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Review Article

Seismology in India

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Recent seismological research in India can be mainly grouped into study of 1) seismogenesis and seismotectonics of the three regions viz., Himalaya, Andaman-Nicobar subduction zone and the Stable Continental region (SCR); 2) Strong motion study and 3) earthquake prediction. Last few years have witnessed significant change in monitoring of earthquakes through about hundred broadband seismographs in National Network and many more in clusters whose data are brought online to two centers at National Centre for Seismology, Delhi and INCOIS, Hyderabad. Extensive research on reservoir induced earthquakes has culminated into "Deep Crustal Drilling" (DCD) in the Koyna-Warna region down to focal depth to understand the nucleation and generation process of earthquakes.

Keywords: Seismotectonics; Himalaya; Andaman Subduction zone; Deep Crustal Drilling; Earthquake Hazard and Precursors

Introduction

Ministry of Earth Sciences (MoES) & Department of Science and Technology, Government of India are the major funding agencies. A new National Center for Seismology (NCS) has been started under MoES in New Delhi by taking out the Seismology Division of India Meteorological Department (IMD). Geological Survey of India (GSI) carries out intensity surveyes and site response studies. Various research institutes involved in seismological research are National Geophysical Research Institute (NGRI, Hyderabad); Institute of Seismological Research (ISR, Gandhinagar, Gujarat); Wadia Institute of Himalayan Geology (WIHG, Dehradun, Uttrakhand); Northeast Institute of Science & Technology (NEIST, Jorhat, Assam); Centre for Mathematical Modeling and Computer Simulation (CMMACS, Bangalore). Various universities carrying out seismological research are - IITs at Kharagpur; Roorkee, Kanpur and Mumbai; IISc, Bangalore; Universities of Delhi, Jadavpur, Krukshetra, Manipur University (Imphal), Osmania University (Hyderabad), Benaras Hindu University (BHU) and Indian Schools of Mines (Dhanbad).

Seismological and geodetic networks in the Himalayan region have provided vital information on the seismicity, seismogenesis, tectonic processes in the region, crustal structure, role of fluids in earthquake occurrence, delineation of shallow structures and about various features of the tectonic domains in the Himalaya. Strong motion data have been used to estimate the attenuation relation. It has been found that the earthquakes in Himalaya occur along a narrow belt, and are influenced by the subsurface ridges on the under-thrusting Indian plate. GPS data, on the other hand, has provided evidence for strain accumulation, spatial extent of locked region and the convergence rate. Seismological waveform data have been used to delineate the deep seismic structure of the Indian shield, western Himalaya, Ladakh, Tibet, Arunachal Himalaya and eastern Himalaya syntaxis.

Seismological research in India got special impetus during 2011-2015 because of great thrust given to seismological monitoring and getting the data online at Delhi and Hyderabad from over hundred broadband seismograph stations of NCS, NEIST, WIHG and ISR. The recent seismological research in India focus on, 1) studies on seismogenesis and seismotectonics (distinctly divided into regions of Himalaya, Andaman-Nicobar subduction zone Stable

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Continental region (SCR); 2) studies on seismic hazard, microzonation and risk; 3) research on earthquake prediction. Outstanding work from India on reservoir induced earthquakes including multi-disciplinary studies in Koyna-Warna region has been reported. As the earthquakes in this region are occurring at 2-8 km depth it was possible to look into the focal zone by deep drilling to unravel the hidden mystery involved with reservoir induced earthquake nucleation and generating processes. Drilling to over a km has been completed. Hard Deccan Trap were encountered down to about 900 m resting over basement rock without any sedimentary layer.

Seismic Monitoring

National Network

India has real time seismic monitoring, information dissemination and archival system through SMS, FAX, email, IVRS under the National Centre for Seismology (NCS). The country-wide network consists of 84 seismological observatories. Data of all these stations of the national network and telemetry clusters is received at Indian National Centre of Ocean Information Services and NCS. In addition to this network there are a few more networks which are operated by a few academic and research institutes and some of them are also connected through VSAT to NCS and INCOIS.

V-SAT Based Telemetry Clusters

A network of 60 broadband seismographs and strong motion accelerographs is run by the Institute of Seismological Research (ISR), Gandhinagar in Gujarat including a sub-network at Sardar Sarovar reservoir area. V-SAT based telemetry cluster (16 stations) in Delhi and in Northeast India (20 stations) are run by NCS. Another network (15 stations) in NE India is by Northeast Institute for Science and Technology (NEIST), Jorhat. National Geophysical Research Institute, Hyderabad has a network in Koyna, Wadia Institute of Himalayan Geology, Dehradun operates a network in Garhwal (10 stations) and in NW Himalaya and the Bhaba Atomic Research Centre, Mumbai operates a network in Gauribidanur, Karnataka. These networks typically include about a dozen broadband seismographs individually.

Organizations Operating Stand-Alone Seismic Stations/Networks

National Geophysical Research Institute maintains over 50 stations at different locations in NE India, Peninsular India and Andaman Islands. One to five broadband seismographs are run by Indian Institute of Geomagnetism, Mumbai; Geological Survey of India, Kolkata; National Institute of Rock Mechanics, Kolar; Central Scientific Instruments Organisation, Chandigarh; Centre for Earth Science Studies, Tiruvananthapuram; Maharashtra Engineering Research Institute; Kerala State Electricity Board, Nat. Hydroelectric Power Corp.; IITs–Roorkee/Kharagpur; Manipur University, Imphal; Indian School of Mines, Dhanbad; Kurukshetra University; Kumaun University, Jammu University etc.

Geodetic Deformation from GPS Measurements

NGRI, Survey of India, CMMACS, IIG, WIHG, ISR and a few other institutes have been maintaining several GPS stations. Many of these stations are connected through VSAST and the data are collated at NCS and INCOIS. Permanent stations include over about 20 in peninsular India, 15 in Andaman Nicobar region, 30 in Himalayan arc, 10 in Indo-Burmese arc. Some 25 stations are in Gujarat. Besides these permanent stations, several institutes are involved in campaign mode studies.

Global Position System data shows Indian plate movement of 5 cm/year in the NE direction. In the north the convergence rates between India and southern Tibet is 11 ± 1mm/y in the arc normal and + 5 mm/y dextral in Kashmir (Schiffman *et al*., 2013; Kundu *et al*., 2014), 15 mm/yr in the northwest Himalaya (Banerjee and Burgmann, 2002), 18 mm/yr in Garhwal–Kumaun Himalaya, 20.5 mm/year in western Nepal, 17.8 ± 0.5 mm/year in central and east Nepal (Ader *et al*. 2012), and 16mm/yr in NE Himalaya. Study by Mukul *et al*. (2010) indicate that the convergence is being accommodated in the NE Himalayan wedge at a rate of about 15–20 mm/yr and approximately 1.5–3.5 mm/yr (~10–20%) of the present-day convergence in the NE Himalayan wedge is being accommodated in the Shillong Plateau.

Detailed analysis of seismicity and the recently acquired GPS data in northeast India provide evidence for present day active deformation front (the plate boundary fault) between the India and Burma plates. Majority of the earthquakes are of interplate type within the subducted Indian plate which is dragged northward along this predominantly strike-slip plate boundary. It is now suggested that the Churachandpur–Mao Fault (CMF), a geologically older thrust fault, accommodates motion of about 16 mm/year through dextral strike–slip manner. The motion across the CMF constitutes about 43% of the relative plate motion of 36 mm/year between the India and Sunda plates. The remaining motion is accommodated at the Sagaing Fault (SF) in central Burma. On the basis of modeling which suggests low friction along the CMF, absence of low-magnitude seismicity along the CMF, lack of historic major earthquakes at the CMF zone and geological field investigations, it is proposed that the motion across the CMF occurs predominantly in an aseismic manner (Kundu *et al*., 2013). An analysis of the recent seismicity data from the Andaman-Sumatra region suggests that the seismic activation started in the middle of July 2000 (about 4.5 years before the 2004 Mw 9.3 earthquake). This includes an increase in the background seismicity rates, particularly in the southern part of the seismogenic zone near the epicenter. The GPS data acquired before the 2004 Sumatra-Andaman mega thrust earthquake Mw 9.3 also support strain accumulation in the region corresponding to a slip deficit rate of about 3 cm/year.

Two great earthquakes of 2012, 100km west of the Sumatra subduction zone are associated with strike-slip faulting due to differential plate motion in between them. The coseismic offsets at several GPS sites around the epicentre are consistent with the finite-fault slip models derived from back projection of the seismic waves recorded by the global networks. Monitoring of crustal deformation using GPS suggests that currently the post-seismic deformation is quite intense in the southern Andaman, Nicobar and Sumatra region. Evidence from paleotsunami investigations suggest that great earthquakes occurred in the past.

GPS measurements have been used to understand the plate motion of the Indian plate, internal deformation or the rigidity of the plate. It is found that the Indian plate moves north-eastward at the rate of ~5 cm/year, and the major Narmada-Son-Tapti fault system does not segment the motion. The localised deformation is consistent with the view that seismicity migrates and deformation rate changes with time.

Around the hypocenter of 2001 Mw7.7 Kachchh earthquake a high velocity and rigid mafic intrusive body has been inferred in a large zone which accumulates high stress/strain. The Bhuj earthquake nucleated from a fluid filled zone at depths of 15-25 km. Kachchh region has significant horizontal deformation that can cause earthquakes. However, there is unusually high uplift up to 2cm/y as revealed by GPS and DInSAR data (Rastogi *et al*., 2012, 2014).

Tectonics of the Indian Region

Indian plate is defined by Indus-Tsangpo suture in the north bordering Himalaya, the left-slip Chaman fault in the west, the right-slip Sagaing fault in the east and continuing southward along Andaman Islands and Sumatra-Java Arc. A large part of the convergence of India and Eurasia is accommodated along the Himalaya arc and the rest is transferred to the north which is responsible for the deformation and eastward extrusion of Tibetan plateau. The Indian plate movement also causes internal deformation which is evident from the infrequent occurrence of moderate earthquakes in the region.

Seismological waveform data have been used to delineate the deep seismic structure of the Indian shield, western Himalaya, Ladakh, Tibet, Arunachal Himalaya and eastern Himalaya syntaxis. For example, the Indian lithosphere is found to be only 90 km thick beneath the Shillong plateau deepening to 135 km on either side suggestive of a lithospheric upwarp related to the plateau uplift. The lithosphere thickens northward, with values reaching ~180 km beneath the Eastern Himalaya. The trend of the LAB north of the foredeep region indicates that the Indian Plate plunges beneath the Eastern Himalaya. In the Garhwal Himalaya, the receiver function images show the Main Himalayan Thrust (MHT), the detachment at the base of the Himalayan thrust wedge, with a flat-ramp-flat geometry. The observed thickness of subducted Indian crust in Garhwal Himalaya is 20-28 km.

In the eastern Himalayan syntaxis zone, the receiver function technique has been used to understand the crustal structure with ~55 km thick crust as against the ~70 km crust elsewhere in the Himalayan arc, and the GPS measurements provide evidence for oblique convergence at 20 mm/year.

After the 2001 Bhuj earthquake, a significant amount of work on the crustal structure, site amplification, attenuation, crustal deformation and seismogensis of the ongoing seismic activity has been done in the Kachchh region by the Institute of Seimological Research (ISR), Gandhinagar, Gujarat. Specifically, it is now revealed that the crustal and lithospheric thicknesses in the region are 35-42 km and 62-78 km, respectively. The numerical block-and-fault model of lithosphere dynamics and seismicity is used to understand crustal motion and seismicity in the Kachchh Rift Basin (KRB), Gujarat. The modeling suggests that an NNW–SSE trending compression is the principal driving force in the KRB which explains the basic features of the regional seismicity, direction of block motions, and the presence of an extensional stress regime associated with the Cambay rift zone.

Through examining the temporal changes in b value and fractal dimension or D value of the seismicity associated with the 2001 Bhuj earthquake source region, it was observed that several episodes of abnormally low b and D values were associated with the occurrences of bursts of seismic activity in 2001, 2005, 2006, 2008, and 2010.

Seismological studies in the Indo-Gangetic plains suggest that the sedimentary thickness varies from 0.5 to 3.7 km with low velocity sediments having shear-wave velocities in the range 0.72-2.5 km/s. Site amplification studies reveal a fundamental frequency of 0.13 Hz; the amplification at this frequency varies between 20 and 60. Calculations based on reasonable earthquake source, attenuation models and application of random vibration theory suggest that peak ground acceleration and peak ground velocity at soft sites near the Himalayan foothills located 100 km from the epicenter would be amplified by a factor of 2-4 and 6-12, respectively.

The 3-D shear velocity structure beneath south India's Dharwar Craton determined from fundamental mode Rayleigh-wave phase velocities reveals the existence of anomalously high velocity materials in the depth range of 50-100 km. Results suggest that intermediate composition for the crust beneath the Eastern Dharwar Craton (EDC) is similar to those for other cratons. In contrast, the mid-Archaean exposed Western Dharwar Craton (WDC) crust has more mafic composition and exceptional thickness, a scenario at variance with the global observations. We interpret this thick mafic crust to represent undeformed geological segment of 3.36 Ga. The EDC with a nearly flat Moho, felsic to intermediate composition of crust and thin basal layer may represent regional delamination during the late-Archaean. The preserved distinct Moho topography across the Archaean terrains suggests it as compositional boundary. Considering the surface exposure of 15-20 km crust, based on P-T condition in the granulite segment of the WDC, it is speculated that a Himalaya-like crustal thickness (50-70 km) beneath the middle Archaean crust exists which points towards a plate tectonic like scenario at ~ 3.0 Ga.

The seismic Lithosphere Asthenosphere Boundary (LAB) or G discontinuity, a seismologically characterized abrupt drop in wave speed in the uppermost mantle, is one of the key issues in current geodynamics. Although plate tectonics started as a theory for the ocean, reports on LAB for normal oceanic regions are scarce due to paucity of seismic data, and whether or not the oceanic LAB grows with age is the key issue to be resolved. This study conducts a systematic survey for the oceanic LAB using **S**-to-**p** converted seismic waves along three margins of oceanic plates whose crustal age ranges from ~10 Myr to ~ 130 Myr, to observe laterally continuous oceanic LAB images. The thickness of the oceanic plate estimated from LABs increases with the plate age, though scattered, suggesting that the evolution of oceanic lithosphere is predominantly governed by temperature and that the oceanic seismic LAB represents a boundary that grows with age.

Deciphering the seismic character of the young lithosphere near Mid-Oceanic Ridges (MORs) is a challenging endeavour. In this study the seismic structure of the oceanic plate near the MORs is determine using the *P*-to-*S* conversions isolated from quality data recorded at five broadband seismological stations situated on ocean islands in their vicinity. Estimates of the crustal and lithospheric thickness values from waveform inversion of the *P*-receiver function stacks at individual stations reveal that the Moho depth varies between ~ 10 ± 1 km and ~ 20 ±

1 km with the depths of the LAB varying between ~ 40 ± 4 and ~ 65 ± 7 km. Evidence for an additional low-velocity layer is found below the expected LAB depths at stations on Ascension, São Jorge and Easter islands which probably relates to the presence of a hot spot corresponding to a magma chamber. Further, thinning of the upper mantle transition zone suggests a hotter mantle transition zone due to the possible presence of plumes in the mantle beneath the stations.

Singh *et al*. (2015) reviewed the variations in crustal and upper mantle structure beneath the Indian subcontinent with emphasis on passive seismic results supplemented by results of controlled seismic sources. Receiver function results from more than 600 seismic stations, and over 10,000 km of deep seismic profiles have been used to produce maps of average crustal velocities and thickness across the region. The crustal thickness varies from 29 km at the southern tip of India to 88 km under the Himalayan collision zone, and the patterns of variation show significant deviations from the predictions of global models. The average crustal shear velocity (Vs) is low in the Himalaya–Tibet collision zone compared to Indian shield. Major crustal features are as follows: (a) the Eastern Dharwar Craton has a thinner and simpler crustal structure crust than the Western Dharwar Craton, (b) Himalayan crustal thickness picks clearly follow a trend with elevation, (c) the rift zones of the Godavari graben and Narmada–Son Lineament show deeper depths of crust than their surroundings, and (d) most of the Indian cratonic fragments, Bundelkhand, Bhandara and Singhbhum, show thick crust in comparison to the Eastern Dharwar Craton. Heat flow and crustal thickness estimates do not show any positive correlations for India. Estimates of the thickness of the lithosphere show large inconsistencies among various techniques not only in terms of thickness but also in the nature of the transition to the asthenosphere (gradual or sharp). The lithosphere beneath India shows signs of attrition and preservation in different regions, with a highly heterogeneous nature, and does not appear to have been thinned on broader scale during India's rapid motion north towards Asia. The mantle transition zone beneath India is predominantly normal with some clear variations in the Himalayan region (early arrivals) and Southwest Deccan Volcanic Province and Southern Granulite Terrain (delayed arrivals). No clear patterns on influence on the mantle transition zone discontinuities can be associated with lithospheric thickness. Over 1000 anisotropic splitting parameters from SKS/SKKS phases and 139 using direct S waves are available from various studies. The shear-wave splitting results clearly show the dominance of absolute-plate-motion related strain of a highly anisotropic Indian lithospheric mantle with delay times between the split S phases close to 1 s. There are still many parts of India where there is, at best, limited information on the character of the crust and the mantle beneath. It is to be hoped that further installations of permanent and temporary stations will fill these gaps and improve understanding of the geodynamic environment of the Indian subcontinent.

During the continental breakup of India from Africa in late Triassic (210 Ma) western India experienced crustal stretching (thinning) and formation of three failed rifts of Kachchh (also spelled as Kutch), Cambay and Narmada. The Kachchh rift is most active with potential of up to M8 earthquakes while Narmada rift has potential of up to M6.5 earthquakes and Camaby rift a potential of up to M6 earthquakes.

In the Kachchh rift (KR) magmatic intrusive were emplaced in the lower crust (may be starting in late Jurassic, 175 Ma). During the process several granitic intrusive rocks have come up to the surface all over Kachchh (Biswas, 2005). The xenoliths found in these intrusive might have originated in lower lithosphere and are dated 75 Ma (Sen *et al*., 2009). The Deccan/Reunion mantle-plume during the end of Cretaceous caused lithosphere thinning and emplaced Deccan Volcanic flood basalt (Rastogi *et al*., 2014).

The Kachchh intraplate rift basin of western India and the intraplate region in or close to the Deccan Traps has been known to be active for centuries and many earthquakes have occurred in recent times: Koyna (Reservoir Induced Seismicity along with M_w 6.3 in 1967 to M_w 5.6 in 2011) along the Kurdwadi rift, Latur (1993, M_w 6.2), Jabalpur (1997, M_w 5.8) and Bharuch (1970, M_w 5.4) in the Narmada rift and Bhuj (2001, M_w 7.7) in the Kachchh rift (KR). The 2001 Bhuj earthquake caused 14,000 deaths and destruction in a heavily populated and industrialized region.

Magnetotelluric Investigations

Magetotelluric (MT) investigations in India are broadly grouped in two categories. First, given the sensitivity of electrical resistivity to fluid content, electrical resistivity imaging in seismic active zones are undertaken to broadly demarcate tectonic domains characterized by differing rheology and heterogeneity to gain an insight on the seismotectonics and seismogenesis of the earthquakes. In the second category, electrical resistivity images of crustal structures form the base to constrain crustal evolution models, thermal resource potential etc.

Close grid (1-3km spacing) 37 MT observations near Bhachau (epicenter of 2001 M7.7 Bhuj earthquake) indicate presence of south-dipping Kachchh Mainland fault and north-dipping South Wagad fault (Mohan *et al*., 2015).

MT measurements in the Garhwal Himalaya bring out an unambiguous evidence of a low angle north-east dipping intra-crustal high conducting layer (IC-HCL) with a well developed ramp at transition from the Lesser Himalaya to the Higher Himalaya. Attributing high conductivity of the layer to the metamorphic fluids, incorporation of the mechanical weakening effects of the fluids explain several facets of seismicity, e.g. clustering of large earthquakes on a linear plane defined by the top of the IC-HCL, later symbolizing brittle-ductile transition help to explain sharp cut-off depth of crustal seismicity; ramp symbolizing a block of low shear strength demarcates narrow belt of moderate magnitude high seismicity.

In the Sikkim Himalaya where strike slip becomes the dominating earthquake mechanism, magnetotelluric survey revealed a steep crustal-scale high resistivity structure with a step offset of 14 km at deep crustal depth, coinciding with the transition between MCTZ and Higher Himalaya. Another independent study relates this high resistivity 15-20 km thick block to the eclogitization of lower crust. The deflection of the arc normal slips by rigid eclogitized Indian crust in the depth range of 40-60 km is the primary source to generate strike-slip dominated large magnitude earthquakes.

Deep electrical images in three different tectonic scenarios, namely: Himalaya, Central Indian Tectonic zone and Southern Granulite terrain, bring out distinctive signature related to continent–continent collision, subduction–collision–accretion tectonics. The geoelectric sections across the Himalaya show near sub-vertical high conductivity structure of the Indus suture zone whereas beneath outer Himalaya, northward dipping signature of the anomalous conductive features at upper to mid-crustal depths are clearly mapped in agreement with the dominance of under thrusting. Such models give a clear evidence for the subduction and collision related dynamics. The profiles across the Central Indian tectonic zone constituting major east-west trending faults and mobile belts provided the evidence for the presence of mantle derived fluids at mid-crustal depths and also gave a clear evidence for the collision processes between the Bundelkhand craton and the Dharwar craton. The collision-accretion tectonic process is observed in Southern Granulite terrain of south India. Evidence for the exhumation of mantle derived fluids to the mid-crustal depths has been observed along the Vattalakundu-Kanyakumari profile, while the subduction-collision-accretion processes have been observed along Kolattur-Palani geotransect.

Synthesis of continuing MT surveys in the Deccan Volcanic Province (DVP) indicate that the thickness of the traps in DVP decreases from about 1.8 km in the west to a few hundred meters (approx. 400 m) towards the east. The traps also exhibit considerable variation in resistivity, with higher resistivity (approx. 150–200 ohm-m) in the western half and lower resistivity (approx. 50–100 ohm-m) in the eastern half of DVP. Two significant fissure/ fracture zones have been detected in DVP, which might have acted as conduits for the outpouring of Deccan lavas in addition to the primary structures along the west coast and the Narmada-Son lineament (NSL) zones.

Exploiting the presence of resistive continental lower crust which serve as a window to resolve electrical conductivity structures of the mantle, it has been shown that the LAB beneath the Eastern Indian Craton is 95 km, only half of the Slave craton. As cratonic signatures, depicted by ultrapotassic rocks from Gondwana coal fields, close to EIC, are preserved at least till early Cretaceous (117Ma), it is likely that Himlayan orogeny could have played a major role in delamination of the lithospheric roots of the EIC in addition to attendant seismicity.

AMT has been carried out in the Bakreswar Hot Spring (BHS) area of eastern India to locate the geothermal source in the vicinity of BHS. The results show that the north-south fault close to Bakreswar is a shallow feature, not deeper than 300 m, and thus cannot act as a heat source. The subsurface formation below the fault zone is highly resistive up to a great depth, indicating the absence of a heat source and geothermal reservoir in the vicinity of the BHS.

MT studies in hot spring areas of Chabsar (near Ahmedabad and close to western boundary of Camabay rift) and Tuwa (near Godhra in Proterozoic rocks 200km east of Ahmedabad) indicate conducting zones and possible source of geothermal energy at depths of about 2.5 km (Mohan *et al*., 2015).

Earthquake Hazard Studies

Seismic Zoning Map of India

Seismic Zoning Map of India (Bureau of Indian Standards, 2000) divides India in zones II, III, IV and V having potential of earthquake intensities VI (M5), VII (M6), VIII (M7) and ≥IX (Me≥8), respectively. This map is prepared on the basis of intensities experienced at places and their tectonic belts. Andaman zone is assigned zone V. Himalayan belt is assigned zone V and IV. Kachchh is the only area outside Himalaya-Andaman belt which is assigned zone V. Koyna and Latur area is assigned zone IV. The Indo-Gangetic plains, Saurashtra peninsula, the west coast region and the Narmada belt is zone III. Most other parts of peninsular India are in zone II.

The national code assigns zone factors (pga) 0.1, 0.16, 0.24 and 0.36 g for zones II, III, IV and V, respectively which are multiplying factors to a response spectra to get spectral acceleration. Response spectra for soft soil, hard soil and rock were prepared a few decades back based on available strong motion for a few tens of worldwide earthquakes.

Seismic Hazard Assessment

Several agencies have prepared Probabilistic Seismic Hazard Assessment (PSHA) map of India. ISR has prepared such a map for Bureau of Indian Standards which will help all the citizens of India in adopting optimum seismic coefficients for earthquake resistant designing of buildings based on the probability of occurrence. The Seismic Zoning Map (SZ Map) of India currently recommended by BIS for designing earthquake resistant buildings is based on the magnitudes of the past earthquakes experienced in different tectonic (geological) zones. The logic used is what has happened at some zone can happen again. However, according to the seismic gap theory some seismologists believe that the areas which have not experienced earthquakes in the past in any tectonic belt may be more prone than the areas which have already experienced the earthquake. Hence the areas in Himalaya which are shown as zone 4 may have potential of zone 5. Moreover, the present SZ Map tells the potential of different zones without assigning any probability of occurrence. The assigned earthquake for a zone may occur tomorrow or after 10,000 yr without giving any probability of occurrence. The Probabilistic Seismic Assessment (PSHA) Map gives the probability of occurrence in different time periods. Hence, the PSHA map is more practical. Also different types of structures need assessment for different return periods for assigning maximum possible earthquake in a tectonic zone. For example the ordinary buildings need only 475 years return period (10% probability in 50 yr, while an LNG terminal will need 2475 year return period (2% probability in 50 yr) and a Nuclear Power Plant will be designed for 10, 000 years return period (0.5% probability in 50 years). The PSHA map provides information towards this need. The PSHA map also provides fine gradation of hazard in a particular tectonic zone.

Parvez and Lyubushin (2010) generated seismic hazard map using Bayesian approach. Probabilistic seismic hazard maps were prepared: for Tamil Nadu by Menon *et al*. (2010), for NW Himalaya by Mahajan *et al*. (2010) and Yadav *et al*. (2011). Raghukanth and Das (2010) applied deterministic approach to assess seismic hazard scenario for Northeast India while Raghukanth (2010a,b) for some other parts of India. An extensive study on peak ground motion predictions in India has been made for different rock sites by several researchers in diverse tectonic environ of India (Nath and Thingbaijam, 2011; Parvez *et al*., 2011). Rajendran *et al*. (2009) found that the historical seismicity corresponds with the present-day seismicity that can ascertain earthquake hazardous zone in the region. Srikanth *et al*. (2010) assessed earthquake vulnerability of existing buildings in Gandhidham and Adipur cities of Gujarat.

Seismic Microzonation

Seismic Microzonation of different cities and areas provide knowledge for seismic safety factor to be considered for different heights of buildings. From this study, structural response curves are determined which give acceleration for different natural periods in 250-500m grid. This analysis involves geotechnical investigations through numerous boreholes and geophysical measurements of seismic wave velocities by seismic survey and PS logging. Site characteristic maps are prepared for many areas based on Vs30, shear-wave velocity to 30m depth measured by MASW shallow seismic and PS logging. Various geological units are assigned ranges of Vs30 values. GIS based shake maps are prepared. The liquefaction potential is also assessed. Effort has been made to standardize the procedure to be adopted by different organizations. Development of seismic microzonation of major urban centres has been recognized as a priority area and Ministry of Earth Sciences (MoES) has constituted a National Steering Committee.

Geological Survey of India has generated first order site response map for several important cities: Dehradun, Jammu, Ahmedabad, Jamnagar, Jalandhur, Bhavnagar, Bharuch, Agartala, Siliguri, Mumbai, Vizag, and Chenai, besides New Delhi, Jabalpur and Guwahati. Detailed seismic microzonation has been completed for the New Delhi and Kolkata cities by the National Centre for Seismology and IIT Kharagpur, respectively. Other academic and research institutions of India, such as IIT Kharagpur, IIT Roorkee, ISR, Gandhinagar, and NEIST, Jorhat are actively involved in conducting seismic Microzonation studies of Indian cities. First level seismic Microzonation has already been completed for Jabalpur, Sikkim, Guwahati, Bangalore, Ahmedabad, Dehradun, Chennai and Chandigarh. An important finding of ISR based on seismic Microzonation of several cities areas of Gujarat is that within 20km from the faults with potential of M6 earthquake the low-rise buildings of 2-4 stories need to have 60-70% higher seismic factor than that recommended in the National Code. For the faults with potential of M8 earthquake the distance range is 30km for low as well as high rise buildings.

Public Outreach

IMD, MoES, NDMA, NIDM, ISR and other agencies through their websites share different types of data sets, information about current earthquakes and catalogues of earthquakes in different states. These agencies allay unnecessary fear of people by explaining the possibilities of damage potential, how to live with that and phenomena like subterranean sounds generated by earthquakes. Builders, industrialists as well as academicians from institutes take regular help of these agencies. Training of engineers, masons, students and Govt. officers about earthquake safety and disaster management is imparted by NIDM, GIDM and various State Disaster Management Authorities like those of Bihar and UP. National code has been formed by Bureau of Indian Standards and periodically modified.

Assessment of Tsunami Hazard and Alert System

Indian coasts are vulnerable to tsunami hazards because of nearness to the tsunamigenic earthquake prone zones of Indonesia and Makran. India has taken effective steps in mitigating tsunami hazard by conducting a series of researches in the Indian Ocean by the Indian National Centre for Ocean Information Services (INCOIS). A state-of the-art tsunami warning system has been set up. The system comprises a network of seismic stations including international stations to compute earthquake parameters, simulated scenarios of travel time and run-up heights at 1800 coastal locations in the Indian Ocean, observing platforms for sea level variations, both in deep sea and coast, robust communication and dissemination system, data centre and decision support system.

Earthquake Forecasting

Long-Term Assessment of Earthquake Potential across Different Faults:

For the long-term assessment of earthquake potential along different faults several permanent and campaign mode GPS stations have been deployed in Himalaya and Kachchh which detect movements as small as 1-2 mm/yr. Vertical deformation is being monitored by InSAR study in collaboration with SAC-ISRO.

Rate of deformation in the past 2Ma is studied by active fault investigations in Himalaya and Kachchh. Dates of earthquakes in the past 20,000 yr are determined by paleoseismological and active fault investigations. Dating of sediments/prehistoric earthquakes is done in Optically Stimulated Luminescence Lab. Dates of pre-historic earthquakes give recurrence rates of large earthquakes in order to assess earthquake hazard along different geological faults. Active fault studies involve thorough examination of 3D satellite imageries, geological investigations supported by geophysical surveys like GPR, shallow seismic and resistivity imaging and finally observation of recent movements in trenches across faults.

Medium- and Sort-term Precursors

Research on medium and short-term earthquake forecasts is done by measuring several types of precursory phenomenon. ISR has established three Multiparametric Geophysical Observatories (MPGO) in Kachchh for earthquake prediction research. Eleven types of precursory parameters are being observed with Broadband Seismographs, GPS, magnetometers, ground water leveler, super - conducting gravimeter, helium and radon detectors. WIHG has established MPGO at Ghuttu in Garhwal Himalaya while IIG at Shillong and Port Blair.

In a small and shallow earthquake zone assured of continuing small to moderate earthquakes with accompanying foreshocks like Koyna it appeared possible to forecast earthquakes. Nucleation method of short-term prediction was successfully applied to forecast M ~ 4-5 Koyna earthquakes a week or two in advance (Rastogi and Mandal, 1999, Gupta *et al.*, 2007)

Significant Roles of some Important Agencies

Seismological Research at National Geophysical Research Institute (NGRI), Hyderabad

NGRI is the premier research institute for seismological research. It maintains GPS networks and telemetered clusters of broadband seismographs in peninsular India and Koyna in addition to tens of stand- alone broadband seismographs at some regions including NE India and Andaman. Research is carried out on Physics of earthquakes and Earth’s interior.

Indian Institute of Technology, Roorkee (IITr)

It has done pioneering work on earthquake engineering, strong motion and seismic hazard assessment of various project sites.

Seismology at Geological Survey of India (GSI)

GSI carries out intensity survey for damaging earthquakes and first order site response study of different cities and areas. It maintains broadband seismograph stations at Nagpur since 1995 and at Jabalpur since 1997. Since 2015 BB, GPS and SM instruments are operated at Mangan (Sikkim), Agartala (Tripura), Itanagar (Arunachal), Nagpur and Jammu.

Seismological Studies by Institute of Seismological Research (ISR)

ISR is involved in earthquake monitoring in the Gujarat state. Earthquake information is processed within minutes with the help of 60 VSAT-connected seismic stations and auto-location. Now earthquake early warning system is being set-up.

ISR estimates seismic hazard for Nuclear Power plants, LNG storage terminals, petrochemical plants, different types of industrial sites, tall structures, ports etc. Seismic hazard maps of Gujarat in respect of peak ground acceleration, spectral acceleration for different natural periods of buildings, amplified frequencies and amplification have been prepared. Seismic Microzonation vulnerability assessment have been done for several cities.

ISR has done active-fault study in Kachchh, Gujarat and found faults of Kachchh Mainland, Allah Bund, Island Belt, Bela and South Wagad to be active. GPS and InSAR (Interferometric Synthetic Aperture Radar) studies have measured deformation along active fault lines. New seismic surveys are being done to know details of some major faults in Kachchh. Mobile arrays of additional 50 seismographs are being deployed to know details of other smaller but active faults.

Seismological Studies by CSIR, Northeast Inst. Sc. & Tech. (NEIST) Jorhat

The Northeast India region is one of the most active zones in the world; the region is jawed between the two arcs, the Himalayan arc to the north and the Indo-Burmese arc to the east. The region bounded by latitude 22-29^{o}N and longitude 90-98^{o}E, produced two great earthquakes (M>8.0) and about 20 large earthquakes (7.0>M>8.0) since 1897. The Shillong Plateau was the source area for the 1897 great earthquake M 8.7, and the Assam Syntaxis zone for the 1950 great earthquake M 8.6. Several large earthquakes occurred along the Indo-Burma ranges. CSIR NEIST-Jorhat carries out research on earthquake seismology based on the data of standalone seismographs since 1982. VSAT connected seismic network is working since 2006. Strong Motion accelerographs and GPS stations are being added.

A new updated catalogue has been prepared for NE India with more local and lower magnitude earthquakes. Earthquake source inversion and high-frequency rupture imaging has been done for some earthquakes of Northeast India. Fractal analysis in Northeast India has been tried. The Studies include 3D travel time tomography, waveform tomography, surface wave inversion, joint inversion, stress inversion. Strain rate is being measured in Northeast India using campaign mode GPS measurements. Crustal imaging using multiple geophysical observations is being carried out.

Probabilistic seismic hazard has been assessed for Guwahati and Shillong which are two most populous cities of Northeast India. Site effects on strong ground motions for these two cities have been worked out by investigating sub-surface soil layering which affect the amplitude, frequency and duration of ground motion through mechanisms of ground response (including impedance and resonance effects). Empirical relations are proposed for the ground motion parameters as a function of earthquake magnitude, distance, fault type, source depth and velocity characteristics of medium. Seismotectonics of the study region is examined and a maximum credible earthquake Ms 8.0 is presumed from the Brahmaputra fault, the nearest source zone in the city area. Such great/major event may cause intensity of 9 or more with a probability of 0.95 in the Guwahati city during time interval of 500 years. Further, the design spectrum with 67 % confidence level is constructed. High resolution satellite data is being used for urban land cover classification in terms of spatial distribution of different types of buildings, the carrying capacity of the street network or the identification of open spaces of Shillong. DEM (Digital Elevation Model) has been prepared to study landslide hazard.

Active fault study is being carried out in the junction area of northwest trending lithotectonic units of the Mishmi block and the almost N-S trending eastern Himalayan lithotectonic units along the Siang fracture. A large window in the Siang river section exposes Paleocene rocks interbeded with Abhor volcanic as the subthrust package and MBT as the roof thrust. Active faulting along the Himalayan Front is observed. Left-lateral strike slip faults displacing Mishmi Thrust Zone had been observed. Morphological and sedimentary records at Siang, Dibang and Lohit rivers at Pasighat, Dambuk, Roing, Tezu and Parsuramkund areas in the NE Himalaya were studied with the help of terraces, for the evidences of the climate-tectonic interplay. Drainage maps were prepared and structurally controlled drainages were observed in the study area. Mishmi Thrust zone is found to be tectonically active with the uplifting of the Quaternary fluvial sediments for a height of about 40m from the present day river channel.

Tectonic stress regime in the Shillong plateau, northeast region of India, is examined by stress tensor inversion of some 97 reliable fault plane solutions. The stress regime varies from western part to eastern part of the plateau. The eastern part of the plateau is dominated by NNE-SSW compression and the western part by NNW-SSE compression. The NNW-SSE compression in the western part may be due to the tectonic loading induced by the Himalayan orogeny in the north, and the NNE-SSW compression in the eastern part may be attributed to the inûuence of oblique convergence of the Indian plate beneath the Indo-Burma ranges. Further, Gravitational Potential Energy (GPE) derived stress also indicates a variation from west to east.

Significant Future Plans

Earthquake Early Warning System

Earthquake Early Warning Systems are being installed in Garhwal Himalaya (100 accelerographs in 250 km x 100km area) by IITr and in Kutch (50 accelerogrphs in 75 km x100km area) by ISR. Deployment of instruments will be completed soon, software has been installed and the issue of data transmission from remote sites to the central recording site is being addressed. Information about magnitude and location of earthquake will be processed in seconds and will enable about 20-40 s early warning at distances of 200 to 300km.

Shake Maps

MoES is providing shake maps soon after significant earthquakes. The GIS based intelligent earthquake hazard maps will be soon available in website which are useful for planning developmental activities. Anyone can log-in and see how much damage can be in an area for different magnitudes in any region and what kind of safety factors are to be considered in a particular area. GIS base Shake maps will be put soon after any earthquake so that the Government and NGOs can plan rescue without delay of precious time in which a number of lives can be saved. It is an important issue as break down in communications invariably happens after the earthquakes.

Concluding Remarks

More than 50% of Indian landmass has severe earthquake hazard and hazard is increasing due to shoddy constructions and increasing population. With fast developing infrastructure and industrial development, various agencies like IMD, ISR, IITkhg and IISc are carrying out earthquake hazard studies and microzonation. It is evident that significant progress has been made to understand the crustal structure, crustal deformation, seismogenesis using various seismological and geophysical methods, The monitoring networks, particularly the seismological and geodetic networks, have been strengthened. Efforts have been made towards mitigating the seismic hazard by taking up seismic microzonation of several cities. Some progress has been made towards deployment of earthquake early warning. It is important that such efforts continue through funding of new projects, particularly dealing with consolidating the observational data base and basic seismological research.

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