6

SOLID EARTH MODELLING

Global Positioning System (GPS) based Geodesy had become capable of yielding sub-cm precision in location 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 the partitioning of strain from Kanya-Kumari to Ladakh in the trans-Himalyas. Over the years C-MMACS has also taken up the arduous task of setting up GPS stations in remote locations in the country to generate the required data base, and to extend application of GPS technology to other areas.

INSIDE

6.1 Karakoram Fault Modelling

The ~ 800 km long Karakoram fault (Figure 1) in the west Himalaya is a major strike slip fault for seperating Ladakh from southwestern Tibet and its slip rate has strong implications the physics of deformation in Indian Himalayas which is the largest of the continental collision regions on earth. The present day slip rates along the Karakoram fault have been a matter of investigation for a long time and the estimated long term slip rates by various investigators range between 2.5 mm/yr to 32 mm/yr. In this study eleven years of GPS derived surface deformation along the Karakoram fault in Ladakh Himalaya has been inverted using the deformation model to derive the geometry and interseismic slip of this buried dislocation.

The Karakoram fault in Ladakh Himalaya was modeled as a finite rectangular fault following its mapped trace along the Nubra valley and Tangste segments (Figure 6.1) with a depth of 10 km and a width ranging between 400 and 700 m, dipping at an angle of 40° .GPS rates in this region indicate that there is no significant shear deformation in Karakoram fault and the fault along its entire length behaves like a creeping fault right up to the surface, slipping with a low slip rate. Assuming a continuous slip on the Karakoram fault, and using dislocation solutions to simulate the fault parallel surface deformation, yield a strike slip rate of ~ 3 mm/year along its Nubra Valley segment and the Tangste segment. The modeled surface deformation corresponding to 3 mm/year slip of the fault best fits the GPS-derived horizontal surface deformation of the Karakoram fault campaign sites as well as the two continuous sites at Leh and Hanle. Assuming that this strike slip motion of 3mm/yr along the Karakoram fault causes 2 mm/year relative surface horizontal motion of sites close to the Karakoram fault and dividing this by the perpendicular distance between them would give an average shear strain of 0.1 Istrain/year in the splayed segment of Karakoram fault, which is significant enough to cause M>5 earthquakes.

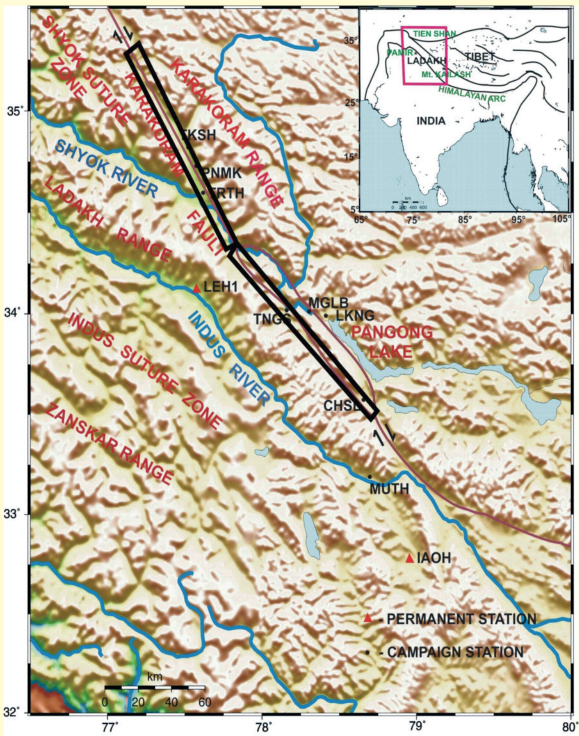


Figure 6.1 Finite rectangular dislocations along the Karakoram fault trace in the Ladakh Himalaya, Inset shows the Indian subcontinent with its northern boundaries and the boxed region is the study region which was modeled.

Sridevi Jade and A J Saigeetha

6.2 Inverse Modelling of GPS Derived Surface Horizontal Deformations

Surface horizontal deformation of earth's crust have been inverted to give insight in to the geometry and slip of buried dislocations during the inter-seismic phase; geometry of the rupture and associated slip during the co-seismic and post seismic phase. Dislocation Modelling is a geophysical inversion technique in which the observed surface displacements are compared with predicted values obtained from an assumed model of any dislocation geometry and slip. The initial geometry of the buried dislocation is generally assumed using prior information on its characteristics obtained from various sources such as fault mapping, earthquake focal mechanisms etc. The inverse modeling technique (in our case) relies on the theories of Elastic Half Space Model and Inverse methods. The simulation of such dislocations which largely define the surface displacement pattern in a region thus becomes an important study to completely understand the mechanism driving it. Numerical models have been developed using elastic dislocation theory and weighted least square inversion. These inversion models were validated for few cases and then used to determine the post seismic slip and rupture in Andaman and Nicobar islands due to 2004 Sumatra earthquake. The priori range for the dislocation parameters are arrived at based on the earthquake focal mechanisms and published results. The best fit postseismic deformation model for Andaman and Nicobar region is given in Figure 6.2. The afterslip patch consists of six segments as shown in the Figure 6.2 and the modeled slip for the segments in the Andaman region (I, II, III, IV and V) varied between 1.9 to 3.1 m while in the Nicobar region, the modeled afterslip patch has a post-seismic slip of 1.5 m. The observed and modeled displacements are also shown in the figure. The inversion model is now being used to model the deformation in northeast India

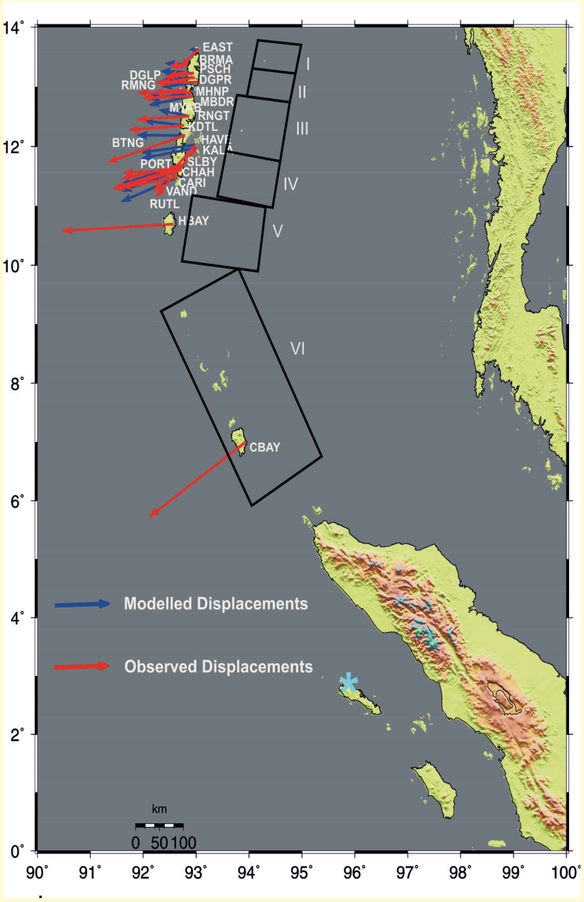


Figure 6.2 Andaman and Nicobar region along with the observed and modeled surface postseismic deformation due to 2004 Sumatra earthquake.

Sridevi Jade and A J Saigeetha

6.3 Post-earthquake Deformation of Andaman and Nicobar Islands from GPS Geodesy

The Solid Earth Modelling Group of C-MMACS was the first in the country to initiate precise geodetic studies at Andaman Nicobar Islands to constrain the tectonic deformation happening there. As a continuation of these initiatives, we analyzed the GPS derived post-earthquake

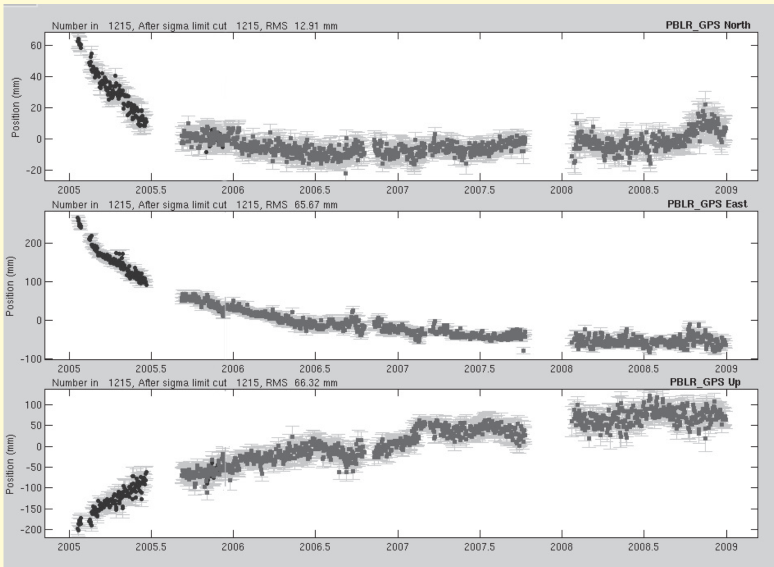
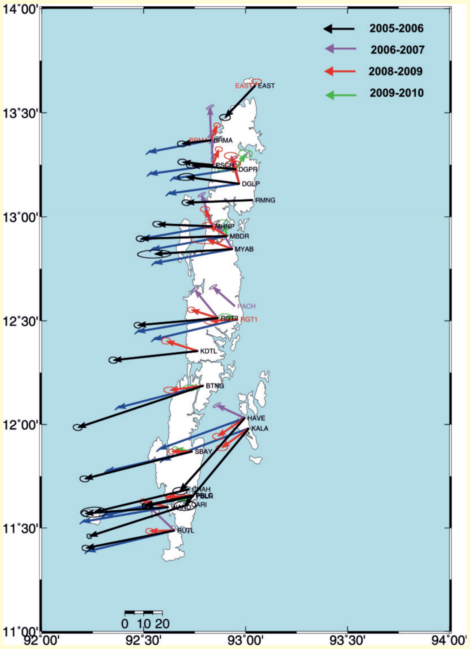


Figure 6.3 GPS derived post-earthquake relaxation pattern for the Port Blair region. Note the steady uplift in the vertical component.



relaxation pattern after the M 9.3 Sumatra Andaman earthquake. Results from this study shows significant amount of relaxation at co-seismically subsided Port Blair (Figure 6.3). Similar GPS derived deformation pattern for the post-seismic period of 2005-2009 shows horizontal displacement vector azimuths orienting initially to south-west, along the co-seismic offsets, and then gradually rotating towards north (Figure 6.4). The amount of vertical relaxation varies during this period between 4 to 300 mm/yr. These GPS derived values are expected to give better constraints on the evolution of after slip, poro-elastic and visco-elastic deformation happening at this plate boundary zone.

Figure. 6.4. Post-earthquake rotation of the GPS displacement vectors for the whole Andaman region.

Anil Earnest, Sridevi Jade and M S M Vijayan

6.4 Volcano Geodesy – Newer Initiatives at Barren and Narcondam Islands.

Barren Island, a possession of India in the Andaman Sea about 135 km NE of Port Blair in the Andaman Islands, is the only presently active volcano along the N-S-trending volcanic arc extending between Sumatra and Burma. Lava flows fill much of the caldera floor and have reached the sea along the western coast during historical and recent eruptions. Narcondam is believed to be a dormant volcanic Island about 257 km from Port Blair in the Andaman sea. The island is approximately 3km×4km with a central peak of ~710 m above mean sea level and is formed of andesite.

Figure 6.5. Geodetic GNSS observations being carried out by CMMACS team at Barren Island.

Figure 6.6 GNSS antenna mounted on the short drilled monument at the Narcondam Island.

Prior to many volcanic eruptions there will be a relatively slow rise of the volcano surface due to the slow rise of magma into a magma chamber or from this into the upper crust. If magma rises to a shallow level beneath a volcano, the ground surface above it will swell, causing benchmarks around the center of the intrusion to move horizontally and vertically away from the source. The pattern of displacements enables us to sometimes estimate the location, depth, and amount of magma intruded. GPS derived geodetic solutions can provide insights into the involved mechanisms and can quantify the surface deformation happening there.

On this regard we initiated precise geodetic measurements at Barren (Figure 6.5) and Narcondam Islands (Figure 6.6) by establishing short drilled geodetic benchmarks and collection of GNSS data from there. Pre-fabricated monuments, instrument assembly with necessary operational accessories were successfully installed at the respective locations of these islands so as to detect any ground deformation happening there. This work was carried out with a great amount of logistical support from the Andaman Nicobar administration, Andaman Nicobar Command and the Indian Coast Guard and the staff of Andaman Marine Police posted at Narcondam Island during February – March, 2011.

Anil Earnest, T S Shrungeshwara, K Rajeev and Sridevi Jade

6.5 Re-occupation of the Precise Geodetic Control Points at Andaman Islands.

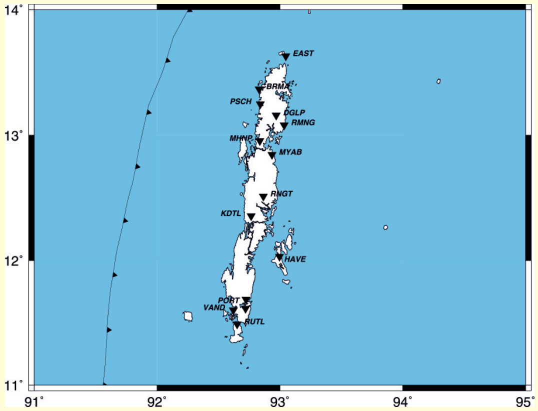


Figure 6.7 The GPS geodetic benchmarks at the Andaman Nicobar Islands.

Figure 6.8 The campaign survey setup set ready at Burma Chad Island, west of North Andaman.

Repeated and systematic re-occupation of the prior established geodetic benchmarks at the Andaman Nicobar Islands (Figure 6.7 & 6.8) helps us in closely monitoring the present day seismo-tectonics of this plate boundary zone aftermath the M9.3 Sumatra Andaman earthquake. These repeated observations helps us in getting GPS derived solutions on the upper-plate deformation and the strain evolution across this margin. In April-May 2010 the continuous GPS station at East Island and Panchavati have been revisited to check their health and also the deformation suffered at these sites due to active seismic activity north of Andamans during this period. On this perspective a continuing re-measurement campaign was carried out at the C-MMACS GPS control points at the Andaman Islands during January-February, 2011. Each of the existing benchmarks were occupied using Trimble NETR5 or Leica GRX1220 GNSS receivers. The duration of the site survey was set in such a way that on the minimum we get two full UTC days data from individual benchmarks. Results from this study are expected to bring out extended finer constraints on the temporal pattern of the seismo-tectonic deformation happening there.

Anil Earnest, T S Shrungeshwara, K Rajeev, Tejpal Singh, M S M Vijayan and Sridevi Jade

6.6 High-rate Precise Geodetic GNSS Reference Observatory at Port Blair

Earlier we had established continuously operating GNSS sites at East Island and Middle Andaman, as part of the CSIR CMMACS initiatives for better constraints on the seismo-tectonic processes happening at the Andaman Nicobar subducting plate boundary zone. For betterment of this network/spatial coverage and to serve as a reference station for the GNSS observation elsewhere in the Andaman Nicobar archipelago we established a precise geodetic GNSS high rate reference station at Port Blair within the premises of Pondicherry University Campus, Brookshabad, Port Blair (Figure 6.9). The site is made on the host rock exposure by making a RCC column pillar of 9ft high anchored to this host rock. The site selection is done by taking into consideration of factors like site stability, satellite visibility, security, long term operations and other logistical aspects. The antenna is mounted on a leveled fixed tribrach. The power requirements are met through external as well as solar panels with ample battery storage. We installed a internet ready Trimble NETR5 receiver at this site with Zephyr Geodetic2 antenna serving as the control point. Co-located met sensor parosceintific MET-4A sensor was also

Figure 6.9 The high rate precise geodetic GNSS station at Pondicherry University Campus, Port Blair.

Figure 6.10 Co-located met-sensor MET- 4A at East Island.

installed along with the GNSS receiver setup so as to get every second supportive measurements of pressure, temperature and relative humidity data in order to convert GPS measurements to IPW values in offline mode at C-MMACS. Similar parosceintific MET-4A sensors were installed at already established continuously operating GNSS sites at East Island (Figure 6.10) and Panchawadi.

Anil Earnest, P M Mohan, T S Shrungeshwara, K Rajeev and Sridevi Jade.

6.7 Giant Earthquakes and the Andaman-Nicobar Plate Boundary

This work is a collaborative effort between C-MMACS and the National Centre for Antartic and Ocean Research (NCAOR), Goa to look for geological proxies that may shed light on the giant paleo-plate-boundary ruptures happened along the Andaman-Nicobar subducting margin. This project involves the collection of target oriented cores along the trench-ward channels and canyon systems of the Andaman-Nicobar subduction zone, for which a reconnaissance survey was carried-out onboard ORV SagarKanya during 1st June to 2ndJuly, 2010. This cruise was primarily meant for NCAOR's exclusive economic zone (EEZ) survey of the Andaman-Nicobar Islands and was chartered for the collection of multi-beam swath bathymetric data from the western coast of Andamans. The survey area partly covered the trench-ward side of Car Nicobar to North Sentinel Island (Figure 6.11). The possibility of identifying turbidity current carrying channels and their resultant fans among these cruise lines were tried by us by making use of the high resolution bathymetric data. We did the core location siting by making use of on-board facilities like sub-bottom profiler and real-time bathymetric data visualizer (Figure 6.12). We were successful in identifying few submarine channels and turbidity depositional features and cored few of them using the on-board gravity corer. ORV Sagar Kanya is

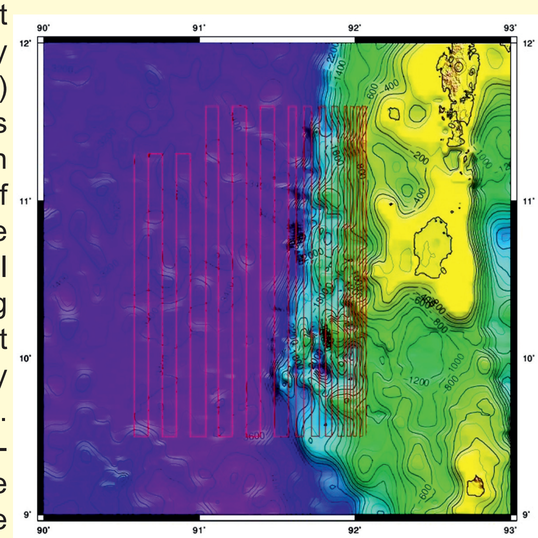


Figure 6.11 Ship tracks for the SK273 cruise. Initial north eastern ship tracks pass through our area of interest which is near to the trenchline axis.

India's geophysical survey vessel owned by Ministry of Earth Sciences (MoES) and operated by NCAOR. Shehas proven capabilities in deep sea coring with sea-bottom sediment/rock sampling devices, cranes, winches, A-frame etc. A functional dynamic positioning system takes care of the ship's position during deployment of the corer to take care of drifting, pitch/roll and heave etc.

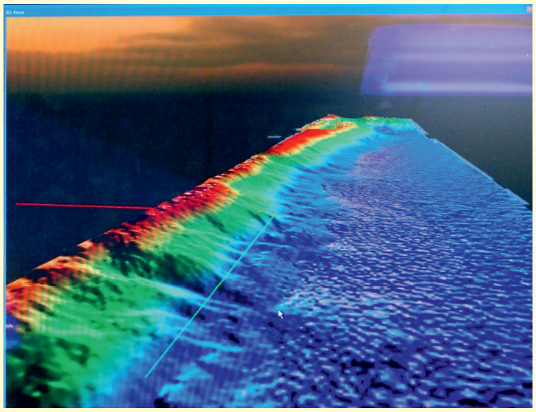


Figure 6.12 The channel systems parallel to the Andaman Nicobar trench line. Also seen is a depositional feature away from the channel axis.

Onboard, the vessel has capabilities for the collecting of multibeam swath bathymetric data using the Elacnautic Seabeam 3000 system. A Geoacoustics make single beam subbottom profiler, which is tuned for a single frequency of 3.5KHz is available for getting the subbottom information. The deep-sea winch, a 1983 Willi Baensch of Hamburg make, has proven operational capability up to a depth of 6000 m with a whooping rope length of 10,000 m. The onboard gravity/piston and box corers are of Norinco make and have recovery lengths up to 6 and 0.5m's respectively of an undisturbed sediment volume from the seabed. We were able to reach coring depths of 3500 m during this cruise.

Anil Earnest and John Kurian

6.8 Estimation of Crustal Deformation in North-Eastern India using Campaign Mode GPS Measurements

To study the internal deformation within the Shillong plateau and the nature of the plateau's mechanical linkage and tectonic relationship with Mikir Hills a GPS campaign mode observation has been carried out during October and November 2010 jointly with Tezpur University, Tezpur, Assam. The campaign site at Tawang, Arunachal Pradesh established by CSIR C-MMACS (figure 6.13) was also reoccupied as part of the GPS campaign in order to estimate the rate of convergence and strain partitioning between Shillong plateau and Arunachal Himalayas. The GPS campaign mode observations were carried out totally at 11 sites spread over in Assam, Arunachal Pradesh and Meghalaya for the period of 3 continuous days at each site (figure 6.13). Some of the campaign sites established in yesteryears were damaged. So, new sites have been established near to such damaged sites. The continuous mode GPS (CGPS) stations of North East India was kept operational without any break during the campaign period. The data collected during this campaign is being analysed along with the data collected in previous campaign mode observations and CGPS data to well constrain the rate of deformation of the study region.

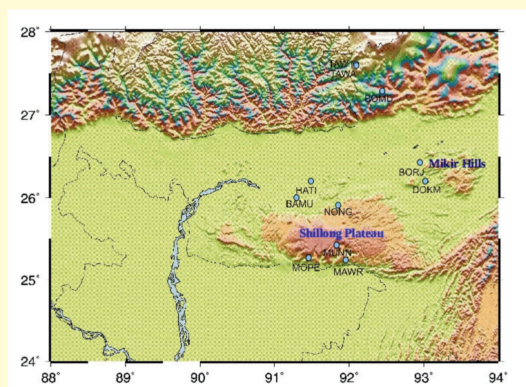


Figure 6.13 Locations of Campaign mode and continuous mode GPS stations are shown over the topographic map of North eastern India

M S M Vijayan, T S Shrugeshwara, Sridevi Jade, Prakash Burman, D R Jagath, Ashok Kumar

6.9 Total Electron Content (TEC) using Dual Frequency GPS Receivers

Growth in spatial spread and density of geodetic GPS stations in India provides an opportunity to the earth science community to explore the ionosphere extensively over the subcontinent in addition to crustal deformation. As an initial experiment, GPS data collected at IISC Bangalore continuous GPS stations for the period of five days have been analysed using a software tool developed in house to estimate the ionospheric Total Electron Content (TEC). Figure 6.14 shows the diurnal variability of TEC over IISC for the period of five days in the year 2004. TEC is being estimated using the data collected at rest of the Indian CGPS stations to further study the diurnal and seasonal variation of TEC over the permanent stations to understand the spatio-temporal variability and regular fluctuations in TEC which will help to model it over Indian subcontinent.

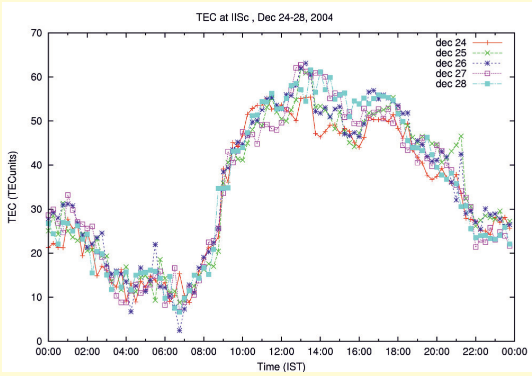


Figure 6.14 Diurnal variation of Ionospheric Total Electron Content (TEC) over IISC derived using stand alone dual frequency GPS receiver.

M S M Vijayan, Kiranmayi Mangalagiri, K Shimna, and Sridevi Jade

6.10 Diurnal Variability of Tropospheric Precipitable Water Vapour (PWV) using GPS

Tropospheric Precipitable Water Vapour (PWV) was estimated using the GPS data collected at Tezpur(TZPR) Continuous GPS station and Bangalore (IISC) IGS station from the year 2006 to 2008 for every two hours. Zenith Tropospheric Delay (ZTD), from which the PWV is derived, is estimated parametrically in the process of geodetic position estimation. In the process of estimation generally the a priori Zenith Tropospheric Delay (ZTD) is modeled using the meteorological values derived from Global Pressure/Temperature (GPT) model and introduced at each epoch and for each station as a stochastic variable. GPT has poor representation of diurnal variability and its accuracy varies over regions. This imposes limitation in achieving the accuracy and precision in PWV estimates. To

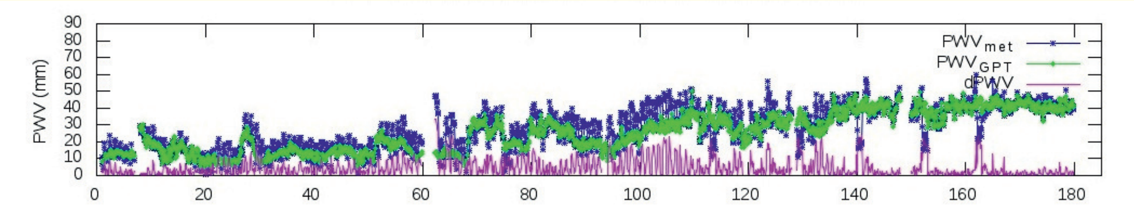


Figure 6.15 Shows the PWV variability at Bangalore for 2009 using GPT model and observed meteorological parameters in estimation.

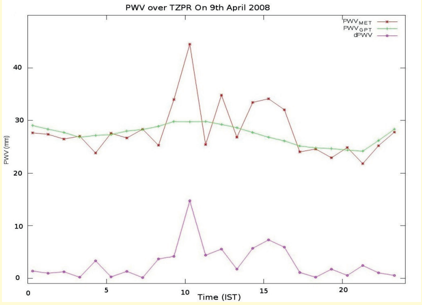


Figure 6.16 Diurnal variability of PWV over Tezpur (TZPR) CGPS stations.

assess the impact of the atmospheric pressure, temperature and humidity on GPS based PWV estimates, observed meteorological parameters at Tezpur and IISC, Bangalore are incorporated in the a priori modeling of ZTD in GPS data processing. The PWV estimates thus obtained are compared with the PWV estimated using GPT model. Figure 6.15 gives the variability in PWV at Bangalore using GPT and observed meteorological parameters. Diurnal variability of PWV over Tezpur(TZPR) CGPS station has been shown in Figure 6.16.

M S M Vijayan, T S Shrungeswara, Sridevi Jade

6.11 GNSS Based Realistic Landslide Hazard Modelling

Presently most Himalayan towns have high landslide risk. Since Himalayas have a high seismic activity, these towns have a danger of being hit by earthquakes and multiple seismically induced landslides. In addition these towns are prone to landslides that result from processes that result out of climatic, geomorphologic or anthropogenic factors as well as human settlements. These call for an entirely new, town-specific landslide hazard assessment to make landslide hazard assessment and mitigation realistic and to take it to a level where the information can be used for decision making and operation issues related to town-planning in the Himalayan regions. Global Navigation Satellite System (GNSS) Geodesy is a recent effective technology for monitoring an active landslide in real time and also for landslide hazard mapping of a specific region. Realistic landlside hazard assessment of a specific region needs an integrated study of the detailed geology, geomorphology, geotechnical mapping of the region along with identification of old, stable and active landslides and slope stability assessment/ monitoring using GNSS geodesy. To start with the surface deformation of a specific study region should be determined using static GNSS geodesy to identify the active deformation in the region. This information should then be integrated with the geology, geomorphology and geotechnical information of the region to identify the landslide related deformation in the region. Based on this presently active landslides in the region should be earmarked and specifically monitored using GNSS in RTK mode. The real challenge is to integrate and model all this data both qualitatively and quantitatively and assess the landslide hazard of the region in a realistic manner. This would require a rare combination of modeling skills and individual expertise in GNSS geodesy, geology and geotechnical areas and would make a difference in developing a realistic landslide hazard assessment methodology and model. This would go a long way in saving loss to property and lives due to landslides in the urban settlements in Himalayan region if these hazard maps are used for location of these settlements and identified design procedures.

Sridevi Jade

6.12 GNSS Geodesy Based Geosciences Research

Global Navigation Satellite System (GNSS) is a satellite based navigation and surveying system capable of giving precise position to millimeter accuracy of any point on the surface of earth using radio signals of these satellites both in real time and post processing mode. Though initially GNSS was primarily developed for defence purposes, subsequently, it was recognized that precise-positioning provided by it could be used in high-precision geodesy for several geosciences applications such as continental deformation studies, landslide hazard mapping, Glacier dynamics, Volcano deformation, troposphere and ionosphere modeling, InSAR (Interferometric Synthetic Aperture Radar), GIS(Geographical Information System) etc. Currently there are several GNSS ground stations in Indian Subcontinent established for specific applications by various agencies like Department of Science and Technology(DST), Ministry of Earth Sciences(MoES), Survey of India (SOI) and Indian Meteorological Department (IMD), Indian Space Research Organisation, Airports Authority of India and Armed forces. These networks were established to monitor siesmo-tectonic activity in Indian subcontinent, estimation of precipitable water vapor (PWV), troposphere and ionosphere studies, ground surveying, air navigation etc…. In India, precise GNSS geodesy is presently being used in geosciences research areas like crustal deformation studies, troposphere and ionosphere modeling. Studies have been recently initiated to use GNSS geodesy for landslide hazard mapping, understanding glacier dynamics , GPS- InSAR and GPS-GIS integration.

Globally, GNSS geodesy is used extensively for landslide hazard mapping, glacier dynamics, GIS and InSAR integration where as in India the research in these areas is in the initiation stage only. Research in the areas of volcano deformation studies and ionosphere modeling using GNSS geodesy is at initial stage both at national and international level. These research areas are of tremendous importance to the Indian community and should be taken up by research organizations and universities at the earliest. Most of the current research in Geoscience using GNSS geodesy is presently being carried out by a few research organizations in the country. There should be a national programme on GNSS based geosciences research with all the agencies involved as stake holders to bring coordination between these agencies and departments involved in this programme to address all the above research areas actively.

Sridevi Jade

6.13 Ground Motion in Delhi City from Regional Earthquake Scenarios

The seismic 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 assessment. Delhi is a fast growing megacity that influences the economic and industrial development of most of the country and falls in the zone IV of the seismic hazard zonation map of India. The city is under threat of seismic risk not only from the local earthquakes but also from those (Figure 6.17) originating in the Himalayan region. The simulated ground motion has been computed using different source types and the rupture mechanism at rock level in Delhi city for two different earthquake scenarios; one form Central Himalayas at a distance of 300 km and other at regional distance of 175 km. In this light, the questions: what is the bedrock level ground motion

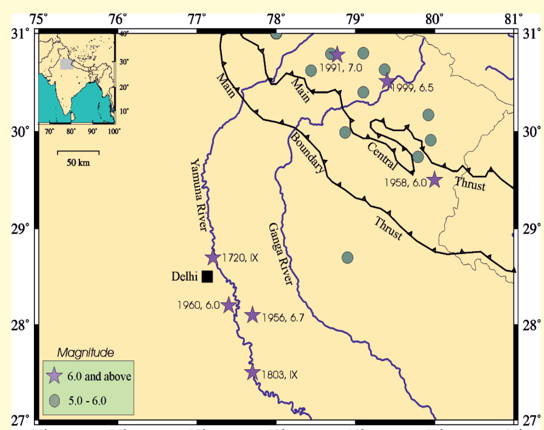


Figure 6.17 The regional map of Delhi and its surrounding areas with the epicenters of the earthquakes which occurred in the region.

in terms of displacement, velocity, acceleration and response spectra in the city is expected due to regional and to the ones originating from the so-called seismic gap in Central Himalayas? The

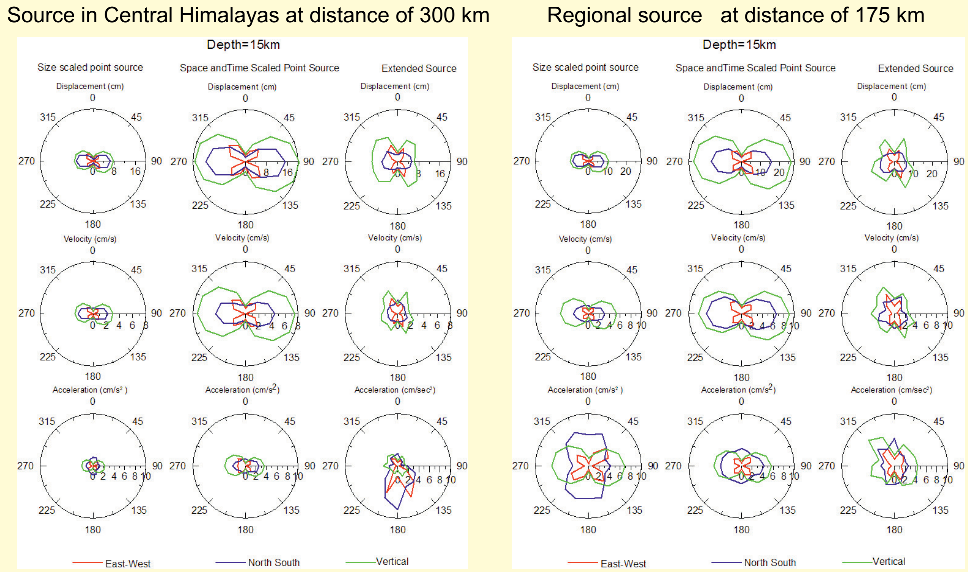


Figure 6.18 Radiation pattern of the peak ground displacement (cm), velocity (cm/s) and acceleration (cm/s2) versus the strike receiver angle (from 0-360°) for a hypocentral depth equal to 15 km, for the three types of source models considered: SSPS (first column), STSPS (central column, ES (last column).

objective of this work is to study and compare the ground motion generated by different source time functions and make evident the main characteristics of the extended source. We study firstly, the ground motion due to the far source and its dependency to the strike-receiver angle and the directivity and subsequently, we carry out a similar study for the regional source. The radiation pattern of the peak amplitude of displacement, velocity and acceleration, have been represented in polar diagrams of peak amplitude versus strike receiver angle (figure 6.18). For the SSPS and STSPS models, the pattern follows strictly the double couple radiation pattern with peaks in one quadrant and trough in the other, while, a more realistic pattern is seen in the case of ES model where the sub-sources effect is clearly seen. The results obtained in this study indicate that the seismic hazard potential in Delhi city due to a possible great earthquake in Central Himalayas and form regional earthquake is generally high, particularly for long period displacement. With the complete time histories (displacements, velocities and accelerations, from which the peak amplitudes have been extracted), we have also jointly used the displacement response spectrum to characterize the seismic input at Delhi. In fact, not only it is of great significance to the modern displacement-based design engineering approaches, but it is probably the best parameter to characterize the destructiveness potential of earthquakes located at great distances from the target sites, since the energy of the seismic input from these events is mainly concentrated at long periods (e.g. greater than 1 s). The ground motion obtained, particularly the displacement at long period, is of the order of ~15-20 cm and it represents a base of knowledge that can be fruitfully used by civil engineers.

Imtiyaz A Parvez, Fabio Romanelli and Giuliano F Panza

6.14 Attenuation of P, S and Coda Waves in the NW-Himalayas, India

In order to investigate the structure of the interior of the earth and to quantitatively predict the strong earthquake ground motion in engineering seismology, the information on seismic wave attenuation plays an important role. Especially, the information on high frequency wave attenuation in the lithosphere is of particular importance. Attenuation parameter Q-1 is an important factor for understanding the physical mechanism of seismic wave attenuation in relation to the composition and physical condition of the earth's interior. Attenuation of seismic waves with frequency strongly depends on the physical conditions of the underground crustal media and is caused by different factors like geometrical spreading, scattering, multipathing and anelasticity. The crustal value

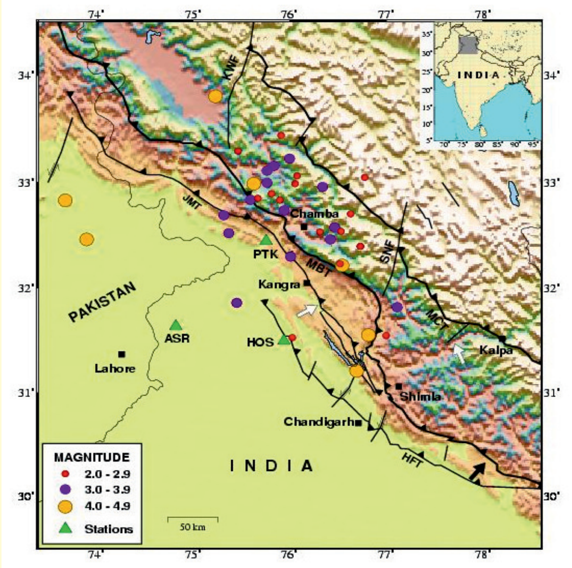


Figure 6.19 General Seismotectonic and topographical map of NW Himalayas and adjoining area. MCT: Main Central Thrust; MBT: Main Boundary Thrust; HFT: Himalayan frontal thrust; JMT: Jawalamukhi thrust; KWF: Kisatwar fault; SNF: Sundarnager fault; earthquake epicentres are plotted by circles, triangles represent the recording stations (PTK: Pathankot; HOS: Hoshiarpur; ASR: Amritsar) and cities are shown by squares.

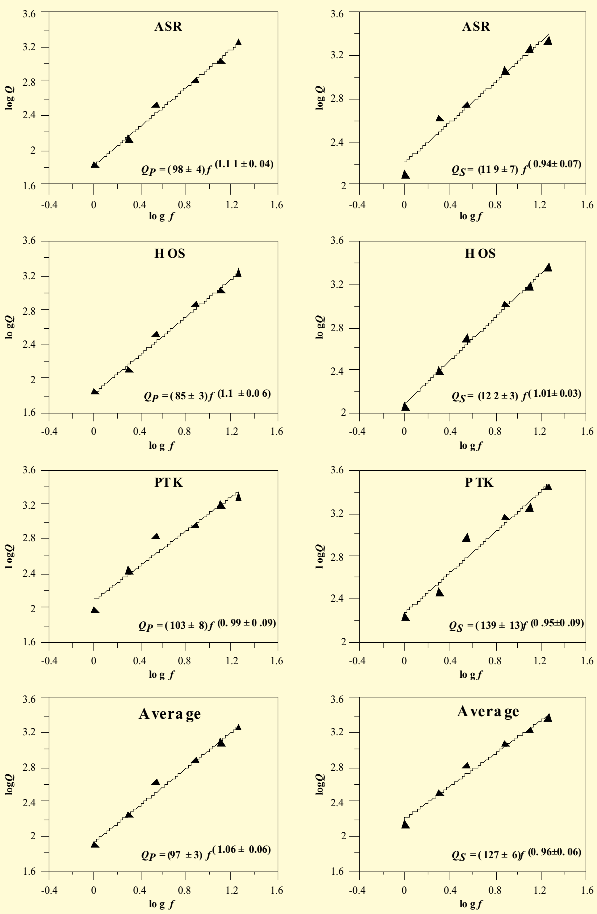


Figure 6.20 Frequency-dependent relation-ships for the three stations ASR, HOS and PTK respectively, along with average of all the three stations

of attenuation, described as the inverse of the quality factor (Q-1). The main objective of this study is to understand the attenuation characteristics of the North-West Himalaya region using different parts of the seismograms including coda waves and body waves. For this purpose, the extended coda normalization method has been used to estimate the frequency-dependent relationships for QP and QS in the NW Himalaya region and that is the first estimate of this kind for this region. The QC estimates for the NW Himalaya region have been previously obtained by us using the single back-scattering model in the present study we integrate and compare the estimated QP and QS with QC obtained by earlier findings. The study area covered comprises of three seismic stations Pathankot (PTK), Hoshiarpur (HOS) and Amritsar (ASR) in NW Himalaya region (Figure 6.19). The first seismic station, PTK is on the top of the Siwalik Hills; the second one, HOS is at Siwalik foothills; while third one, ASR station is located on the Gangetic plain.

The seismograms have been filtered using Butterworth band pass filter with six frequency pass bands of 0.5-1.5 Hz, 1-3 Hz, 2-5 Hz, 5-10 Hz, 10-15 Hz and 12-24 Hz. We plotted the quantity ln ((Ap/Ac) r) and ln((As/Ac)r) versus r along with the least square fitted lines and the slopes of the best fitted lines are used to estimate QP and QS for six different frequency bands. We find a clear frequency dependency of QP and QS as they increase with frequency and that indicates the frequency-dependent nature of Q estimates in the region. We have plotted log QP and log QS with the log of frequency to estimate the frequency-dependent relationships as shown in figure 6.20. The average frequency-dependent relations for the region are QP = (97 ± 3) f (1.06 ± 0.06) and QS = (127 ± 6)f (0.96±0.06). We have estimated QC earlier for NW-Himalayas using the back-scattering model and we have found QC = 158f1.05 for the NW Himalaya region. We compared QC, QP and QS for this region and it has been found that QC is always greater than QS and QP for all the frequency ranges, that indicates a possible high frequency coda enrichment. This study is an attempt to understand the attenuation of P-, S- and Coda- waves in the NW-Himalayas of the India using the different parts of the seismograms. The attenuation parameters obtained in this study are useful for the estimation of source parameters and simulation of earthquake ground motions in the region which is needed to assess the seismic hazard in the region of NW Himalaya, India.

Imtiyaz A Parvez , Preeti and Nagaraj K

6.15 Preliminary Results from Broadband Array in Dharwar

A Network of five Broadband seismographs has been establish during April 2010 across Dharwar Craton along with previous 5 seismic stations which was operated by NGRI to create a high resolution shear velocity Image of Dharwar crust. The Netwok has been planned to operate in several phases. Phase I is now close to its completion. In phase II the array will be extended further SE with six stations which are procured at the beginning of this year (see Figure 6.21). Six new REFTEK 130 Data logger with GPS time synchronization have been procured at the beginning of this year. New data Acquisition System (DAS) will be installed with existing Lennartz sensors and Existing broadband stations, with an extension of profile towards SE. Earthquake waveform data are being recorded continuously at 100 sps. An example of East Coast Honshu Japan mega event of Magnitude (Mw=9.1) recorded by our station is shown in Figure 6.22. Shell scripts have been developed to automate selection and the

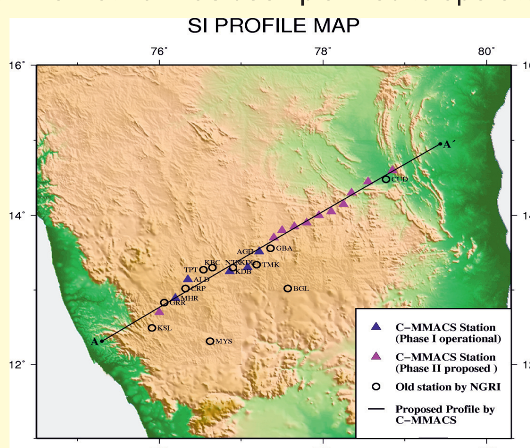


Figure 6.21 Regional map of South India showing C-MMACS stations location of Phase I (blue triangle), NGRI stations (circle) and proposed station for Phase II (pink triangle).

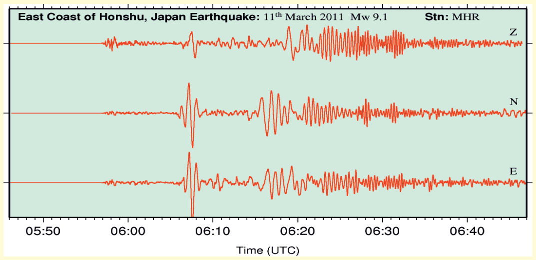


Figure 6.22 The three component waveform of the Honshu Japan mega event of Magnitude (Mw=9.1) recorded by C-MMACS broadband network.

extraction of earthquake waveforms (by magnitude and distance) reported by USGS catalog's and converted to SAC format for archival of the data. The receiver function is calculated by using time domain iterative deconvolution for all distant earthquakes. The Receiver function analysis allows determination of the time delay between near-vertically travelling direct P waves, and converted S waves that travel to the seismometer from subsurface interfaces with velocity contrast. Delays between the direct and converted wave are proportional to the depth of the interface and depend on the transmission velocities along their paths, while the amplitude of the converted arrival depends on the magnitude and sign of the velocity contrast. No significant azimuthal variation is observed which removes the possibility of dip and anisotropy in the crust. Delays between the direct and converted wave are proportional to the depth of the interface and depend on the transmission velocities along their paths, while the amplitude of the converted arrival depends on the magnitude and sign of the velocity contrast. The delay times can be converted to interface depths assuming a velocity model. No significant azimuthally variation is observed which remove the possibility of dip and anisotropy in the crust. High quality stacks are generated, in a range of ten degree back azimuth and five degree of delta, to enhance single to noise ratio.

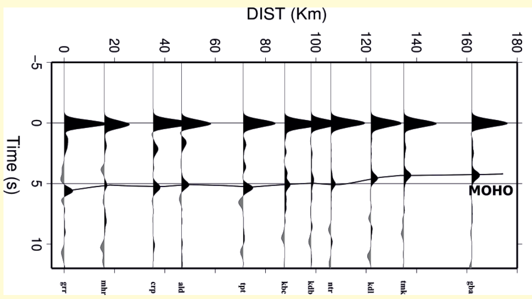


Figure 6.23 Time section of stacked Receiver Function (RF) showing geometry of Moho (marked as a line) along SW-NE profile.

A time section has been generated from stacks, for 60-70 degree back azimuth, to infer the geometry of MOHO along the profile (Figure 6.23). Ps time varies from ~6 sec in SW to 5~5 sec in NE of profile. Time section shows thicker crust to thinner crust as we move from SW to NE.

Ashish and Imtiyaz A Parvez

6.16 Paleoseismogeological Investigations in a "Seismic Gap" in the Northwest Caucasus compared to the West Himalayan Region

In this study, we have made an attempt to apply the notions on "Seismic Gap" to the zones of seismic quiescence within the individual segments of the Alpine-Himalayan mobile belt. The integrated field seismotectonical investigations carried out in the Northwest Caucasus in recent years showed that in the past, strong earthquakes occurred in the zones of some active faults, which left well manifested seismodislocations on the surface. These investigations were conducted in the central part of the North-west Caucasus, where the forecast seismic potential of Mmax previously obtained is 6.5–6.8. On the other hand, the level of the seismic intensity registered is low. In order to identify active faults i.e. the faults considered as ruptured zones, which were active during the period of the Late Pleistocene Holocene (in the past 100000 years), the method of morphotectonic analysis was used. The study of active faults using geophysical methods and in the development of mines allowed us to characterize the amplitudes of young displacements and to identify the manifestations of strong earthquakes. Based on the results of paleoseismogeological studies carried out, six strong seismic events that occurred during the Holocene were identified. The age of their manifestation correspond to the time borders of about 8500, 7500–7000, 5500–5000, 3000–2500 and 200 (1799) years ago. The recurrence period is 1000–1500 years on average. It is interesting that in the western area of the seismically active Himalayan Belt of India a similar situation is observed. Here, along the Himalayan Frontal Thrust, in historical times there were strong earthquakes such as Kangra in 1905 (M = 7.7) and the Bihar-Nepal in 1934 (M = 8.1). The seismogenic displacement along the zone of the Frontal Thrust observed in the trenches and that belonged to the second seismic event was more than 5 m, which is evidence of an earthquake with a magnitude of over 8.0. Probably, these dislocations correspond to the time of the earthquake in the Himalayas that occurred in 1505 (M = 8.2) As a result of investigations, one can conclude that the recurrence period of earthquakes with a magnitude close to Mmax, in the frontal area of the Western Himalayas is about once every thousand years, and the recurrence period of strong earthquakes with a lower magnitude is once every 500 years.

E A Rogozhin and Imtiyaz A Parvez

6.17 Effect of Rotation and Initial Stress in Propagation of Shear Wave in a Non Homogeneous AnisotropicIncompressible Medium Under Gravity Field

The present work deals with the effect of rotation and initial stress on the characteristics of Shear waves propagating in a non-homogeneous anisotropic incompressible medium under gravity field in the framework of linear theory including Coriolis and Centrifugal force. Analytic analysis reveals that the velocity of propagation of shear waves depends upon the direction of propagation, the anisotropy, gravity field, effect of centrifugal force and corolisis forces, non-homogeneity of the medium, and the initial stress. The frequency equation that determines the velocity of the shear wave has been obtained. Numerical computation shows that the presence of centrifugal force and corolisis force in the medium affect the velocity of propagation. It is found that the variation in parameters associated with anisotropy and non-homogeneity of the medium directly affects the velocity of the wave. The velocity of wave also depends on the inclination of direction of its propagation. An increase in the inclination angle decreases the velocity in the beginning and takes minimum value before increasing. The effect of rotation on the propagation of shear wave in a non homogeneous anisotropic incompressible and

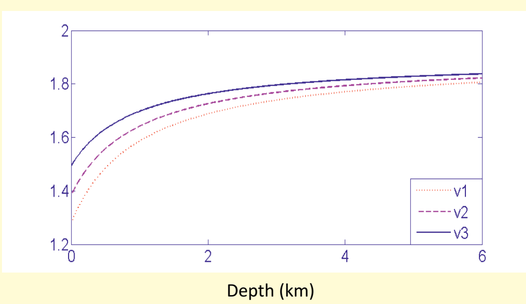


Figure 6.24:velocity ratio's$(\bar{c})$ vs depth $(\bar{b})$ for different values of rotational velocity Ω

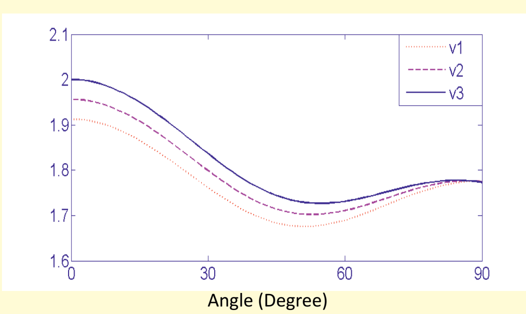


Figure 6.25:velocity ratio's$(\bar{c})_1$vs angle (θ) for different values of rotational velocity Ω

initially stressed medium under gravity field has been discussed using the wave equations which are satisfied by the displacement potentials. The frequency equations that determine the velocity of the shear wave has been obtained. The dispersion equations have been obtained, and investigated for different cases. Numerical results are presented for variation of velocity of shear waves with respect to depth and angle. Numerical results are presented including the effect of rotation, non-homogeneous, initial stress and gravity field. The variation of velocity with depth using different numerical values of the model parameters are shown in the following figures 6.24 and 6.25.

Numerical computation shows that the presence of initial compressive stress in the rotating medium, gravity field reduces the velocity of propagation while tensile stress increases it. It is found that the variation in parameters associated with anisotropy and non-homogeneity of the medium directly affects the velocity of the wave. The velocity of propagation also depends on the inclination of the direction of propagation; an increase in the inclination angle decreases the velocity in the beginning, takes a minimum value before increasing. Finally, it is concluded that the increasing values of initial stress (compression, without initial stress, and tensional initial stress), the shear wave velocity decreases.

Sushant Shekhar and Imtiyaz A Parvez