2

SOLID EARTH MODELLING PROGRAMME

Global Positioning System (GPS) based Geodesy had become capable of yielding sub-cm precision inlocation by the early 1990s and the possibility of it being used to determine crustal strain rates in India was recognised at C-MMACS in 1993 following the Khillari earthquake. Research at C-MMACS has since yielded fairly well constrained figures for the velocity of the Indian plate and partitioning of strain from Kanya-Kumari to Ladakh in the trans-Himalya. Over the years C-MMACS has also taken up the ardous task of setting up GPS stations in remote locations in the country to generate required data base, and to extend application of GPS technology to other areas.

Inside

- GPS based Atmospheric Precipitable Water Vapor Estimation
- Investigaton of Postseismic Deformation in Andaman Region after 2004 Sumatra-Andaman Earthquake
- Reconnaissance Geodetic Survey at Barren Island, Andaman and Nicobar
- Interseismic Deformation in Northeast India: Estimates from GPS Measurements
- Postseismic Deformation of the 2001 Bhuj Earthquake from Gravity, GPS and InSAR Data
- A Kinematic Study of Active Shear/fault Zones in the West-southern Peninsular Shield of India- Implications on Seismogenesis
- Calibration of Different Make of GPS Receivers to Inter-compare the Precision
- Active deformation in the Darjiling-Sikkim Himalaya based on 2000-2004 Geodetic Global Positioning System Measurements
- The Geometry and Kinematics of the Darjiling - Sikkim Himalaya, India
- Site Charecterization of Bangalore City using Ambient Noise
- Site Response in Ahmedabad City using Microtremor Array Analysis
- Coda Q Estimates on the Andaman Islands using Local Earthquakes
- Ground Motion at Bedrock Level in Delhi City from Regional Earthquake Scenarios

2.1 GPS based Atmospheric Precipitable Water Vapor Estimation

This study for the first time used the Indian GPS network data along with the interpolated NCEP/ NCAR (National Center for Environmental Prediction/ National Centre for Atmospheric Research) reanalysis meteorological data to estimate the precipitable water vapor over the Indian atmosphere for a four year period (2001-2004) at 21 Indian GPS and 7 IGS stations. The site specific daily average meteorological data required for water vapor estimation at these sites is obtained by performing vertical interpolation on 2.5°x 2.5° gridded NCEP/ NCAR global reanalysis data set available at 17 pressure levels and horizontal interpolation on similarly gridded NCEP/NCAR data set available at the surface. GPS PWV estimates thus obtained at different geographical regions compare well (bias < 3 mm) with the PWV estimates from the near by radiosonde sites as well as with the horizontally interpolated NCEP PWV values (bias < 5 mm) except for few sites located in the highly undulated terrain. These GPS PWV values (Figure 2.1) of the Indian network (4º N to 35º N) are then used to model the spatial variability of PWV over the Indian subcontinent as a function of Zenith Wet Delay (ZWD).

$$\left(\frac{PWV}{ZWD}\right) = \Pi(\phi, H) = e^{a+b.H+c\phi^2}$$

Where

a = -1.82, b = $-1.7´10^{-5}$ (1/m), c = $-9.64´10^{-6}$ (1/degree), H = MSL height in m, φ = Latitude in degrees. The modeled spatial variability function gives a quick and reliable estimate of near real time GPS PWV in Indian subcontinent directly from ZWD thus eliminating the need of site specific weighted mean temperature values.

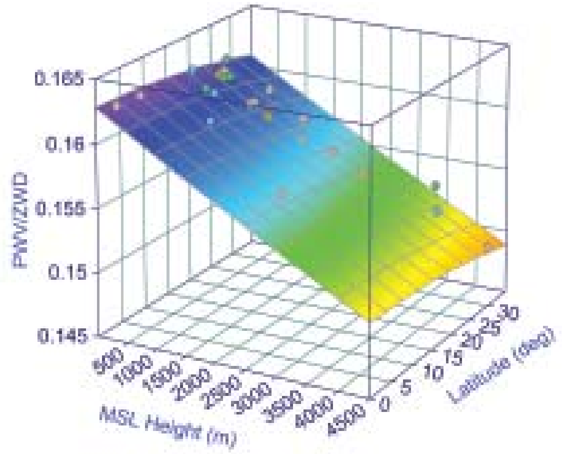

Figure 2.1 Variation of PWV/ ZWD ratio for all the sites with respect to height and latitude along with the spatial variability function.

This study for the first time used the NCEP weather data and the interpolation schemes the Indian atmosphere and gave precise and reliable estimates of water vapor values. It indicates a cost effective way to estimate water vapour in atmosphere using GPS along with the available global weather data basis. This study provides a viable alternative to using collocated meteorological sensors at all GPS sites, instead, equip a few of the crucial national network sites with the meteorological sensors thus significantly saving on the costs of installation of GPS Met sensors. Indian meteorological department (IMD) weather station data and radiosonde data from IGRA archive can also be used to surface meteorological parameters in the Indian subcontinent. The spatial variability function modeled in this study which also represents the variability of water vapor over the Indian subcontinent can be used to estimate water vapor directly from ZWD thus eliminating the need of site specific weighted mean temperature values. This study gives precise water vapour measurements over highly undulated terrain like the Himalayas and Tibetan Plateau which will be helpful to investigate the land-atmosphere interactions and their effect on the Asian monsoon circulation in terms of driving forces and feedback mechanisms.

Sridevi Jade and M S M Vijayan

2.2 Investigaton of Postseismic Deformation in Andaman Region after 2004 Sumatra-Andaman Earthquake

Static offsets due to the 26 December 2004 Sumatra- Andaman earthquake have been reported from the campaign mode GPS measurements in the Andaman-Nicobar region by several researchers. However, these measurements contain contributions from postseismic deformation that must have occurred in the 16– 25 days period between the earthquake and the measurements. Analysis of GPS coseismic displacements, tide gauge measurements of coseismic deformation, a longer time series of postseismic deformation from GPS measurements at Port Blair continuous GPS station in the South Andaman and aftershocks, suggests that postseismic displacement not larger than 7 cm occurred in the 16–25 days following the earthquake in the South Andaman and probably elsewhere in the Andaman Nicobar region. Earlier, this contribution was estimated to be as large as 1 m in the Andaman region, which implied that the magnitude of the earthquake based on these campaign mode measurements should be decreased. Our study suggest an M_w for this earthquake as 9.23.

Unfortunately, we cannot reliably estimate the contribution of 16–25 days postseismic deformation in the campaign mode coseismic displacement at all other sites in the Andaman-Nicobar region, as the tide gauge data at other places and continuous measurements of postseismic deformation are not available. However, our estimate of the missed postseismic displacement based on longer time series at other campaign mode sites in the Andaman Nicobar does not exceed more than 10 cm which suggests that only modest postseismic deformation occurred in the early postseismic period and hence the coseismic displacement derived from the campaign mode GPS measurements do not contain large contribution from the following 16–25 days period of postseismic deformation. In that case, it will not be justified to bring down the magnitude of the earthquake on account of this.

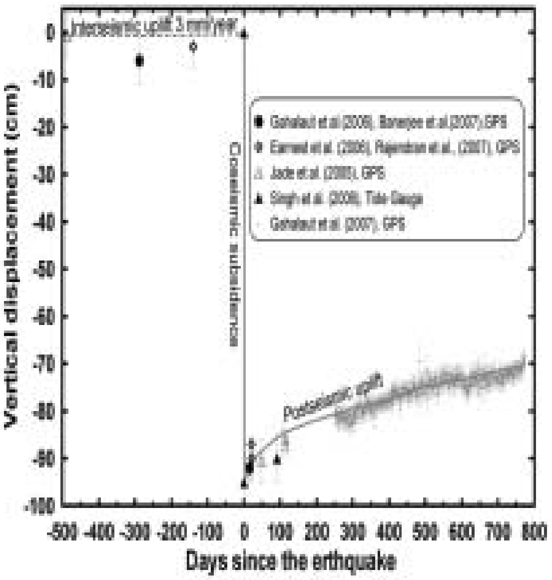

Figure 2.2 A composite graph of temporal variation of up component from campaign mode GPS measurements and tide gauge at and around Port Blair. Jade [2004] reported interseismic uplift rate of 3 mm/year.

V K Gahalaut, J K Catherine, Sridevi Jade, R Gireesh, D C Gupta, M Narsaiah, A Ambikapathy, A Bansal and R. K. Chadha

2.3 Reconnaissance Geodetic Survey at Barren Island, Andaman and Nicobar

In March 2007 C-MMACS, with the help of Indian Coast Guard, carried out a reconnaissance survey at Barren Island (Figure 2.3), the lone active volcano in the India region. As part of this survey we established geodetic markers and collected precise geodetic data for a span of three days. The data collected will be to carry out precise geodetic GPS surveys in future at these islands in search of any active volcanic deformation signatures and thus the associated hazards. The Sunda – Andaman subduction margin had produced major volcanic eruptions in the historic times, including the giant 1883 Krakatoa eruption. Subduction along the Sunda - Andaman trench system has given rise to a

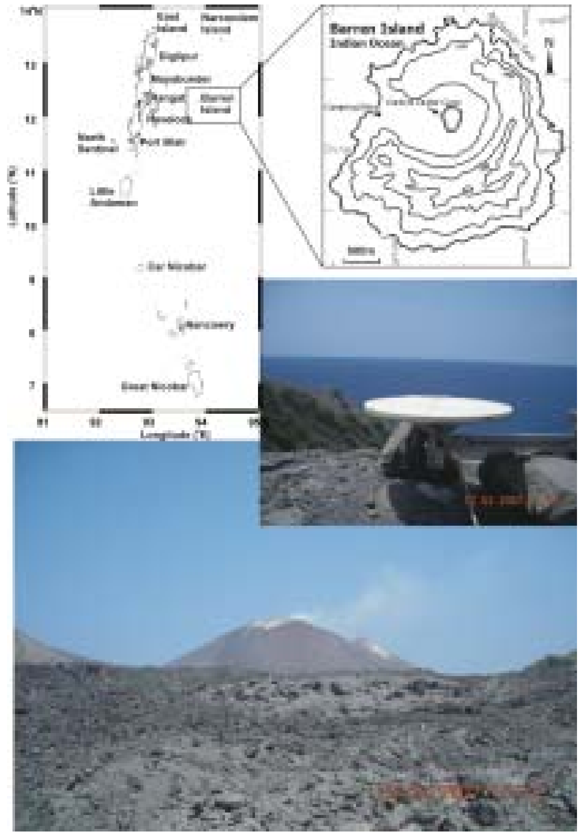

Figure 2.3 Location map of Barren Island in the Andaman Nicobar archipelago. Fuming cone of Barren volcano, as on March, 2007. Inset shows the GPS survey on progress.

discontinuous belt of submarine volcanic sea mounts with sporadic volcanism in the Andaman Sea, with its sub-aerial expressions at Barren Island and the Narcondam Islands. This study is first of its kind being done in India.

Anil Earnest, M S M Vijayan and Sridevi Jade

2.4 Interseismic Deformation in Northeast India: Estimates from GPS Measurements

Interseismic deformation in northeastern India (Figure 2.4) has been estimated from the GPS measurements at eight permanent stations (2003–2006)and six campaign sites (1997–2006). The Euler pole of rotation of Indian tectonic plate in ITRF2000 determined from the present data set is located at 51.7±0.5 °N, “15.1±1.5 °E with angular velocity of 0.469±0.01Myr”1. The results show that there is a statistically insignificant present-day active deformation within the Shillong Plateau and in the foreland spur north of the plateau in the Brahmaputra valley. The arc-normal Indo-

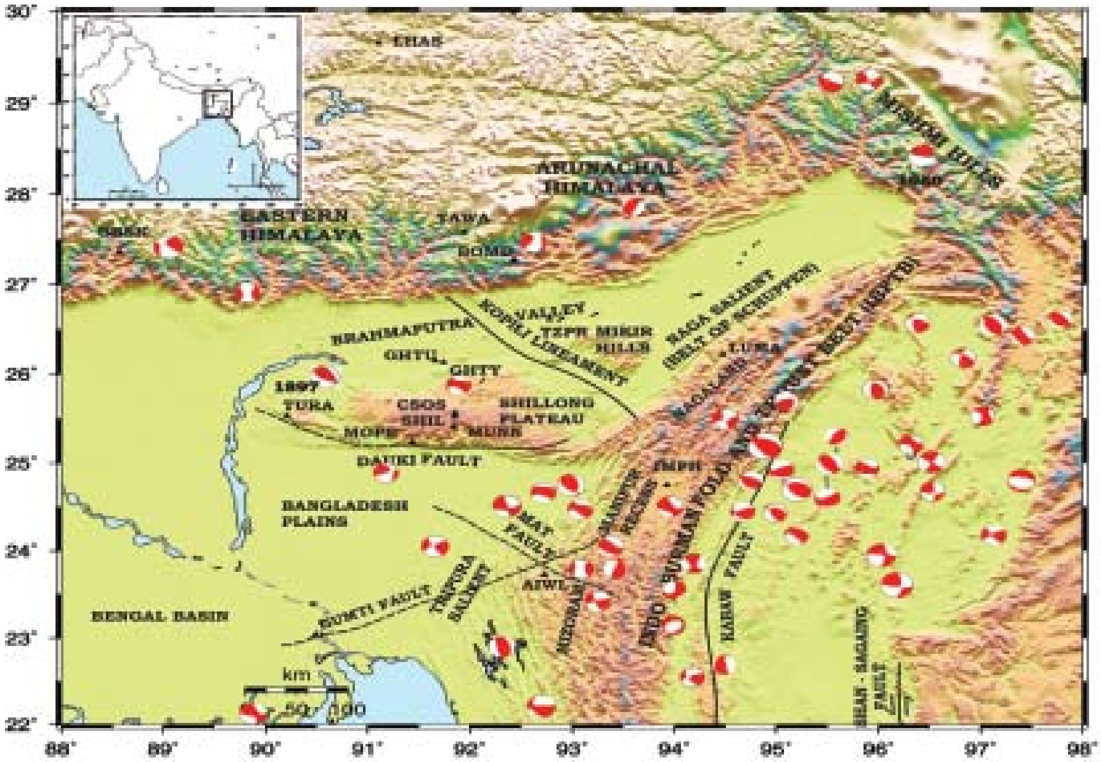

Figure 2.4 Topographic map of northeast India (boxed area in the inset map of India) showing main tectonic elements in the region along with the focal mechanisms (source: http://www.globalcmt.org/CMTsearch.html) and the location of GPS stations.

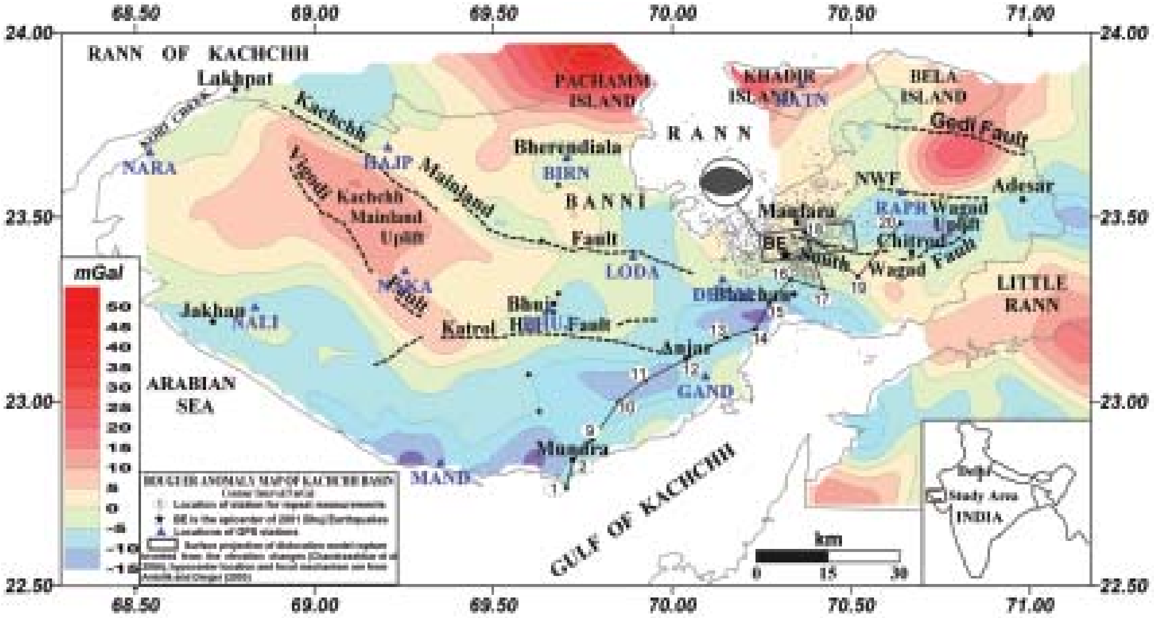

Figure 2.5 Bougher anomaly map of Kachchh showing major tectonic elements and stations occupied for GPS and repeat gravity observation

Eurasian convergence rate is 16±0.5 mm/yr across the northeastern boundary, similar to arc-normal convergence rates determined in central Nepal along the Himalayan arc. However, unlike central Nepal, in the Arunachal Himalaya the 16 mm/yr shortening is distributed between the Lesser as well as the Higher and Tethyan Himalayas. The results indicate that the deformation in the Indo-Burmese Fold and Thrust Belt (IBFTB) is segmented into N–S blocks along E–W transverse zones exhibiting dextral slip between Naga salient (NS)– Imphal Recess (IR) and sinistral slip between IR and TRS (Tripura–Mizoram salient). Convergence rate of 10±0.6 mm/yr between Aizawl and Imphal points to the existence of an active transverse zone in this region.

The above results provide significant numbers pointing to the present-day deformation regimes in different tectonic elements in northeastern India and also point to regions where there is a need for more detailed investigations. Densifying campaign mode GPS surveys over the Shillong Plateau, Brahmaputra valley, Arunachal Pradesh, Indo-Burman fold and thrust belt will to some extent help in resolving the deformation along the existing notable geological features. These long-term GPS data sets thus generated will help in the future to construct possible models of present-day deformation regimes in highly complex northeastern India. These results also underline the desirability of sustaining continuous GPS monitoring operations in the region with a dense network of campaign sites around them.

Sridevi Jade, Malay Mukul , Anjan Kumar Bhattacharyya, M S M Vijayan, Saigeetha Jaganathan , Ashok Kuma, R P Tiwari, Arun Kumar, S Kalita, S C Sahu, A P Krishna, S S Gupta, M V R L Murthy, V K Gaur

2.5 Postseismic Deformation of the 2001 Bhuj Earthquake from Gravity, GPS and InSAR Data

The Bhuj earthquake of January 26, 2001 (Figure 2.5) in Kachchh, India is one of the largest events (Mw=7.6) in the last 50 years in an intraplate region. We use GPS, gravity and InSAR measurements and models of postseismic deformation caused by the Bhuj earthquake to assess the viscosity of the lower crust and upper mantle. To fit the observed motions we calculate synthetic postseismic deformation using the relaxation response of a layered viscoelastic earth to the earthquake. For a model with an elastic plate overlying a viscoelastic half-space, we find that the elastic thickness is ~36 km, which is close to the local crustal thickness. We find an upper mantle viscosity of 1020 Pa s, the presence of weak mantle is consistent with results from independent seismological and petrological studies that show an abnormally hot upper mantle beneath easternmost extent of Kachchh rift basin near Cambay basin. The viscosity of the lower crust is though not well constrained. The GPS data do not require a viscous lower crust but permit a lower bound viscosity of 1020 Pa s indicating a strong lower crust. Using our best fit upper mantle and lower crust viscosities, we find that the postseismic effects of viscoelastic relaxation on present day horizontal GPS velocities are small ~ 3 mm/yr. The observed displacements cannot be explained by physically plausible afterslip on or above the coseismic fault reaching the surface. However, local deformation across the coseismic surface rupture is consistent with a contribution from deep afterslip.

D V Chandrasekhar, R Bürgmann , Sridevi Jade, T Kato, S Likhar, C D Reddy, D A Schmid, P S Sunil

2.6 A Kinematic Study of Active Shear/fault Zones in the West-southern Peninsular Shield of India- Implications on Seismogenesis

The southern peninsular region is covered by major shear / fault zones such as Moyar-Bhavani, Bavali, Palghat-Cauvery and Achankovil shear zones. Many of the low to moderate earthquakes that have occurred in the region correlate with some of these shear zones. The seismicity of Kerala in general exhibits some sort of spatial clustering and are located around 1) Achankovil-Punalur 2) Idukki-Pala and 3) Thrissur-Palakkad areas. Almost all earthquakes reported from the southern peninsula were of shallow focus except the 1900 Coimbatore event which is a deeper (50-70 km) event. Quantitative estimate of seismic hazard in the region require i) identification of potential faults/shear zones which show considerable seismic activity through high resolution mapping of microtremors, ii) quantifying the time varying deformation field across suspected active faults / fractures in the region. This project was aimed at quantifying the time varying deformation field in this region using GPS geodesy which can be used to model the deformation mechanism, fault kinematics in this seismically active region. (Figure 2.6).

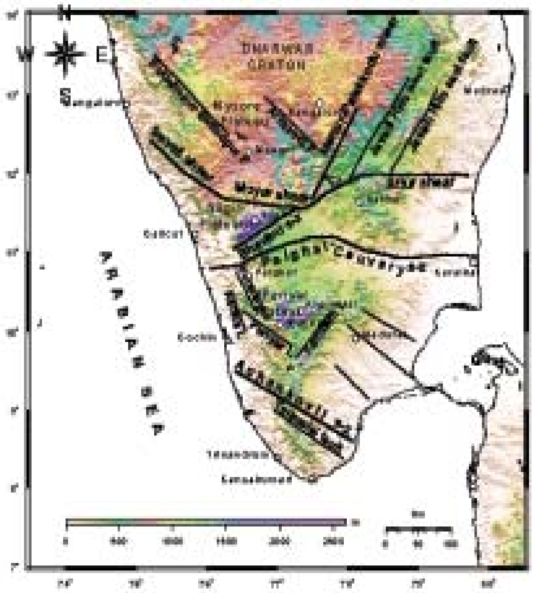

Figure 2.6 The tectonic map of Southern Penninsular Shield of India, showing the major faults, lineaments and shear zones.

Analysis of GPS campaign data (2003-2006) in the Achankovil shear zone and adjoining areas indicates significant changes in eastward velocities (50-60mm/yr ± 3mm/yr) in the ITRF 2000 reference frame. Relative to IISC, these eastward velocities range between

5- 10mm/yr ± 3mm/yr. However, estimation of long term deformation (1994-2004) from old C-MMACS sites gives rise to very low strain rates in the South Indian Shield. This insignificant strain rate (decadal range) of the order of few nano further confirms the earlier results that South India moves as a rigid plate with velocity approximately equal to the Indian plate velocity. The co-seismic surface deformation associated with intra-plate earthquakes (such as Indian peninsular earthquakes) cover a few tens of kilometers, therefore any detection of these events through GPS geodesy require a more dense array of GPS sites through out India. The stations occupied under this study, to some extent, serves this purpose and would be useful for long term deformation estimations in this area. We recommend a more robust and continuous monitoring of the SGT, especially the potential seismogenic zones/areas like Achakovil, Palghat-Cauvery, Periyar-Idamalayar Lineaments and Salem- Attur shear.

Anil Earnest, M S M Vijayan, Sridevi Jade, P Dileep Kumar, Nilof Pasha and M R Radhakrishna

2.7 Calibration of Different Make of GPS Receivers to Inter-compare the Precision

As per the directive of GPS expert group of Department of Science and Technology, an independent experiment was carried out for calibration of different make of GPS receivers for inter comparison of the accuracy and precision of relative positioning. Millimeter level accuracy and precision in relative positioning is vital especially in case of geodetic studies. In India different kind of receiver antenna pairs are used in permanent as well as campaign geodetic measurements to estimate and model ongoing deformation of the Indian plate. Hence, calibration of different GPS receiver antenna pair is necessary to capture the feeble signals of the active tectonics. It is very clear from results that the receiver-antenna pair of same make has very less number of cycle slips, RMS and phase residuals compared to receiver-antenna pair of different make, even though the repeatability plots gives almost similar errors in position and baseline estimation, the daily rms, phase residuals and cycle slips reveals that the same make receiver-antenna pair are very reliable. The results of this calibration study suggests the use of same make of receiver-antenna pair to get reliable and accurate estimates of relative positioning in all kind of geodetic measurements. Kindly note that the objective of the calibration experiment completely lies on the question of accuracy and precision of receivers with same and different make of the antenna.

Anil Earnest, M.S.M. Vijayan, Sridevi Jade and Malay Mukul

2.8 Active deformation in the Darjiling-Sikkim Himalaya based on 2000-2004 Geodetic G P S Measurements

High precision Geodetic Global Positioning System measurements have become important for studying present-day tectonics in active orogenic belts such as the Himalaya. Geodetic Global Positioning System measurements in the Darjiling-Sikkim Himalaya (DSH) during 2000-2004 indicate that the frontal part of the Darjiling Himalaya is locked to the Indian plate and statistically negligible shortening is accumulating there at present. While this observation is in conformity with observations made in Nepal to the west of the DSH, it differs in the fact that about 12 mm/yr of convergence is accommodated in the DSH and the western Bhutan Himalaya as opposed to about 20 mm/yr in Nepal Himalaya. About 14 mm of convergence is accommodated in the Arunachal Himalaya to the east of DSH of which about 6 mm is accommodated in the Lesser Arunachal Himalaya. These observations indicate that there is a fair amount of heterogeneity in the way convergence is accommodated along the length of the Himalayan arc and Himalayan seismic hazard estimations need to account for this. Seismicity patterns in the DSH indicate that active deformation in the area is driven by strike-slip as well as thrust tectonics. Strain accumulation in the DSH during 2000-2004 appears to be dominated by strike-slip tectonics in the region and about 4-5 mm/yr of sinistral strike-slip is observed along a NNE-SSW trending near-vertical fault identified in the area (named as the Gish transverse fault).

Malay Mukul, Sridevi Jade and Abdul Matin

2.9 The Geometry and Kinematics of the Darjiling - Sikkim Himalaya, India

The Darjiling-Sikkim Himalayan (DSH) fold-thrust belt lies in a zone of arc-perpendicular convergence between the Indian and Eurasian plates. A series of south-vergent folded imbricate thrusts are exposed along the Tista and Rangit valleys; from N to S these are: (1) the upper Main Central thrust (MCT1) that carries high-grade (sillimanite-bearing) Kanchenjunga-Darjiling gneisses in its hanging wall. (2) The lower Main Central thrust (MCT2) carries intermediate grade (biotite-garnet) Paro and Lingtse gneisses; together these two sheets form the Greater Himalayan sequence. (3) The Ramgarh thrust (RT) carries Daling phyllites and graywackes. (4) The Main Boundary thrust (MBT) carries the Daling, Buxa and Gondwana units; the RT and MBT sheets together comprise the Lesser Himalayan sequence. (5) The Main Frontal thrust (MFT) carries Sub-Himalayan Siwalik rocks onto the foreland. In southern Sikkim the MCT1, MCT2 and RT sheets are regionally antiformally folded over the Lesser Himalayan Rangit duplex, whose roof and floor are the RT and MBT respectively and which is exposed in the Rangit window. Farther south, the Darjiling klippe exposes these sheets in a synformally folded stacked sequence.

We have used INDEPTH geophysical data, the template constraint and return to regional dip arguments to constrain the depth to basal detachment, which varies from ~5 km at the mountain front to ~9 km under the Rangit duplex to ~13 km under the MCT1 and MCT2 ramps; the regional detachment dip is ~3°. Using this in combination with surface structures we have constructed a regional balanced cross section across the DSH. Minimum restorations suggest that the MCT1 and MCT2 sheets have each been translated ~100 km southward. In addition, the RT sheet has been translated ~50 km, and the MBT a minimum of 28 km. Including shortening within the Rangit duplex we estimate a total minimum regional shortening of ~350 km.

Kathakali Bhattacharyya, Gautam Mitra and Malay Mukul

2.10 Site Charecterization of Bangalore City using Ambient Noise

Site response analysis is a fundamental part of assessing seismic hazard in earthquake prone areas. Although there are number of methods to evaluate seismic hazard, but due to its low cost and simplicity, ambient seismic noise (microtremor) measurement is preferred by many. Microtremors are short period vibrations that results from human activity (traffic, machinery), atmospheric loading, wind etc. The main objective of this project is to compute the horizontal to vertical spectral ratio (H/V ratio) using Nakamura's technique, which generates the peak period fundamental frequency. In addition, on soft soil sites, where contrast is high between bedrock and top soil they usually exhibit a clear peak that is well correlated with the fundamental resonant frequency. It is now commonly accepted in the earthquake engineering community that soft soils can play a large role in ground motion and must be included in seismic zoning. The phenomenon responsible for the amplification of the ground

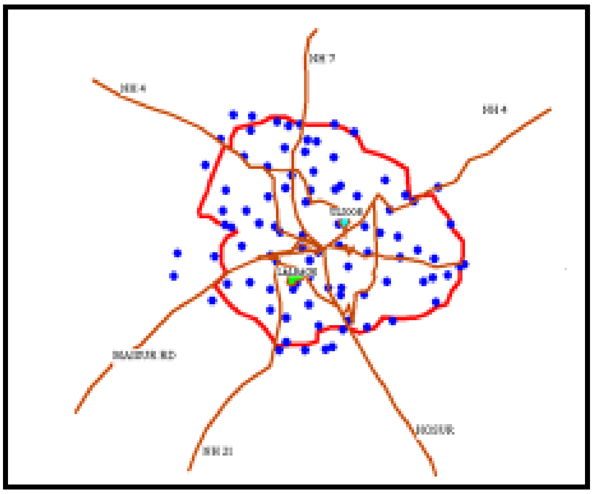

Figure 2.7 Location of single station sites used in ambient noise survey in Bangalore City.

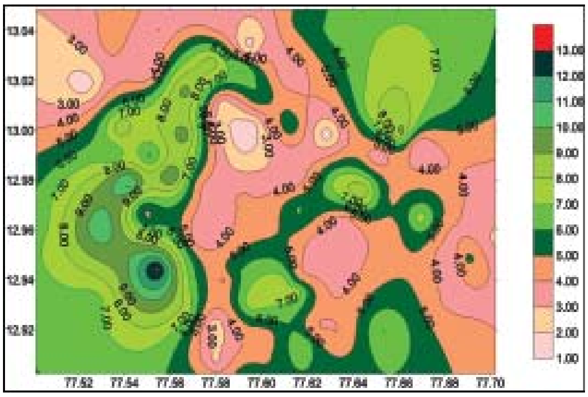

Figure 2.8 Fundamental frequency mapping in Bangalore City.

motion in areas with soft sediments is the trapping of seismic waves within sediments due to acoustic impedance contrast between sediment and bedrock. The interference of these trapped waves leads to resonances whose shapes and frequencies are well correlated with geometrical and mechanical characteristics of the structure.

Bangalore- a highly developed and dense city becomes a centre of attraction for the youth and many industries due to its expansion in industry, trade and commercial value leading to a rapid growth of the city and large scale urbanization. The goal of this study is to map site characterization of Bangalore city. More than 90 noise measurements were performed covering the Bangalore Metropolis area of about 220 sq km (figure 2.7). For computation of the spectral ratio using Nakamura's method, the GEOPSY programme has been used. The fundamental frequencies (f_0) from the ambient noise H/V spectral ratio for each site were calculated and they are found in the range of 1.2 Hz-14 Hz. It has also been found that frequency in the south-western part is highest compared to the south-eastern part (figure 2.8). The results were validated by comparing them with the borehole data. The soil depth obtained from the borehole data varies from 6 to 34 meters.

The corresponding contour maps were produced so that the predominance frequency could be compared one to one with the overburden thickness inferred from various borehole locations (figure 2.9). The resonant frequencies and soil thickness compares very well. The mapping of predominant frequency of resonance permits identification of zones at risk. It can be used as a tool for prevention planning and retrofitting measures and also to define safety zones for reconstruction after a destructive earthquake.

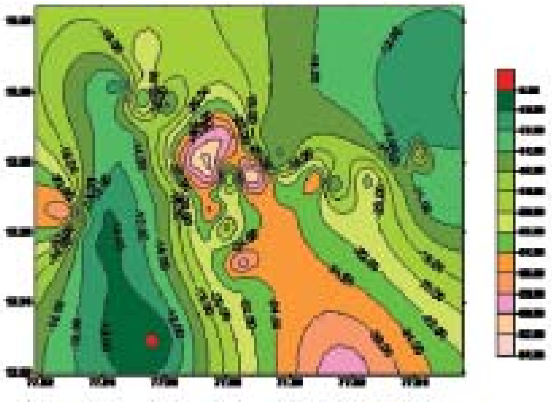

Figure 2.9 Overburden thickness in Bangalore city

Imtiyaz A Parvez and Rekha Bharali

2.11 Site Response in Ahmedabad City using Microtremor Array Analysis

The Ahmedabad city, located on the banks of Sabarmati River 100 km north of the Gulf of Khambhat, was founded in 1411 AD by Sultan Ahmad Shah. The present day Ahmadabad is a bustling commercial hub with the district having a population density of 567 persons/sq km. The agglomeration is located in the Cambay graben that is occupied by 400 m thick Quaternary sediments. Though falling in Zone III of the Seismic Zoning Map of India, the city has been severely jolted by the distant Kutch earthquakes of 1819 and 2001. This vulnerability of the urban complex under the influence of long period seismic waves, as well as its importance as a rapidly growing commercial centre has necessitated a deeper understanding of the site characteristics on seismic excitation. The Department of Science and Technology, Government of India took up site response in Ahmedabad city using microtremor array observations with the objectives of studying the site response using H/V spectral ratio; 1-D shear velocity of subsurface soil using f-k and SPAC method; and finally the simulation of ground motion for specific earthquake source scenarios. The microtremor arrays around 100 different sites in the city have been used to record the ambient noise in three campaign mode. The last campaign was done during February 2008. This time, we have also studied the building parameters by installing the stations at different levels of the building. On most of the sites, more than one array was deployed to capture the lower and upper geological properties. To get the first order response of site characteristics, the most commonly used Nakamura (H/V ratio) technique has been adopted using the ambient noise recorded by an array of seven Lennartz 5 sec seismometers. Most of the sites have shown a fundamental resonance frequency at 0.6 Hz. Very few sites have the peak frequency between 2-6 Hz, however, the first peak at 0.6 Hz is also explicit on these sites. This indicates that the thickness of the upper soft soil is very deep (~350-400 metres) which corresponds to the frequency of 0.6 Hz. Geologically, Ahmedabad city is sitting on thick Quarternary sediments and there is no direct evidence of basement rock. H/V spectral ratio confirms that most of the sites have fundamental frequency around 0.6 Hz without any sharp peak that means there is no high impedance contrast in geological structure beneath the top layer and it changes gradually as semi-consolidated material overlying the beds below 400 m. The sites along the river and other water body (e.g. lakes) show the fundamental frequency above 2 Hz which means that the new soft sediments are brought to the sites by river. However, the 0.6 Hz fundamental frequency still dominates these sites. There is no one-to-one correlation with the damage that occurred in Ahmedabad consequent to the Bhuj earthquake 2001 with the site response results obtained in this study. Most of the newly constructed apartment buildings with 8-9 floors were damaged mainly in areas to the west of Sabarmati River. However, fundamental frequencies of such buildings do not fall in 0.6 Hz ranges. There were clusters of damage in Maninagar area with relatively low rise apartments (4-5 floors) that lies between Chandola and Kakaria lake. This can be treated as damage due to site effects as in this region, higher resonance frequency have also been obtained. The phase velocity dispersion curve is also estimated by frequency-wave number (f-k) and spatial auto correlation (SPAC) methods using microtremor arrays of 7 stations recording ambient noise for at least one hour at each site. Phase velocities have been inverted to obtain the 1-D shear velocity at each site. Generally, the top layers upto 0.1 to 20 metres show shear velocities between 150-300 m/s, and below this down to 100 m, velocities vary between 600 and 800 m/s. These velocity models have been used to simulate the ground motion along five geological cross-sections of Ahmedabad city made by the Central Ground Water Board using different source zones. Response spectra ratio (RSR) that also correlates with the frequency around 0.5-0.6 Hz has been obtained.

Imtiyaz A. Parvez

2.12 Coda Q Estimates on the Andaman Islands using Local Earthquakes

The attenuation property of Andaman Island has been investigated analyzing coda waves from 57 local earthquakes in the magnitude range of 2.0 - 4.9 using the single back-scattering model (figure 2.10).

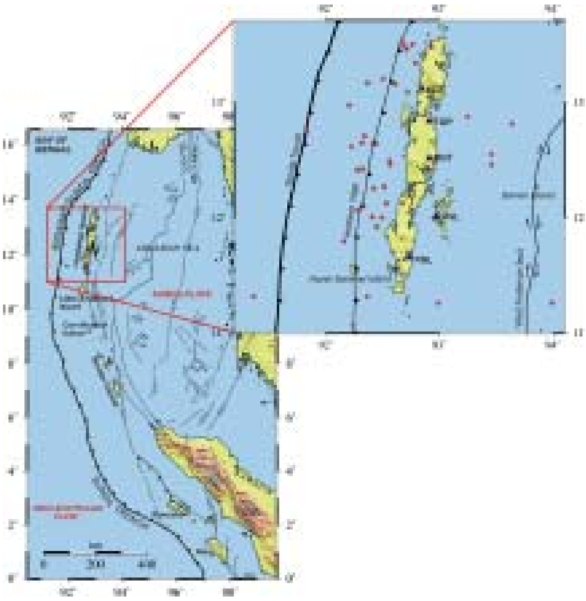

Figure 2.10 General geological and tectonic map of Andaman region. Earthquakes used in the present study are plotted by circle and triangles represent the recording stations.

These earthquakes waveforms, recorded on five broadband seismographs sited over the island from north to south during Nov 2003 to March 2004, have been used to calculate the frequency dependent Coda Q (Q_c) applying the time domain coda-decay method. The Coda Q, computed at central frequencies from (0.5-12) Hz and five lapse time windows from 40 to 80 s, progressively increases from 105 $f^{0.88}$ in the north Andaman to 135 $f^{0.79}$ in the south Andaman with an average of 119 $f^{0.80}$ (figure 2.11).

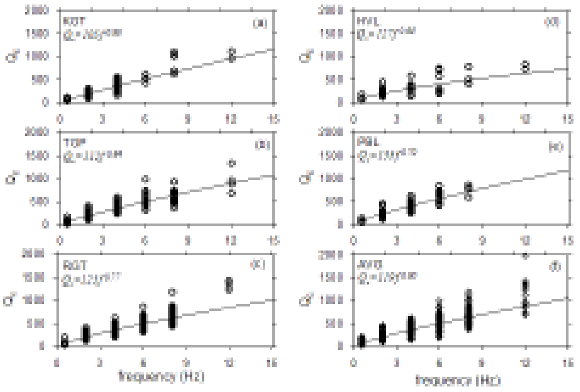

Figure 2.11 Plots of quality factors and central frequencies for all stations with linear regression frequency dependent relationship, (a) to (e) show the plot of Qc with fm (central frequency) for stations KGT, TGP, RGT, HVL and PBL respectively. (f) is the average of all the stations.

The average Q_c values vary from 75±42 at 0.5 Hz to 697±54 at 12 Hz central frequency for 40 s lapse time window, while for 80 s lapse time window its variation is from 117±38 at 0.5 Hz to 1256±115 at 12 Hz. The Q_c estimated at different lapse times shows a significant variation from 122$f^{0.75}$ to 174$f^{0.73}$ corresponding to lapse time window lengths of 40 and 80 s respectively. We have also compared our result with the seismogenic zone of India and other parts of the world. For such comparison it is important to select the results same windows of the other tectonic and seismic active regions of world.F In order to compare our results, we calculated the average Q_c for central frequency 1.5 Hz for the lapse time from 40 – 80 sec. lapse time varies ,a,y, 3comparisonvarying using constant slapse timelapse The Q_c^{-1} values of Andaman region is towards the higher side than any other regions of India, particularly for the frequencies higher than 4 Hz, however, it is well comparable at lower (1.5 Hz) frequency. Koyna region (Gupta et al., 1998) is also comparable in lower frequencies, whereas, it is again less than our results along the high frequencies range. Similar trend is shown by Naresh et al. (2005), for NW Himalayas and Gupta et al., (2006) for Kachchh as compared to our results for Andaman. Seismogenic regions in Italy (Tuve et al., 2006) and Turkey (Akinci et al., 1996) shows higher Q_c^{-1} values than any Indian region at all the frequency range. This confirms that the coda attenuation observed in our study are comparable to other Indian regions but are more sensitive to high frequencies, which shows the region is more

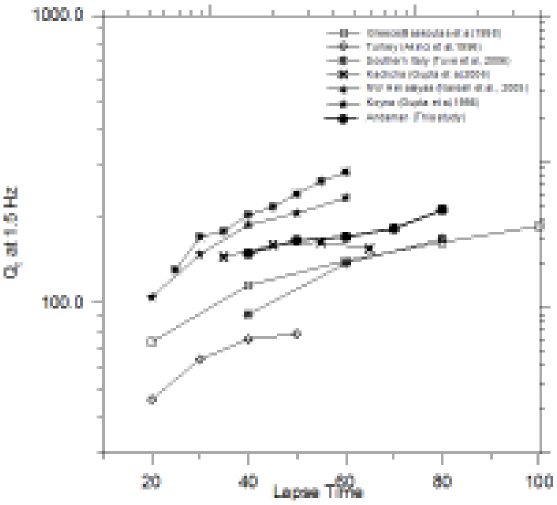

Figure 2.12 Comparison of coda-Qc with lapse time variation of Andaman region with reported coda-Qc of other regions of India and of the world.

heterogeneous as compared to other parts of the country.The variation of Q_c with frequency, lapse time and also with the location of seismograph reflects the marked structural and compositional inhomogeneity with depth along the Andaman island. These observations are well correlated with the seismicity pattern and distinct high angle subduction beneath the island.

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2.13 Ground Motion at Bedrock Level in Delhi City from Regional Earthquake Scenarios

The source process and seismic ground motion time histories are two very important topics in seismology and earthquake engineering as they are necessary for seismic hazard mitigation. One of the basic concepts associated with the study of seismic hazard is to determine the seismic ground motion time histories at a given site, due to an earthquake of certain magnitude (or moment) at a certain epicentral distance. In order to increase the knowledge in this aspect, huge records of ground motion are required and in practice however, such database is not available. In this paper, a preventive tool is proposed by the realistic modeling based on computer codes developed from the knowledge of the seismic source and of the propagation of seismic waves associated with the earthquake scenarios. Delhi the capital of India - is prone to a severe seismic hazard threat from local, regional and also from the Himalayan earthquakes at 250-300 km distance. In this study, we simulate the earthquake ground motion, at bedrock level, in Delhi city, by the modeling of the source of Mw=8.0, located at a regional distance of 175 km of epicentral distance from Delhi city. We simulate the time histories using Size Scaled Point Source (SSPS), Space and Time Scaled Point Source (STSPS) and Extended Source (ES) models. We consider the earthquake source depth=10, 15 and 20 km, dip=10 deg, rake=95 deg, strike-receiver angle=0º-360º, length of fault=178 km and width of fault=45 km. The maximum amplitude of ground motion is searched as a function of the strike-receiver angle. The peak values – displacement of 9.30 cm (vertical comp.), velocity of 7.34 cm/

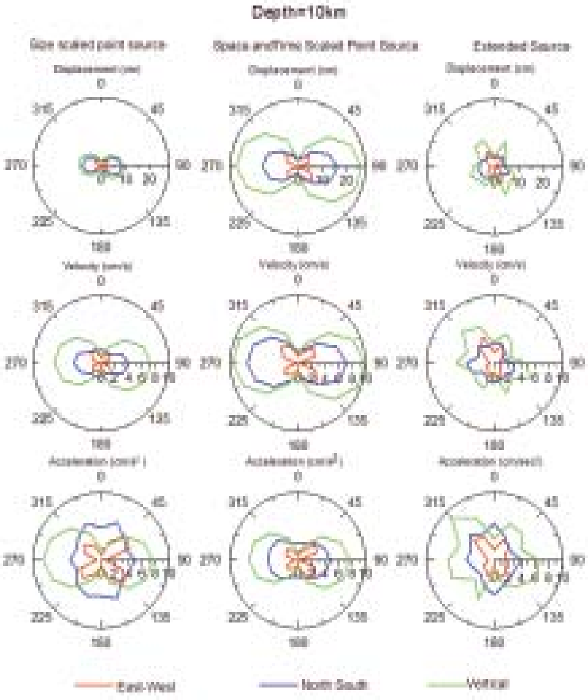

Figure 2.13 Radiation pattern of peak ground displacement, velocity and acceleration along the strike receiver angle from 0-360 for the source depth of 10 kmin Delhi city for regional earthquake of Mw=8.0.

sec (vertical comp.) and acceleration of 8.53 cm/sec^2 (vertical comp.) are obtained using Size Scaled Point Source Model and displacement of 30.27 cm (vertical comp.), velocity of 11.23 cm/sec (vertical comp.) and acceleration of 10.95 cm/sec^2 (vertical comp.) are obtained for Space and Time Scaled Point Source Model. For extended source the peak values - displacement of 12.16 cm (vertical comp.), velocity of 6.54 cm/sec (vertical comp.) and acceleration of 8.84 cm/sec^2 (vertical comp.) - are obtained at the source depth 10 km. Similarly, keeping all other parameters fixed, we estimated the ground motion when the source is at depths of 15 and 20 km and the dip is 20 deg. The radiation pattern of peak ground displacement, velocity and acceleration along the strike receiver angle from 0-360 for the source at depth 10 km is shown in figure 2.13. A similar study will be performed for sources at local distances, to analyze and to assess likely earthquake scenarios driving the seismic hazard in Delhi city.

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