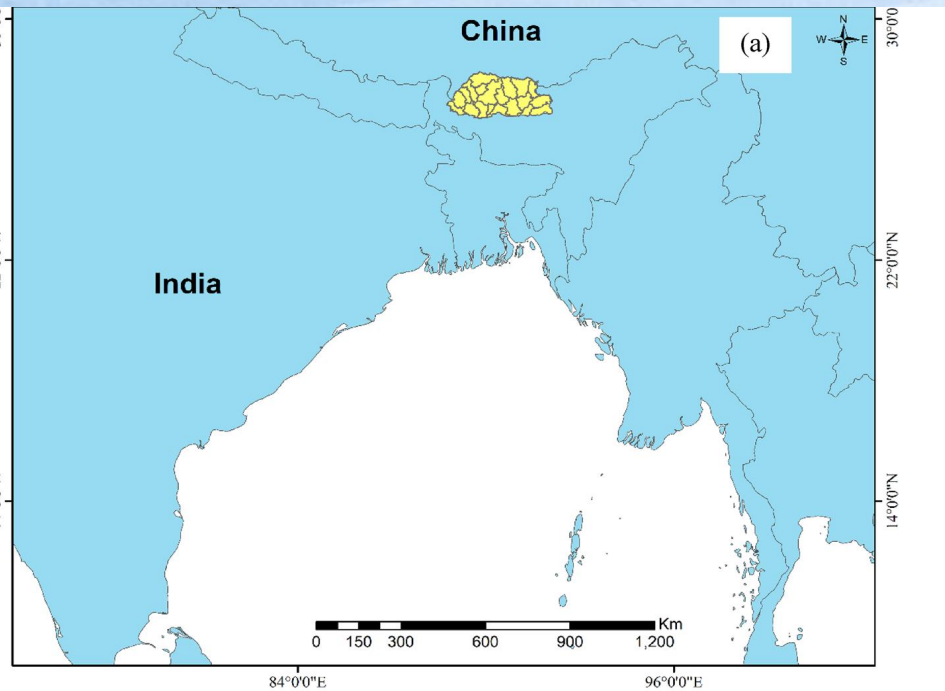
Seismotectonic map of Uttarakhand and adjoining area



PHA for 10% probability of exceedance in 50 years;

Nayak, M., Sitharam, T. G., & Kolathayar, S. (2015). A revisit to seismic hazard at Uttarakhand. *International Journal of Geotechnical Earthquake Engineering (IJGEE)*, 6(2), 56-73.

Case Study of Bhutan Himalayas



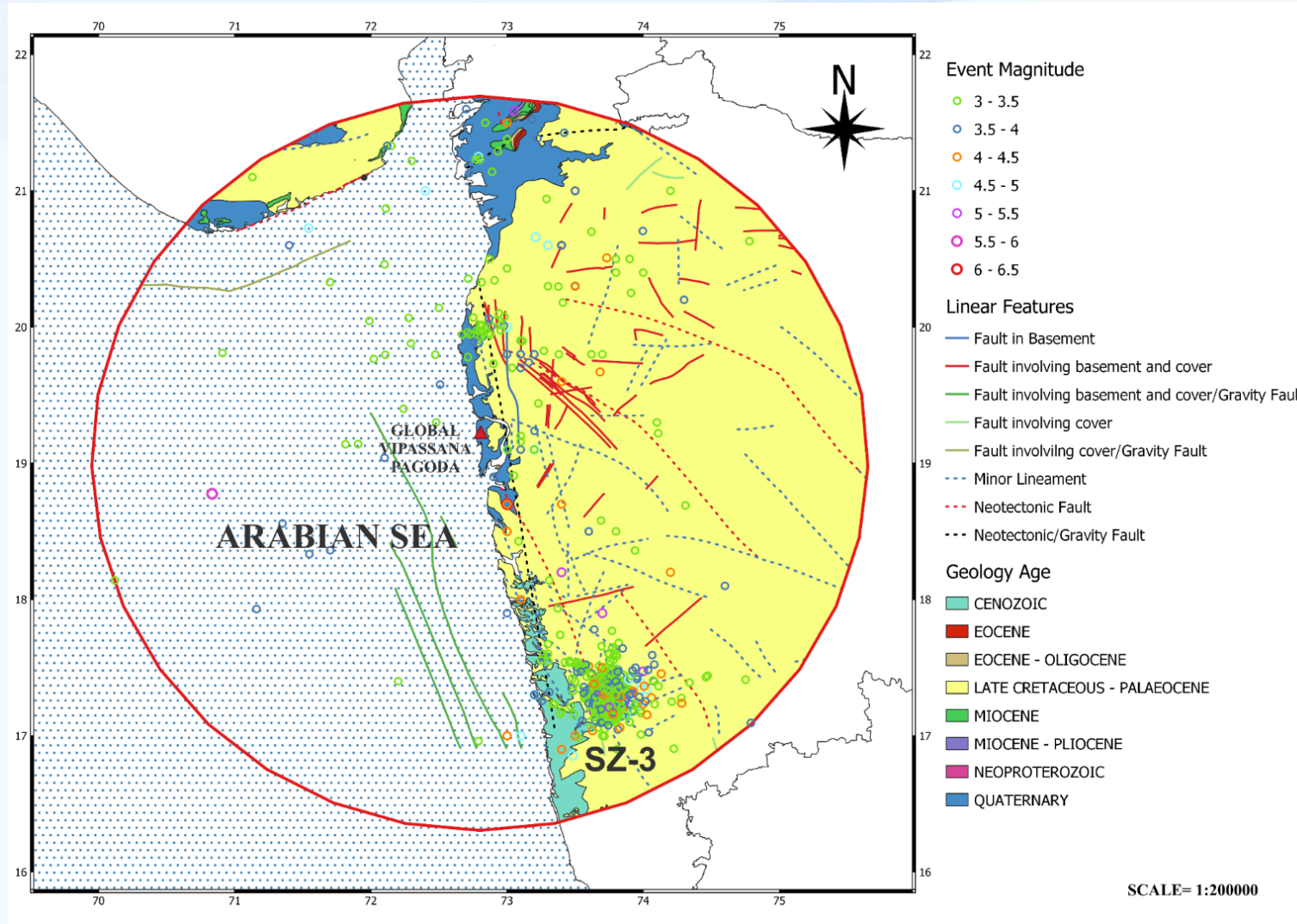
LOGY KARNATAKA

Global Vipassana Pagoda Mumbai



- Biggest Masonry dome structure in the world
- Borivali west, Mumbai.
- Construction 1997-2008.
- Height=97 m.
- Ex. Dia=98 m.
- Stones and lime used the construction materials.
- Design life is more than 2000 years.

Seismotectonic Map

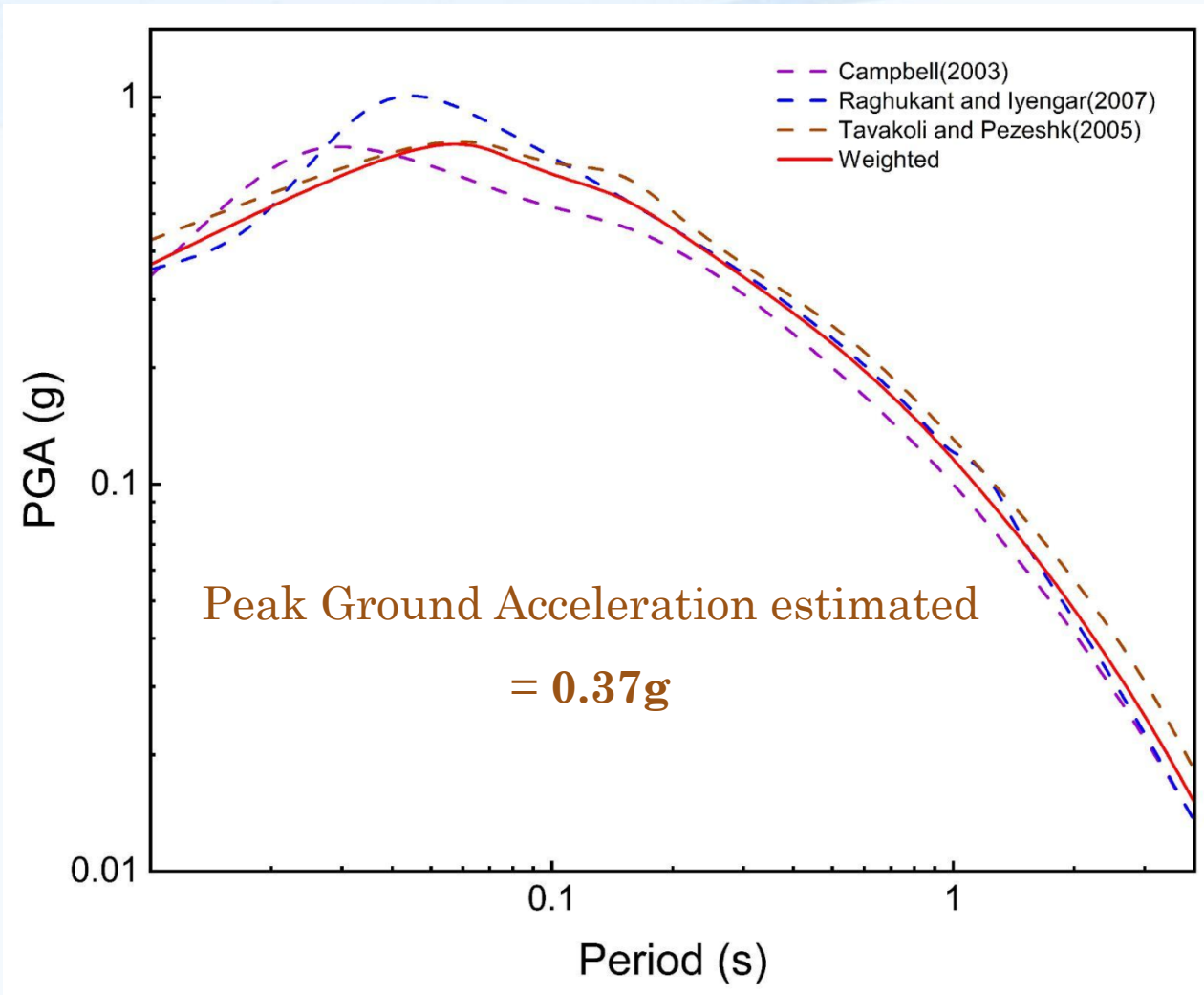


Seismotectonic Map for Current Study Area

The declustered data was superimposed on the fault map of the study area using the open-source software QGIS and a Seismotectonic map was

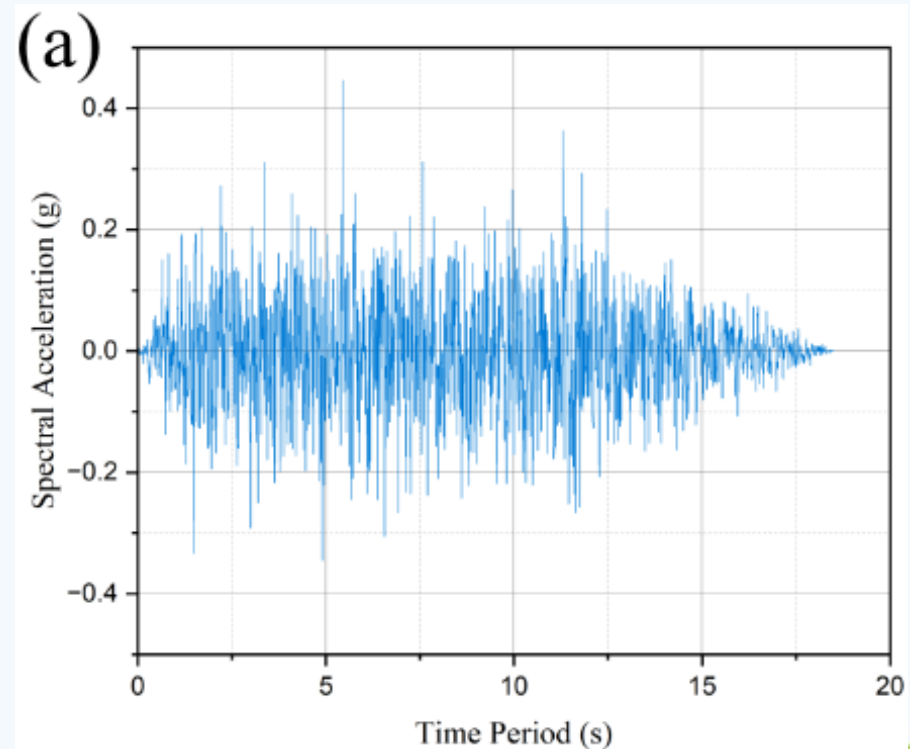
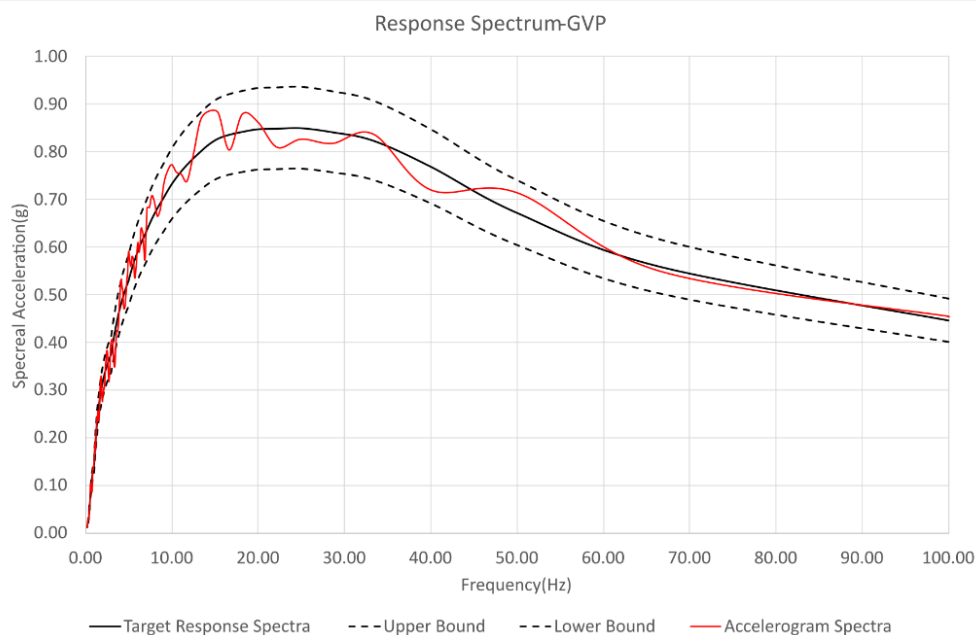
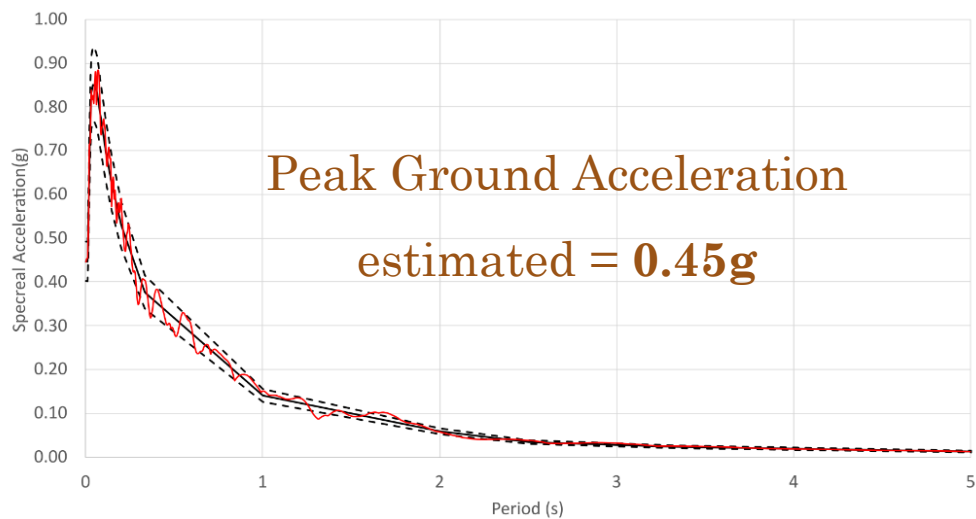
Response Spectra for DSHA

16-07-2026



- **Ghod Lineament** was identified as the closest and most critical seismic source influencing the project site.
- It represents a prominent linear tectonic feature within the Deccan basalt province and is capable of generating moderate magnitude intraplate earthquakes.
- **MCE = M_w 6.3**

Response Spectra & Acceleration Time History Developed for PSHA

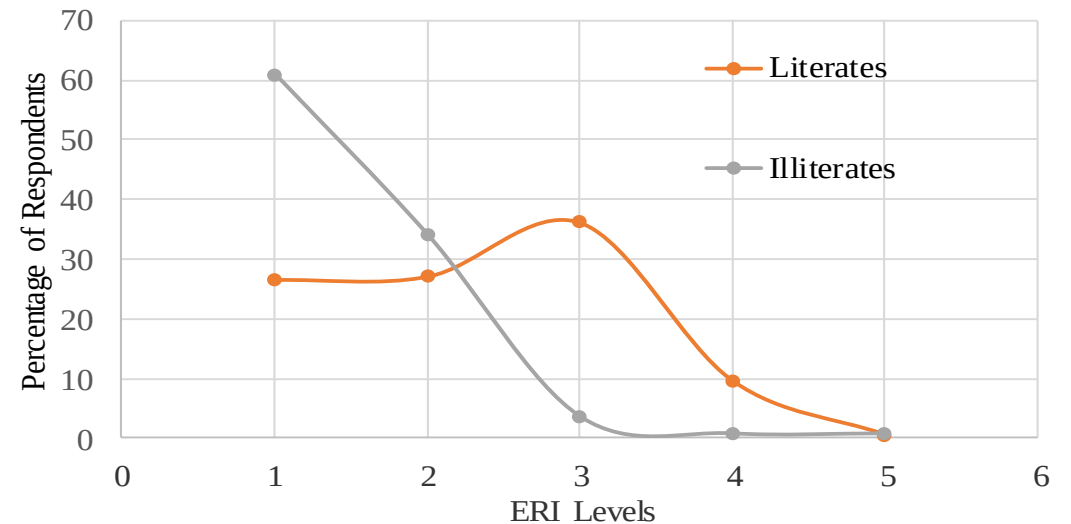


Acceleration time history for GVP

Earthquake Readiness Index: Valid and reliable tool to assess household and community preparedness

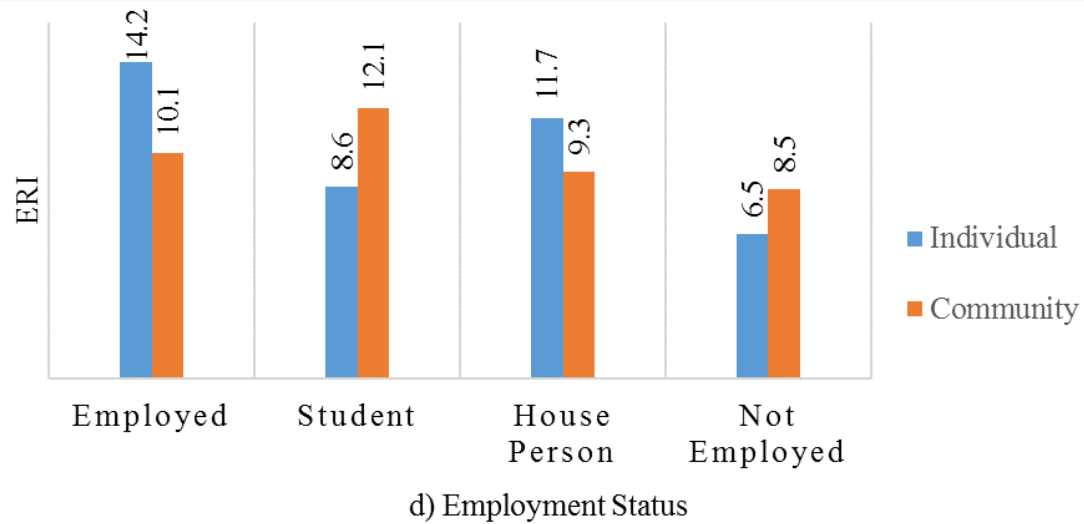
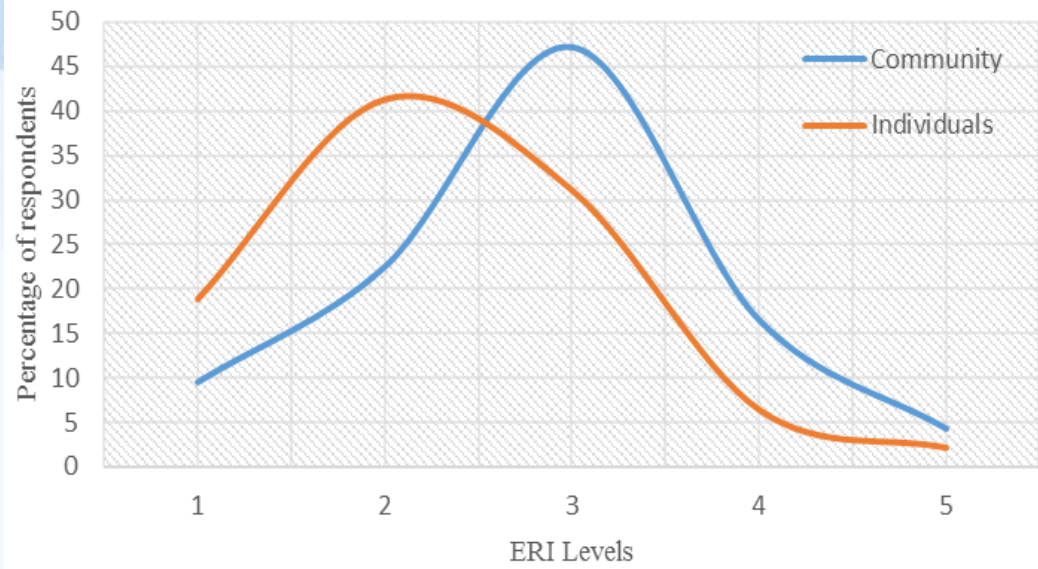
Sl No.	Factors for ERI for Individuals	Item	Variance	Factors for ERI for Community	Item	Variance
1	Emergency needs	x12, x14 ,x17 ,x20 ,x22 ,x26	23.96	Community Participation	y1, y2, y3, y4, y5	20.1
2	Personal Safety	x9, x10, x11, x16 ,x27	12.3	Trust	y13, y14, y15, y16, and y17	12.38
3	Outdoorr Safety	x21, x23, x24, x25	7.24	Collective Efficacy	y8, y9, y10	10.99
4	Indoor Safety	x4, x5, x7, x8, x13	4.86	Willingness	y18, y19, y20	7.98
5	Structural Safety	x1, x2, x3, x6	4.33	Empowerment	y11,y12	5.54
6	Mitigation	x15,x18, x19	3.91	Intension	y6,y7	5.37

Level	% activities completed	Degree of preparedness	ERI range for Individuals	%respondents for ERI for Individuals	ERI range for community	%respondents for ERI for Community
1	upto 20	Very poor	0-5	18.89	0-4	9.5
2	upto 40	Poor	5-10	41.30	5 -8	22.5
3	upto 65	Moderate	11-17	31.11	9-13	47.25
4	upto 85	Good	18-23	6.48	14-17	16.5
5	above 85	Excellent	24-27	2.22	18-20	4.25

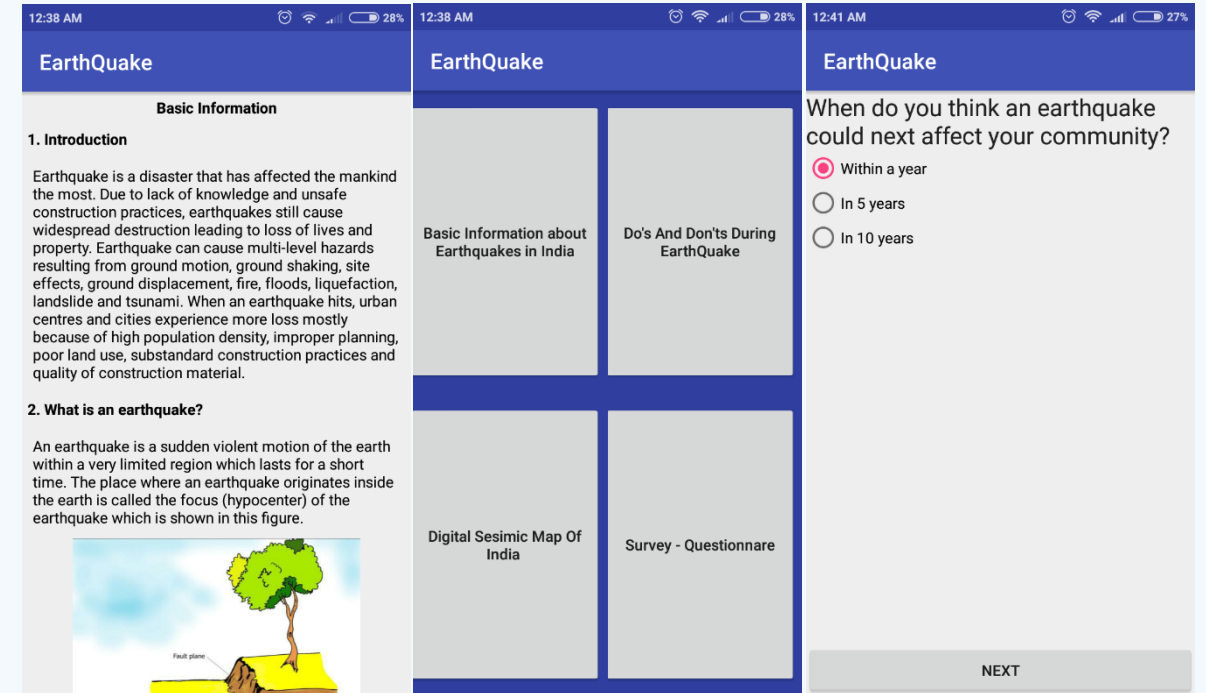


Kolathayar et al. (2018) Development of Earthquake Readiness Index Tool to assess Individual Earthquake Preparedness Level, ASCE India Conference, New Delhi.

Community preparedness



BhookampRaksha Mobile app



Kolathayar et al (2018). Development of Mobile Application to Assess and Enhance Earthquake Preparedness Level of Individuals and Community in India. Proceedings of 5th GeoChina International Conference (Springer)

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Authors: Sitharam, T. G., Kolathayar, Sreevalsa

Presents an earthquake risk reduction and management plan developed by the Authors which is endorsed by Indian Society of Earthquake Technology

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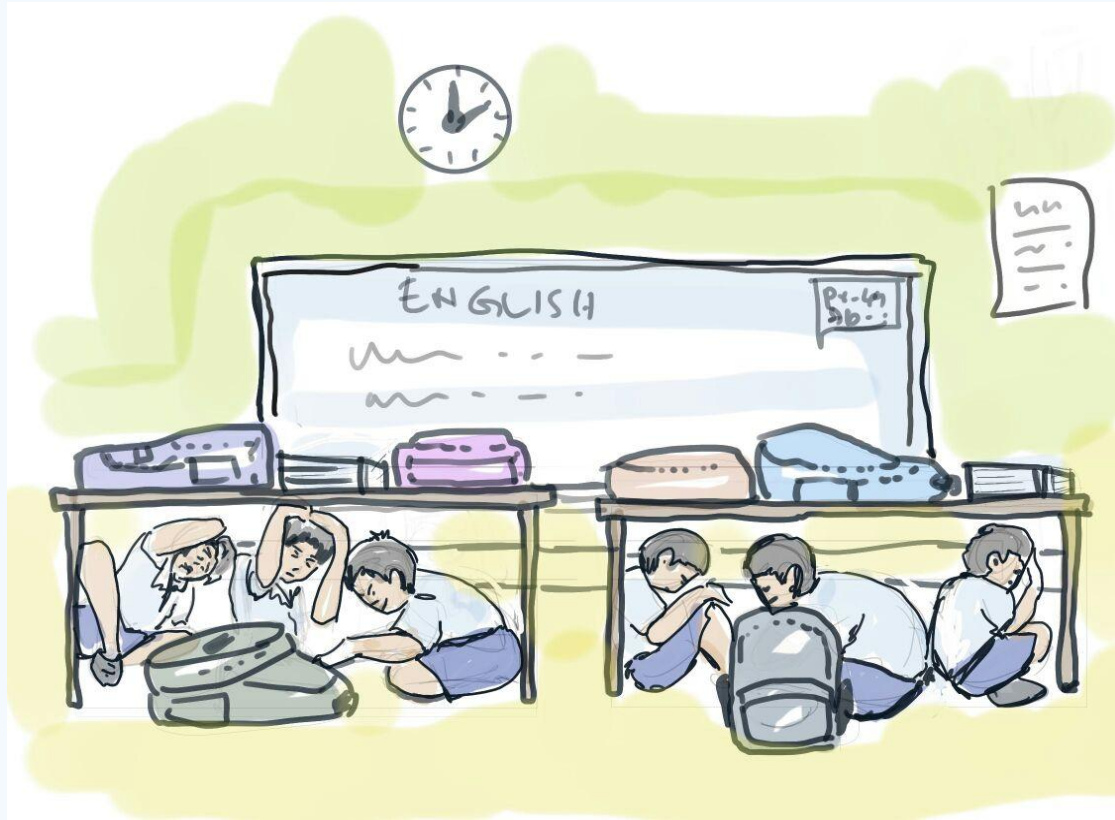
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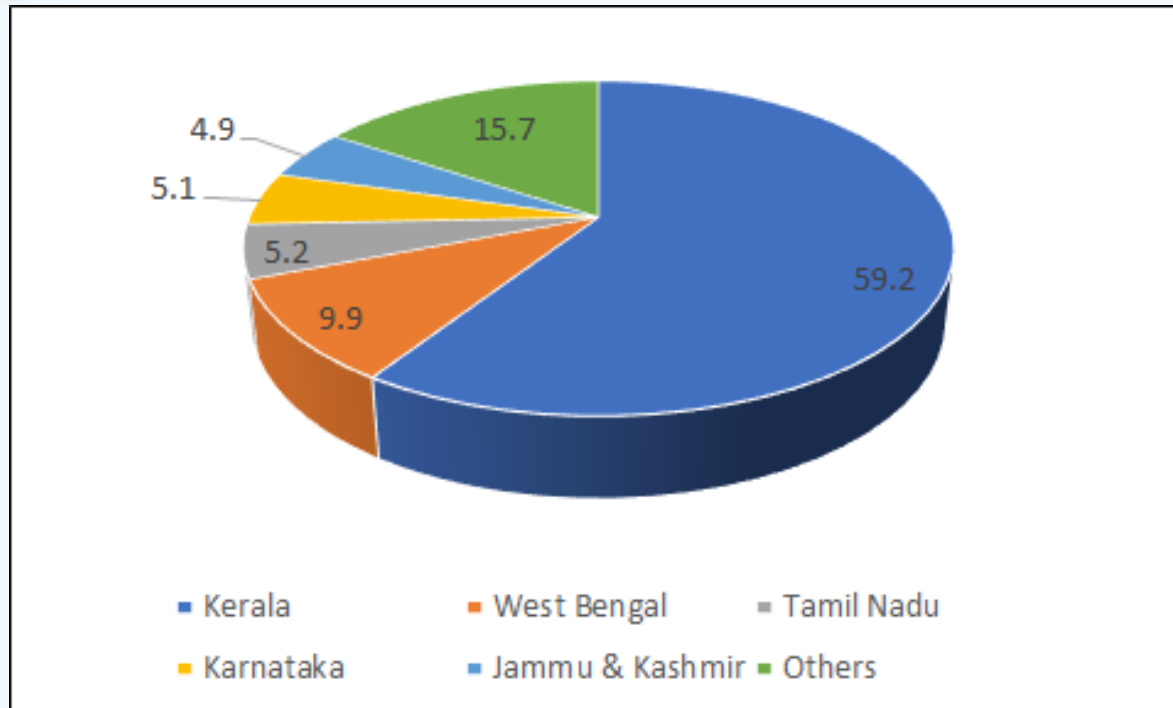
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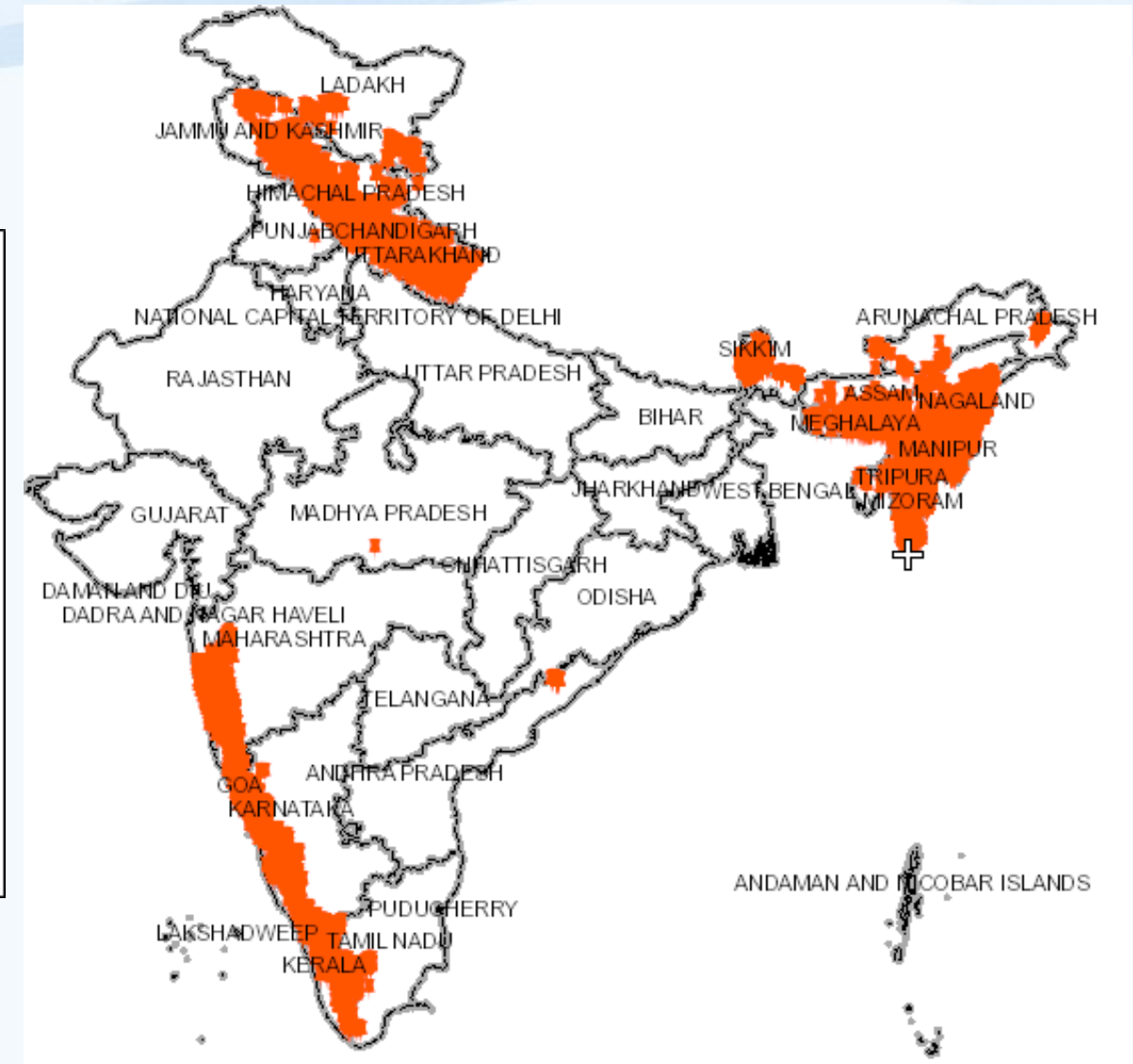
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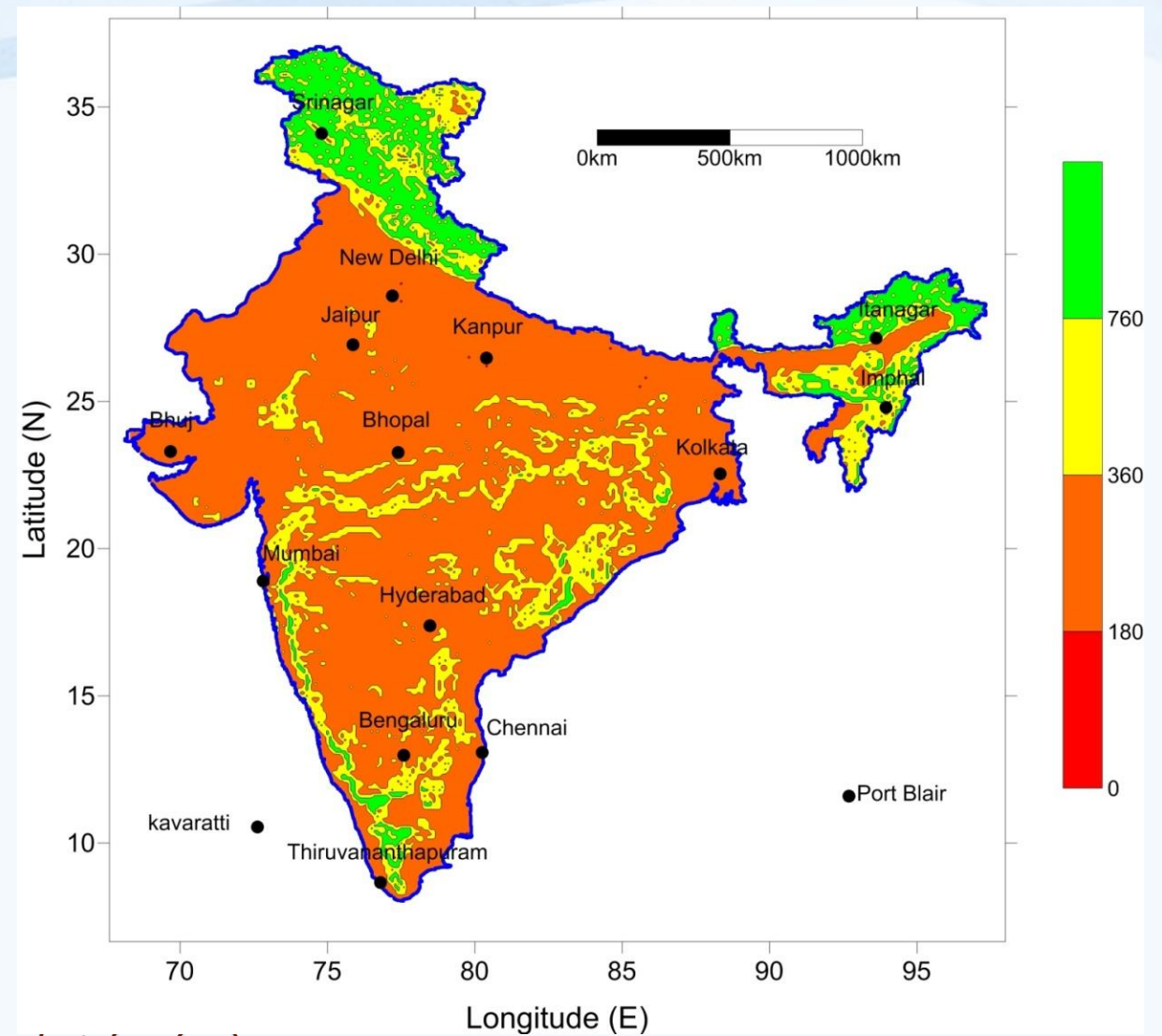
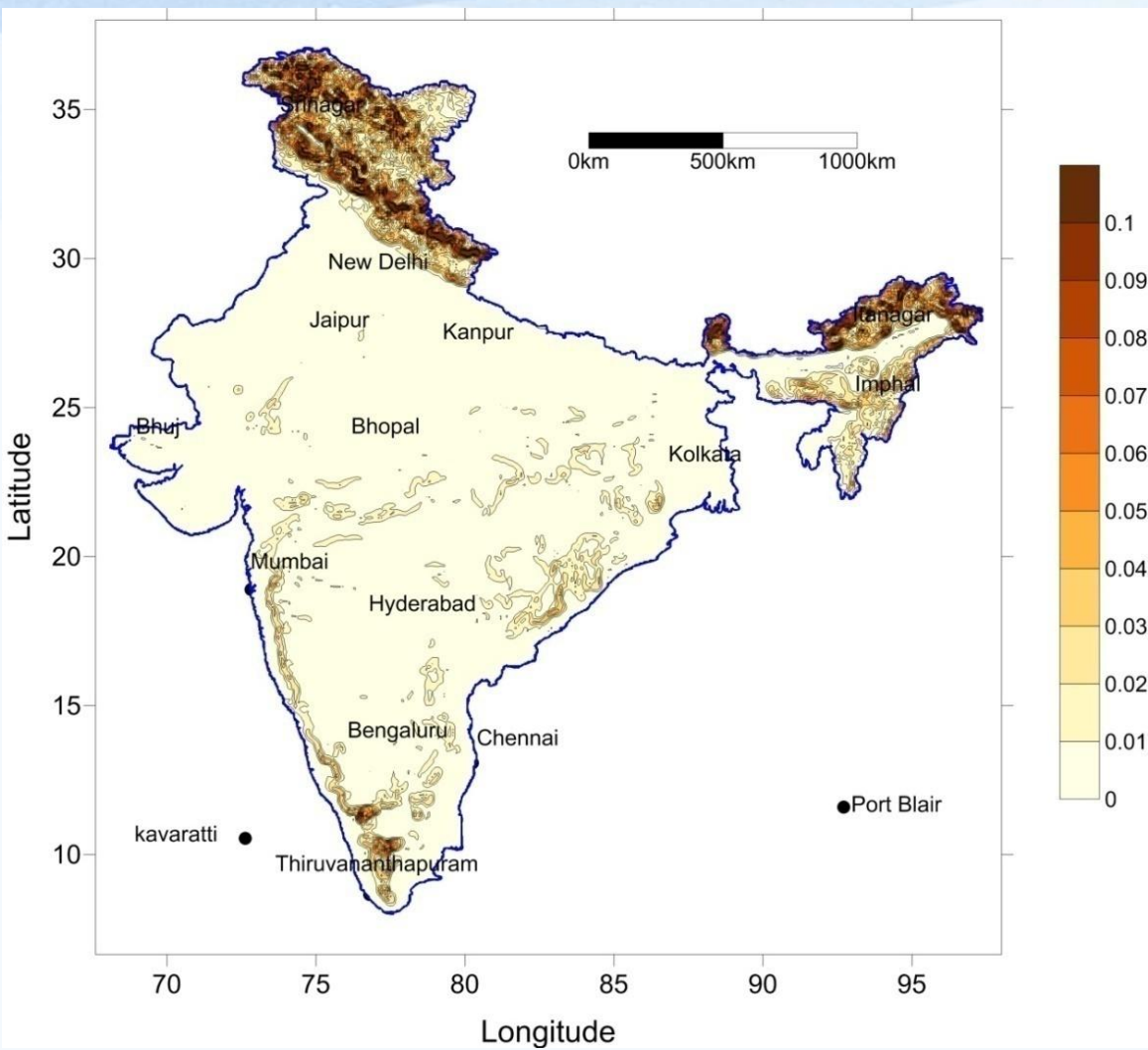




Landslides during 2015-2022
(Source: GSI)



Landslide susceptibility map
(Source: NLSM – GSI)

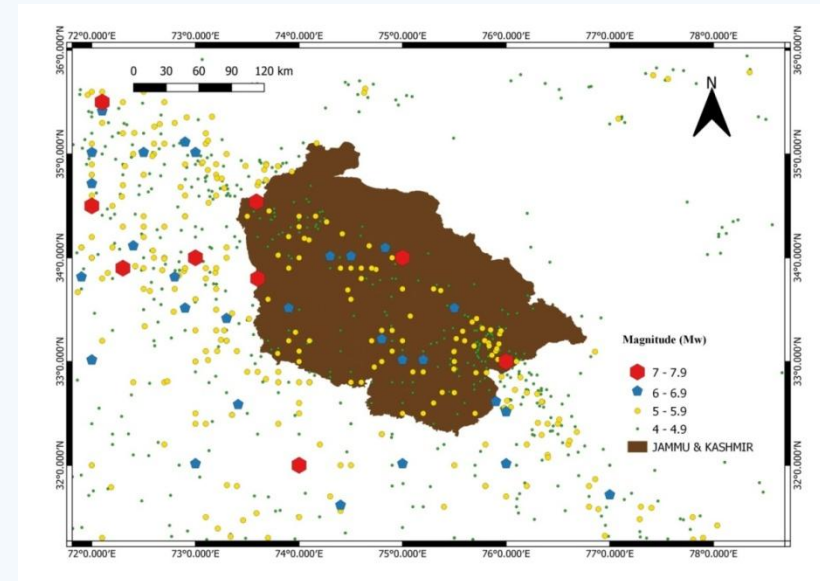
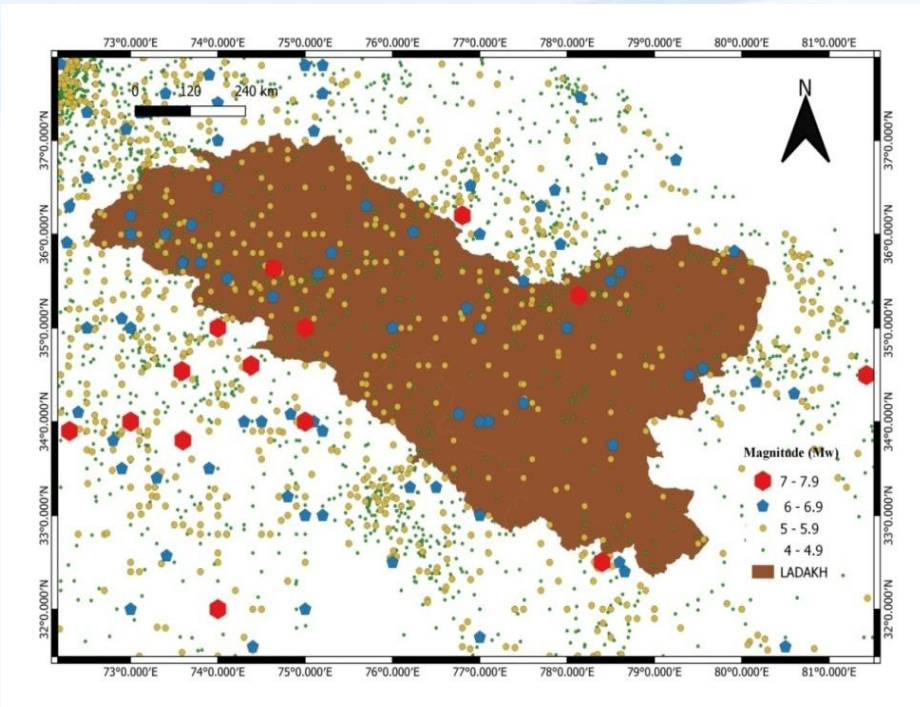


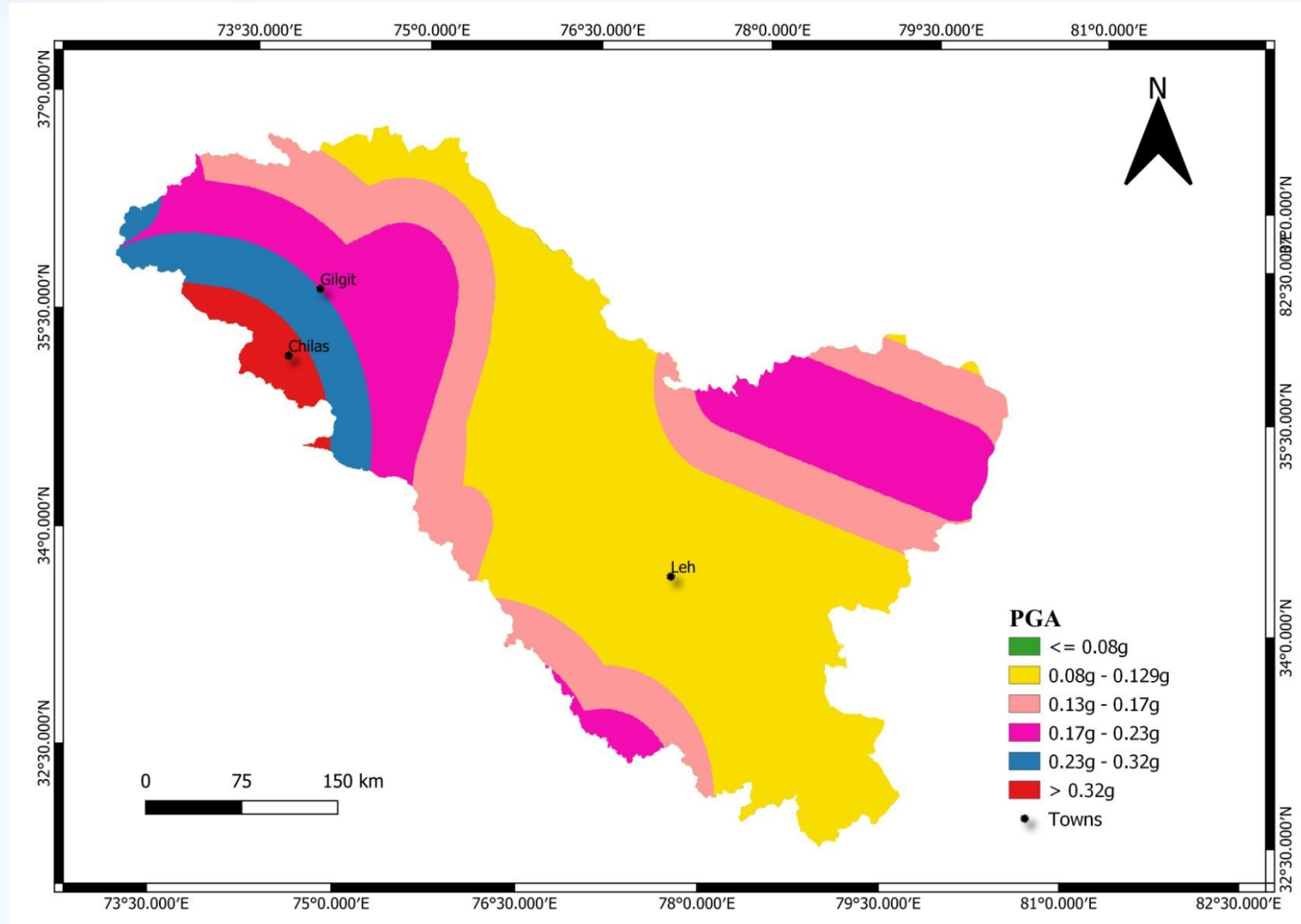
Contour map showing the spatial variation of slope value (m/m)

VS30 (m/s) contour map derived from the slope values

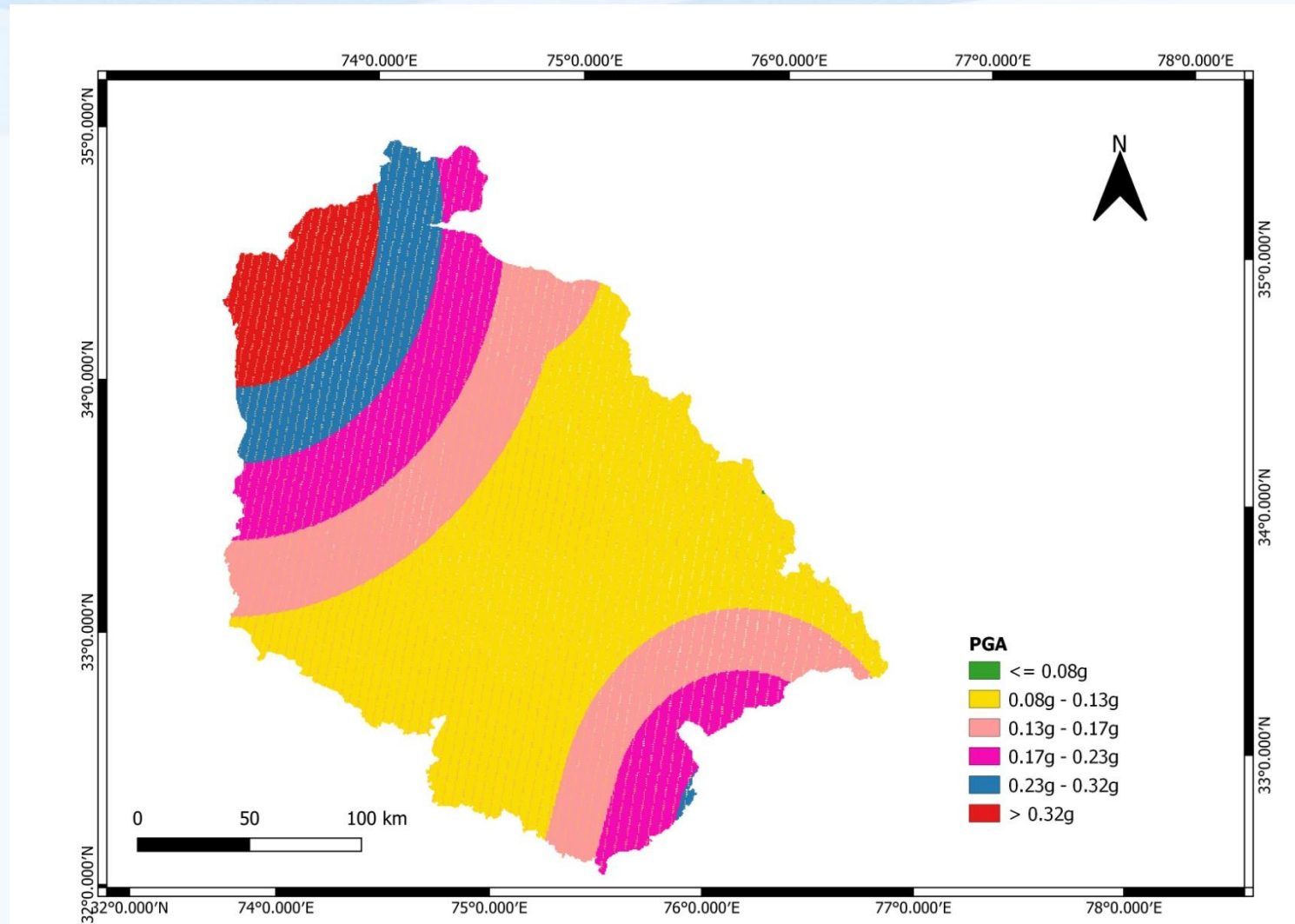
T.G. Sitharam, S. Kolathayar, and N. James (2015) In **Geoscience Frontiers** (2015), Volume 6, Issue 6, Pages 847–859, (IF: 4.28)

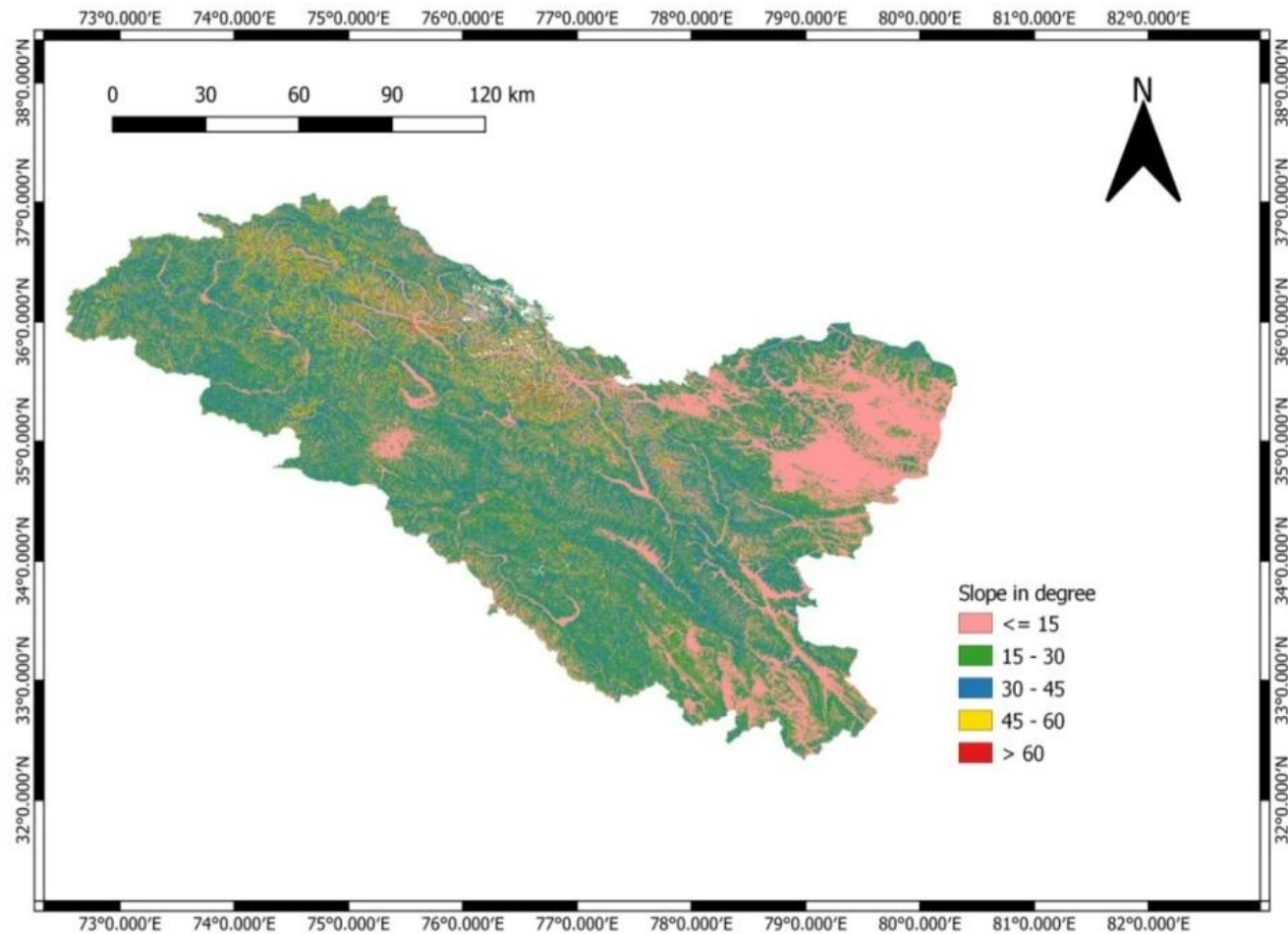
Seismically Induced Landslide hazard analysis by Newmark's methodology

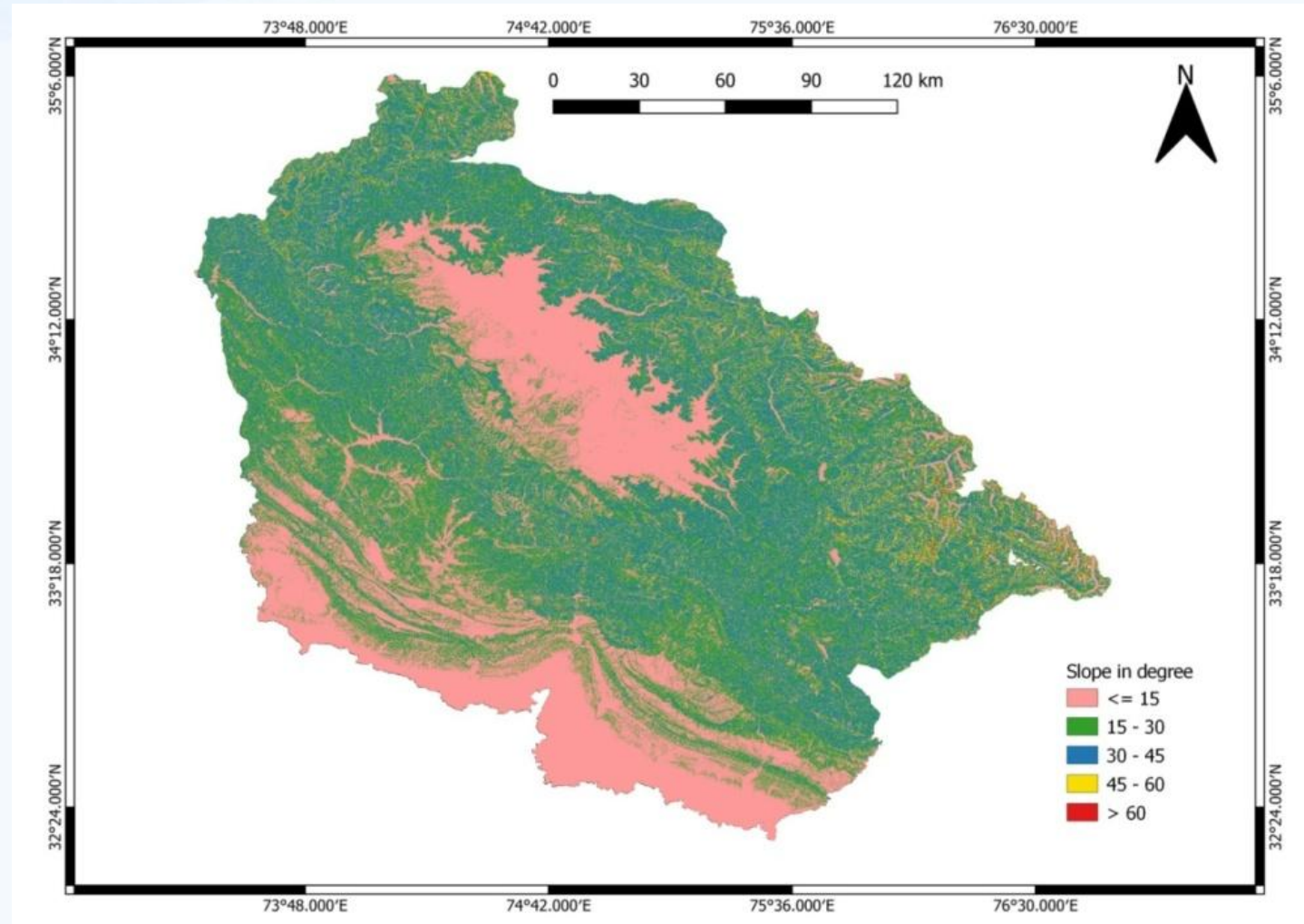


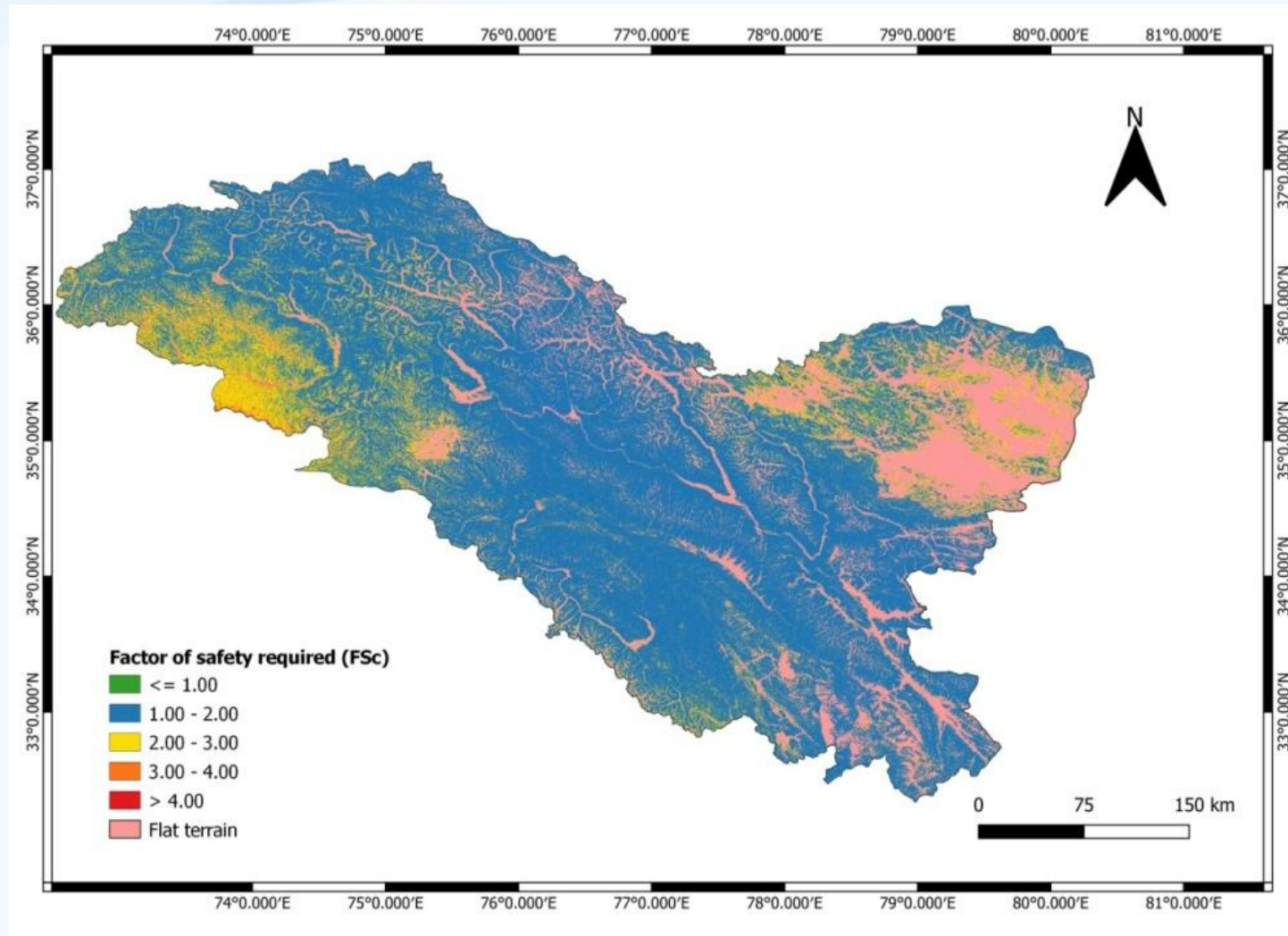


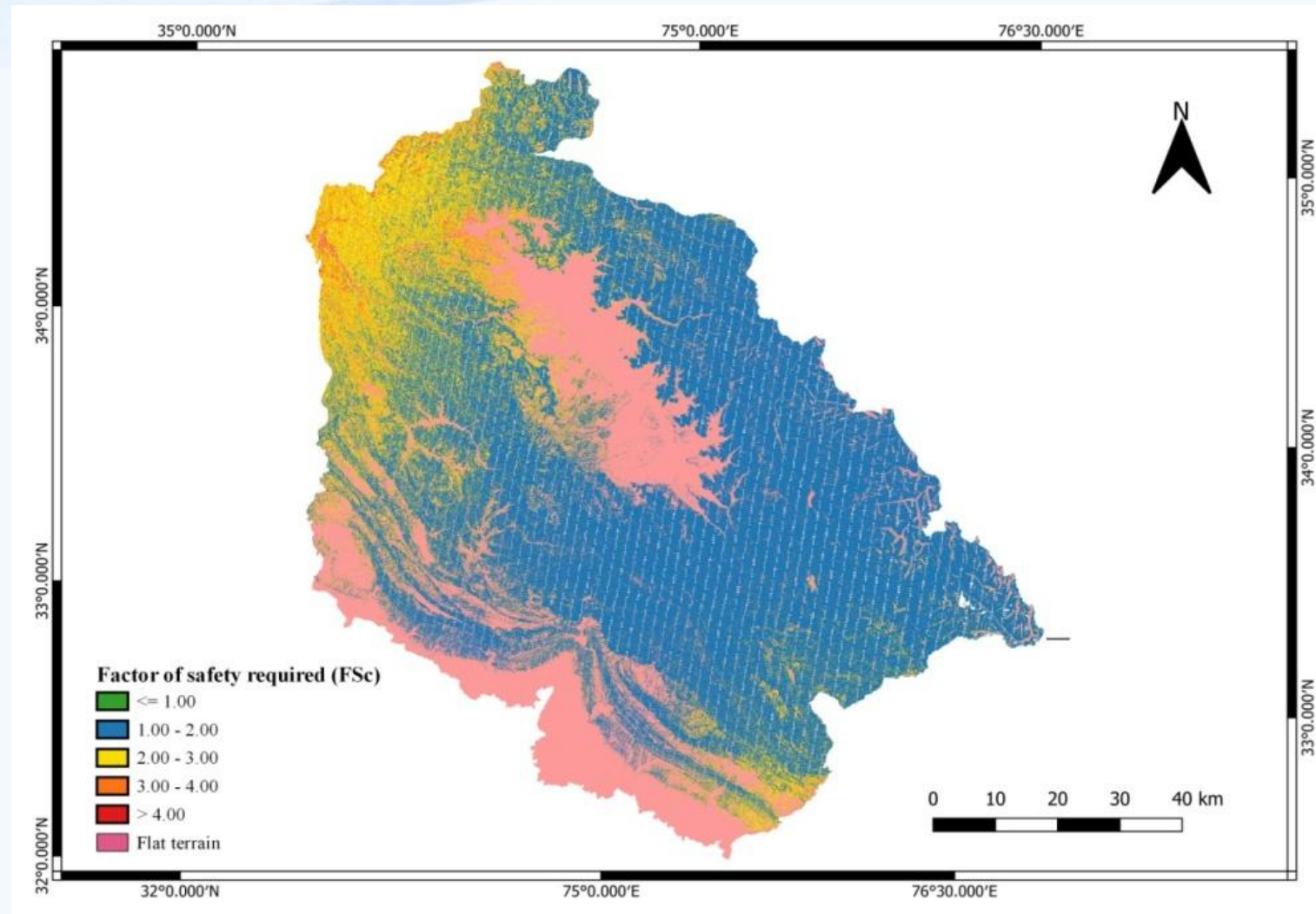
PHA at bedrock level obtained from DSHA for Ladakh



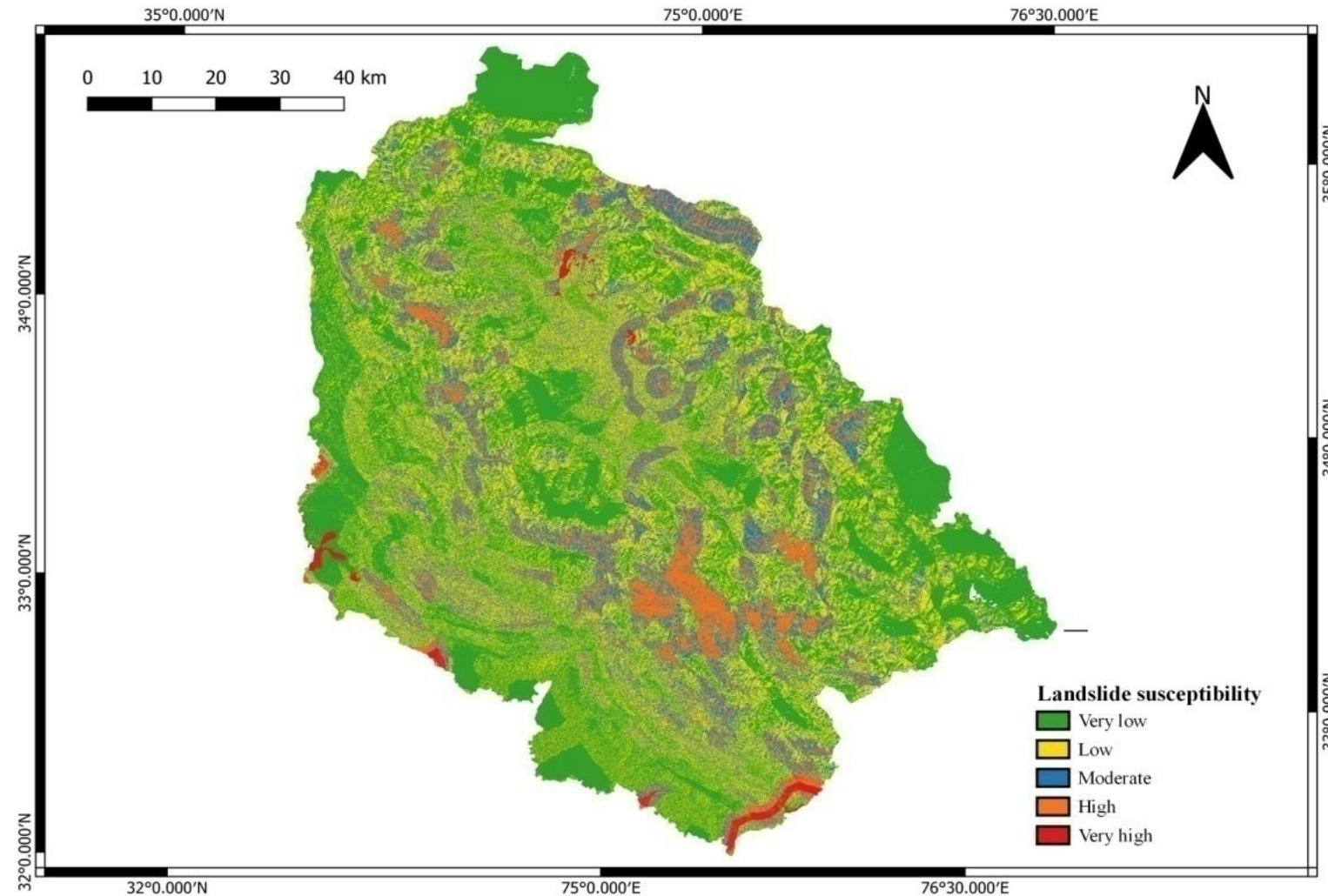




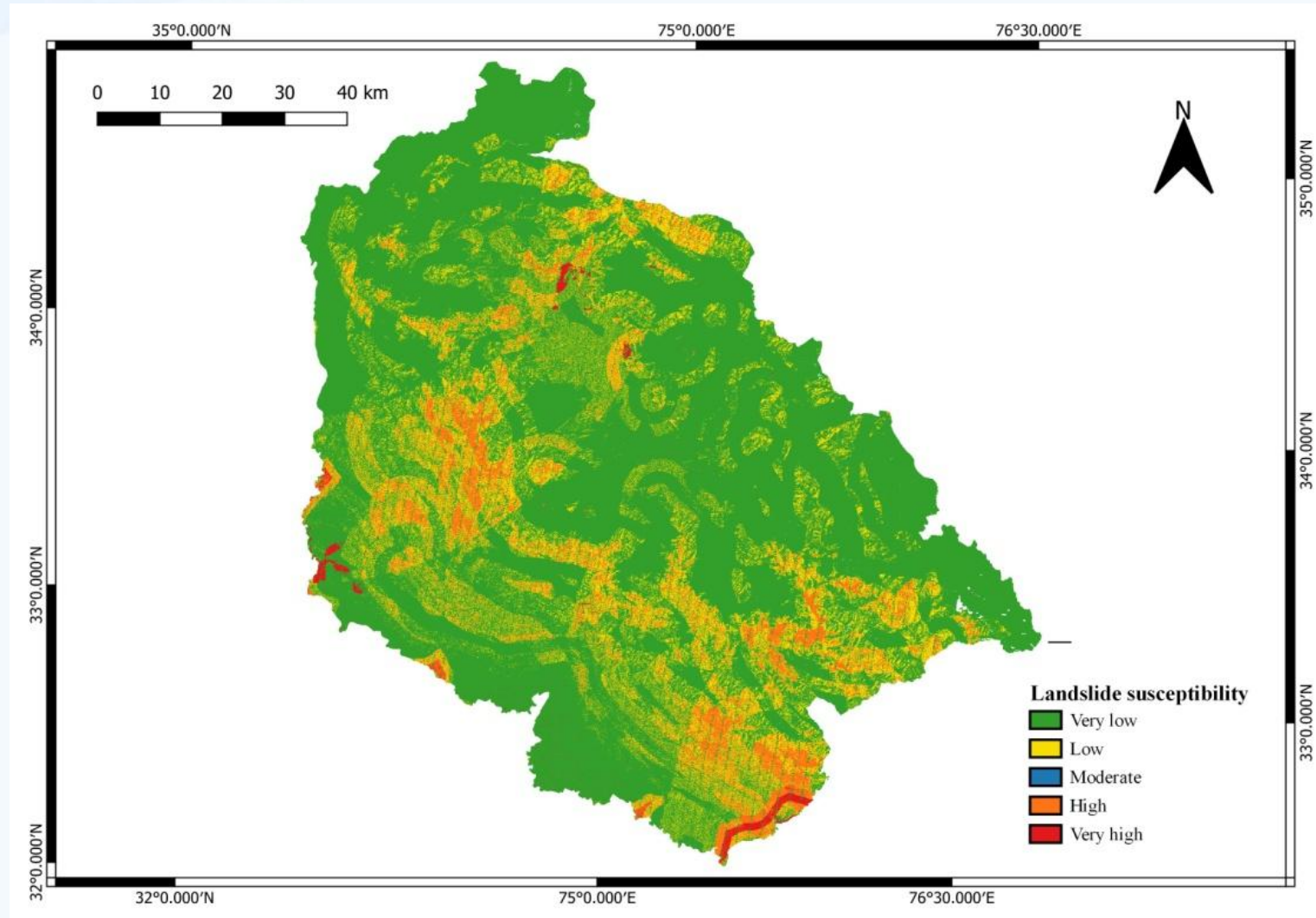




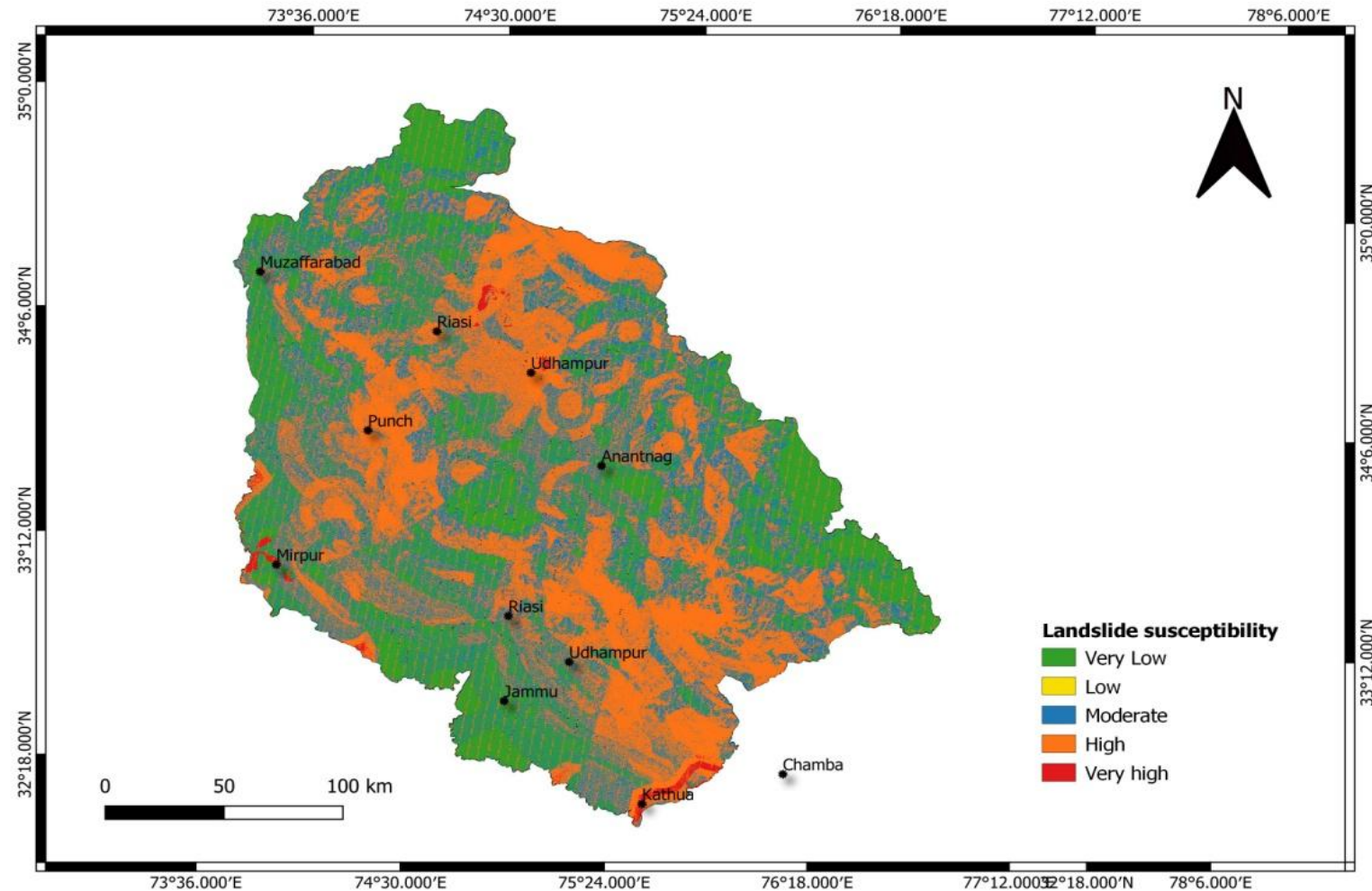
Rainfall and earthquake induced landslide analysis by Frequency Ratio method (cont..)



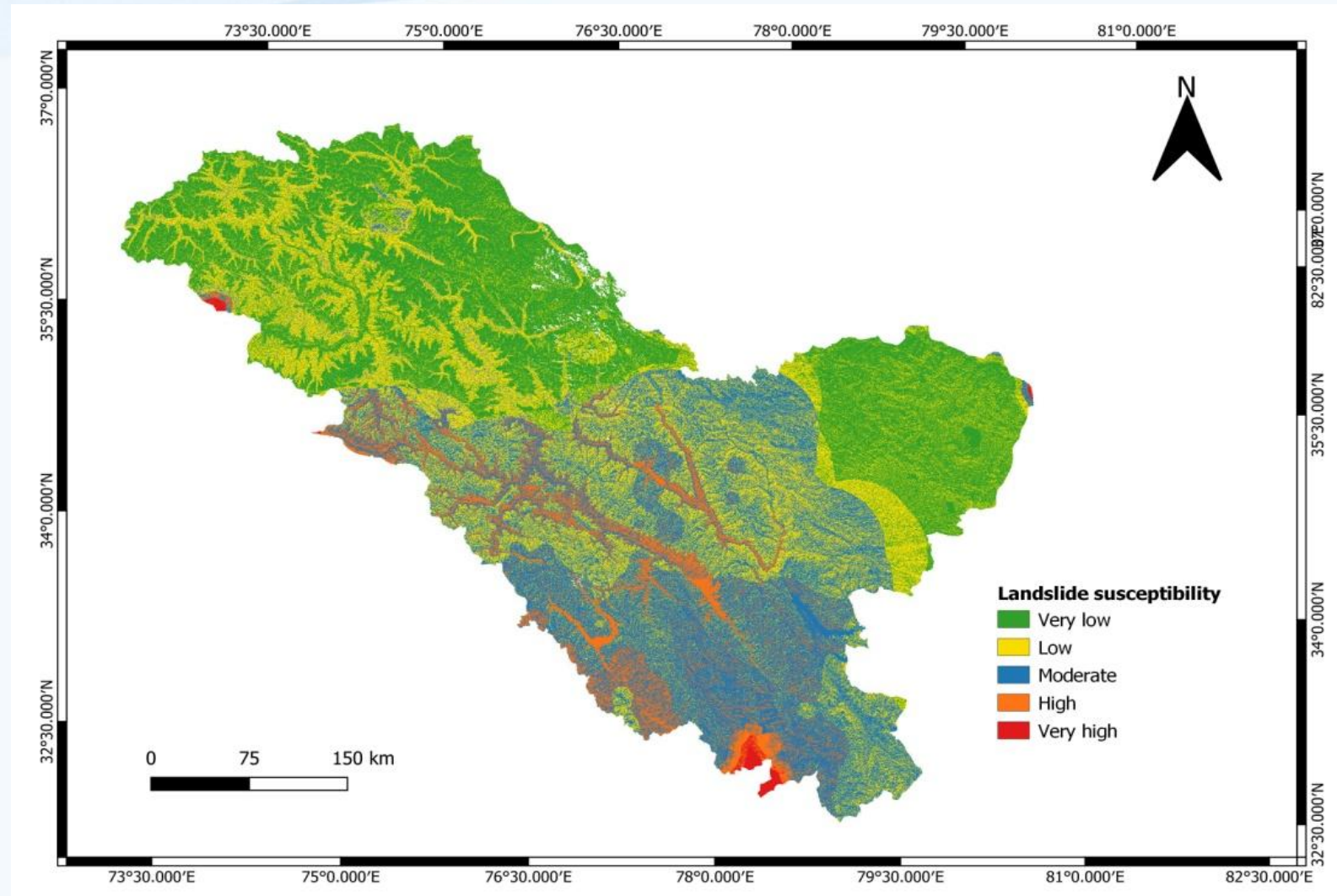
Rainfall and earthquake induced landslide analysis by Frequency Ratio method (cont..)



Rainfall and earthquake induced landslide analysis by Frequency Ratio method (cont..)

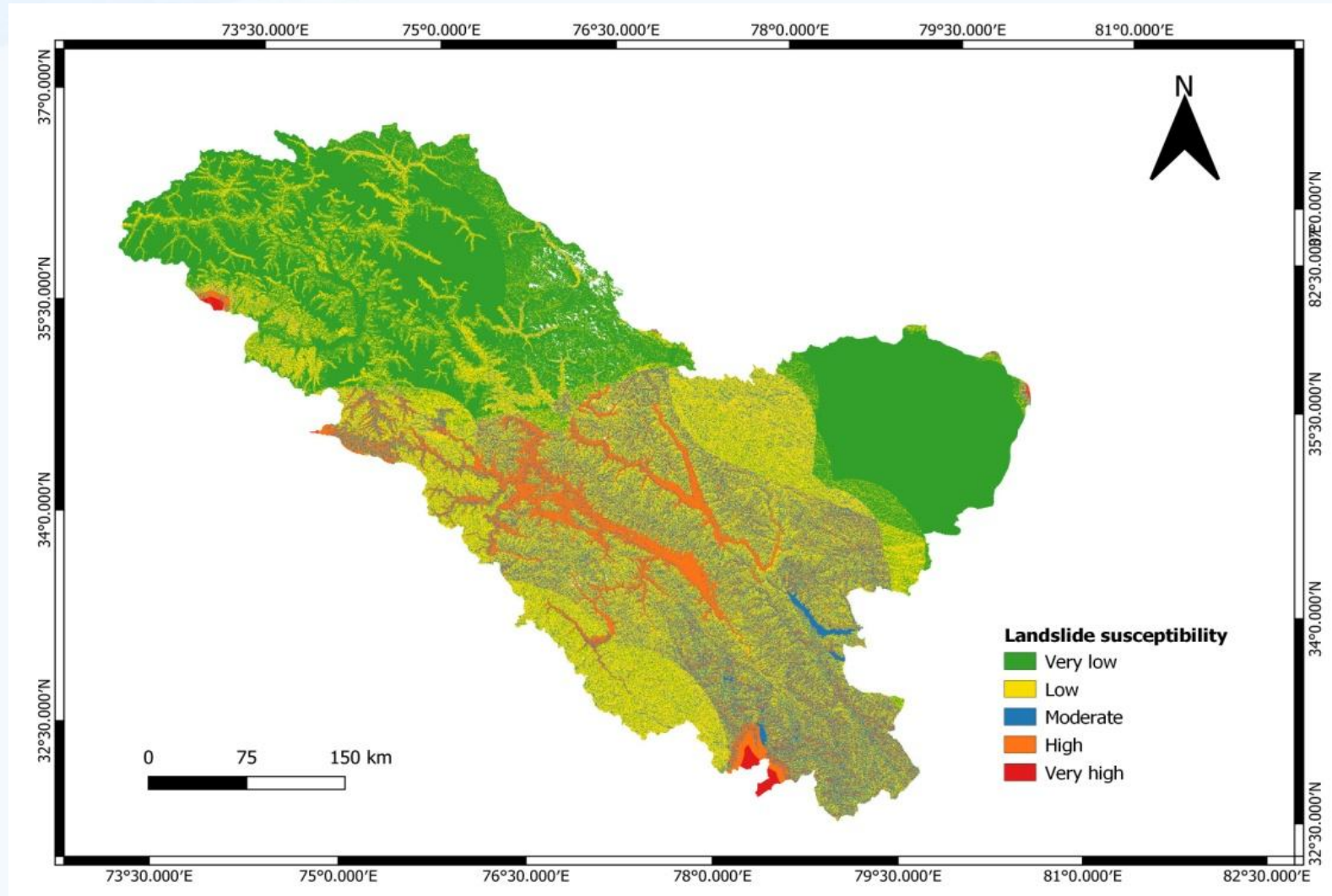


Rainfall and earthquake induced landslide analysis by Frequency Ratio method (cont..)



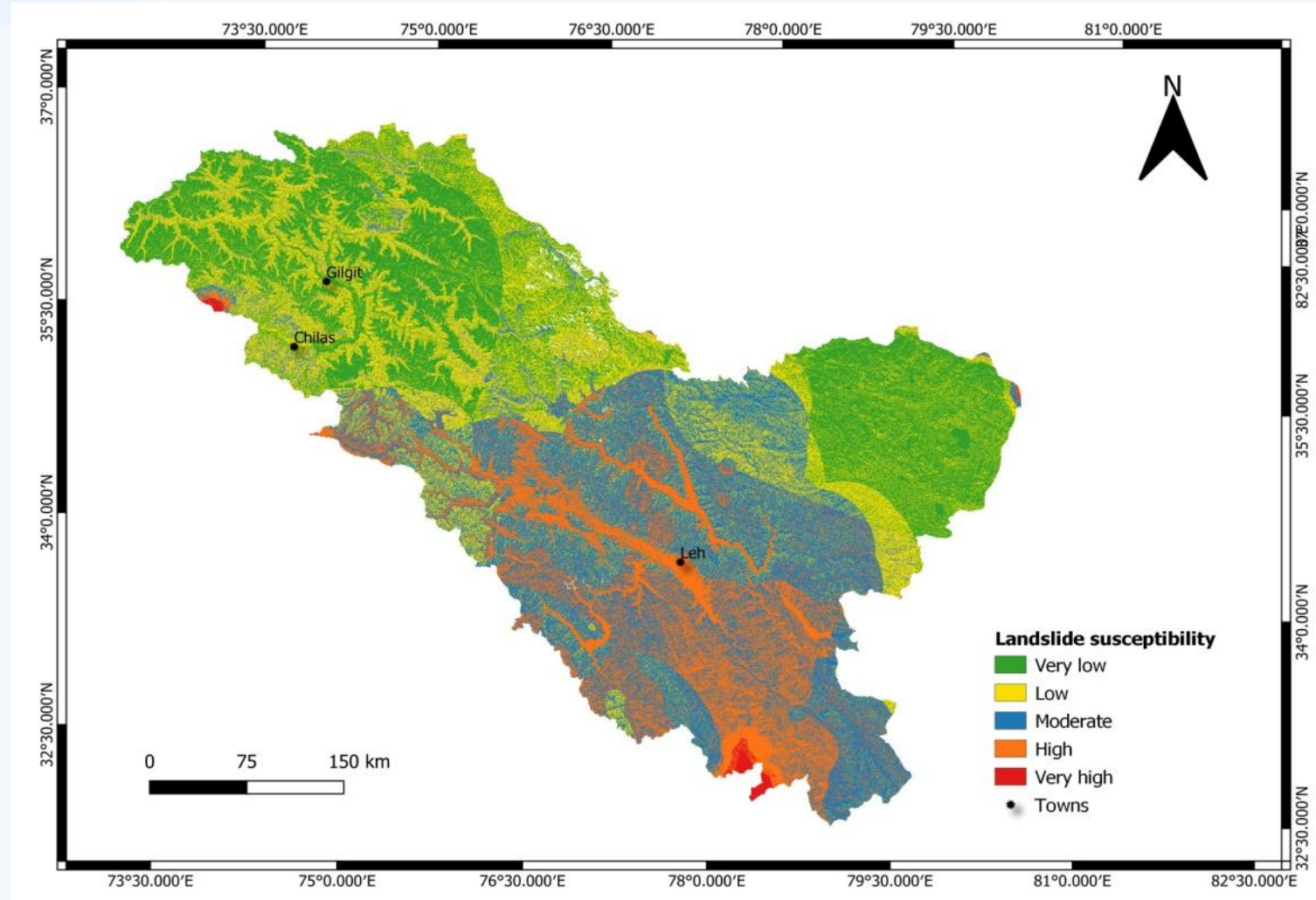
Rainfall induced landslide susceptibility map of Ladakh.

Rainfall and earthquake induced landslide analysis by Frequency Ratio method (cont..)



Earthquake induced landslide susceptibility map of Ladakh

Rainfall and earthquake induced landslide analysis by Frequency Ratio method (cont..)



Combined rainfall and earthquake induced landslide
susceptibility map of Ladakh

Concluding Remarks

- Assessment of Earthquake Hazard is important to plan future construction activities and retrofitting of existing buildings
- In DSHA, Ground motion parameters are estimated for the maximum credible earthquake assumed to occur at the closest possible distance from the site of interest.
- PSHA assumes many scenarios considering all magnitudes, all distances and all effects. PSHA characterizes uncertainty in location, size and frequency of earthquakes & combines all of them to compute the hazard.

Concluding Remarks...

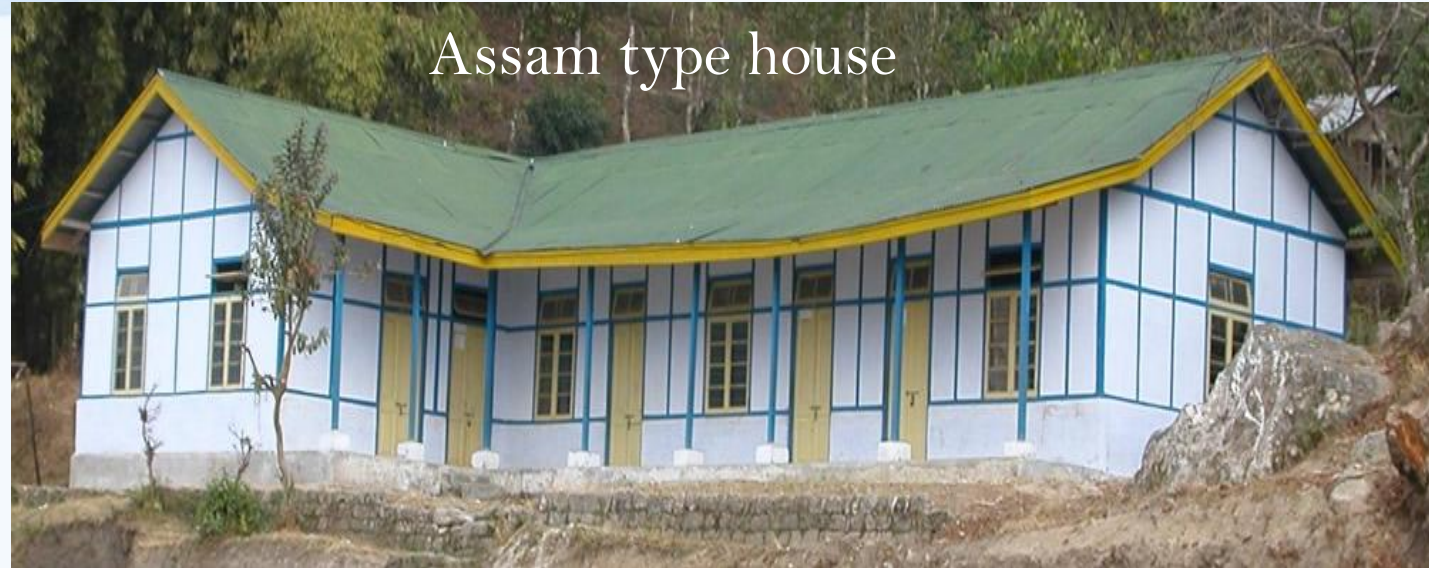
- Local soil conditions amplify the seismic waves. Design of structures require good estimate of this site amplification.
- Shear wave velocity profile is major input for ground response analysis. There are correlations available to convert conventional geotechnical parameters to V_s
- The estimated PGA values are important in assessing the seismic safety of geotechnical structures and to evaluate liquefaction potential at a site.
- Spectral acceleration values corresponding to different periods (Response spectra) are useful in studying the response of structures.
- ¹⁰⁸Preparing the community to face future earthquakes is the need of the hour

- Traditional Earthquake Resistant Construction methods



Traditional House in Kutch Region of India

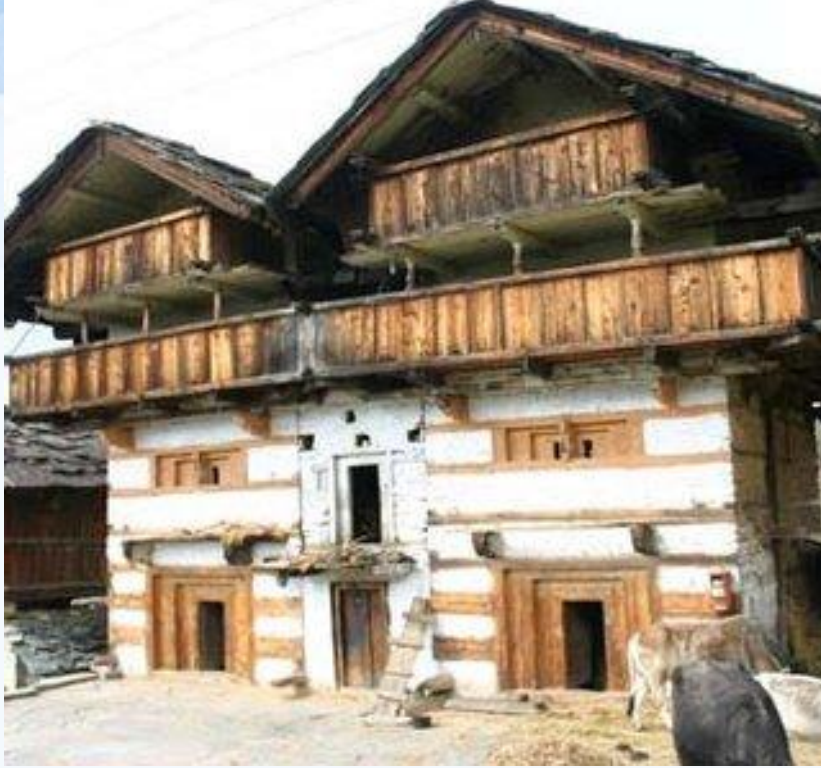
Bhungas, circular mud huts, are both **resilient** in the face of quakes and central to the **Kutch** identity. All the bhungas of this little village in **Kutch** survived the tremor of 2001, when every other **house** collapsed. ... A bhunga uses a circular shape for its maximum advantage against the lateral forces of an **earthquake**.



Assam type house

Assam-type houses are commonly found in the northeastern states of India. These are generally single dwelling units and do not have common walls with adjacent buildings. The house is made largely using wood-based materials. Performance of Assam-type houses has been extremely good in several past earthquakes in the region. Structural strengths that influence earthquake safety of the house include light-weight materials used for walls and roofs, flexible connections between various wooden elements at different levels, etc.

Koti Banal Architecture of Uttarakhand



Buildings of this construction type can be found in in the northern part of the state Uttarakhand and the southern part of the state Himachal Pradesh in Northern India. The reasons that these buildings outlived so many centuries mainly lie in their structural configuration which clearly demonstrate that their builders already had the idea of dynamic earthquake actions, particularly out-of-plane failure of masonry walls.

Dhajji dewari buildings, Kashmir



Dhajji Dewari system - a valid construction in seismic area got its recognition after Kashmir earthquake in 2005. Due to its resemblance in the appearance to quilt patchwork of Persian weavers it is called as “Dhajji”. It is quite prevalent in the earthquake prone areas of Jammu and Kashmir. Significant earthquake resistance, cost effective, use of indigenous available resources and skill, swift in construction process makes it a selective choice for earthquake disaster re-inhabitation. It is also referred in the Indian Standard Codes as brick nogged timber frame construction. .

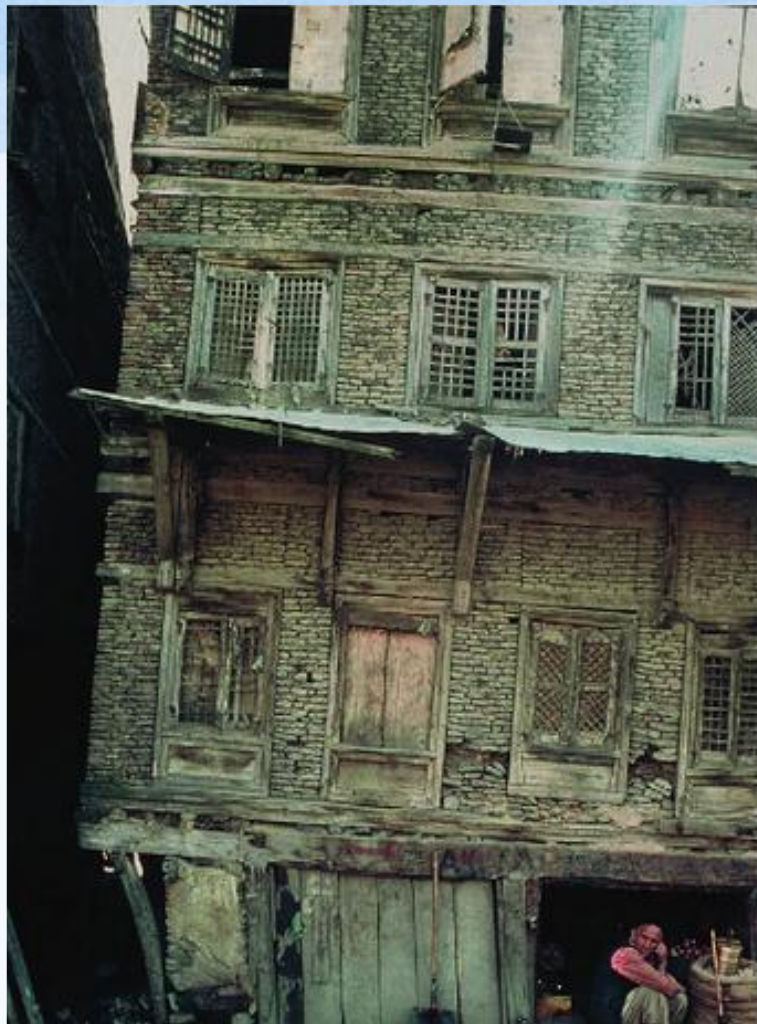


Plate 1: Out-of plane collapse of wall of a school building (Sastur)



Plate 2: Timber post supported wall of a shop building intact after earthquake (Sastur)

Latur earthquake of September 30, 1993



Typical **Taq** construction in Srinagar city
Some observations

- Staggering of windows
- Division of masonry into piers & spandrel panels
- Presence of Horizontal timber members

Thanks to Prof KS Nanjunda Rao



Traditional rural **Bahareque** housing in El Salvador. No outer render has been applied
(It is known as **wattle-daub** in UK)



Taquezal house in Leon, Nicaragua



**View shows the response of two neighboring buildings in the 1999 Duzce Turkey earthquake
On the left is the timber laced masonry building with only one panel of masonry missing
whereas on the right the reinforced concrete framed building has collapsed**

Timber-laced traditional construction in different parts of the world



Timber laced masonry construction practice in Turkey called "HIMIS"

View of five storey building constructed with traditional *Taq* technique (left) and four storey building constructed with *Dhajji -dewari* technique (right) in the Srinagar (India) city center (Photo taken in 2005)

Ancient Vibration Isolation Technique – Sandbox



*Ramappa and Thousand Pillar temples which were built on foundations laid using
sandbox technique*

The technique involved filling the pit dug up for laying foundation with a mixture of sand lime, jaggery (for binding) and karakkaya, before the buildings were constructed on these 'sandboxes'.

The sandbox in the foundation acts as a cushion. Most of the vibrations caused by earthquake get deamplified while passing through the sand by the time they reach the actual foundation of the building.

Every town should have at least one large open ground



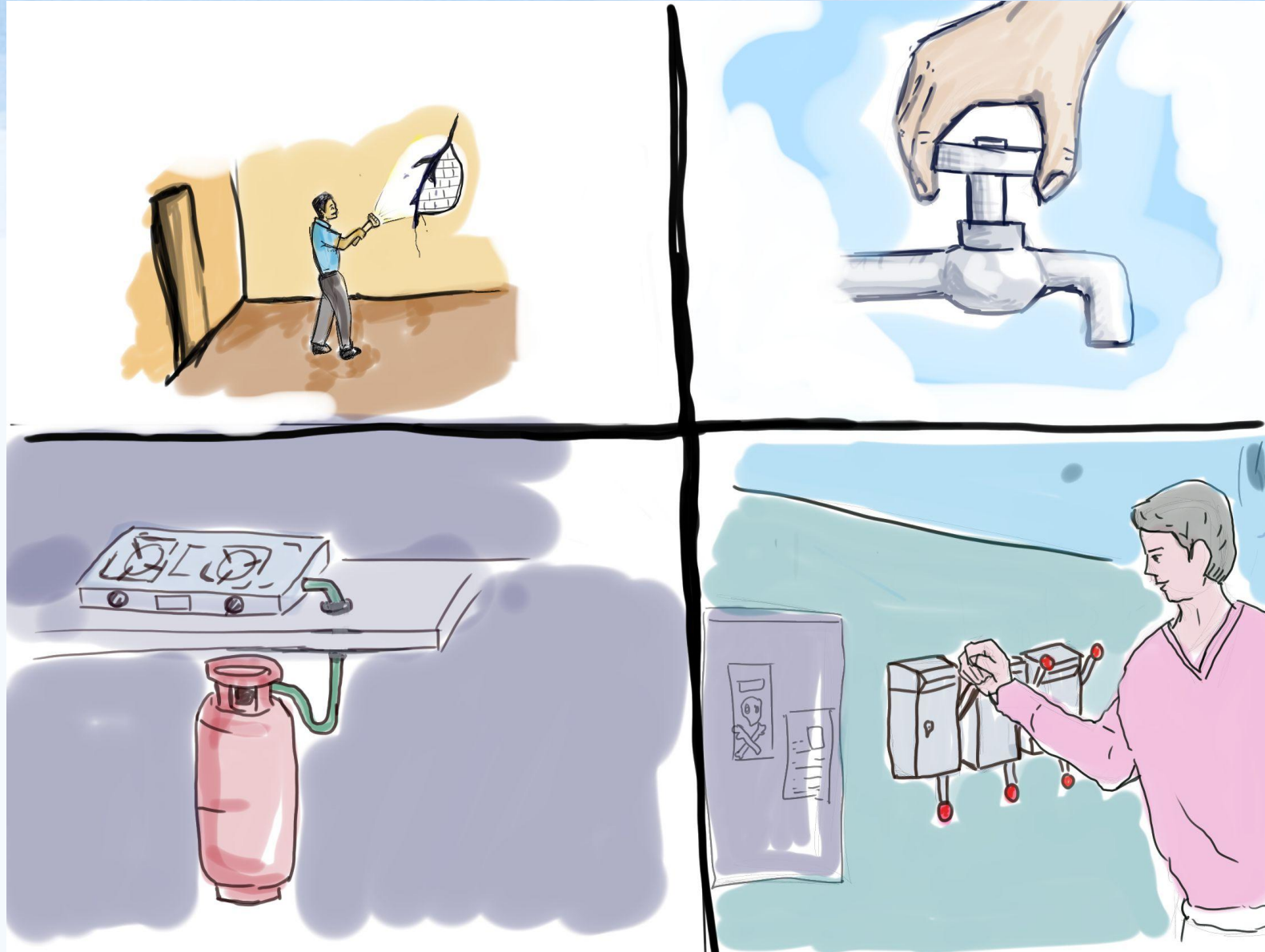
116

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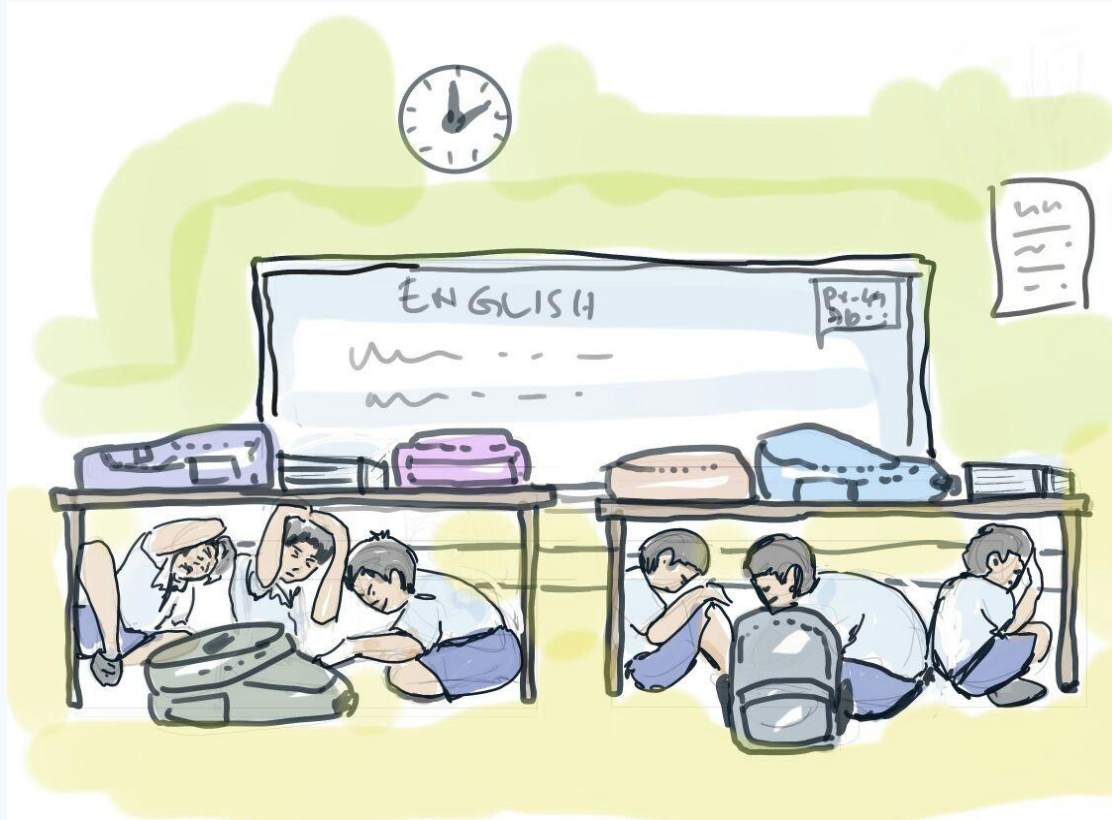
Nepal Earthquake: Kathmandu's Open Grounds Turn Into Camps for Frightened Residents



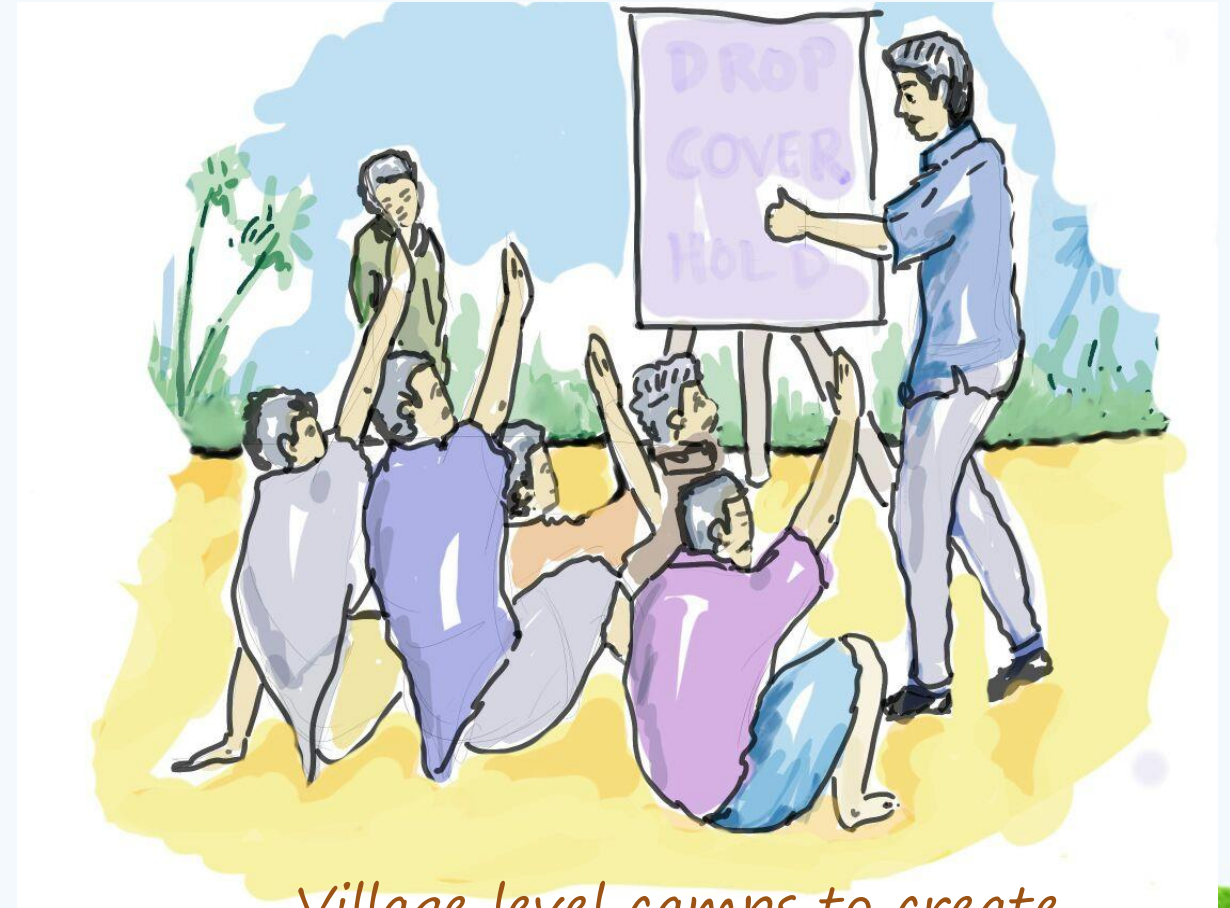




After an earthquake, check for damage in the building,
save water, switch off gas supply and switch the mains off



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 Mock drill at school on what to do during an earthquake



Village level camps to create awareness on earthquake preparedness

Thank You



Time-Frequency Analysis

- FT can recognize the frequencies in a non-stationary signal, but it does not disclose these frequencies' spatial data.
- This can be handled by JTFA techniques which demonstrates how the signal energy is distributed simultaneously over time and frequency domain (Kumar, 2002, Rezaeian and Luco, 2012, Devi and Sharma, 2016, Kumar, 2016)
- Due to the limitation given by the principle of uncertainty, the outcome of STFT is affected by windowing effects (Qian and Chen, 1999, Huerta-Lopez et al., 2000) as well as the amount of leakage (Shemeta et al., 2009, Upegui-Botero et al., 2012).
- Gabor Transform (GT) uses a Gaussian window function – which has better control over the frequency resolution and spectral leakage (Zielinski 2001, Soendergaard, 2009, Kumar et al., 2015)
- Further, Gabor transforms the time-domain into a time-frequency domain while CF represents the time-domain signal after time

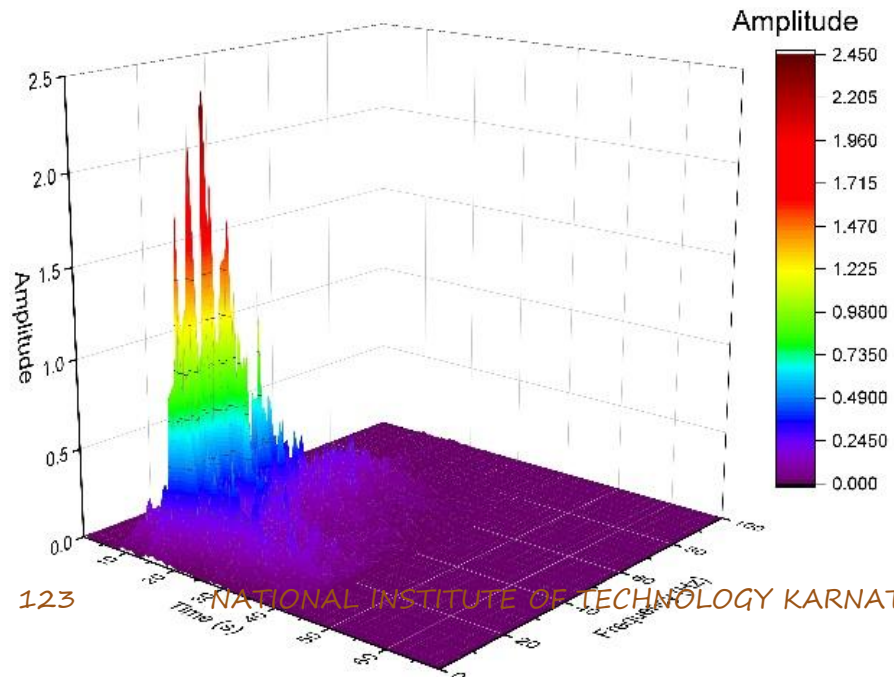
- Recorded Acceleration Data
- Classification of Data
- Gabor Transform of signals
- Estimation of MGAC
- Gabor Expansion

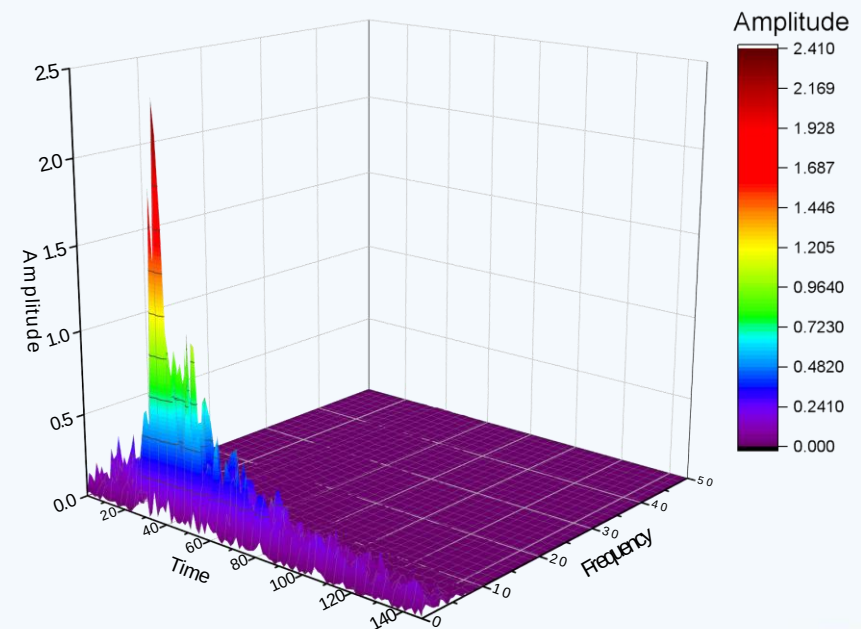
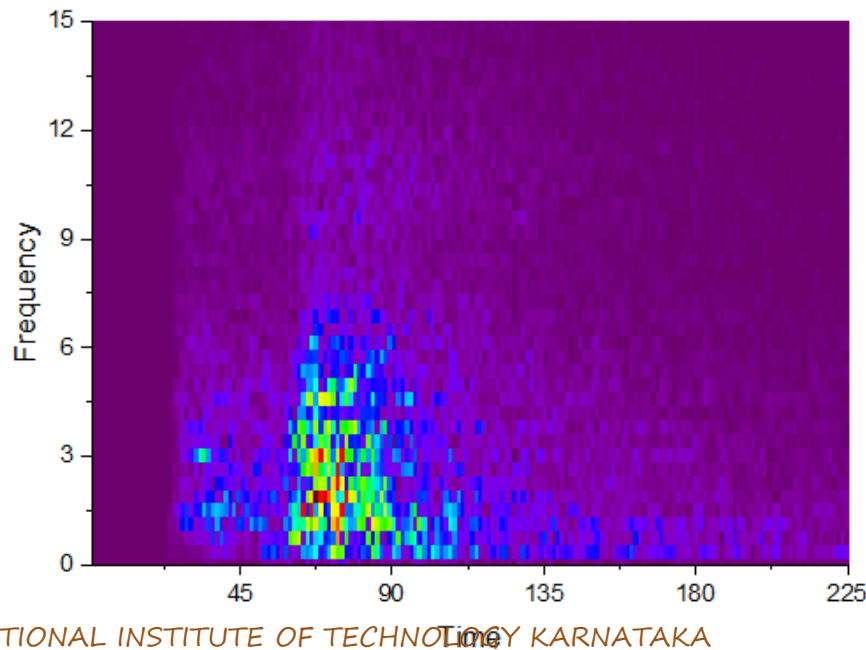
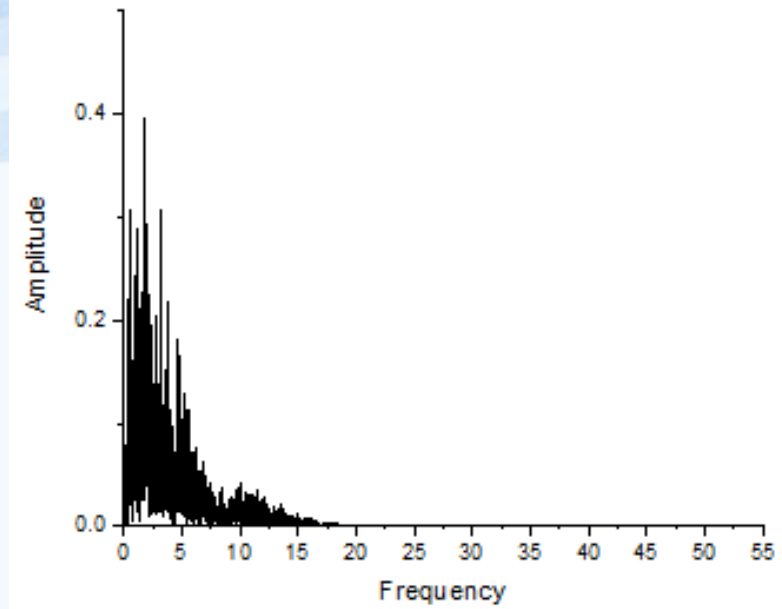
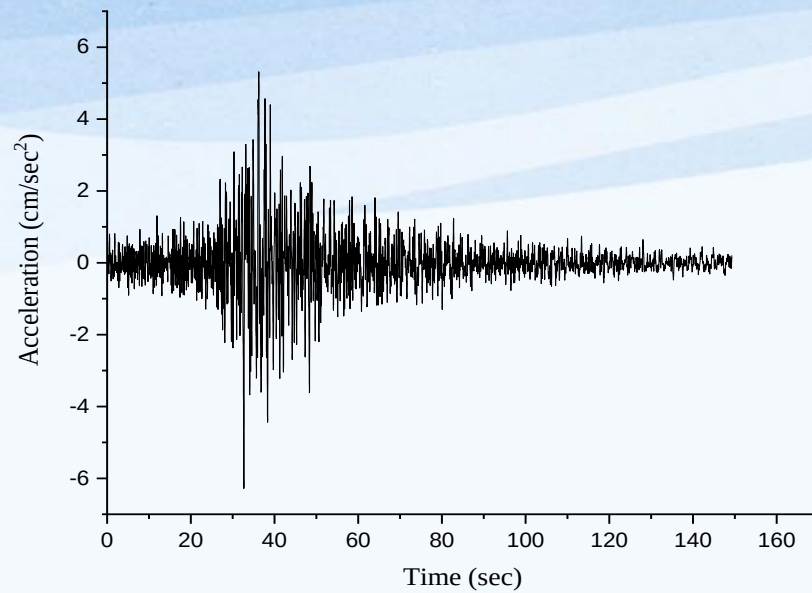


Synthesis of Signals



- Assessment of frequency contents
- Response spectra development
- Comparison and validation using FT, Response Spectra, Spectrogram and Physiogram





124

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Acceleration vs time for the 2011 India-Nepal border earthquake of magnitude 6.8 - Fourier Transform showing amplitude and frequency contents - Spectrogram with Gaussian window (GT) d) GT¹²⁴

Earthquake data classification

- Recorded strong motion data of 55 earthquakes obtained from PESMOS and categorized for synthesis of time-histories and response spectra for NCH.
- 19 $M_x D_y$ combinations using 211 recorded time-histories for horizontal and vertical time-histories.

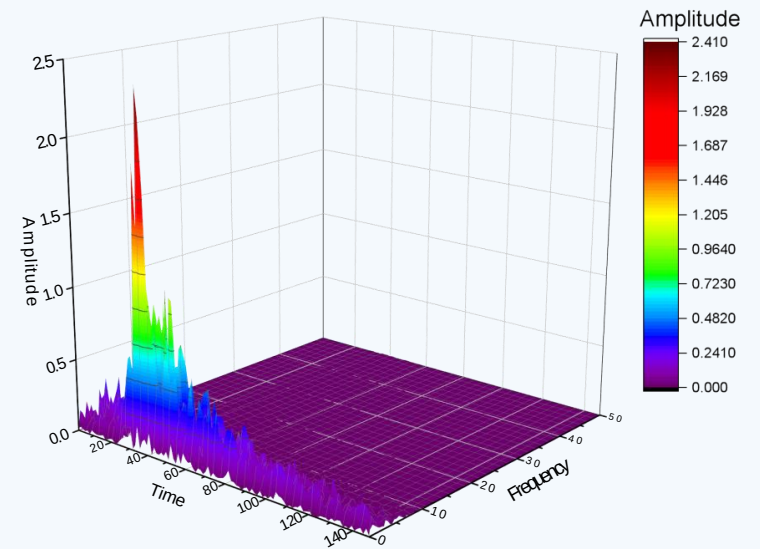
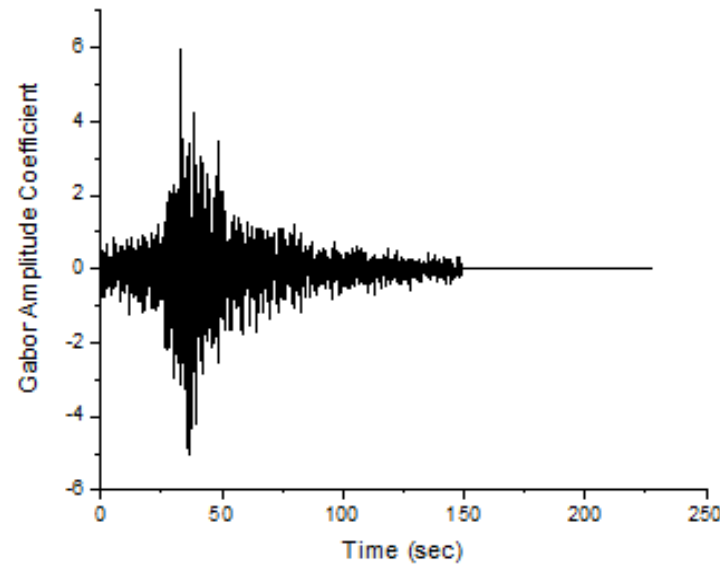
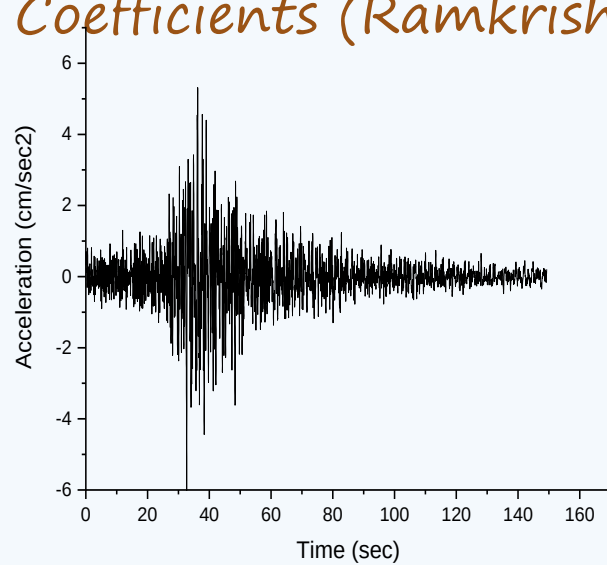
Magnitude range, M_x (M_L)	Distance range, D_y (km)	Number of Recordings
4.0 – 4.5	0 – 40	27
	40 – 80	23
	80 – 120	8
	120 – 160	9
	160 – 200	4
4.5 – 5.0	0 – 40	17
	40 – 80	28
	80 – 120	11
	120 – 160	20
	160 – 200	9
	240 – 280	4
5.0 – 5.5	40 – 80	5
	80 – 120	8
5.5 – 6.0	40 – 80	5
	80 – 120	7
	120 – 160	9
	160 – 200	6
	200 – 240	4
	240 – 280	3

- Recorded strong motion data of 33 earthquakes obtained from PESMOS and categorized for synthesis of time-histories and response spectra for NEH.
- 11 $M_x D_y$ combinations using 72 recorded time-histories for horizontal and vertical time-histories

Magnitude range, M_x (M_L)	Distance range, D_y (km)	Number of Recordings
4.0 – 4.5	0-40	7
	40-80	12
4.5 – 5.0	40-80	5
	80-120	6
5.0 – 5.5	120-160	9
	200-240	4
	440-480	4
5.5 – 6.0	200-240	7
	360-400	5
	440-480	6
6.0 – 6.8	120-160	7

Accelerogram Normalization and GT

- To compare and merge a set of earthquake motions in a given $M_x D_y$ range, they are normalized based on their PGA.
- The acceleration values are divided by their PGA to obtain a normalized acceleration value in the range of -1 to 1.
- All the normalized signals are transformed using GT using an algorithm developed in National Instruments LabVIEW platform to obtain their Gabor Amplitude Coefficients (Ramkrishn



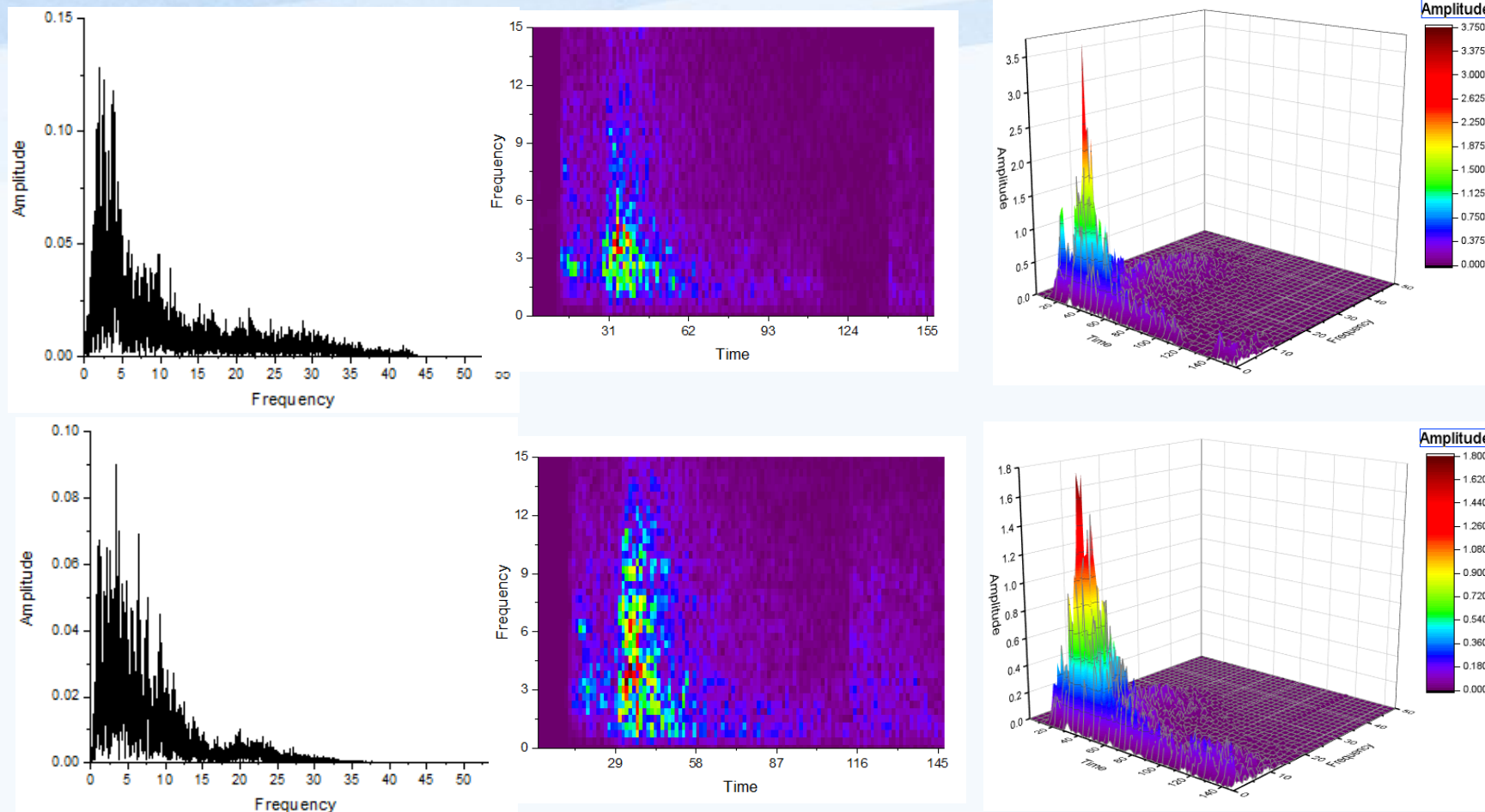
127 NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA
Actual accelerogram of 2009 Bhutan earthquake of magnitude 6.2: acceleration vs time, Gabor amplitude coefficients, Physiogram

* Ramkrishnan R., Deepa Devaraj, Sreevalsa Kolathayar, T. G. Sitharam (2020), "Recent Developments in Synthesis of Earthquake Motions Using Linear Joint Time Frequency Analysis Techniques", 17th World Conference on Earthquake Engineering 17WCEE 2020 Sendai Japan (Published)

GE and Synthesis

- Mean Gabor Amplitude Coefficients (MGAC) of all the transformed signals in a selected $M_x D_y$ range is estimated.
- MGAC smoothens out the unwanted features in the signal like noise, without losing its key temporal frequency contents (Kumar et al., 2016, Ramkrishnan et al., 2020*).
- Gabor Expansion (GE) is then applied using LABView to invert the MGAC and yield back a synthetic time history, which is representative of the recorded signals in the selected $M_x D_y$ range.
- Response spectra, FT, Spectrograms and Physiograms of the synthetic signals are developed further for comparison and validation.

* Ramkrishnan R., Deepa Devaraj, Sreevatsa Kolathagari, T. G. Sathyan (2020), "Joint Time Frequency Analysis Based Synthesis of Acceleration-Time History and Response Spectra for Japanese Earthquakes", 7th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics ICORAGEE 2020, Bangalore, India. (Accepted)



(Top) Fourier Transform, Spectrogram and Physiogram of Bhutan earthquake of Sep 21, 2009 having magnitude 6.2 (Bottom) Fourier Transform, Spectrogram and Physiogram of the synthetic signal representing $M_{6.0-6.8}D_{120-160}$ (Deepa et al., 2020*)