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Review Article

Standards and Methodologies of Seismological Data Generation, Processing and Archival & Guidelines for Data Sharing and Supply

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The process of dealing with earthquake disasters essentially involves three most important and inter-dependent components – (i) comprehensive understanding of the earthquake generation processes and the interior of the earth, (ii) disaster mitigation and preventive measures, and (iii) work through the ultimate goal of earthquake prediction. The basic and primary requirement towards addressing all these tasks is - high quality seismological data which is homogeneous and complete in time and space. India Meteorological Department (IMD), under the Earth System Science Organization (ESSO), Ministry of Earth Sciences (MoES), is the nodal agency of Government of India for monitoring earthquake activity in and around the country. IMD maintains the national seismological network consisting of a total of 82 observatories spread over the length and breadth of the country. The paper aims at discussing different methods/approaches adopted by IMD and other major agencies in the country for generation of various types of earthquake data products in standard formats, the analyses and archival tools and policy guidelines for supply and sharing amongst the user agencies. The paper also deals with the types of seismic instrumentation/networks in operation, network growth through historical times, data completion aspects, present level(s) of earthquake detection and location, future requirements and plans of upgradation. The policy guidelines being followed for seismological data sharing and supply have also been highlighted.

Key Words: Seismological Data; Processing and Archival; Standards and Methodologies; Data Sharing and Policy Guidelines

Introduction

Earthquakes are amongst several natural hazards that severely affect the human habitation and economic activities. Unlike other natural hazards such as, cyclones, floods and droughts, earthquakes strike without any warning and practically leave no scope for any remedial actions. It is, therefore, imperative to work out sustainable strategies towards better preparedness in dealing with earthquakes. IMD continues to render seismological services to the nation since the establishment of the first seismological observatory of the country in 1898 at Kolkata. As part of this service, information on earthquake occurrences in the country is transmitted to all concerned user agencies including public information channels, press, media etc. The information relating to tsunami-genic earthquakes in and around the country is also generated and disseminated to all concerned agencies. However, the Indian National Centre for Ocean Information Services (INCOIS), Hyderabad is mandated to issue tsunami related alerts, messages and warnings. The earthquake information is disseminated using various modes of communication, such as SMS, FAX, Email, IVRS and is also uploaded on IMD's Website. Towards meeting the above stated objectives, a nation-wide network of seismological observatories

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is operated and maintained by IMD. All the seismological data sets generated by IMD over the years are systematically archived at the National Center for Seismology IMD, New Delhi for posterity. The paper deals with various methodologies and standards adopted for generation of various seismological data sets, their archival and policy guidelines for data supply and sharing.

Seismological Data Generation

The history of instrumental earthquake monitoring in India dates back to 1898, with the first seismological observatory of the country having been set up at Alipore (Calcutta) on 1st December, 1898 after the great Shillong plateau earthquake of 1897. The occurrence of devastating earthquakes such as, Bihar-Nepal (1934), Assam (1950) and so on, provided the necessary impetus to strengthen the national network progressively from a paltry 6 in 1940 to 8 in 1950, 15 in 1960 and 18 in 1970. During the fifties, IMD started indigenous design and development of a few analog seismograph systems viz., Wood-Anderson, Sprengnether and Electromagnetic type, which were deployed in various network observatories. Early sixties marked a very important landmark in the history of seismic monitoring, when the WWSSN (World Wide Standardized Seismic Network) stations started functioning globally. Four stations of IMD, located one each at New Delhi, Shillong, Pune and Kodaikanal, became part of WWSSN during early 1962-1963 with the installation of matched 3-component short period and long period seismograph systems. Another significant addition was an L-shaped seismological array at Gauribidanur near Bangalore by Bhaba Atomic Research Centre (BARC), Bombay in 1965. Another station with 3-component short period Benioff seismometers and long period Press-Ewing type seismometers, confirming to WWSSN standards, was established by National Geophysical Research Institute (NGRI) at Hyderabad in 1967. A broadband system under a French collaboration, called GEOSCOPE, was subsequently added to NGRI observatory. A Seismic Research Observatory (SRO), consisting of a broadband borehole seismometer and a digital data recording system, was established at Central Seismological Observatory (CSO), IMD, Shillong in 1978. The seismometer was installed in a borehole at a depth of 110 meters to reduce the wind-generated noise in the long period band. Prior to the 90s, the seismological network of IMD primarily consisted of conventional analog type of seismograph systems with photographic/smoke/ink/heat-sensitive paper recording devices and separate short period and long period sensors to record the near and distant events. However, the advent of computer based digital and communication technologies led to the development of high resolution force balance broadband sensors, large dynamic range digital recording systems and VSAT based communication facilities for high speed data transmission. These in turn have greatly contributed in improving the seismic monitoring and research capabilities in the country.

During mid-Nineties, IMD upgraded 10 of its analog observatories, located mostly in the peninsular shield region, to the standards of Global Seismograph Network (GSN), after the Latur earthquake of 1993. These were the first series of digital seismographs inducted in the national seismological network of IMD. Subsequently, 14 more analog observatories of the national network were upgraded with similar digital broadband seismograph systems during 1999-2000. Semi-automatic transmission of digital waveform data from field stations and interactive mode of processing of earthquake waveform data commenced around the same time with the installation of SEISNET and SEISAN analysis software (Havskov and Ottemoller, 2000), at IMD HQ, New Delhi. SEISAN analysis software was also used to prepare monthly seismological bulletins, in addition to the estimation of earthquake source parameters in operational mode. Bhattacharya and Dattatrayam (2000) and Srivastav *et al*. (2003) gave a detailed overview of the history and developments in seismic instrumentation in India covering the period till the end of the last millennium, including the induction of first generation of digital broadband systems in the national network.

Seismological observatories are also being operated and maintained by various other agencies in the country for specific purposes as part of their mandate. Some of these institutions include: National Geophysical Research Institute (NGRI), Hyderabad; Wadia Institute of Himalayan Geology (WIHG), Dehradun; North East Institute of Science & Technology (NEIST), Jorhat; Institute of Seismological Research (ISR), Gandhinagar, Gujarat; Geological Survey of India (GSI), Kolkata; Indian Institute of Geomagnetism, Mumbai; Maharashtra Engineering Research Institute (MERI); Gujarat Engineering Research Institute (GERI), Kerala State Electricity Board (KSEB), Indian Institute of Technology (IIT), Roorkee; Indian Institute of Technology (IIT), Kharagpur; Indian Institute of Science, Education and Research (IISER), Kolkata, etc.

National Seismological Network

The national seismological network operated by IMD consists of a total of 82 observatories (Fig. 1). This includes two telemetered clusters, one each in and around National Capital Territory (NCT) of Delhi and North East region of the country and a real-time seismic monitoring network (RTSMN) for monitoring earthquakes of tsunami-genic potential. The existing network is in the process of augmentation and upgradation. A complete list of seismological stations operated by IMD is available on their website. The real time waveform data received from the field stations is processed and analyzed on a round-the-clock basis at National Center for Seismology, IMD (MoES), New Delhi using state-of-the-art facilities and software. Depending on the azimuthal coverage of the recording stations, the national network is currently capable of locating earthquakes of ~M>3.5 in peninsular shield and ~M>4.0 in extra-peninsular shield and M≥5.0 across the boundaries of the country. Srivastav *et al*. (2005) carried out a detailed

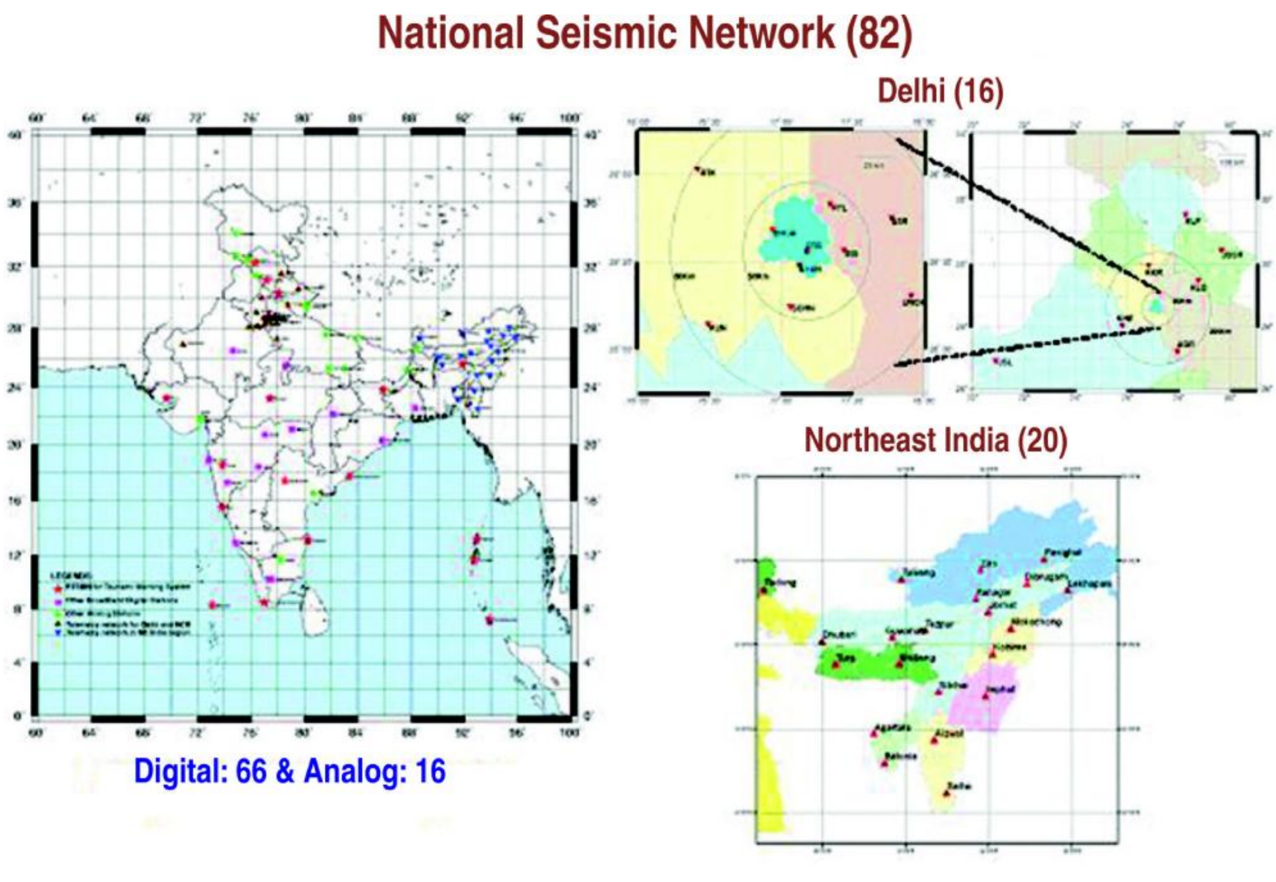

Fig. 1: Seismic monitoring network maps of India Meteorological Department

exercise and recommended a design optimum seismological network of 177 stations in India to be able to locate all earthquakes of M:3.0 and above uniformly in any part of the country. IMD is currently in the process of upgrading its existing network by adding 78 new broadband equipment/new stations, to improve the detection capabilities for locating all significant earthquakes in the country with reasonable degree of accuracy. Efforts are also being made to integrate some of the existing seismic stations being operated by various other agencies, under the MoES sponsored programs, to provide better azimuthal coverage for improving the earthquake location and detection capabilities.

The upgraded digital broadband seismological and strong motion network(s) had generated very useful and unique weak motion and strong motion data sets for several significant earthquakes during the last about two decades. Analysis of these data sets helped greatly in improving our understanding about the earthquake processes and bringing out refinements in the crust and upper mantle structure and attenuation characteristics of the Indian sub-continent. (Singh *et al*., 1999a, b, 2003, 2004a, b, 2005, 2006).

Earthquake Monitoring for Early Warning of Tsunamis

The country witnessed the disastrous effects of a great under-sea earthquake on 26th December, 2004, which had triggered unprecedented tsunamis on the coastal areas of all the Indian Ocean rim countries. Subsequently, an early warning system for tsunamis in the Indian Ocean region was established at INCOIS, Hyderabad, which is operating on a 24/7 basis. The system provides, in least possible time, advance information on tsunamis that are likely to affect the coastal areas of the country (Dattatrayam, 2006; Nayak and Kumar, 2008). As part of the Early Warning System for Tsunamis, a 17-station Real-Time Seismic Monitoring Network (RTSMN) was made operational during October 2008 by IMD (Dattatrayam *et al*., 2009). The network provides real information on the source parameters of earthquakes capable of generating tsunamis in the Indian Ocean region in a fully automated mode using various modes of communication channels. The RTSMN system employs state-of-the-art auto-location software, called 'Response Hydra' (v-1.2), to make preliminary estimates of earthquake source parameters immediately (within a few minutes) after the occurrence of an earthquake. The source parameters include the time of occurrence, location (region), magnitude and focal depth of the earthquake. The system is also capable of providing moment tensor solutions (CMT/MT) for large (M≥5.5) magnitude earthquakes to help quantify the faulting mechanism and assess the tsunami-genic potential of under-sea earthquakes. Based on the earthquake information provided by the real-time seismic monitoring network and other ocean level information, INCOIS issues necessary messages on watch, alert and warnings in the likelihood of a tsunami generation. To further improve the detection and location capabilities of the seismic network, data available freely on internet from international stations of IRIS (Incorporated Resrarch Institutions in Seismology) is also being utilized. The real-time earthquake information products generated by the RTSMN system for a sample earthquake event are shown in Fig. 2. Also, the real-time waveform data of seismological observatories at Port Blair, Shillong and Minicoy is being transmitted through internet to SeedLink server of IRIS, Washington for sharing with international community. The RTSMN system has enabled improving the response time of earthquake reporting to within ten minutes of the occurrence of earthquakes, as demonstrated in Fig. 3.

Telemetry Clusters and Local Earthquake Monitoring

A 16-station VAST based seismic telemetry network was commissioned in and around Delhi region during 2001, to monitor seismic activity of the region, which lies in seismic zone IV (Srivastav *et al*., 2001). The network has nine field stations in a radius of 80 km covering the NCR, Delhi and remaining seven in a radius of 200 to 400 km. Of these 16 stations, 4 are equipped with three-component short-period seismometers and remaining 12 with single-component short-period sensors (S-13) and

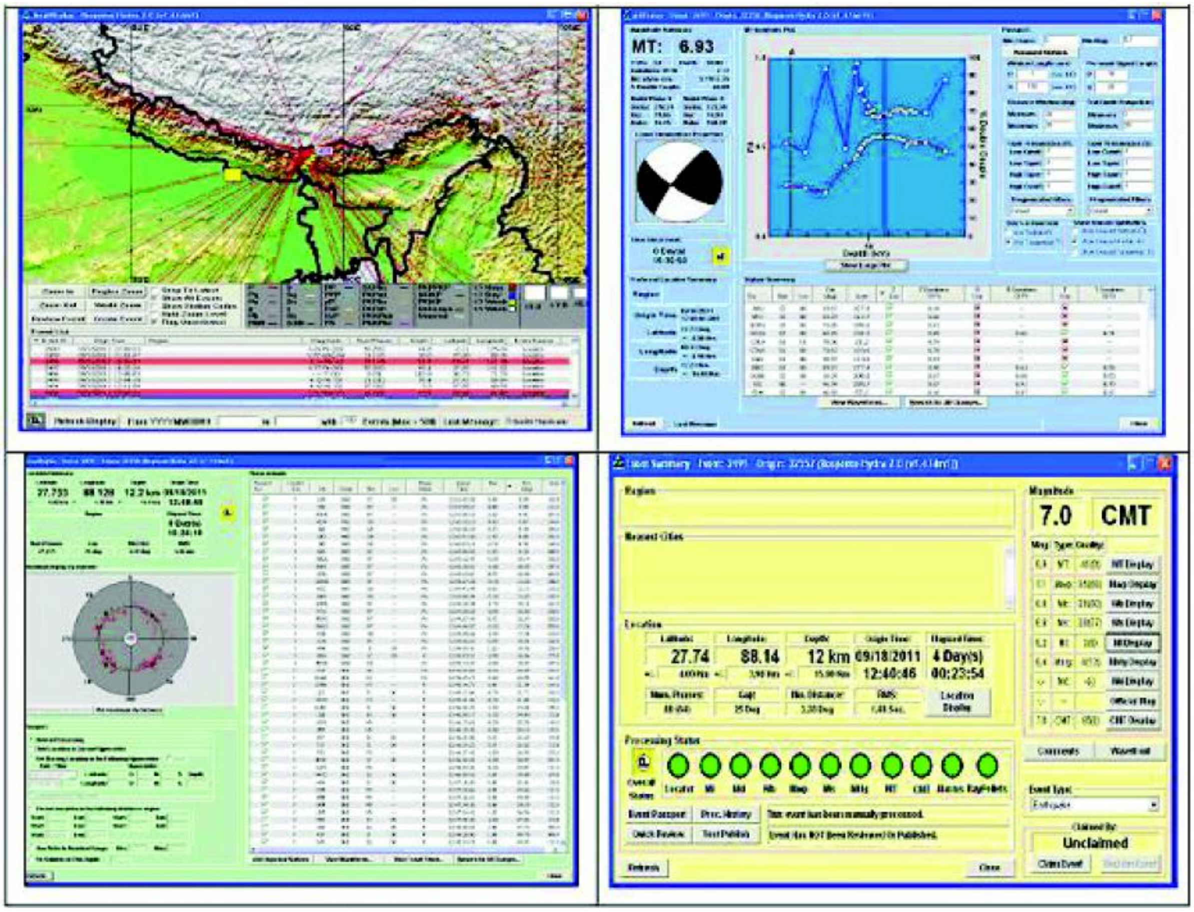

Fig. 2: Real time earthquake products generated by the RTSMN system for the Sikkim earthquake of 18th September, 2011

accelerometers. The system consists of 24-bit digitizers of Reftek make (Model No. 72A07) connected to short-period seismometers (S-13). The recorded data from all the field stations is acquired at central site, IMD HQ, New Delhi, through VSAT

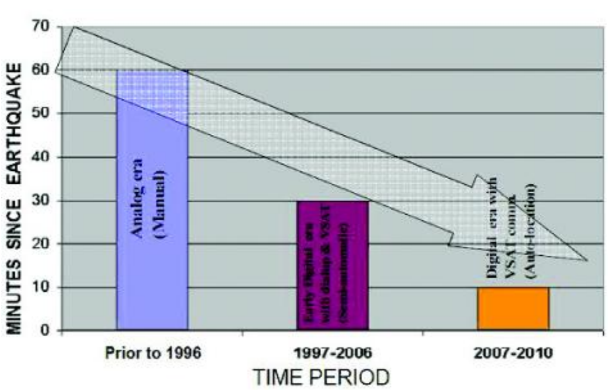

Fig. 3: Response time of earthquake reporting from the analog era to digital era with autolocation capabilities

communication facilities using Reftek Protocol Data Server (RTPD) acquisition software installed under Windows XP. The recorded data is in Steim-1 compressed PASSCAL format. The event data as per user criteria may be downloaded from its waveform archive directory in SEISAN format for analysis. The continuous PASSCAL data in archive directory is copied in CDs or tapes for permanent archival.

The network has generated very useful data sets for the region and brought out improvements in the detection and location capabilities of earthquakes in the region. The network data has enabled identification of two seismicity clusters around Mahendragarh-Dehradun sub-surface fault (MDSSF) trending NNE-SSW and (ii) Delhi-Sargodha ridge (DSR) trending NW-SE, which are also corroborated by the fault plane solutions with nodal planes trending either along DSR or MDSSF (Shukla *et al.*, 2007).

The site response has been estimated for the Delhi region using the S-wave spectra of earthquakes recorded by the digital seismic telemetry network around Delhi (Nath *et al*., 2003). Also, through waveform modelling of three recent earthquakes in and around Delhi region, it has been found that earthquakes in the region are characterized by faulting mechanism of predominant strike-slip with normal component and one of the nodal planes coinciding with NE-SW trend of lineaments in the region (Singh *et al*., 2010). An assessment of expected ground motions for a scenario earthquake of M:5.0 in the region has also been made (Bansal *et al*., 2009).

Northeast India region, which forms part of the major Alpide-Himalayan belt, is the seat of two of the largest known earthquakes of the world, the June 12, 1897 earthquake in Shillong Plateau and the Great Assam earthquake of August 15, 1950. In addition, the region had also experienced more than a dozen earthquakes of magnitude greater than ~7.0 and several shocks of slight to moderate magnitudes. To monitor seismic activity in the region on a real-time basis, a 20-station VSAT based real-time seismic monitoring network was established by IMD in the year 2011 (Shukla *et al*., 2011). The network covers all the 8 states of northeast India. The ground motion data from the field stations is received in real-time through VSAT communication at the two Central Receiving Stations (CRS) located at IMD, New Delhi and Central Seismological Observatory (CSO), Shillong. The field stations are unmanned and are equipped with 3-component broadband seismometers and strong motion accelerographs. The auto-location of earthquakes is carried out by the CRS, New Delhi, using ‘SeisComp3’ software developed by M/s Gempa, Germany.

Micro-Earthquake Monitoring

A ‘micro-earthquake’ is defined as an earthquake of magnitude less than 3.0. A network of closely spaced and highly sensitive seismograph stations is set up to monitor the seismicity at low magnitude levels. Micro-earthquake monitoring networks are powerful tools in monitoring seismicity associated with aftershocks/swarm type activity and for earthquake precursory studies, mapping of active faults, investigation of the structure of crust and upper mantle, study of induced seismicity, monitoring of volcanic activity, exploration of geothermal resources, etc. The data generated by such micro-earthquake networks is of high precision and quality, particularly with the deep seismic sounding (DSS) experiments and is very useful in delineation of detailed crustal structure of the region under consideration (Kamble *et al.*, 1974; Dube *et al.*, 1979; Srivastava *et al.*, 1983; Srivastava *et al.*, 1984 and Mittal *et al.*, 1990). In India, such short-term and long-term micro-earthquake networks have been operated and/are in operation in Himalaya, Northeast India and Peninsular Shield regions by various departments/ organizations in the country. Two such networks operated, one each in Beas-Salal Dam site in Himalayan region by IMD and in Koyna region by NGRI and MERI, were set up as early as sixties and have yielded very useful data sets for more than four decades (Shukla *et al.*, 2012). Using the microearthquake data generated by Beas-Salal networks, Kamble *et al.* (1974) worked out a detailed crustal structure for the Mandi section of Himachal Himalayas. Dattatrayam and Kamble (1994) analyzed the data sets, generated by the Beas-Salal network and Mobile network around Delhi operated by IMD, from fractal dimension approach and observed that the former exhibits strong temporal clustering in comparison to the later. Bhattacharya and Dattatrayam (2003) gave a detailed review of various microearthquake sequences reported in the country based on field investigations carried out by IMD and other agencies in the country. Based on the data sets generated by such microearthquake networks, various investigators have also worked out detailed crustal velocity structure for the regions concerned.

GSI has an established practice/mandate of carrying out post earthquake field surveys after the occurrence of significant (or damaging) earthquakes in the country and bring out official reports containing the maximum intensity experienced, maps of iso-seismals, damage pattern in engineering and non-engineering structures, ground deformation patterns, etc. IMD, on the other hand, deploys additional portable seismic equipments in the earthquake affected areas for detecting, locating and reporting low magnitude aftershock events. These field surveys are normally conducted by various geosciences related agencies in the country in a coordinated manner by pooling the resources. These surveys would in turn also help understand the detailed source characteristics of the entire earthquake sequence and the crustal structure of the study region (Mandal and Jose, 2006). A new approach is now being explored by IMD to make an assessment of intensity/damage pattern of an earthquake, by seeking voluntary reports (in the form of a questionnaire) on the effects of earthquakes on persons, ground and structures, etc. from various individuals through internet (Rajesh Prakash, *et al.* 2011). Recently, IMD had procured state-of-the-art digital portable seismic equipments for monitoring micro-earthquakes/aftershocks and swarm type activities and site response related studies. The system features facilities for rapid deployment of equipment in the field and real time transmission of continuous data from field stations to a Central Receiving Station through mobile GPRS modem for processing. The auto-location of events is done using an upgraded Local Response Hydra server/local event processor. The event parameters are disseminated through SMS to various central and state government agencies/authorities and other user agencies associated with relief and rehabilitation measures.

Strong Motion Networks/Arrays

The conventional seismograph systems go off the scale during violent ground vibrations due to large earthquakes in the vicinity of the epicentral zone. To effectively record these strong ground motions, another set of instruments, which are capable of recording the ground accelerations directly with very low sensitivity are used. Under a DST (Department of Science & Technology) sponsored project on 'National Strong Motion Instrumentation Network', Indian Institute of Technology, Roorkee (IITR) installed about 300 state-of-the-art digital strong motion accelerographs (SMAs) covering various states in northern and northeastern India, to record strong ground motions in seismic zones -V and –IV and in some heavily populated cities in seismic zone-III (Mittal *et al.*, 2006). Average station-to-station distance is kept at ~40-50 km, to ensure triggering of at least two or more accelerographs (set at trigger level of 5 gals) for an earthquake of $M \geq 5.0$. This network was further strengthened in 2007, with the installation of another 20 digital SMAs in Delhi region. All the field stations at district level are connected through VSAT/leased line to NIC headquarters in Delhi. The data from NIC headquarters at Delhi to IIT, Roorkee flows through a 2MBPS leased line of Bharat Sanchar Nigam Limited (BSNL). The SMAs located in sub-divisions/ towns are connected through the State Wide Area Network (SWAN). All the data from the 20 SMAs in Delhi region is transmitted to IIT, Roorkee through the Mahanagar Telephone Nagar Limited (MTNL) network. Currently, about 220 accelerograph stations can be accessed remotely from IIT, Roorkee. The network has so far generated about 500 time histories for about 170 earthquakes in a span of four years. (Ashok Kumar, *et al.*, 2012). A few other institutions, viz., Central Building Research Institute (CBRI), Roorkee, IMD, etc. are also engaged in operating SMAs for addressing region specific issues/ as per the mandate. These data sets are of utmost importance in deriving attenuation characteristics of the medium, estimation of ground motions from future large earthquakes and structural response related studies, which have tremendous application in engineering design of important structures.

Seismic Hazard and Microzonation Studies

The current major thrust in Seismology is towards application of existing knowledge/use of available data to significantly reduce the economic losses and human misery during future earthquakes. 'Seismic microzonation' has emerged as a major tool towards our efforts for preparedness and mitigation of losses due to earthquakes. 'Seismic microzonation' is a process of classifying a region into zones of relatively similar exposure to various earthquake-related effects and has emerged as a major tool towards providing user-friendly, GIS-based and site-specific hazard and risk related information products to enable appropriate planning of pre- and post-disaster management strategies. The exercise is a multidisciplinary task involving collection and analysis of a variety of seismological, geological, geophysical, geotechnical, geomorphological and other data sets. These data sets, which are prepared in the form of maps, include surface geology, seismotectonics, site amplifications, bedrock depths, soil profile, ground water depth, geomorphology, shallow shear-wave velocity structure and various other geotechnical attributes. The approach involves four important components relating to (a) Seismic hazard assessment (b) Evaluation of ground motion characteristics (c) Estimation of ground motion modifications and (d) Estimation of secondary effects of ground motions, such as liquefaction potential, etc. Following this approach, seismic hazard and risk related maps are prepared for critical areas on different scales, depending upon their utilization for various applications. Some of the applications include, land use planning, urban development, disaster mitigation & management, design & construction agencies, defense installations, heavy industries, public utilities & services and risk assessment of critical structures, etc. The Earthquake Risk Evaluation Centre (EREC) set up earlier in IMD had the mandate to generate and disseminate user-friendly GIS-based and site-specific hazard and risk related information products to enable appropriate planning of pre- and post-disaster management strategies. The Centre had completed microzonation of Delhi region on 1:50,000 scale (Fig. 4) and played a key role in various studies relating to the seismic microzonation of other cities, such as, Jabalpur and Guwahati. The Center is currently in the process of finalizing the seismic microzonation of NCT, Delhi on 1:10,000 scale.

Seismological Data Processing and Archival

The earthquake waveform data received from all the field stations is compiled, processed, analyzed and archived systematically at the National Center for Seismology (NCS), IMD, New Delhi and the Indian National Center for Ocean Information Services (INCOIS), Hyderabad, on a regular basis, as per the details given below:

1. Data Processing and Location Procedures

Earthquake location is a nonlinear problem and there is no full-proof method to locate an earthquake 'uniquely'. For almost a century, during the analog era, readings taken from paper seismograms of various seismological stations were used for estimation of earthquake source parameters. Till about 1970's, triangulation method was used for estimating the earthquake source parameters manually making use of spherical globe. With the advent of digital recording and advances in telemetry, there has been a sea change in earthquake data processing, data archival and information dissemination mechanisms.

Since late seventies, a computer program, called Hypo-71, (Lee *et al.*, 1972) was extensively used for locating local earthquakes, using arrival times of recorded seismic phases at several stations, accurate station coordinates and a reasonable crustal velocity model. The program was based on flat-earth ray tracing through constant-velocity layers using a stepwise statistical regression procedure. This computer program became the basis for the development of various modified versions of location programs in offline mode, such as, Hypoinverse2000, Hypocentre, Hypoellipse, Hyposat, hypoDD, ISCLoc, etc. Concurrently, several seismological application software were developed by research and academic groups across the globe. These include, PITSA, SEISGRAM, SEISAN, SAC, Seismic Handler, etc. A brief description on the methods / approaches of estimation of earthquake source parameters, features of various application software and their utility, etc. is given by Bhattacharya and Dattatrayam (2000).

The Great Sumatra earthquake (M:9.3) of 2004 reiterated the urgent need for establishing a real time seismic monitoring network in the country. As discussed in the preceding paragraphs, a state-of-the-art real time seismic monitoring network (RTSMN) system, with auto-location capability, was set up by the Ministry of Earth Sciences/India Meteorological Department, as part of the early tsunami warning system. The RTSMN system employs auto-location software called, 'Response Hydra', designed and developed by USGS/NEIC. It is currently used for detection, processing and reporting of world-wide

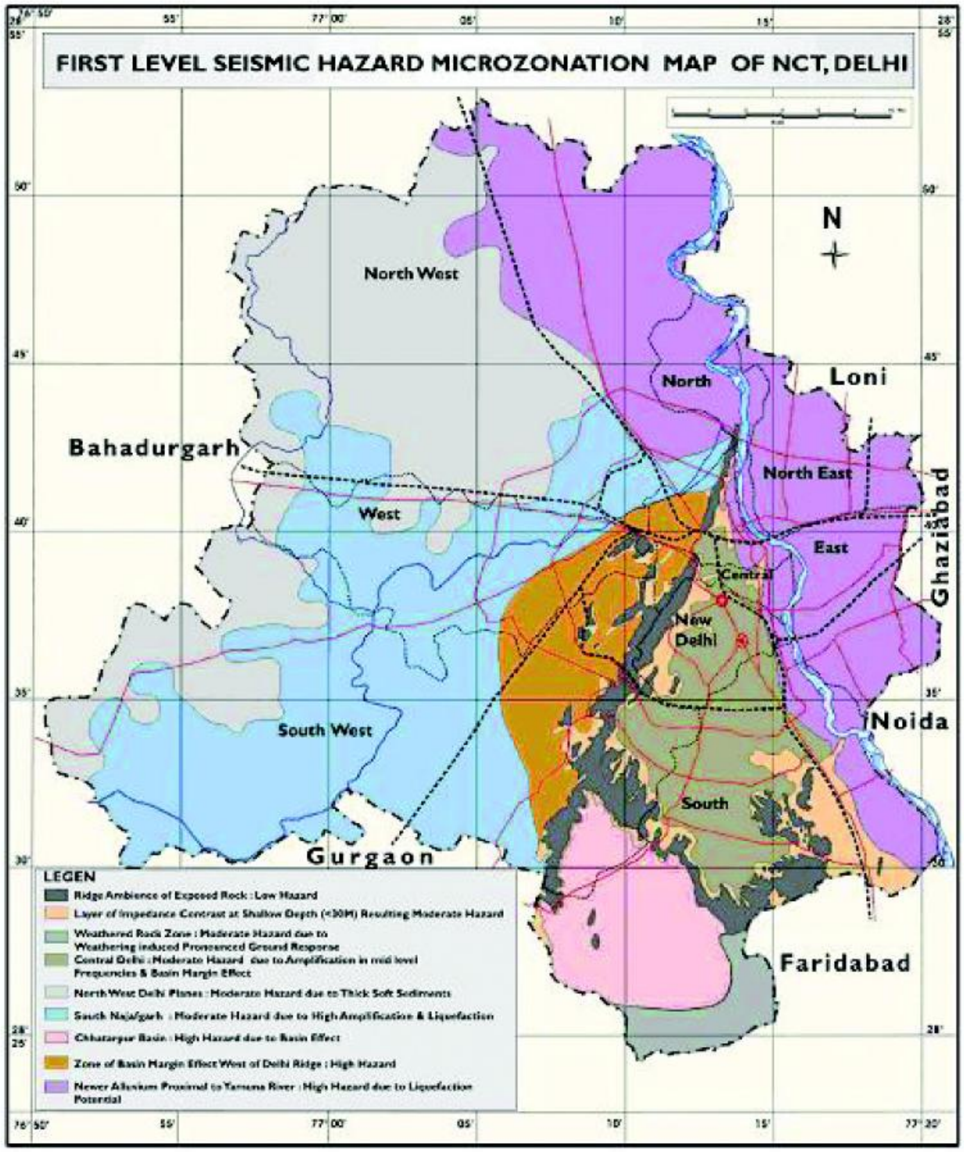

Fig. 4: Seismic microzonation map of NCT, Delhi on 1:50,000 scale

earthquakes by the National Earthquake Information Center, Golden, Colorado. 'Response Hydra' acquires real-time seismic data from SeedLink Server utility and/or NaqServer (Nanometrics) utilities. Real time data processing is performed by Earthworm-based protocols. 'Response Hydra' provides the analyst the ability to process trace data for picks, associate picks into origins, determine initial rough locations and insert all data into Oracle Hydra database for further processing. 'Response Hydra' communicates with 'Athena Publisher' software for dissemination of earthquake source parameters through various modes of communication, including IMD's website. The real time products of earthquake locations made by the RTSMN system may be accessed through IMD's website (www.imd.gov.in/'Unscrutinized earthquake events'). Dattatrayam *et al.* (2009) gave a detailed description of the features of the RTSMN system.

The real time seismic monitoring network recently established by IMD in northeast India employs SeisComp3 software for auto-location of the earthquake events. SeisComp3 is one of the most widely distributed free-ware software packages, designed as a high standard fully automatic data acquisition and (near-) real-time data processing tool including quality control, event detection and location as well as dissemination of event alerts. SeisComP3 (or third-generation SeisComP) was released in 2008 by the GEOFON group at GFZ Potsdam in Germany. Its data transmission protocol 'SeedLink', became a de-facto world standard. SeedLink is a TCP/IP based real-time data acquisition protocol and client-server software that implements this protocol. SeedLink uses a plug-in concept to import waveform data from all established formats and sources. It is the most common protocol to exchange waveform data world-wide and is supported by all main data centres, e.g. IRIS, GEOFON and ORFEUS.

All the location programs referred above employ velocity models developed separately for local, regional and teleseismic events. The *J-B* tables, published by Jeffrey and Bullen in 1940, had been in use as standard earth model till late 1980's, which was later revised with more data and computer power and called as '*iasp91'* model. The *iasp91* model was developed by Kennett and Engdahl (1991) as part of an effort of the sub-commission on 'Earthquake Algorithms' of the International Association of Seismology and the Physics of the Earth's Interior (IASPEI) to generate new global travel time tables for seismic phases. The most significant differences between the '*iasp91'* and the older J-B travel-time model are for the upper mantle and core phases. Subsequently, Kennett *et.al.,* (1995) produced another model called, '*ak135'*, which gives a significantly better fit to a broad range of phases than the '*iasp91'*. The differences in velocities between '*ak135'* and '*iasp91'* models are generally quite small except at the boundary of the inner core, where reduced velocity gradients are needed to achieve satisfactory performance for *PKP* differential time data. The '*ak135'* is now considered the best model for global earthquake locations. Presently, IMD employs 'local velocity structure models', where available, for locating local events and '*iasp91'* model for locating regional (1,000–2,000 km) and teleseismic events (>2000 km), using *Hypocenter* program, which is integrated with SEISAN software for locating local, regional and teleseismic events. While the 'Response Hydra' autolocation software of RTSMN system uses '*ak135'* velocity model, the S*eisComp3* software of northeast telemetry system employs '*iasp91'* velocity model.

2. Earthquake Data Products

IMD is the custodian of all earthquake related data sets generated through operation of seismological observatories for over more than a century. Making use of the raw analog/digital waveforms produced by the network observatories, different types of earthquake data products are generated and archived for various applications, as detailed below:

(a) Preliminary Earthquake Report (PER)

It is the first-hand information report generated in operational mode immediately after the occurrence of an earthquake (events of significance in India and the larger ones away from India) for dissemination to all concerned user agencies. PER consists of 'preliminary' information on origin time, latitude and longitude of the epicenter, focal depth and magnitude of an earthquake. The information is disseminated to various state and central government agencies dealing with relief and rehabilitation measures, disaster management, civil/defense authorities, electronic and print media, as per standard list through various modes of communication. The information is also posted on IMD's website (www.imd.gov.in). The earthquake source parameters reported in PER are subsequently refined by incorporating all available data from the network stations to form part of the final monthly seismological bulletins.

(b) Monthly Seismological Bulletin (MSB)

Each seismological station of the network prepares and sends a monthly listing of various seismic phases recorded in the daily seismograms, to Seismology Division, IMD HQ office at New Delhi in a standard format. Based on these and using appropriate velocity models for local, regional and teleseismic events, the earthquake source parameters are refined and published as 'Monthly Seismological Bulletins' (MSB). The MSBs contain refined locations of all significant earthquakes in and around the country including the phase data, rms errors, etc. in standard Nordic format. The MSBs are sent to the International Seismological Center (ISC), UK, on a regular basis and as per fixed schedule, for incorporation in the ISC's Seismological Bulletins, which contain data of all global stations (www.isc.ac.uk). IMD is a permanent member of the International Seismological Centre (ISC), UK since its inception and data from Indian stations is incorporated in all the seismological bulletins of ISC, which are one of the world's most widely referred publications on global earthquakes. The other reliable and widely referred source of global earthquakes for the modern instrumental era is the one compiled by US Geological Survey (USGS). While the ISC bulletins have a lag time of about one-and-a-half year, the USGS and other seismological centers are more timely but utilize fewer stations' data and report fewer events than does the ISC. In recognition of the efforts made by India in improving the earthquake monitoring capabilities in the recent past, IMD nominee - the first author has been elected as one of the members of the Executive Committee (EC) of ISC in the year 2011 for a period of four years. The EC is charged with the responsibility of evaluating the activities of the ISC on a regular basis towards suggesting improvements in the preparation and exchange of seismological bulletin data.

(c) Earthquake Catalogues

The earthquake catalogue contains information on origin time/date, latitude and longitude of epicenter, focal depth, magnitude, region, etc. of all earthquakes located in a region over a given time period, in a standard format (Nordic). The basic data input for comprehensive seismic hazard assessment of any given region is a catalogue of past earthquakes, which is uniform and complete both in space and time and extends over sufficiently large time period. For the Indian region, the earthquake catalogues cover a total time span of about 200 years. The first catalogue of earthquakes occurring in India and neighborhood from the earliest times to 1869 was prepared by T.Oldham, a former Director General of Geological Survey of India. The catalogue served as a good reference for the earthquakes of historical times. Similar attempts were also made by Montesses de Ballore, Robert Mallet, West, John Milne, Banerji, *et al.* to produce such earthquake catalogues. A very comprehensive list of global earthquakes, covering the early instrumental era, was compiled by Gutenberg & Richter (1954) for the period 1904-1952, which was later extended to 1965 by Rothe (1969). The primary data source for this catalogue was the ISS (International Seismological Summary) bulletins, which were available for the period 1918 to 1963. Tandon & Srivastava (1974), carefully examined and reassessed the magnitudes and locations of earthquakes included in the earlier catalogues and compiled a list of Indian earthquakes with $Ms \geq 5.0$ for the period up to 1971. This catalogue formed the basis for the computerized earthquake catalogue (database) maintained and updated periodically by IMD. This catalogue, which is made available on IMD's website, contains information on earthquakes occurring in and around the Indian region covering the geographical area bounded by 0^o N to 40^o N Latitude & 60^o E to 100^o E Longitude.

The completeness of earthquake catalogues in space and time for any given region is often a matter of discussion and debate. Compilation of earthquake catalogues based on instrumental data dates back to the very end of the nineteenth century. Accordingly, the pre-twentieth century (pre-1900 period) is termed as 'pre-instrumental era' and the period 1900-1963 as 'Early instrumental era'. The year 1964 marks a very important land mark in the history of seismic instrumentation, when the WWSSN stations started functioning globally. The period 1964-onwards, is thus termed as 'modern instrumental era'. The 'digital era' in IMD started in the year 1996. The earthquake detection capabilities and the location accuracies increased progressively with the advancements in scientific instrumentation. The compilation of earthquake catalogues for the pre-instrumental era depended mostly on information collected through reports, intensity and the effects of ground motion on people, land or structures. Such assessments are often qualitative in nature and are prone to serious errors, sometimes. A histogram depicting the cumulative number of earthquakes versus magnitude, is shown in Fig. 5 for the IMD catalogue. From an

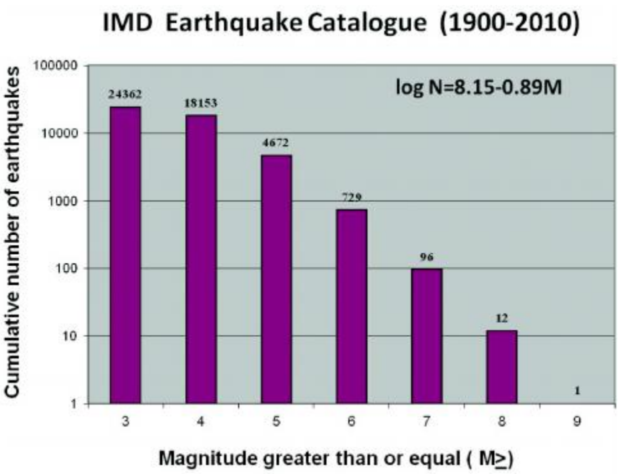

Fig. 5: Histogram showing the cumulative number of earthquakes vs. magnitude from IMD database for the period 1900-2010

analysis of all earthquakes of magnitude 4.5 and above (with magnitude interval of 0.5) for the period 1900 to 2010, the a- and b-values work out to be 8.15 and 0.89 respectively in Gutenberg-Richter recurrence relation. A seismicity map of India and neighborhood for the period upto June, 2011 for all earthquakes of magnitudes 5.0 and above is also shown in Fig. 6.

Under an Indo-Russian collaborative project, a new earthquake catalogue for the Northwest India was prepared from IMD data archives. Using this catalog and the GeoProcessor software / Geographic Information System (GIS), the spatial and seismotectonic characteristics of the region were studied (Gitis *et al.*, 2008). IMD catalogue has been scrutinized for identification of errors and corrections and then compared with other global catalogues for events of magnitude 6.0 and above occurring in India and neighborhood. Using various approaches and the “MagUnif” software, magnitude completeness over different time periods and space domains has also been examined.

(d) Analog Seismograms and Vector Digitization

IMD has in its’ archives a huge number of analog seismograms accumulated through the beginning of twentieth century. The number of seismic stations increased gradually over a period of time and regular charts for many stations became available since 1965 onwards. The analog seismograms contain 24-hour continuous record of short period/long period ground motion time histories, made on photographic /heat-sensitive/smoke recording papers, at a seismological observatory. Because of the uniqueness of traditional paper seismograms and lacking opportunities for producing high-quality copies at low cost, original analog waveform data was cumbersome to handle/ store and sometimes prone to damage or even loss with time. While most of the available seismograms in IMD’s archives are in good condition, few are fading due to aging effects. Seismograms of significant/large magnitude historical earthquakes have, of late, become very important in seismological research due to their rarity. It is, therefore necessary to archive them properly in a suitable electronic media for posterity. Also, Seismologists normally prefer to work with digital seismograms that can be processed and analyzed easily and quickly. It is, therefore, necessary to extract the information by vector digitizing the analog seismograms. Modern technologies now offer unique opportunities for cataloguing and efficiently reproducing the digital versions of scientific records.

IMD has taken up a project on “Archival and digitization of seismic analog charts” to preserve the historical seismograms in electronic form. Under this project, state-of-the-art infrastructure facilities have been established at the Seismological Observatory, Kamla Nehru Ridge, Delhi. To achieve high quality of raster scanning, A0 size flat bed scanners along with high-end servers, desktops and high capacity storage systems have been installed. Images, thus produced, have usually a resolution of 600/800 dpi with 256 gray levels. The standard format used to store these images is ‘plain TIFF’. This choice requires a storage capacity of approximately 150-200 MB for analog charts measuring 90×30/60x30/48x23 cm. One of the most widely used application software available in public domain for digitization of seismograms is called ‘Teseo’, which was developed by Instituto Nazionale di Geofisica e Vulcanologia (INGV), Italy. ‘Teseo’ is a open source license software available on the Sismos site at http://sismos.ingv.it. ‘Teseo’ has been customized in IMD

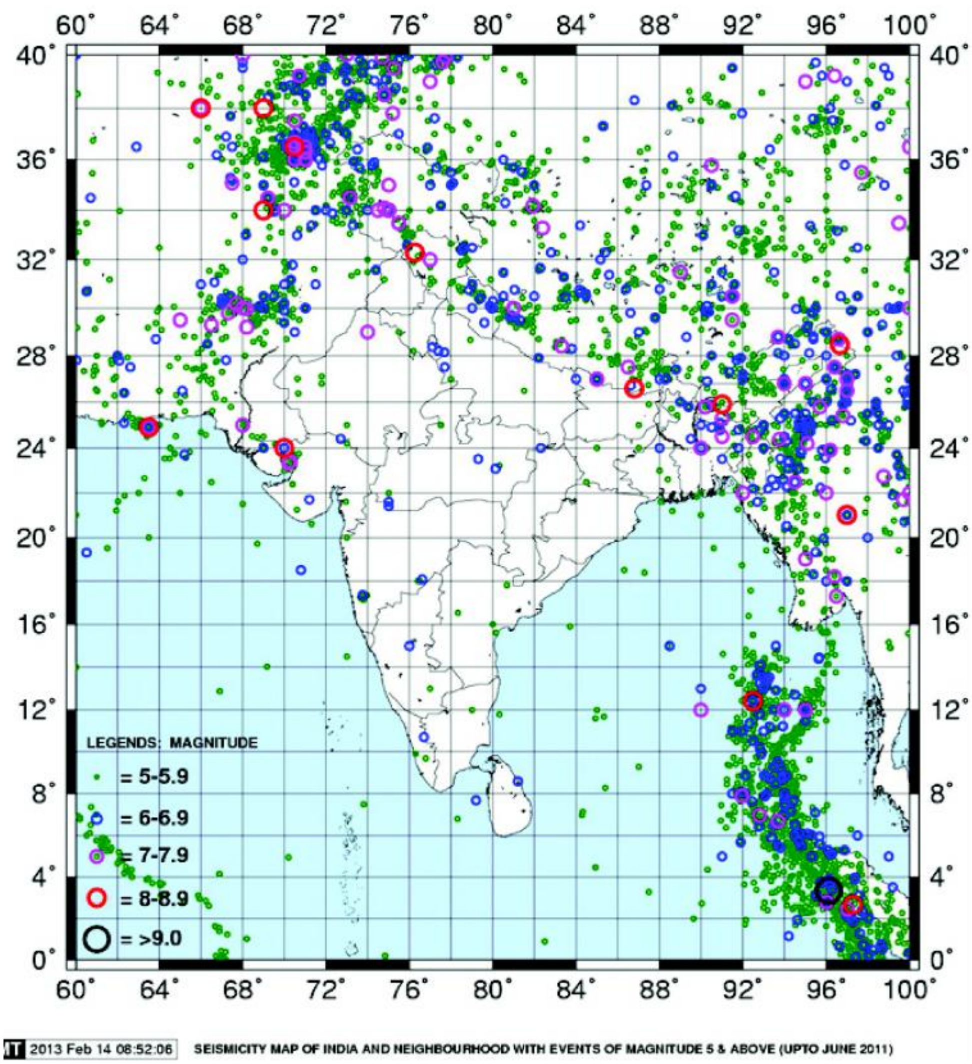

Fig. 6: Seismicity map of India (M≥5.0) and neighborhood for the period upto June, 2011

to best fit the requirements. A web browser was developed in-house for creating user friendly environment and smooth processing of image processing and upload/retrieval of scans/vector files from storage system. A SQL data base was created to handle the data from data base though front end servers. Following the procedure outlined in Pintore *et al*., (2005), the event portion of charts are vector digitized and output waveform files generated in ASCII and SAC formats. A sample output of a digitized seismogram of the Anjar, Gujarat earthquake of 21.7.1956 (M:7.1) recorded at Pune is shown in Fig. 7. The techniques and approach followed for raster scanning of seismograms, vector digitization of earthquake events contained in the seismograms using Teseo inbuilt GIMP were found to be successful in handling various types of analog charts available with IMD. A total of about one lakh analog charts have been raster scanned and about 5,000 earthquake events have been digitized, so far, under the project.

(e) Digital Waveform Data

Continuous digital waveform data generated by digital seismograph systems is extensively used in modern seismological research, particularly for studying the source, site and path characteristics of the media. IMD maintains the digital waveform data generated by all its' digital stations in a systematic manner. The continuous raw waveform data in respect of the Real Time Seismic Monitoring Network

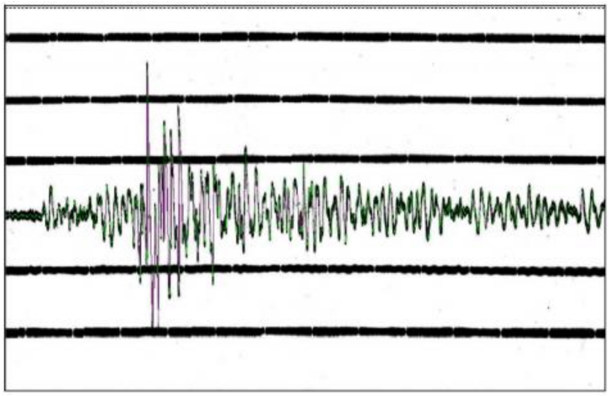

Fig. 7: Digitized seismogram superimposed on the original analog record of Anjar, Gujarat earthquake (M:7.0) of 21.7.1956 recorded at Shillong

(RTSMN) is generated in NP (Nanometrics Protocol) format and subsequently converted into hourly miniSEED format for archival in DLT/ USB hard disks. For autolocation of the earthquake events by the Response Hydra software, the continuous data of RTSMN stations is made available in ring buffer in EarthWorm (EW) format along with data from other regional/ local networks (WIHG, NGRI, etc.) and global IRIS network. The earthquake source parameters estimated by the Response Hydra software are finally stored in MySQL data base of Athena server along with phase picks and CMT/ MT solutions calculated for large magnitude ($M \geq 5.5$) events. Provision exists for retrieving data of any selected duration of an event in SEISAN format.

While the continuous raw waveform data in respect of the standalone GSN standard stations (equipped with Quanterra make equipment) is stored in miniSEED format, the same is stored in Passcal format for Reftek make equipment installed in the VSAT based Delhi telemetry network and Northeast telemetry network. The desired waveform data of an event can be retrieved in SEISAN format. For the autolocation of earthquake events by the SeisComp3 software in the Northeast telemetry system, the continuous data is converted into SEED format and stored in ring buffer. The same is also made available in separate database for archival purposes. The complete instrument response of field stations are stored in the dataless SEED format. Provision is also available for exporting the hypocentral parameters along with phase picks of auto located events along with event waveform into the SEISAN database. All the continuous data sets are stored in different USB hard disks/CDs and are used for manual retrieval of the desired waveform data of individual stations in mSEED/SEISAN format. Continuous waveform data of a few seismological observatories operated by various agencies under MoES sponsored programs is also available in CDs/tapes in different formats. In addition to the continuous waveform data sets referred above, waveforms pertaining to significant earthquake events located by the national seismological network are also available in SEISAN format, which may be retrieved along with corresponding hypo-central parameters, phase data and other details from the SEISAN database.

(f) Future Plans for Data Transmission and Storage

Towards improving and standardizing the existing seismic and GPS data transmission and archival facilities in the country, Ministry of Earth Sciences is implementing a major multi-institutional program with IMD and INCOIS as the two lead organizations for permanent data storage and supply. The objective of the project is to facilitate (i) systematic collection and standardization of high quality, real time data from various seismic and GPS stations/networks being operated by IMD and other agencies under various MoES programs at two different geographically located centers (IMD, New Delhi and INCOIS, Hyderabad) for real time monitoring of earthquake activity and (ii) develop infrastructure for reliable exchange and permanent archival of data in homogeneous and standard formats viz., SEED/Mini SEED (for seismic data) and RTCM/ RINEX (for GPS data) format, for use by research community.

The first component of the project envisages establishment of VSAT communication facilities at 170 (130 seismic + 40 GPS) field stations with dedicated VSAT Hub at INCOIS and IMD and interconnecting all the regional centers located at NEIST, Jorhat; NGRI, Hyderabad; ISR, Gandhinagar and WIHG, Dehradun with data centers at INCOIS, Hyderabad and IMD, New Delhi through terrestrial /

leased line facilities. The second component of the project deals with setting-up of state-of-the-art infrastructure facilities to implement data acquisition modules, SEEDLINK server for real time data exchange, data storage, networking and integration of data access infrastructure with regional centers, offline data exchange and information management. Data recovery in case of system failure is ensured not only by providing sufficient redundancy in the infrastructure but also through the mode of operation. Around half the sensors send the data to the VSAT Hub at IMD and the other half to VSAT Hub at INCOIS, making use of two different satellites. These two hubs are, in turn, connected by two numbers of 2-Mbps leased line circuits (one line for redundancy purpose) for online replication of continuous data received at each VSAT Hub. The continuous data from the regional centers mentioned above will be sent to both IMD and INCOIS through terrestrial links. Installation of VSAT Hub at INCOIS and IMD and interlinking of regional centers through high speed leased line connectivity have been completed and currently, installation of VSAT equipments at field stations under Phase-1 (60 seismic stations) of Component 1 of the project is in progress.

Seismological Data Supply and Sharing

IMD supplies earthquake data/information and seismicity reports of specific regions to various user agencies including, insurance companies, industrial units, power houses, river valley projects etc. Seismological data and earthquake related information is also supplied to various user agencies dealing with relief and rehabilitation measures, earthquake disaster mitigation and management related matters, seismic zoning, etc. Earthquake data is supplied, on request, to various scientific, academic and R&D institutions in India and abroad for research purposes. Consultancy services are also provided to various state and central government agencies on earthquake related matters. The procedures and guidelines followed for the supply/sharing of earthquake data with various users are provided on IMD’s website and are briefly given below:

(a) A certificate on earthquake occurrence, for the sake of settling damage claims, is issued to the concerned insurance company, on payment basis. For obtaining such a certificate, the insurance company should make a formal request indicating the name of the claimant and his/her full address, Policy No., Claim No., exact date and approximate time of occurrence of earthquake and place of damage due to earthquake, etc.

(b) Seismicity reports/earthquake data, in respect of different places/sites for setting up various types of projects, such as hydroelectric, thermal power, refineries, high rise buildings, railway bridges, community centers and other structures of importance, is supplied to the concerned authorities of central/state governments, public undertakings, multinational & private companies, disaster managements agencies etc, on payment basis.

(c) Earthquake data/copies of seismograms are supplied, free of cost, to educational/research institutions for promoting research in seismology and allied fields.

(d) Digital waveform data of earthquakes is also supplied, free of cost, to various academic and research institutions (national/international) after proper scrutiny of the request & approval of competent authority, following the guidelines recommended by MoES/GoI for the purpose.

(e) Continuous seismic waveform data of three IMD stations located at Port Blair, Minicoy and Shillong is available freely to the entire global community on real time basis, through IRIS SeedLink Server, to facilitate monitoring of large magnitude earthquakes of tsunamigenic potential in the region.

(f) For obtaining earthquake data/reports from IMD as above, the applicant/agency should make a formal request to Head, National Center for Seismology, India Meteorological Department, Lodi Road, New Delhi 110003, providing all the details pertaining to the data request.

(g) The earthquake data/reports are supplied by

IMD only after proper scrutiny and assessment of actual requirement of data and seeking approval of competent authority of the department.

(h) A certificate of undertaking in a prescribed format is required to be furnished by the competent authority of the concerned office / organization on whose behalf the request for the data is being made, in all the cases referred above.

Conclusions

The importance of systematic generation and archival of high resolution seismological data sets towards carrying out R&D related studies in Seismology and allied fields for better understanding of earthquake generation processes and disaster mitigation related measures is very well recognized. Although the instrumental earthquake data available for the country as a whole spans a little over a century, it may not be treated as uniform in space, time and minimum magnitude of detection threshold, as is the case with any other country. This may be attributed primarily to the inhomogeneous nature of network density (both in space and time) and the seismic instrumentation (and hence the data types and formats) employed over different periods of time. The paper has very lucidly brought out various methodologies and standards being followed for seismological data generation and tools for processing and archival of the data covering the entire period of early-instrumental era to modern digital era. The policy guidelines being adopted by the India Meteorological Department, the nodal agency for earthquake data generation, sharing and supply, have also been highlighted.

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References

Kumar Ashok, Mittal Himanshu, Sachdeva Rajiv and Kumar Arjun (2012) Indian Strong Motion Instrumentation Network *Seismological Research Letters* **83** doi:10.1785/gssrl.83.1.59

Bansal B K, Singh S K, Dharmaraju R, Pacheco J F, Ordaz M, Dattatrayam R S and G Suresh (2009) Source study of two small earthquakes of Delhi, India and estimation of ground motion from future moderate local events *Journal of Seismology* **13** 89-105

Bhattacharya S N and Dattatrayam R S (2000) Recent advances in seismic instrumentation and data interpretation in India *Current Science* **79** 1347-1358

Bhattacharya S N and Dattatrayam R S (2003) Some characteristics of recent earthquake sequences in Peninsular India. Published as a special volume on Seismicity of Central India in the *Journal of Gondwana Geological Magazine* **5** 67-85

Dube R K, Bhayana J C and Chaudhury H M (1979) Crustal structure of the peninsular India *Pure and Appied Geophyics* **109** 1718-1727

Dattatrayam R S and Kamble V P (1994) Temporal clustering of earthquakes – A fractal approach *Current Science* **67** 107-109

Dattatrayam R S (2006) Earthquake monitoring in India – Status and future plans, 'The Great Indian Ocean Tsunami of 2004 – An overview of a National Disaster', *National Institute of Advanced Studies* Bangalore 58-66

Dattatrayam R S, Bhatnagar A K, Suresh G, Baidya P R and Gautam J L (2009) Real time earthquake monitoring for early warning of Tsunamis in Indian Ocean region. *Mausam,* Diamond Jubilee Volume, 253-264

Gitis V, Yurkov E, Arora B, Chabak S, Kumar N and Baidya P R (2008) Analysis of seismicity in North India *Russian*

Journal of Earth Sciences **10** ES5002, doi: 10.2205/2008ES000303

Gutenberg B and Richter C F (1954) Seismicity of the Earth and Associated Phenomena, 310, Princeton University Press, New Jersey

Havskov J and Ottemoller L (2000) SEISAN earthquake analysis software *Seismological Research Letters* **70** 532-534

Jeffreys H and Bullen K E (1940) Seismological Tables. London: British Association for the Advancement of Science

Kamble V P, Verma R K and Chaudhury H M (1974) Crustal structure in the Mandi section – Himachal Himalayas *Indian J Met Geophys* **25** 229-233

Kennett B L N and Engdahl E R (1991) Travel times for global earthquake location and phase identification *Geophysical Journal International* **122** 429-465

Kennett B L N, Engdahl E R and Buland R (1995) Constraints on seismic velocities in the Earth from travel times *Geophysical Journal International* **122** 108-124

Lee W H K, Bennet R E and Meaghu K L (1972) A method of estimating magnitude of local earthquakes from signal duration *U.S. Geological Survey Open File Report*

Mandal Prantik and Jose Pujol (2006) Seismic imaging of aftershock zone of 2001 Mw:7.7 Bhuj earthquake, India *Geophysical Research Letters* **33** (L05309) 1-4

Mittal H, Gupta S, Srivastava A, Dubey R N and Kumar A (2006) National strong motion instrumentation project: An overview. In *13th Symposium on Earthquake Engineering, Indian Institute of Technology, Roorkee, Dec 18-20, 2006*, 107-115, New Delhi: Elite publishing.

Mittal V K, Bhattacharya S N and Srivastava H N (1990) Crustal investigations and microearthquake survey along Hirapur, Jabalpur, Mandla profile using deep seismic sounding explosion data *Mausam* **41** 59-64

Nath S K, Sengupta P, Srivastav S K, Bhattacharya S N, Dattatrayam R S, Prakash Rajesh and Gupta H V (2003) Estimation of S-wave site response in and around Delhi region from weak motion data *Proceedings of Indian Academy of Sciences (Earth & Planetary Sciences)* **112** 441-462

Stefano Pintore, Quintiliani Matteo and Franceschi Diego (2005) Teseo: a vectoriser of historical seismograms *Computer & Geosciences* **31** 1277-1285

Prakash Rajesh, Singh R K, Shukla A K, Singh D, Rana B S, Jaryal J S, Bhatnagar A K and Bali S (2011) Intensity and isoseismal map of 25th November 2007 Delhi earthquake, *Mausam* **62** 417-424

Rothe J P (1969) Seismicity of the Earth 1953-65, UNESCO, Paris

Nayak Shailesh and Srinivasa Kumar T (2008) The first Tsunami Early Warning Centre in the Indian Ocean, Risk Wise, Tudor Rose Publications, 175-177

Shukla A K, Rajesh Prakash, R K Singh, Mishra P S and Bhatnagar A K (2007) Fault plane solution of some recent earthquakes in Delhi & its environs and seismotectonic implications *Current Science* **93** 1848-1853

Shukla A K, Rajesh Prakash, Pandey A P, Singh R K, Mondal H S, Singh D and Baidya P R, (2011) Overview of Seismic Hazard & Mitigation in North East India Region, *IMD Report*, 94

Shukla H P, Dattatrayam R S and Bhatnagar A K (2012) Seismicity of the region around dams in Northwest India, *Mausam*, **63** 261-274 (550.348.098.64)

Singh S K, Dattatrayam R S, Shapiro N M, Mandal P, Pacheco J F and Midha R K (1999a) Crustal and Upper Mantle Structure of Peninsular India and Source Parameters of the 21 May, 1997, Jabalpur Earthquake (Mw=5.8): Results from a New Regional Broadband Network *Bulletin of Seismological Society of America* **89** 1631-1641

Singh S K, Ordaz M, Dattatrayam R S and Gupta H K (1999b) A spectral analysis of the 21 May 1997, Jabalpur, India, Earthquake (Mw=5.8) and estimation of Ground Motion from future earthquakes in the Indian shield region *Bulletin of Seismological Society of America* **89** 1620-1630

Singh S K, Bansal B K, Bhattacharya S N, Pacheco J, Dattatrayam R S, Ordaz M, Suresh G, Kamal and Hough S E (2003) Estimation of ground motion for Bhuj (26 January 2001; Mw 7.6) and for future earthquakes in India *Bulletin of the Seismological Society of America* **93** 353-370

Singh S K, Pacheco J F, Bansal B K, Perez-Campos X, Dattatrayam R S and Suresh G (2004a) A Source Study of the Bhuj, India, Earthquake of 26 January 2001 (Mw 7.6) *Bulletin of Seismological Society of America* **94** 1195-1206

Singh S K, Garcia D, Pacheco J F, Valenzuela R, Bansal B K and Dattatrayam R S (2004b) Q of the Indian Shield *Bulletin of Seismological Society of America* **94** 1564-1570

Singh S K, Dattatrayam R S, Suresh G, Iglesias A, Bansal B K, Perez Xyoli, Ordaz M, Gupta H K, Baidya P R, Gautam J L, Kumar G and Singh R K (2005) The Great Sumatra Earthquake of 2004: Regional Broadband Seismograms from India *Seismological Research letters* **76** 684-692

Singh S K, Iglesias A, Dattatrayam R S, Bansal B K, Rai S S, Perez-Campos X, Suresh G, Baidya P R and Gautam J L (2006) Muzaffarabad earthquake of 8 October 2005 (Mw 7.6): A preliminary report on source characteristics and recorded ground motions *Current Science* **91** 689-695

Singh S K, Kumar A, Suresh G, Ordaz M, Pacheco J F, Sharma M L, Bansal B K, Dattatrayam R S and Reinoso E (2010) Delhi earthquake of November 25, 2007 (Mw:4.1): implications for seismic hazard *Current Science* **99** 939-947

Srivastava H N, Dubey R K and Verma G S (1983) Crustal studies along Indore-Khandwa section of Narmada basin by Deep Seismic Sounding *Mausam* **34** 267-274

Srivastava H N, Verma R K, Verma G S and Chaudhury H M (1984) Crustal studies of the Koyna region using explosion data from Deep Seismic Sounding *Tectonophysics* **110**

Srivastav S K, Bhattacharya S N, Shukla A K, Prakash Rajesh, Shukla H P, Baidya P R and Dua S C (2001) Near real time seismic monitoring system in and around National Capital Region of Delhi. Paper presented at International Conference on Seismic hazard with particular reference to Bhuj earthquake of January 26, 2001, held at New Delhi, during October 3-5, 2001

Srivastav S K, Bhattacharya S N, Gupta H V, Dattatrayam R S, Shukla A K, Baidya P R, Prakash Rajesh, Suresh G, Shukla H P, Ghose A K, Singh Hargian, Kondal J S, Gautam J L, Dua S C and Ravindran V V (2003) Recent developments in seismic monitoring and analysis capabilities in India *Geological Society of India*, Memoir No. **54** 231-251

Srivastav S K, Prakash Rajesh, R S Dattatrayam, Arora S K and Bansal B K (2005) Configuration of an optimum seismological network for India *Mausam* **56** 465-472

Tandon A N and Srivastava H N (1974) Earthquake occurrence in India, Earthquake Engineering, Jaikrishna Volume, Sarita Prakasan, Meerut.