16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 3348 (Abstract ID)

Registration Code: S-T1461952080

TOWARDS NEXT GENERATION ATTENUATION MODELS FOR INDIA

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Abstract

Ground motion prediction equations (GMPEs) were developed in the past using stochastic point source models and pseudo-finite fault approaches, in addition to sparse data usually is not sufficiently well sampled in magnitude (Mw) distance from fault (R) space. Showing the localized and regionalized nature of attenuation models developed for India, along with the unified model released by NDMA for entire India, ways to arrive at the next generation attenuation models for India have been examined by considering the catalogue of earthquakes for India and its surroundings. The catalogue of India from National Centre for Seismology is compared with that of the international catalogue, which contains only earthquakes for, jut over a century but includes additional information like moment tensor solutions for about four decades. By analyzing the spatial distribution of focal mechanism for the available earthquakes, trends and patterns have been discussed which could help narrow down the range of possible values for the seismological parameters used in simulation based approaches for developing GMPEs.

Keywords: ground motion prediction equations (GMPEs); earthquake catalogue; Hindukush, indo-burmese

1. Introduction

From the standpoint of minimizing economic losses and fatalities due to earthquakes, structures have to be designed to withstand the intensity of shaking felt at its location due to the maximum possible earthquake in its vicinity. Several intensity scales were established from late 19th century to mid 20th century depending on the extent of damage felt. Having prior knowledge of maximum possible intensity could aid engineers in optimal design of structures. From the solution of elastodynamic equations to simple forcing terms embedded in elastic homogeneous full space, it could be easily seen that larger magnitude (or potency) events produce greater displacements at any location of interest and that the (peak) displacements decrease with distance from the source. However, establishing the rate of decay with distance or the way peak ground motion increases with magnitude for propagating sources in heterogeneous half spaces is not trivial to solve analytically and hence engineers rely on empirically derived Ground Motion Prediction Equations (GMPEs), also known as attenuation relationships. GMPEs for a region gives peak ground accelerations (PGA) or spectral accelerations at various time periods for a known magnitude and distance from the source. Gradually, GMPEs around the world got upgraded to include additional dependent parameters like site conditions, focal mechanism, directivity, hanging wall effects etc. This article focuses on how GMPEs for India have evolved and discusses ways forward in obtaining a comprehensive relation for spectral ordinates.

2. Existing GMPEs of India

India has felt shaking from tectonic activity all round the Indian plate from the Great Himalayas in the North to the Indo-Burmese subduction zone in the east and the Makaran subduction zone in the west. India has also experienced intraplate earthquakes like the 1993 Latur earthquake, the 1997 Jabalpur earthquake and the 2001 Bhuj earthquake. Strong motion acceleration (SMA) data of India is limited most to a set of small arrays in the North-East and parts of Himalayas. With these limited SMA records, one of the earliest attenuation relationship for Himalayan region developed by [1] was a power-law in distance and exponential in magnitude for peak ground acceleration (PGA) of the horizontal components of ground motion, whilst that of [2] includes additional exponential dependency with magnitude as shown in Eq. (1).

$$
\begin{aligned}
\log_{10}(PGA) &= 1.14 + 0.31M + 0.65\log_{10}(R) \\
\ln(PGA) &= -4.135 + 0.647M - 0.00142R - 0.753\ln(R)
\end{aligned}
\tag{1}
$$

where M is the magnitude and R is the distance from the source. For Koyna-Warna region, North-East, Indo-Burmese subduction zone and Himalaya-Zagros region proposed functional forms by [2], [3], [4] and [5] respectively are in Eq. (2)

$$
\begin{aligned}
&\log_{10}(PGA) = 1.7615 + 0.9325(M-6) - 0.0706(M-6)^2 + \ln R - 0.0086R \\
&\log[PSV(T)] = c_1(T) + c_2(T)M + c_3(T)h + c_4(T)\log(\sqrt{R^2+h^2}) + c_5(T)v \\
&\log(PGA) = C_1 + C_2M + C_3h + C_4\sqrt{D_{fault}^2 + D^2} - g\log\sqrt{D_{fault}^2 + D^2} + C_5(s/S_C) + C_6(s/S_D) + C_7(s/S_E) \\
&\log[PSA(T)] = b_1(T) + b_2(T)M - b_3(T)\log(\sqrt{R_{JB}^2 + b_4^2}) + b_5(T)S + b_6(T)H
\end{aligned}
\tag{2}
$$

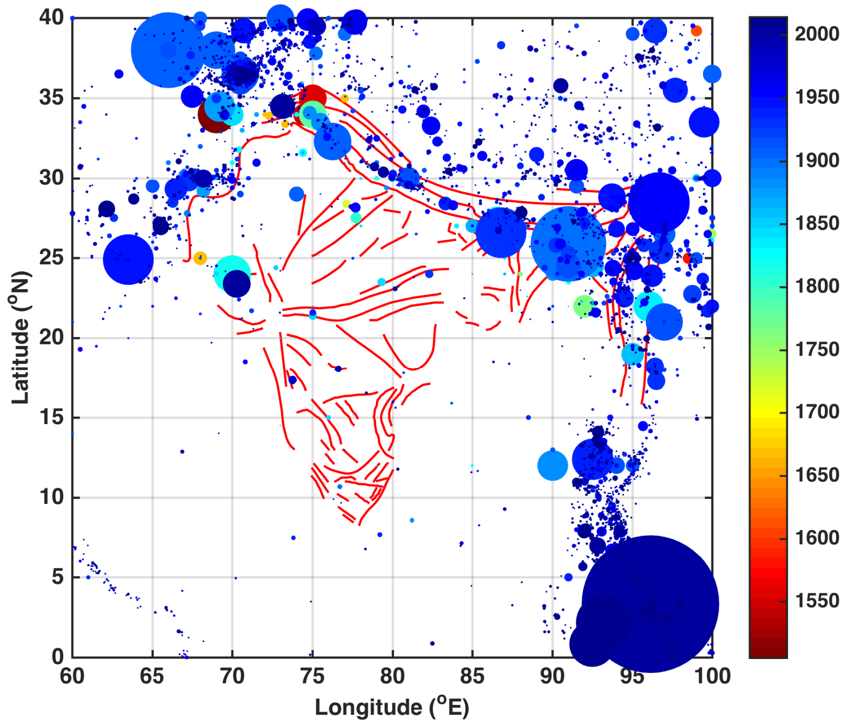


Fig. 1 – Indian Seismicity from Indian catalogue. Size of the circle represents magnitude of the earthquake and color scale represents the time in year. Faults are digitized from GSI (2001)

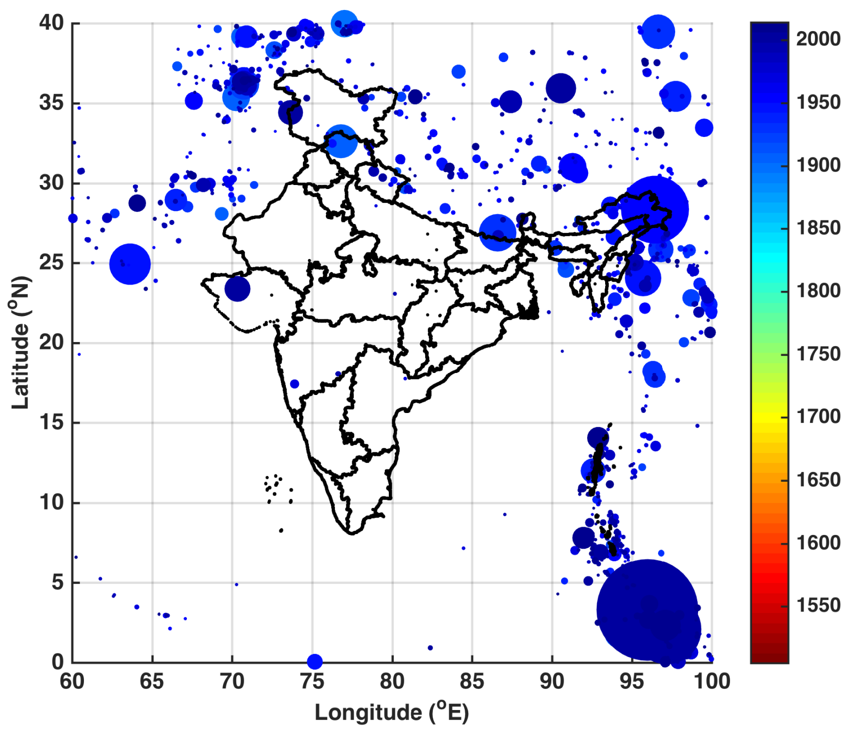


Fig. 2 – Indian Seismicity from ISC-GEM catalogue. Size of the circle represents magnitude of the earthquake and color scale represents the time in year.

Other GMPEs existing for India at regional or state level and microzonation efforts have led to city level GMPEs for a few other cities in India. The idea of this article is not to give an exhaustive list of all the GMPEs for India but to show how localized these relations are. The National Disaster Management Authority (NDMA) of India has released a report in 2011 [9] that contains an unified GMPE for all over India and the coefficients of it for certain time periods of engineering interest by dividing India into seven prominent zones. The GMPE of [9] assumes the functional form shown in Eq. (3)

$$\ln(Sa/g) = C_1 + C_2M + C_3M^2 + C_4r + C_5\ln(r + C_5e^{C_7M}) + C_8\log(r)\max(\ln(r/100),0) \tag{3}$$

Clearly, the unified equation for India for prediction ground motion does not differentiate among faulting types. Also, the shear wave velocity of the shallowest layers is not taken into account.

3. Earthquake Catalog of India

The Indian Meteorological Department (IMD) is the most authoritative source of earthquake catalogue for India. A few years ago, a National Center for Seismology (NCS) has been established under the Ministry of Earth Sciences (MoES), India to overlook the seismological and earthquake hazard related information within India. The earthquake catalog of India from January 1505 to February 2014 maintained by NCS is plotted in Fig. 1 colored by time of occurrence and sized by magnitude. The International Seismological Center (ISC) – Global Earthquake Model (GEM) catalogue is plotted in a similar fashion in Fig. 2 for comparing with the Indian catalogue. The ISC-GEM catalogue is available only from 1900 and so no red or green circles are seen in Fig. 2. Apart from that, there are also discrepancies in terms of location and magnitude of events. Although global seismologists were involved in preparation of the ISC-GEM catalogue, more weightage is given to the Indian catalogue in this work, as it is derived based on local and regional information. Also, recurrence intervals of Great earthquakes typically are 100's of years or more, and so it is worth using catalogue that spans well over a century. Only magnitudes (Mw) 5 and above have been shown in Figs. 1 & 2.

The distribution of magnitudes with time, in Indian catalogue, is shown in Fig. 3. The lack of occurrence of magnitudes close to 5 in the 16th, 17th and 18th centuries (Fig. 3) is debatable and could be attributed to the detectable thresholds during that period. Global Centroid Moment Tensor (GCMT) solutions have come into existence in 1976 (previously known by the name Harvard CMT) from which the focal mechanism information of earthquakes all over the world is available. Out of those GCMT events, we focus on those that occurred in and around India within the [0°N 40°N] latitudes and [60°E 100°E] longitudes. The beach-balls of earthquakes in the region of this study are shown in Fig. 4. It can be seen that not many of these are pure double couple sources. While there is a possibility of demarking zones of various focal mechanisms from Fig. 4, there are certain zones that have mixed pattern of faulting types probably because these earthquakes occur at various depths. In an effort to isolate the depth information, the earthquakes are separated into shallow focus (those lying at depths less than 70 km), intermediate focus (those lying at depths between 70 km and 300 km) and deep focus (those that are deeper than 300 km). Both catalogues show no deep focus earthquakes for the latitudes and longitudes considered here. The strike, dip and rake of shallow focus and intermediate focus earthquakes are shown in Figs. 5 & 6 respectively.

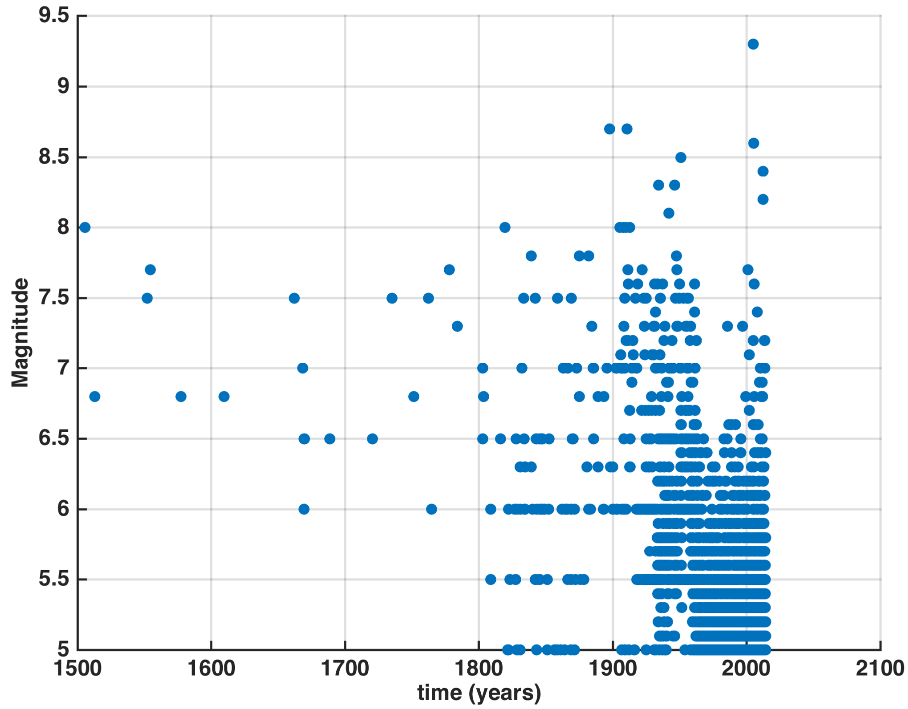


Fig. 3 – Available magnitudes as a function of time in Indian catalogue

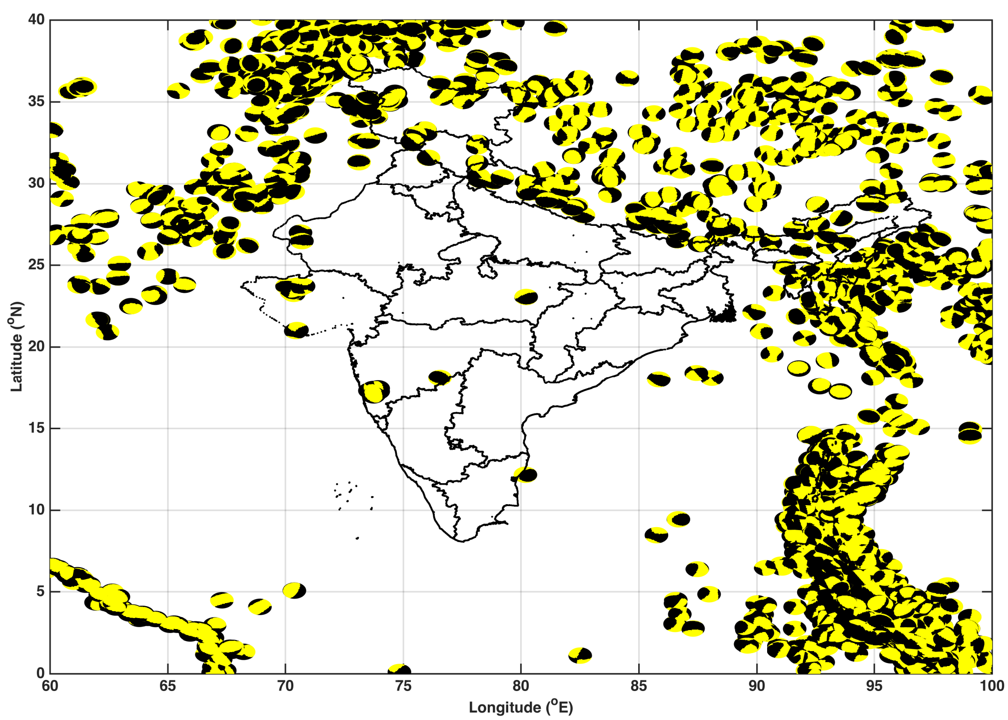


Fig. 4 – Available focal mechanisms from Global CMT catalog. Tension axis is shown by yellow color.

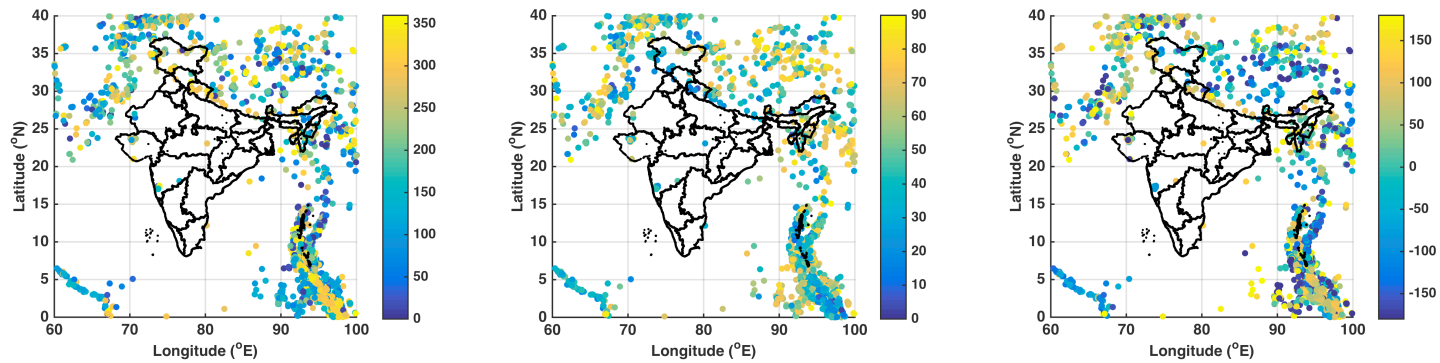


Fig. 5 – Strike (left) Dip (middle) Rake (right) of shallow focus (depth < 70 km) earthquakes

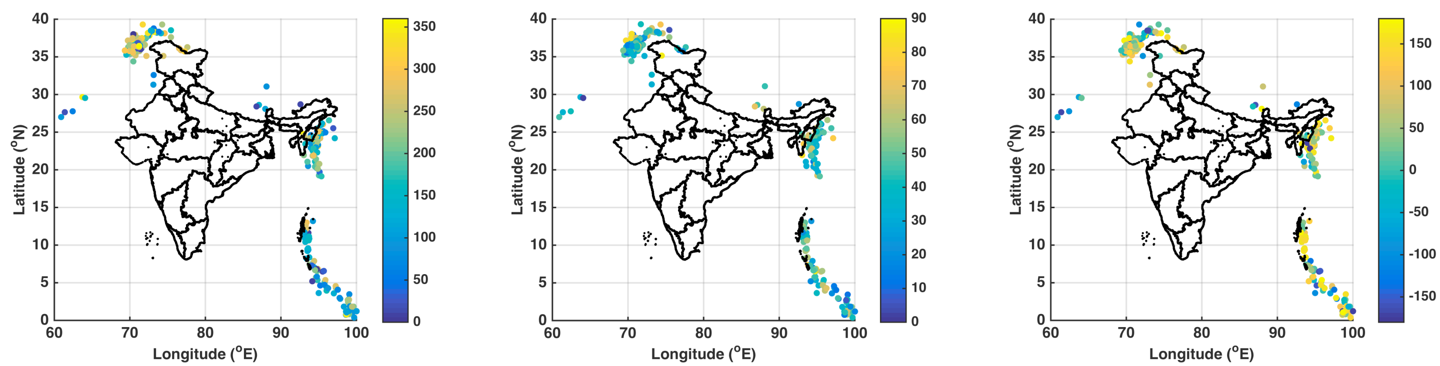


Fig. 6 – Strike (left) Dip (middle) Rake (right) of intermediate focus (70 km <= depth < 300 km) earthquakes

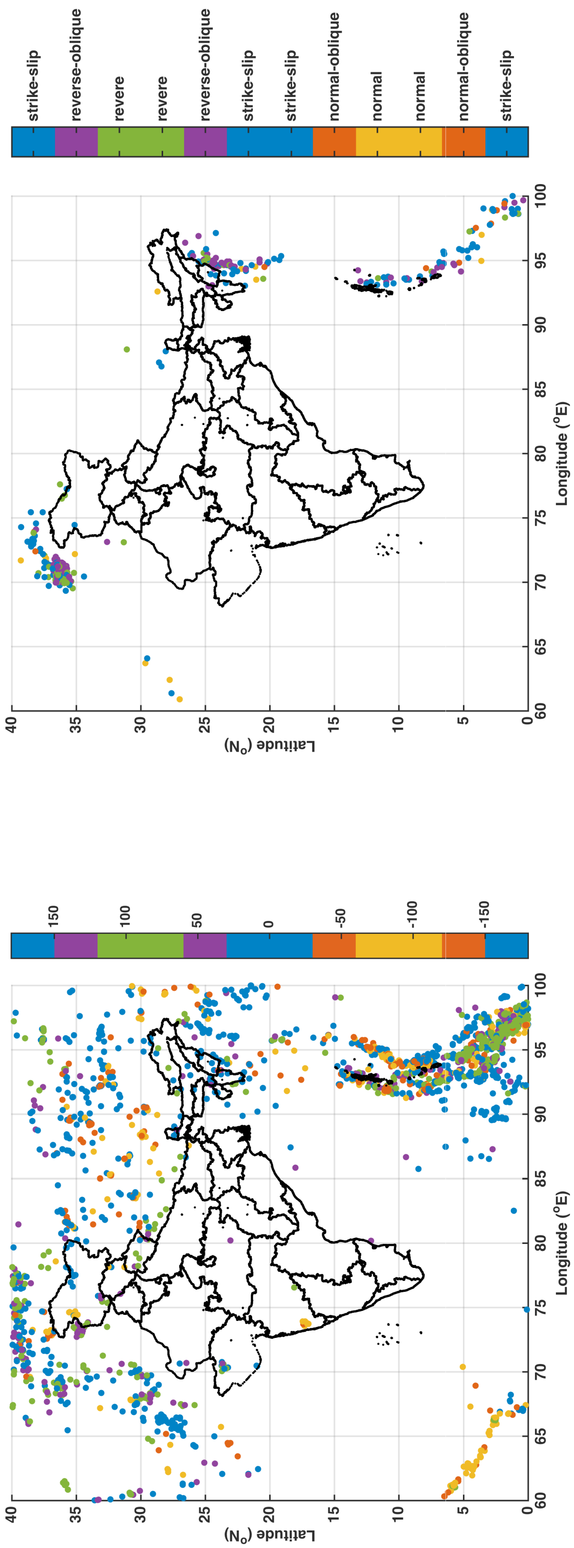


Fig. 7 – Mechanism of shallow (left) focus (depth < 70 km) and intermediate (right) focus (70 km <= depth < 300 km) earthquakes based on rake angle.

Joining the fault planes based on strike along a plate boundary could result in traces of the faults, though this has to be done at a particular depth. For instance, the Main Frontal Thrust (MFT) of the Himalayan fault system could be traced from the yellow the span from the Uttarakhand state of India continuing along the Indo-Nepal border (Fig. 5). The dip angle of shallow focus earthquakes show a trend of increasing dip angle from low-angle to near-vertical along the direction in which the Indian plate is underthrusting the Eurasian plate starting from the Himalayas. The Sumatra region has predominantly low angle faults while the Indo-Burmese border is characterized largely by vertical faults (Fig. 5). The Hindukush region, however, seems to be a mixture of all kinds of fault inclinations with the surface of the Earth. The intermediate focus earthquakes, which are mainly in the Hindukush, the Indo-Burmese border and the Sumatra-Andaman region show a narrow range of variations in strike and dip than the shallow focus earthquakes and so need to be simulated (for simulation based, as opposed to data driven) separately from the shallow focus earthquakes in developing GMPEs. Rake angles are grouped into six faulting types and are shown as categories in Fig. 7. Rake angles lying between 60 and 120 are categorized as reverse faults and those lying between -120 and -60 are labeled as normal faults. Thirty degrees on either side of normal faulting rake angles are classified as normal-oblique, and similarly for reverse faults thirty degree beyond both ways of its rake angle range is termed as reverse-oblique. The left over range of rake angles are considered to exhibit strike-slip mechanism. This classification does not differentiate between left-lateral and right-lateral faulting. It can be seen from Fig. 7 that the Hindukush region is dominated by reverse and reverse-oblique faulting while the strike-slip mechanism overshadows the other faulting in the Indo-Pakistan region. The south-west corner clearly exhibits normal faulting with a few normal-oblique mechanisms. The Indo-Burma border and the Shillong Plateau are to a large extent slipping along or opposite to the strike direction. The Himalayas are clearly thrust faults but as we march in the North-East direction from Himalayas, the direction in which India plate is moving towards the Eurasian plate, it is possible to see normal faulting in a few hundreds of km, which further changes to strike-slip mechanism at about thousand km perpendicular to the Himalayas. The Andaman-Sumatra region unveils all kinds of mechanisms both in shallow focus as well as intermediate focus regimes, probably owing to the complex fault geometries in this region. The Indo-Burmese border seems to favor reverse-oblique mechanism at intermediate depths, as opposed to the predominant strike-slip behavior at shallow depths. Majority of the intermediate focus earthquakes in the Hindukush region are reverse and reverse-oblique surrounded by a few strike-slip events.

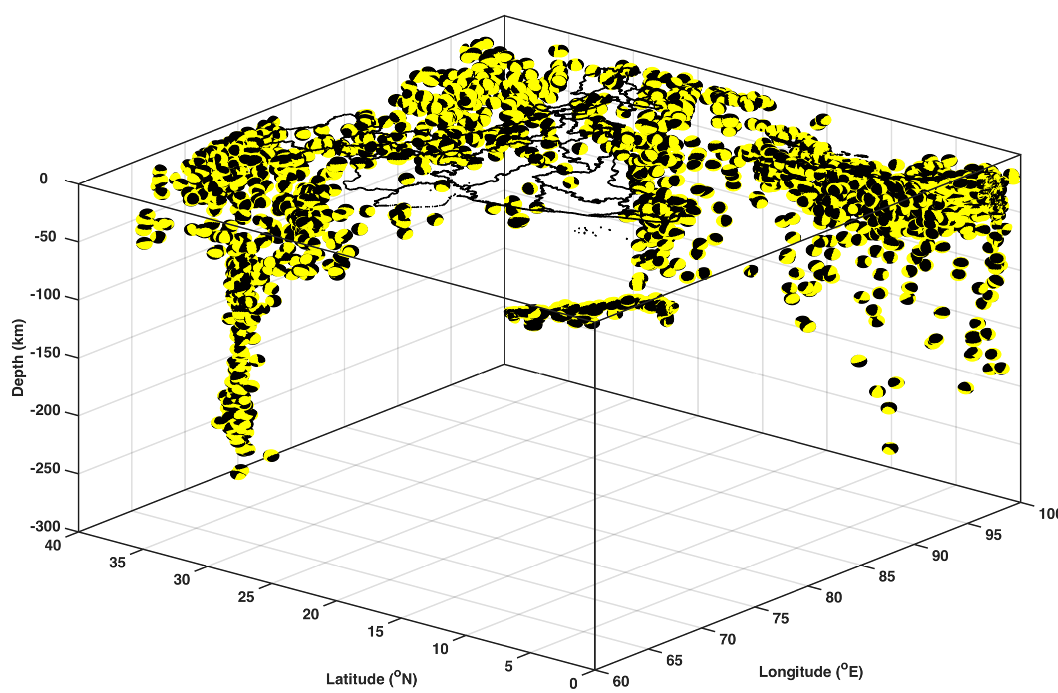
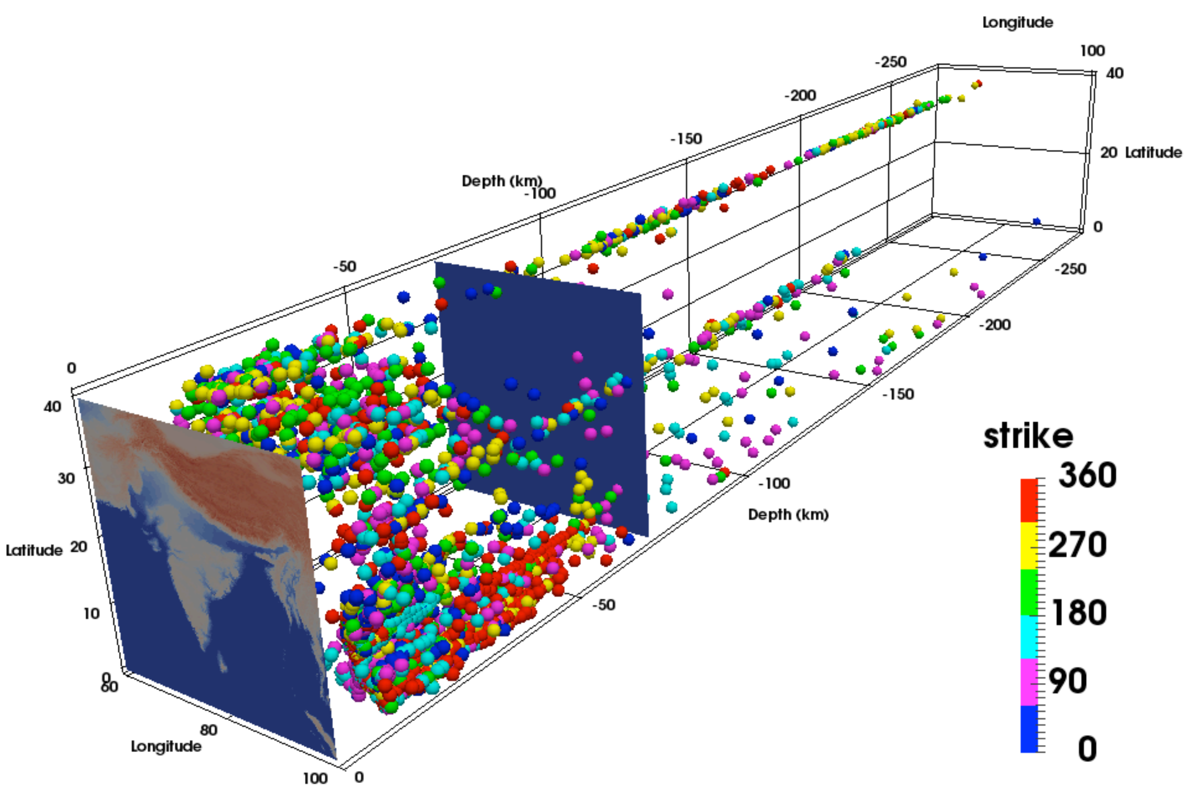


Fig. 8 – Depth view of focal mechanism of earthquakes in and around India.

In addition to the simple classification of earthquakes based on depth, plotting all the earthquakes as a function of depth for the entire latitude-longitude range under consideration (Fig. 8) allows for decipher patterns underneath the surface of the earth. For instance, the earthquakes in the Hindukush region shown in Fig. 8 reveals a plume-like structure that is confined to about at 5^{o} x 5^{o} latitudes and longitudes and is continuous with depth for more than 250 km. Furthermore, the depth dependence of strike, dip and rake is shown in Fig. 9. The front surface of Fig. 9 features the topography of India and a partition surface is introduced at 70 km depth to isolate intermediate focus earthquakes from the shallow focus earthquakes. The balls in this figure are color coded by the corresponding focal mechanism parameters. Fig. 9 can straightaway give rough idea about the seismogenic depth of earthquakes pertaining to any latitude-longitude combination. A streak of red dots from depths of 10 to 60 km, at roughly middle of the map view of Sumatra trench show strike angle in excess of 300. This could be one deep stretch of a fault plane, which is also evident as a streak of yellow dots (thrust faulting) at same positions in the depth view of rake (Fig. 9). The dip angle under the Hindukush mountains from depths of about 100 km to 180 km has faults dipping in excess of 45 degree but as depths below 190 km dip angle continuous to stay below 45 degree.



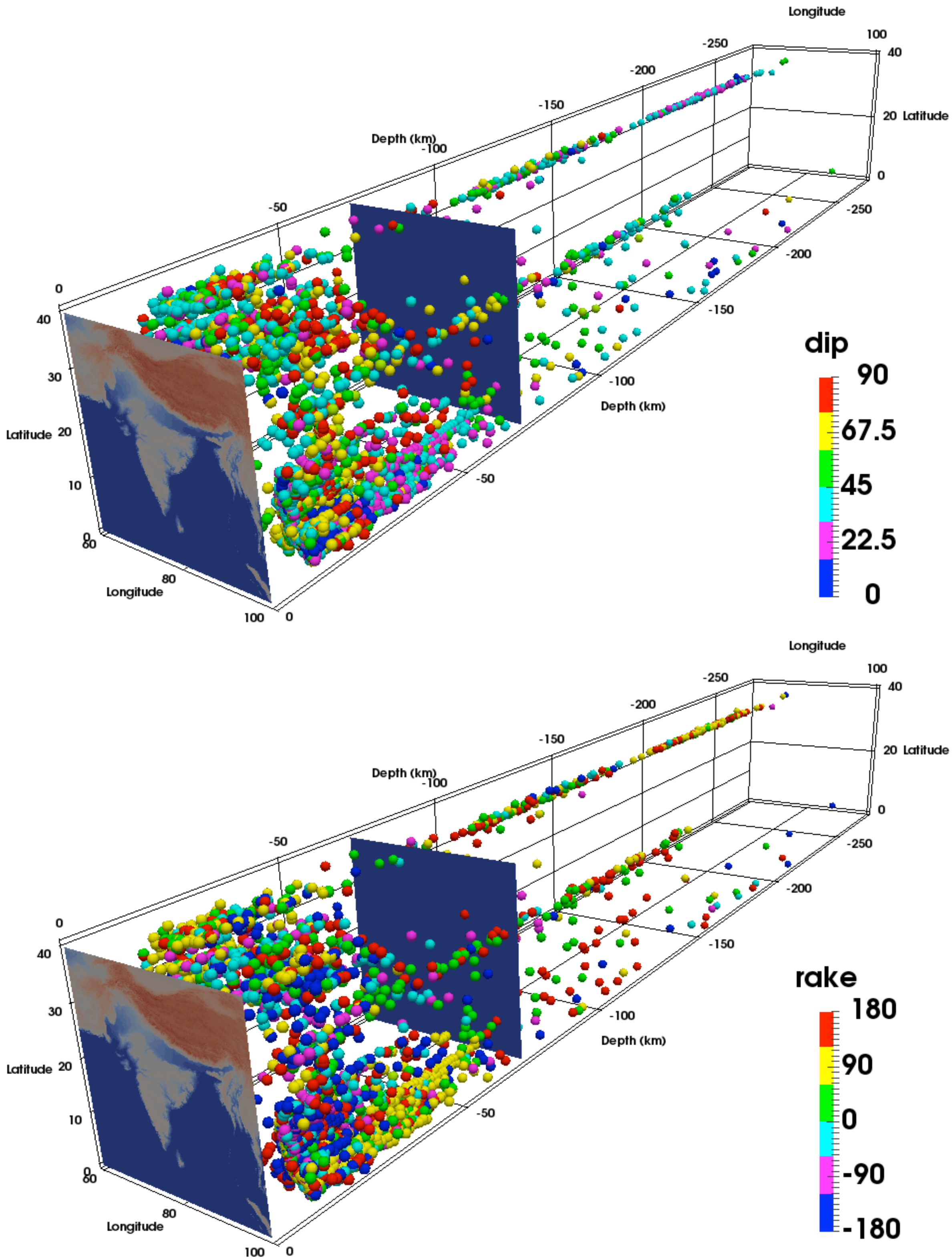


Fig. 9 – Depth view of strike, dip and rake of seismicity in India and adjoining regions.

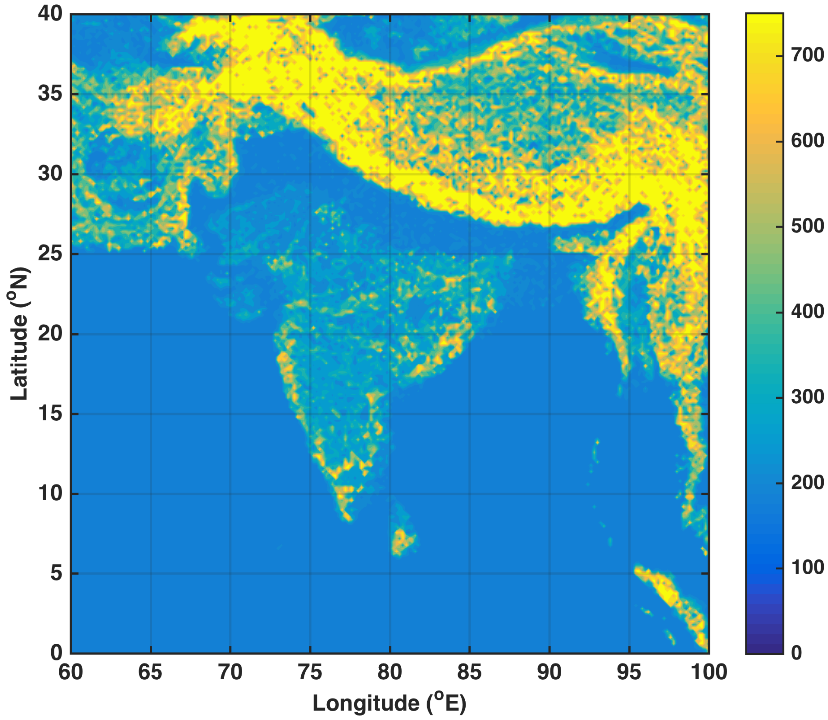


Fig. 10 – Shear-wave velocity in the shallow 30m (Vs30) estimated from topographic slope for India and surroundings based on [10]

4. Discussions and Conclusions

This work aims at identifying available information about faulting conditions that could be used to improve the best available unified GMPEs applicable to entire India. The NDMA [9] relation has been proposed based on simulation of various magnitudes from 4 to 8.5 at various distances (up to 500 km) by dividing India into seven regions and identifying the ranges of stress drops, dip angles, focal depths and the quality factor from literature for each of these regions. From [9], (Fig. 4.3) the only region to which the Hindukush (earthquakes from this region are often felt in New Delhi, the capital city of India, as reported in media) would belong to among the seven regions is the Himalayan region but the focal depths considered in their work are only 5-40 km. However, it is clear from Figs. 8 & 9 that earthquakes in that zone extend more than 250 km. Furthermore, parameters like dip angle, focal depth are modeled as random variables for wider ranges (in most cases dip angles are 10 to 80 degrees), which could be narrowed down as seen from various figures, presented in this study. Additionally, binning can be done to account for variation in these parameters better. Voroni tessellations could be done to segregate regions based on the observed trends. Also, the shear-wave velocity for the shallowest layers of India (Fig. 10) could be incorporated in deriving the next generation GMPEs of India.

5. Acknowledgements

We thank the Director and Scientists of National Centre for Seismology (NCS), part of Ministry of Earth Sciences (MoES) for sharing the Indian catalogue. Financial support of DST-SERB ECR Award SERB/F/2778/2016-17 acknowledged.

5. References

[1] Singh, R. P., Aman, A., & Prasad, Y. J. J. (1996). Attenuation relations for strong seismic ground motion in the Himalayan region. *Pure and Applied Geophysics*, *147*(1), 161-180.

[2] Iyengar, R. N., & Kanth, S. R. (2004). Attenuation of strong ground motion in peninsular India. *Seismological Research Letters*, *75*(4), 530-540.

[3] Das, S., Gupta, I. D., & Gupta, V. K. (2002). A new attenuation model for north-east India. In *Proceedings of the 12th Symposium on Earthquake Engineering, Roorkee* (pp. 151-158).

[4] Gupta, I. D. (2010). Response spectral attenuation relations for in-slab earthquakes in Indo-Burmese subduction zone. *Soil Dynamics and Earthquake Engineering*, *30*(5), 368-377.

[5] Sharma, M. L., Douglas, J., Bungum, H., & Kotadia, J. (2009). Ground-motion prediction equations based on data from the Himalayan and Zagros regions. *Journal of Earthquake Engineering*, *13*(8), 1191-1210.

[6] Mandal, P., Kumar, N., Satyamurthy, C., & Raju, I. P. (2009). Ground-motion attenuation relation from strong-motion records of the 2001 Mw 7.7 Bhuj earthquake sequence (2001–2006), Gujarat, India. *Pure and applied geophysics*, *166*(3), 451-469.

[7] Shiuly, A., & Narayan, J. P. (2012). Deterministic seismic microzonation of Kolkata city. *Natural hazards*, *60*(2), 223-240.

[8] Nath, S. K., Raj, A., Thingbaijam, K. K. S., & Kumar, A. (2009). Ground motion synthesis and seismic scenario in Guwahati city—a stochastic approach. *Seismological Research Letters*, *80*(2), 233-242.

[9] NDMA (2010). Development of probabilistic seismic hazard map of India. *Technical report by National Disaster Management Authority, Govt. of India.*

[10] Wald, D. J., & Allen, T. I. (2007). Topographic slope as a proxy for seismic site conditions and amplification. *Bulletin of the Seismological Society of America*, *97*(5), 1379-1395.