Recent advances in seismic instrumentation and data interpretation in India

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During the later half of the twentieth century, seismic instrumentation had seen rapid growth, enabling generation of very useful data sets not only for unravelling the very important features of the earth's interior but also in understanding the complex geodynamic processes. By the middle of the twentieth century, the optomechanical seismographs in operation at seismological observatories in India were upgraded with electromagnetic seismographs. During the 1970s, these observatories were upgraded with visible seismographs. Since early 1990s, a trend has emerged to upgrade and replace the existing analogue seismographs with digital broadband seismographs to increase the dynamic range and frequency band of recording, by using the digital recorders and force balance seismometers. Time keeping has also been improved by GPS synchronization. The data acquisition systems of some of the observatories are connected to Central Receiving Station, India Meteorological Department (IMD), New Delhi, by telephone modem for near real time data reception. At present, there are 212 seismological observatories being operated in India by various R&D institutions, river valley authorities and universities. The Department of Earthquake Engineering (DEQ), University of Roorkee is operating an Indian National Strong Motion Instrumentation Network (INSMIN) and few strong motion arrays in the Himalayan region and north-east India. IMD is engaged in the manufacture of analogue seismographs since 1960s. Portable analogue recorders are being manufactured at the Central Scientific Instruments Organization (CSIO), Chandigarh, where design of digital recorders is also in progress. The digital data processing and analysis in time and frequency domains, has greatly improved the hypocentral location capability and ability to evaluate detailed source parameters.

1. Introduction

Seismic instrumentation in India started in 1898 with the installation of the first seismograph of the country at Alipore (Calcutta) by India Meteorological Department (IMD). Till 1930s, there were only four seismological observatories in operation at Calcutta, Mumbai, Kodaikanal and Agra. However, these were supplemented by the observatories at Dehra Dun, Colombo and later at Hyderabad with the co-operation of Surveyor General of India, the Superintendent of Colombo Observatory and the Director of Nizamia Observatory, respectively.

By the year 1970, IMD seismological network had grown to comprise 18 permanent observatories under the national network and 12 observatories in North India for studying seismicity around river valley projects and Delhi region. During 1963–1964, the observatories at Shillong, New Delhi, Poona and Kodaikanal were upgraded to conform to World-Wide Standardized Seismological Network (WWSSN) standards under the U.S. Geological Survey (USGS) collaboration. During 1965, Bhabha Atomic Research Centre (BARC) established a seismic array station at Gauribidanur near Bangalore. In India, at present there are 212 seismological observatories run by various central and state government organizations, research institutions and universities. The analogue seismographs are being steadily replaced by digital seismographs at many of these observatories.

The conventional approach of analysing the seismograms produced by analogue seismographs was mostly confined to identification of various phases, in an attempt to locate the hypocentral parameters. With the advent of computer-aided digital recording systems, the seismic data analysis became possible not only in time domain but also in frequency domain, so that more detailed information about earthquake source and the earth's interior can be inferred. Seismic instrumentation in India was earlier reviewed by Srivastava[1]. In the present article we shall concentrate on a brief review of conventional seismographs and recent advances in seismic instrumentation as well as some approaches to digital data analysis and interpretation.

2. Seismic instrumentation

The main objective of the seismic instrumentation is to record the ground motion arising due to natural and man-made disturbances and, in particular, to monitor the seismicity of a given region. A network of observatories equipped with seismographs is operated to record the ground displacement/velocity. Depending on the nature of application, the interstation spacing of the network may vary from few tens or hundreds of metres in mines,

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through kilometres to tens of kilometres for monitoring of seismicity towards mapping of active faults, investigations of crustal structure, study of induced seismicity, aftershock studies, etc. The regional/national networks cover a few hundreds of kilometres depending on the geographical extent of the region. It may be added that the data collected from such seismological observatories during the 20th century had greatly contributed in understanding the structure and physics of the earth's interior and geodynamic processes.

2.1 *Seismographs*

A seismograph consists of a seismometer which senses the ground motion, and a recorder to record the motion. In a vertical component seismograph, a heavy mass is made to hang through a spring from a rod fixed to the ground. With the movement of the ground, the rod as well as the recorder move, but the mass does not move initially due to its inertia and therefore the spring extends. Thus, relative to the recorder, the mass moves up or down in a vertical direction and this relative motion is recorded on the recorder. The mass continues to move up and down for some time, like a free pendulum, even after the ground ceases to move. To avoid this, a damping arrangement is made, so that it responds only to the ground movement[2,3]. Using the same principle, the horizontal component of the ground motion can also be recorded with a suitable arrangement by making the pendulum to move like a two-way swing door. In order to get a three-dimensional representation of the ground motion, it is necessary to record it in three orthogonal (perpendicular) directions, generally, in vertical (Z), north-south (N) and east-west (E) directions.

2.1.1 *Inertial pendulum seismometer*: As stated above, the ground motion causes the mass of the seismometer to undergo forced motion of a damped pendulum. The damping of a seismometer is defined by a parameter h. A pendulum is called critically damped ($h = 1$) if, (i) after moving in one direction, it comes back to the equilibrium position without crossing over to the other direction and (ii) the time T' taken to come back from extreme position to equilibrium position is half the free period of the pendulum, (i.e. period without damping). If T' is more than half the free period, the pendulum is overdamped ($h > 1$) and if the pendulum does not satisfy the condition (i), it is underdamped ($h < 1$).

The ground motion can be represented by $\Sigma_j A_j \exp(i\omega_j t)$ or, in a simpler way, $\Sigma_j A_j \sin(\omega_j t)$, where angular frequency, $\omega_j = 2\pi/T_j$ and T_j is the period. Considering one representative term of the summation, i.e. $A \sin(\omega t)$, the motion of the mass of the seismometer is given by, $B \sin(\omega t + b)$, where

$$B/A = 1/\sqrt{[\{(T/T_s)^2 - 1\}^2 + 4h^2(T/T_s)^2]}, \quad (1)$$

$$b = \arctan\{2hTT_s/(T_s^2 - T^2)\} \quad (2)$$

Here T_s is the free period of the seismometer mass, T is the period of the ground motion under consideration and h is the damping coefficient[2,4]. $B/A = I(T)$, is known as the dynamic magnification (response) of the seismometer and b is the phase change. $I(T)$ is plotted against T/T_s in Figure 1, for different values of h. It may be seen that $I(T) = 1$ when $T/T_s \ll 1$. However, $I(T)$ is nearly equal to 1 up to $T/T_s = 1$, if h is between 0.60 and 0.71. Thus, to get a flat response nearly up to the free period of the seismometer, it is kept somewhat underdamped with a value of h between 0.60 and 0.71, with most favoured value as 0.707 ($= 1/\sqrt{2}$).

2.1.2 *Optomechanical seismograph: Wood–Anderson seismograph*: In order to record small ground motions, seismographs are designed to magnify the ground motion before it is actually recorded. *Magnification* of a seismograph gives the factor by which the ground motion is magnified. We have seen earlier that with $h = 0.7$, the maximum magnification is only 1. However, we can achieve higher magnification by employing optical methods. In an optomechanical seismograph, a ray of light is made to fall on a mirror fixed to the mass of the seismometer and the reflected light is recorded at a distance on a

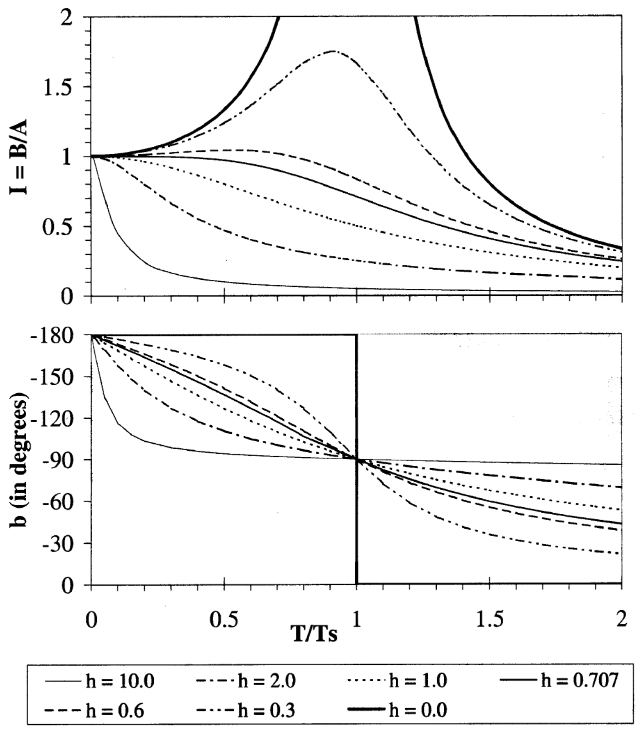

Figure 1. Dynamic magnification $I(T) = B/A$ and phase change b as a function of T/T_s for a given damping constant h; here T_s is the natural period of the seismometer and T is the period of the ground motion.

photographic paper. An example of one of the earliest seismographs of this type is Milne–Shaw seismograph, which records the horizontal component of ground motion. In this seismograph, static magnification (V_s) = 250 to 300, h = 1 and T_s = 10 to 12 s. Actual magnification of a seismograph is the product of dynamic magnification (I) and the static magnification (V_s). Another important example of this type of seismograph, which is widely in use, is *Wood–Anderson seismograph*. This seismograph also records horizontal component of the ground motion and was developed in the 1920s by two scientists, Wood and Anderson. Here the pendulum consists of a cylindrical mass (generally made of copper), which is attached to a vertical suspension wire[5,6]. During ground motion, the cylinder rotates around the axis of the wire and a mirror attached to the cylinder reflects a light beam on the photographic paper wrapped on a recorder drum. A horse-shoe magnet surrounding the copper cylinder acts as a damping (eddy current) device. For a standard Wood–Anderson seismograph, T_s = 0.8 s, h = 0.8 and V_s = 2800. However, Wood–Anderson seismographs with V_s = 1000 are also in use.

2.1.3 *Electromagnetic seismometer*: The initial part of this seismometer is the same as an inertial pendulum seismometer. In addition, here a coil is attached to the mass (M), which is kept in a magnetic field as shown in Figure 2. As the ground moves, the coil attached to the mass also moves in the magnetic field and generates a voltage across the coil terminals, which is proportional to the velocity of the mass of the seismometer. The constant of proportionality is referred to as the electrodynamic constant, G [mv/(mm/sec)] of the seismometer. The output voltage of the coil terminals gives the measure of the ground motion. An external resistance provides the required electromagnetic damping of the seismometer.

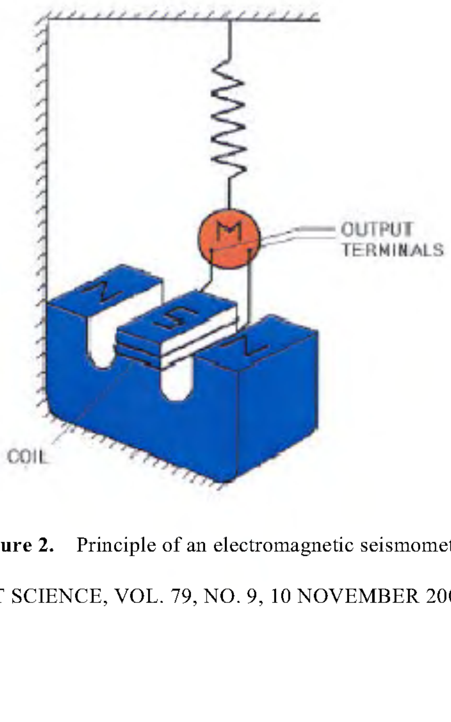

Figure 2. Principle of an electromagnetic seismometer.

2.1.4 *Electromagnetic seismograph*: Here the output of an electromagnetic seismometer is connected to a sensitive mirror galvanometer. The mirror reflects a light beam towards a photographic paper on a recorder. In an electromagnetic seismograph, the seismometer and galvanometer are connected by a combination of resistances to give proper damping to the seismometer and the galvanometer, as well as to have suitable magnification[4,7,8]. Electromagnetic seismographs offer much higher magnifications in comparison to optomechanical seismographs.

2.1.5 *Broadband seismometer*: During an earthquake, the ground vibrates mostly in the period range of 0.02 to 1000 s depending on how far the earthquake is from the recording station and how big it is. To increase the frequency range of recording, it is necessary to increase the free period of the seismometer. But increase of free period of a pendulum seismometer causes instability and nonlinearity. Today, *broadband seismometers* with electronic feedback mechanism can provide increased period without compromising stability and linearity. In a pendulum-type seismometer, relative motion between the frame and the mass produces the signal. The force on the mass due to ground motion is equal to the product of the mass of the seismometer with the sum of acceleration of the frame and the relative acceleration between the frame and mass. However, if a force is applied by the frame to the swinging mass in such a way that the relative displacement (and consequently, the relative velocity as well as acceleration) between the frame and the mass is reduced to zero, the applied force would then be a direct measure of the acceleration of the mass. This can be done in principle by detecting the relative displacement between the frame and the mass, generating a current signal corresponding to it and feeding the current back to the coil moving with the mass and the magnet fixed on the frame. In such a system, the mass–spring arrangement becomes much less critical so far as the response characteristic is concerned. However, the feedback amplifier has to be of wide bandwidth and high dc gain. By making the gain of the feedback loop dependent on frequency, a very wide variety of response characteristics can be obtained. For example, the STS2 seismometer from Streckeisen SG, has only a 300 g mass. It uses a capacitive displacement transducer, and a feedback coil with a force constant of 50 Newton per Ampere, which is fed from the displacement transducer via a network. The response of the seismometer is the same as that of a pendulum seismometer with a free period of 120 s and electrodynamic constant (G) of 1500 mV/(mm/sec).

2.1.6 *Visible recording seismograph or modern analogue seismograph*: The conventional photographic recording is getting obsolete because of high recurring costs involved in photographic charts. Further, it is sometimes necessary to observe the recording continuously. In a visible seismograph, the output from the electromagnetic seismometer is fed to an amplifier; the amplified voltage is fed to a galvanometer attached to a pen for recording on a paper. Visible recording is usually made through (a) ink recording on a plain paper, or (b) scratching on a smoked paper/heat sensitive paper. In the heat sensitive recording mode, the pen remains hot and it removes the white chemical cover of the recording paper by scratching, to bring out the black background.

Figure 3 explains the steps in the measurement of the ground velocity on a recorder. From Figure 3, it may be seen that the ratio of trace amplitude to the ground velocity, may be expressed as,

$$[BGSK \sin(\omega t + b)]/[A \sin(\omega t)] = IGSK [\sin(\omega t + b)/\sin(\omega t)], \quad (3)$$

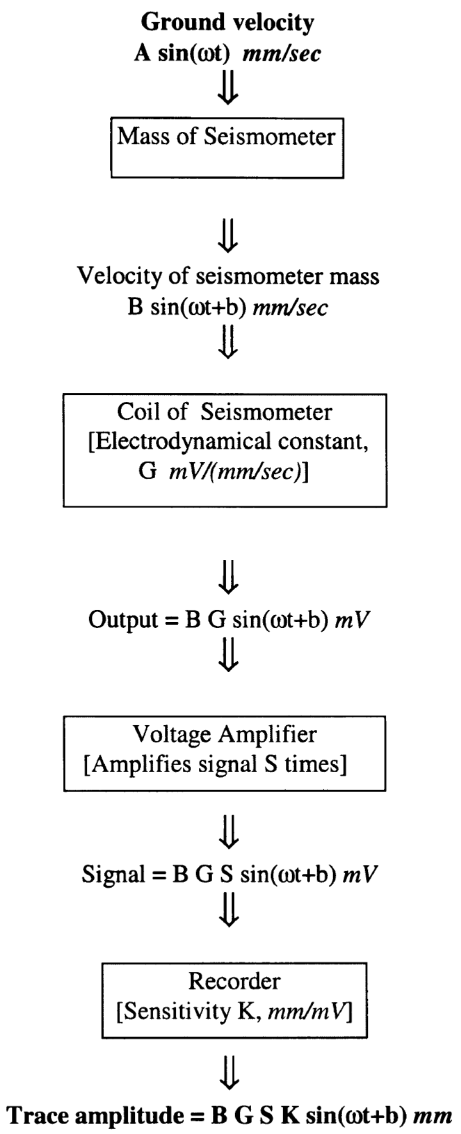

Figure 3. Flow chart for a visible seismograph: Actual ground motion through recorded signal trace.

where $I = B/A$ eq. (1). Here S and K are the gain of amplifier and recorder sensitivity, respectively. Thus,

$$\text{Velocity magnification} = IGSK, \quad (4)$$

where I and S are functions of angular frequency ω. It may be noted that $\omega = 2\pi f = 2\pi/T$, where f is the linear frequency in Hz and T is the period in seconds. $S(\omega)$ is normally constant from a very low frequency to about 50 Hz. Since G and K are constants, $GSK = C$, is nearly a constant. Thus from eq. (4),

$$\text{Velocity magnification} = CI(\omega),$$

which shows that the velocity magnification curve is nearly parallel to the magnification curve $I(\omega)$ of the inertial pendulum seismometer over a wide band; the expression for $I(\omega)$ can be obtained from eq. (1) by changing $T = 2\pi/\omega$ and $T_s = 2\pi/\omega_s$. However, in seismology we use period more often than frequency and we may also write

$$\text{Velocity magnification} = CI(T). \quad (5)$$

We can obtain displacement magnification by multiplying the velocity magnification with ω or $2\pi/T$. We note that at low periods, displacement magnification rapidly increases as the period decreases. However, at low periods, background noise, mostly arising from cultural sources, also increases rapidly as period decreases, due to which we need to decrease magnification at low periods. For this reason, we use a low pass filter in amplifier, which decreases the gain below a desired period.

The response of a seismograph is described by its dynamic range and bandwidth. *Dynamic range* is expressed as,

$$\text{Dynamic range (db)} = 20 \log_{10} (\text{maximum amplitude/resolution}).$$

For example, the MEQ800 visible recorder with smallest readable signal amplitude of 0.2 mm and maximum pen deflection of 25 mm has a dynamic range of 42 db.

Corner period (or frequency) of a seismograph is defined as the period at which the magnification drops by 3 db of peak value (i.e. 0.707 of peak magnification). One corner period *Tlc*, is at the lower side of the period range and the other corner period, *Thc*, on the higher side of it. The range (*Tlc–Thc*) is defined as the *bandwidth*. This is the period range within which the seismograph is most sensitive to ground motion. For an inertial pendulum seismometer, the magnification drops exactly by 3 db at the free period of the seismometer, when we set $h = 0.707$.

2.1.7 *Digital recording seismograph*: In a digital recording seismograph, the amplifier output is fed to a digital recorder, which records the ground motion in terms of digital counts. Thus, a ground velocity of $A \sin(\omega t)$ gives an output of $BGS \sin(\omega t + b)$ mV from the amplifier (Figure 3). The output from the amplifier then goes to a digital recorder, which converts the voltage to counts, say, L counts/mV. Thus, it records $BGSL \sin(\omega t + b)$ counts. The velocity magnification is $IGSL = CI(T)$ counts/(mm/sec). With $h = 0.707$, maximum value of I is 1 and hence maximum velocity magnification is $C = GSL$.

In a digital recorder, the analogue-to-digital converter (ADC), also called as digitizer, samples the input signal at regular intervals, defined by N samples per second (SPS). For a unique representation, any harmonic must have at least three samples per wavelength. Thus, the frequency defined by $f_N = 0.5$ N represents the harmonic with lowest frequency and is called, the Nyquist frequency. Contamination of computed spectra at frequencies higher than f_N is termed as *aliasing*. To remove the effect of aliasing, a sharp (high order) low-pass filter called *anti-alias filter* is generally set at 0.4 N.

The minimum digitization step is called a *dig*it or *count*. The smallest unit of a digital value or word is called Byte (= 8 bits). A 16-bit ADC can count values from – 32768 (-2^{15}) to 32768 (2^{15}), giving a dynamic range of 90 db. On the other hand, a 24-bit ADC, which can count from – 8388608 (-2^{23}) to 8388608 (2^{23}) gives a dynamic range of 138 db. Higher dynamic range in digital recording, compared to analogue recording, gives the advantage to record the ground motions from very small magnitude earthquakes as well as from large magnitude earthquakes without saturation. The three parameters crucial in the design of a digital seismograph are bandwidth, dynamic range and the bit resolution of the digitizer.

A 3-component digital seismograph recording continuously at a sampling rate of 20 SPS per channel with an ADC resolution of 24 bits (3 bytes) would require a storage capacity of 3 (comp.) × 20 (SPS) × 3 (byte) × 24 (hour) × 3600 (sec) ≈ 15.5 MB per day. Several types of large storage devices (of the order of few gigabytes) and data compression techniques are available to store the data so generated. The present-day systems offer recording in different streams, for example, one stream shall record at 20 SPS in continuous mode and other stream shall record at 80 or 100 SPS in trigger mode, i.e. when signal amplitude exceeds a predefined threshold value. In the trigger mode, normally recording is based on the ratio of short-term average (STA) to long-term average (LTA) of the recorded signal. The time at which this ratio exceeds a predefined threshold value is called *trigger time*. The recording starts a few seconds (set by *pre-event time*) before the trigger time. The recording continues till the signal amplitude restores to the background value, or, till such time, set by *post-event duration*, after the STA/LTA ratio falls below the threshold value. Some of the commonly used combinations of seismometer–data acquisition systems in India are discussed next:

(i) *STS2–Q680*: This is a combination of a force balance seismometer (STS2) and data acquisition system (Q680LVG, in short, Q680) of Quanterra make. The seismometer has a free period of 120 s and electrodynamic constant $G = 1500$ mV/(mm/sec). The gain of Q680 (which includes amplifier) is $SL = 0.42735 \times 10^3$ counts/mV. With $h = 0.707$, the seismograph has a bandwidth up to 120 s and the peak velocity magnification is $GSL = 641.0 \times 10^3$ counts/(mm/sec).

(ii) *CMG40T–72A*: The broadband sensor CMG40T of GURALP make is also a force balance seismometer and is equivalent to an inertial seismometer with free period of 30 s; the electrodynamic constant is 800 mV/(mm/sec). The data acquisition model RT 72A of Reftek make has a gain of 0.52466×10^3 counts/mV. With a damping of $h = 0.707$, the seismograph has a bandwidth up to 30 s and the peak velocity magnification is 419.0×10^3 counts/(mm/sec).

(iii) *L4C–72A*: In this case, the data acquisition system referred in (ii) above is connected to a short period electromagnetic seismometer L4C or L4C3D with 1 s free period and $G = 240$ mV/(mm/sec). With damping $h = 0.707$, the seismograph has a bandwidth up to 1 s and peak velocity magnification is 125.9×10^3 counts/(mm/sec).

The data acquisition systems described above have 24-bit resolution and employ a timing device which includes a crystal clock synchronized by Global Positioning System (GPS) receiver. The magnification curves for the above combinations are shown in Figure 4. These broadband seismograph systems have astounding capabilities over the conventional analogue systems and thus have revolutionized the seismic instrumentation in India. They are capable of simultaneously recording very long period surface waves and high frequency body waves ranging from minimum earth noise levels up to the strong accelerations expected from large nearby earthquakes. They

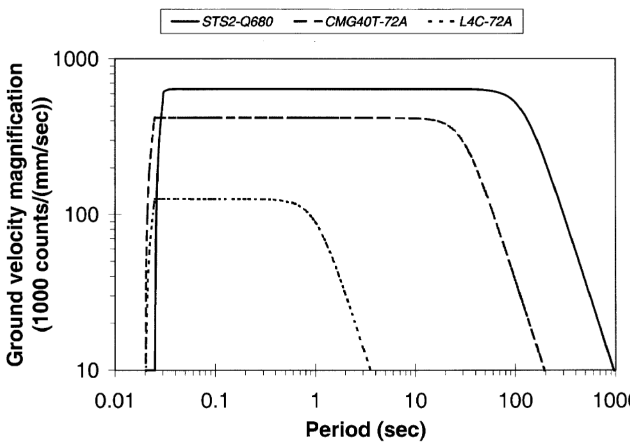

Figure 4. Period response of ground velocity for digital seismographs STS2–Q680, CMG40T–72A and L4C–72A.

offer excellent digital data processing options, viz. filtering, rotation of seismograms, conversion of seismogram traces through differentiation/integration, etc. Figure 5 depicts vertical, radial and transverse component broadband velocity and displacement seismograms of a Koyna event recorded at Karad.

2.2 *Strong motion accelerographs*

During violent ground vibrations due to large earthquakes, the seismographs meant for recording weak motions of the ground either go off the scale or stop functioning after recording the onset. To effectively record

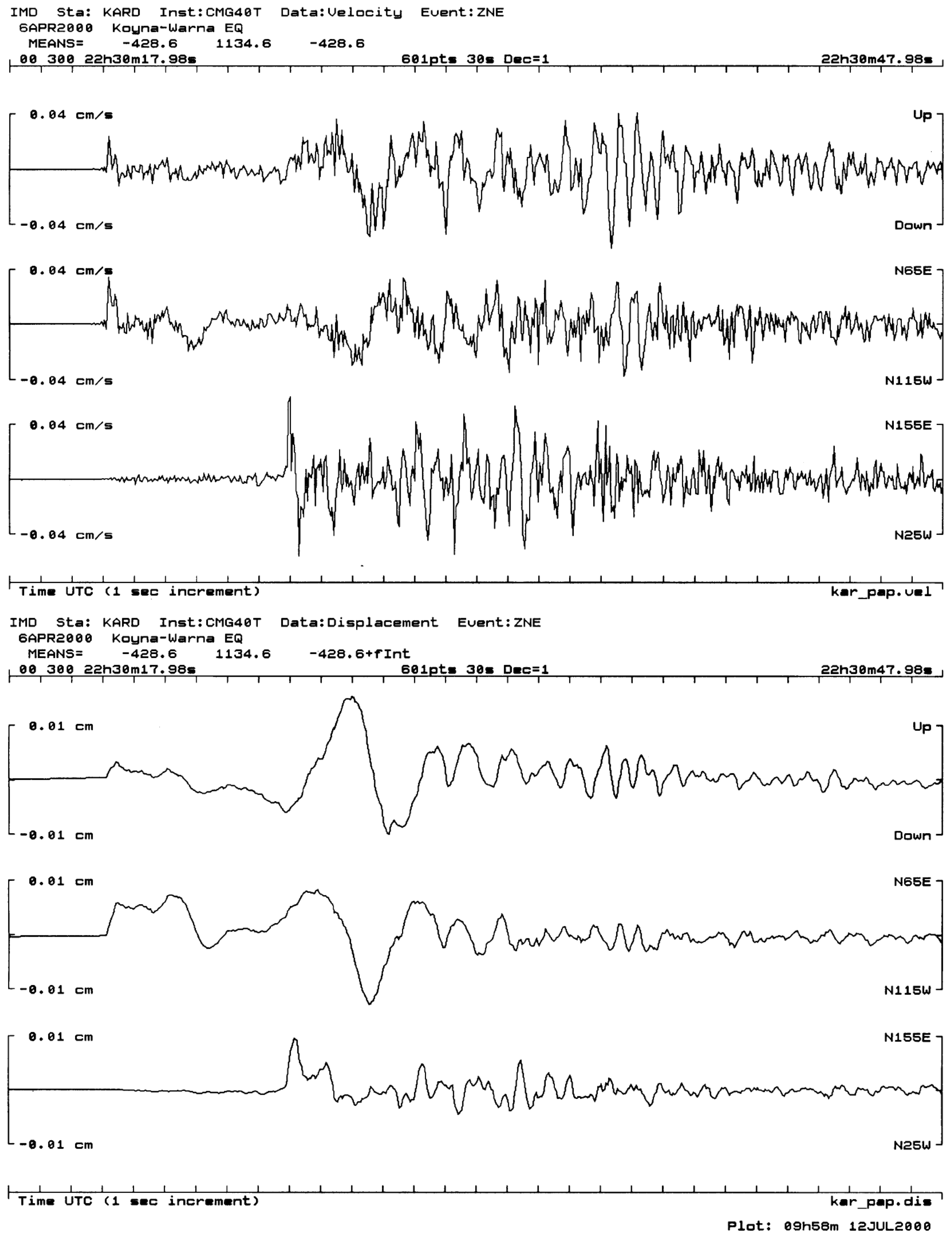

Figure 5. Broadband seismograms of an earthquake in Koyna–Warna region of Maharashtra recorded at the seismological observatory, Karad, on 6 April 2000. The top three traces are vertical, radial and transverse component waveforms of ground velocity and the bottom three traces are vertical, radial and transverse components of displacement waveforms of the same earthquake obtained through integration of the respective velocity waveforms given at the top. Length of each waveform is 30 s.

such strong ground motions in near epicentral zone, another type of instrument, called strong motion accelerograph (SMA) is used. In the design of SMAs, we use electromagnetic sensors or force balance sensors of very low period, so as to make the output voltage proportional to ground acceleration instead of ground velocity as in weak motion sensors described earlier. In analogue SMA, recording is taken on a 70 mm photographic film, normally without absolute time marks. In digital SMA, recording is done in the digital mode with absolute time using GPS synchronization. Since such instruments are meant to activate only during a strong motion, a triggering device is used for recording. Modern digital accelerographs have provided excellent near-field data sets for several significant earthquakes which are useful in understanding the effects of ground shaking on structures and also to assess the attenuation characteristics of the media.

2.3 *Seismological observatories*

IMD operates and maintains the national seismological network consisting of 45 observatories spread over the length and breadth of the country. Till 1970, these observatories were equipped with photographic recording seismographs such as Milne–Shaw, Wood–Anderson and electromagnetic seismographs. However, in the 1970s, many of these observatories were upgraded with visible seismographs. A Seismic Research Observatory (SRO) system with a broadband bore-hole seismometer and a digital data recording system was installed at Central Seismological Observatory (CSO), Shillong, in 1978. IMD started operation of five stand-alone digital seismographs during the early nineties. The seismological observatory at National Geophysical Research Institute (NGRI), Hyderabad equipped with WWSSN-type analogue seismograph system was upgraded during the early nineties with a very broadband seismograph in collaboration with GEOSCOPE.

During 1996–1997, ten seismological observatories under the national network in peninsular India had been upgraded to the standards of Global Seismic Network (GSN) by deploying STS2–Q680 seismograph system at each of these observatories. The data acquisition system Q680 records 80 SPS data in trigger mode and 20 SPS data in continuous mode. It has also got provision for recording data of any two streams on an analogue drum recorder for continuous display. Presently one short-period vertical component and one long-period vertical component simulated streams are being recorded on analogue drum recorders. A digital recorder (Atlus K2 of Kinematrics make) with an internal triaxial force balance accelerometer (FBA) serves as a secondary data acquisition system at each of these observatories. The Q680 also records the output of FBA. In these observatories, the Q680 is connected locally to a computer where the data can be downloaded and analysed. The Q680 at each of these 10 observatories is also accessed from the Central Receiving Station at New Delhi, where the data is downloaded in near-real time using telephone modem. During 1999–2000, fourteen more existing observatories of the national network have been upgraded with another type of broadband digital seismograph (CMG40T–72A). Although recording at these observatories is possible in different data streams, viz. continuous, ratio and amplitude trigger, etc., presently, recording is being done in continuous mode at 20 SPS. Trigger times are also stored in a separate stream as an event log file.

In addition to IMD, a number of R&D institutions, universities and state governments are also operating seismological observatories in different parts of the country (Table 1 and Figure 6). These observatories, adding up to 212, may be classified according to the affiliation of organizations maintaining them. The three broad categories of organizations operating these stations are R&D institutions (106 stations), river valley project authorities (79 stations) and universities (27 stations). These include the radio telemetered seismic networks operated in Tezpur and Nainital by NGRI and Kumaun University, respectively. Another landmark development in the new millennium in seismic instrumentation is a 16-element VSAT-based seismic telemetry system being deployed in and around Delhi by IMD.

Table 1. Distribution of seismological observatories in India under different organizations

Organization	Abbreviation	No. of stations
India Meteorological Department	IMD	57
National Geophysical Research Institute	NGRI	20
Wadia Institute of Himalayan Geology	WIHG	11
Regional Research Laboratory, Jorhat	RRLJ	10
Bhabha Atomic Research Centre	BARC	2
Indian Institute of Geomagnetism	IIG	2
Geological Survey of India	GSI	1
National Institute of Rock Mechanics	NIRM	1
Central Scientific Instruments Organization	CSIO	1
Centre for Earth Science Studies	CESS	1
Subtotal		**106**
Maharashtra Engineering Research Institute	MERI	31
Gujarat Engineering Research Institute	GERI	17
Sardar Sarovar Narmada Nigam Ltd	SSNN	9
Narmada Valley Development Authority	NVDA	10
Kerala State Electricity Board	KSEB	12
Subtotal		**79**
Guru Nanak Deb University	GNB Univ.	3
Delhi University	D. Univ.	3
University of Roorkee	UOR	9
Osmania University	O. Univ.	1
Manipur University	M. Univ.	4
Indian School of Mines	ISM	1
Kurukshetra University	Kur. Univ.	1
Kumaun University	Kum. Univ.	5
Subtotal		**27**
Grand total		**212**

2.4 *Microearthquake surveys*

Monitoring of microearthquake activity in a small area has many applications, such as, evaluation of seismotectonics, study of aftershocks, swarm type activities, etc. Till the mid-seventies, such surveys were conducted by employing bulky electromagnetic seismographs requiring photographic recording with dark room facility. However, since the late seventies these have been replaced by portable visible seismographs with smoke paper recording. More recently, digital portable seismographs such as L4C3D–72A with GPS time synchronization are being used in such surveys to generate very high resolution data. Such digital portable seismographs were operated for monitoring (a) swarm-type activity in Pandhana Tehsil of Khandwa in Madhya Pradesh during 1998–1999 and (b) aftershock activity of Chamoli earthquake of 1999.

2.5 *Strong motion networks/arrays*

The spatial variability of earthquake intensities near the source plays a key role in the prediction of strong ground motion and response of engineered structures. To achieve this objective, specially designed strong motion arrays/networks are operated in highly seismic areas. Under a project sponsored by the Department of Science and Technology on Himalayan seismicity, the University of Roorkee (UOR) has been operating three strong motion arrays, one each in north-east India (45 stations), Pithoragarh region (50 stations) and Garhwal Himalaya (45 stations). These instruments record 3-component ground accelerations in digital form along with actual time. These strong motion arrays have yielded very valuable data sets for several important earthquakes, including the Chamoli earthquake of 29 March 1999. The data has enabled estimation of attenuation characteristics of the region under consideration and response spectra of structures, which have significant application in engineering design of critical structures. An Indian National Strong Motion Instrumentation Network (INSMIN) with a set of strong motion accelerographs and Structural Response Recorders (SRR) is also being maintained by the Department of Earthquake Engineering, University of Roorkee (DEQ-UOR). The SRRs are meant for directly recording the response

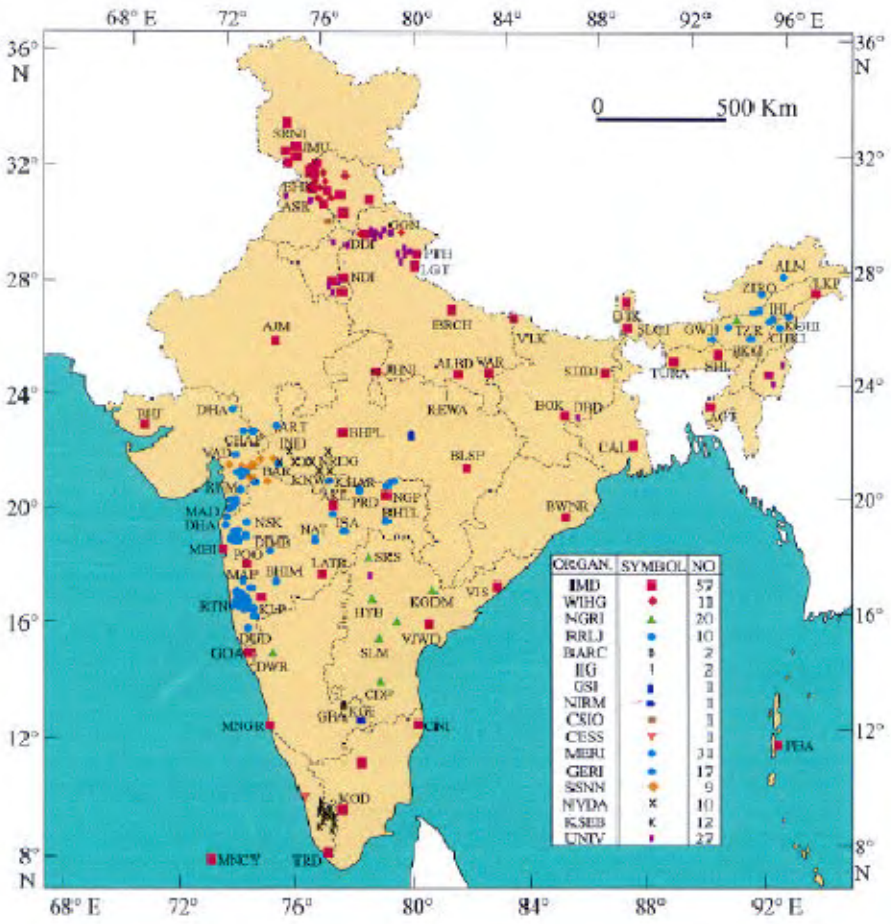

Figure 6. Map showing seismological observatories in India operated by different organizations (see also Table 1).

of structures (buildings, etc.) in the event of an earthquake.

2.6 *Design and development of seismic instruments*

IMD has been engaged in the manufacture of Wood–Anderson seismometers and electromagnetic seismometers together with their recording systems since the 1960s. The galvanometers required for the electromagnetic seismographs were, however, imported. These systems are still in production and use at various observatories of the national network of IMD. Conventional type time marking devices, viz. pendulum and crystal clocks were also developed by IMD during the fifties and seventies respectively. During the last two decades, the Central Scientific Instruments Organization (CSIO), Chandigarh made serious efforts towards indigenous development and manufacture of visible analogue recorders, digital recorders and time marking systems using crystal clocks. Analogue visible recorders and time marking systems of CSIO are being used at some of the IMD observatories. A 16-bit digital data acquisition system has also been developed by CSIO. An analogue radio telemetered seismic network developed by BARC in the 1980s was in operation in and around Bhatsa in Maharashtra till mid-1990s. SRRs and analogue SMAs are also being manufactured at the DEQ-UOR since mid-1970s.

3. Seismic data interpretation: Recent advances

With the availability of digital waveform data, several standard software packages have been developed in recent years for routine analysis and processing of the data. The International Association for Seismology and Physics of the Earth's Interior (IASPEI) has developed a library of standard programs for various kinds of seismological data processing and analysis, which is used extensively by the seismological community; the most important of these are PITSA and SEISGRAM. Scientists at University of Bergen, Norway have also developed a SEISmic ANalysis software, called 'SEISAN', suitable for operation in single- and multi-user environments. A seismic network automation software called SEISNET, was also developed by this group for remote access of waveform data. The software effectively combines various types of seismic data sources into one virtual seismic network, to bring all the data to one central site. SEISNET can only be used in combination with SEISAN, since SEISAN programs and the database structure are used by SEISNET. A general purpose interactive program, called Seismic Analysis Code (SAC), designed for the study of time series data by University of California, is also available. The software works in UNIX environment and has extensive graphics capabilities. Since it would not be within the scope of this paper to discuss all the applications of seismic data analysis and interpretation, an attempt has been made to give a brief description of various techniques/software widely in use for estimation of earthquake source parameters and the crust and upper mantle structure.

3.1 *Analysis of seismograms*

Identification of various phases in a seismogram is an essential and foremost task of any seismic data interpretation. The actual arrival times and amplitudes of various phases help, respectively, to estimate the hypocentral location and magnitude of a seismic event. Identification of various phases in a seismogram used to be a very tedious task in the pre-digital era. It is now possible to simulate the arrival times of various phases employing any travel-time model and display along with the waveform. The SEISGRAM package of IASPEI software has the facility to display Jeffreys–Bullen predicted phase arrival times for a given origin time, epicentral distance and focal depth. Similarly, the SEISAN software package has also got the facility to simulate the IASPEI91 predicted phase arrival times for any located event. The operator can also interactively select various phases on the seismogram, which can be combined and stored as a single event file (S-file), to locate the event subsequently. These S-files contain the phase data and the names of the corresponding waveform files. The database part of SEISAN consists of two directories, REA and WAV. The REA directory and its sub-directories contain phase readings and derived source information of all located events, while all the waveform data are normally stored in the WAV directory.

3.2 *Determination of hypocentral parameters*

The conventional method of determining the hypocentral parameters, viz. origin time, epicentre and focal depth, utilizes the times of arrival of various phases recorded at different stations. Over the years, this method of locating hypocentres has been replaced by computer-based analytical methods. A number of techniques and algorithms have been developed for quick and accurate estimation of hypocentral parameters. The procedure essentially, involves assuming a trial solution and then computing the theoretical travel times with respect to the assumed solution. By applying an appropriate method, for instance, least-squares method, the arrival-time residuals are minimized to get a new set of location parameters. The procedure is repeated through an iterative process till an acceptable error criterion is met. The final adjusted parameters are then accepted as the best possible estimate of the source location. These algorithms also take care of the possible errors in the data by assigning suitable weights and judging the quality of results in the form of statistical estimates of errors. Although a number of source location algorithms are available in the literature, the HYPO71 program developed by Lee and Lahr[9] is the most commonly used program. Few other programs, such as HYPOLAYERS, HYPOINVERSE and HYPOELLIPSE are also used by some research workers. However, these programs are useful for locating earthquakes recorded by near observatories.

The HYPOCENTRE location package[10] of SEISAN software has capabilities to locate earthquakes locally, regionally and globally. It uses the travel-time tables of IASPEI91. However, if specified, it can adopt local crustal structure to calculate travel times for those stations which are within a given hypocentral distance range. Depending upon the epicentral distance, it is possible to estimate various kinds of magnitudes like m_b, M_s, M_L and M_c of an earthquake, making use of the wave amplitudes and periods and coda duration. Given the instrumental response, it is also possible to simulate seismograms of Wood–Anderson and few other types, which can in turn be used to estimate corresponding magnitudes like M_L, m_b and M_s. The SEISAN software package has got the facility to plot the initial motions (polarity of first onset) on an equal area projection map to work out plausible fault plane solutions.

Accurate estimation of focal depth very often poses problems for want of depth phases from nearby stations. The uncertainty in focal depth estimation increases as the epicentral distance from the nearest seismograph station increases. However, with the help of digital broadband records, it is possible to decipher the depth phases normally through filtering, which are otherwise not very clear in the narrow band seismograms. The focal depth of the 1997 Jabalpur earthquake could be accurately determined, using the sPn phase recorded in the broadband seismograms with a low pass filter at 2 Hz and waveform inversion techniques[11,12]. The GPS time synchronization available with the modern digital systems facilitates improvement in the time resolution necessary for accurate estimation of hypocentral parameters.

To monitor earthquake activity in the operational mode, the Central Receiving Station (CRS), New Delhi, of IMD, pools every half an hour through dial-up modem using SEISNET, the information pertaining to the detected triggers from each of the ten broadband stations equipped with STS2–Q680 seismographs. On identification of a trigger attributable to an event, the operator at CRS decides to download the waveform data of desired stations using dial-up modem, and then processes the data for hypocentral location. The hypocentral parameters thus evaluated in the operational mode are improved later by incorporating data from other observatories and a monthly seismological bulletin is prepared in the standard Nordic format using the SEISAN software package. Efforts are being made to connect all the broadband stations of IMD to CRS through VSAT communication facilities.

3.3 *Estimation of crust and upper mantle structure*

As is well known, most of the present knowledge about the otherwise inaccessible deep interior of the earth regarding its composition and structure is based on seismic observations. There is an intense effort to determine the internal structure with very high precision, so that the composition and dynamic processes of the earth's interior can be better understood. It is possible to delineate, to a first approximation, most of the one- or two-dimensional features of the earth's crust using the regional broadband network data. However, a much more dense and closely spaced seismic network would be required to model the three-dimensional complexities in the curst.

Dube *et al.*[13] used body wave travel-time data to derive crust and upper mantle structure. On the basis of body wave travel time data of shallow earthquakes in India, Krishna *et al.*[14] found that the *P*-wave travel time data reveal significant variations, while *S*-wave data show comparatively better agreement with respect to the Jeffreys–Bullen tables. Both *P* and *S*-wave velocities in the sub-crustal region of the Indian sub-continent are relatively high, compared to other regions of the earth.

Seismic observations through Deep Seismic Sounding (DSS) by controlled explosive source constitute the most reliable approach for exploring the structure of the crust and upper mantle. The source location and the time information can be controlled accurately so that the derived structure would be very accurate. For a review of the work done using explosion data, the reader may refer to Kaila and Krishna[15]. These studies have helped not only in deriving the crustal structure but also in addressing specific geological problems like delineation of subterranean sedimentary structure and basement configuration, formation and evolution of sedimentary basins and tectonic framework depicting fault-controlled crustal blocks. Seismic body waves recorded by conventional short period seismographs on fast-run recorders (1 cm = 1 s) in various DSS field surveys were also extensively used by IMD to obtain average crustal structure[16–18]. These results have helped in improving the hypocentral locations of local earthquakes.

The dispersion of seismic surface waves has also been made use of in deriving the crust and upper mantle structure by various investigators. Bhattacharya[19] gave a comprehensive review of the crust and upper mantle models derived through inversion of the observed dispersion data for the Himalaya, Indo-Gangetic plain and peninsular shield regions. Singh[20] estimated the crustal structure of Bay of Bengal Fan and Indian Ocean, making use of the surface wave dispersion of fundamental and higher modes. Singh *et al.*[12] derived the crust and upper mantle structure of the peninsular shield region by making use of the broadband data of the 1997 Jabalpur earthquake.

Another important development employing high-speed computation is the three-dimensional imaging of the earth's interior, called seismic tomography. The technique essentially involves reconstruction of an image of the internal structure in terms of, say, time residuals of *P*- and *S*-waves. Rai *et al.*[21] evaluated the 3D velocity structure of the south Indian shield. Rai *et al.*[22] made use of the data generated by a digital array operated in Koyna region to map the 3D velocity structure and study the seismicity in detail. On the basis of preliminary analysis of the data, they have inferred a high velocity zone beneath the region of observed seismicity. Using the well-constrained locations of the local events, the seismicity patterns were also accurately delineated. Gupta *et al.*[23] also used this data for making coda Q_C estimates for the region.

3.4 *Estimation of detailed source parameters*

The physical model for the tectonic earthquake source is usually conceived as release of strain energy due to rupture along a fault plane in the rocks. The actual faulting in an earthquake is a very complex phenomenon. Nevertheless, the character of faulting in an earthquake can be inferred from observed distributions of the directions of the first onsets in waves arriving at the recording stations, supplemented by the *S*-wave polarization angles. From a well-determined polarity pattern of first *P*-wave motions, it is possible to locate two nodal planes, one of which represents the fault plane. Fault identification is normally made from field evidence or distribution of aftershocks. Computer algorithms are available to generate a set of fault plane solutions within a given error criterion in terms of inconsistent polarities. The fault plane solution so obtained describes the faulting pattern in terms of strike and dip of the fault plane, slip direction, etc. For significant earthquakes, it is now a routine practice to work out the fault plane solutions.

Based on the equivalence theorem, the displacement field produced by the dislocation on a plane element in an elastic body equals that produced by a double couple applied at the center of the source. Thus, the strength of an earthquake source can be represented by a seismic moment. For a simple fault source, it can be expressed as the product of average slip, the fault area and the modulus of rigidity of the medium. Using digital data, it is also possible to estimate seismic moment from the far field displacement spectra. The spectra allow estimation of other important parameters, viz. corner frequency, source radius, stress drop and the moment magnitude. Using the SEISAN and IASPEI software, these source parameters are being obtained on a routine basis.

In case of significant earthquakes, synthetic seismograms of body and surface waves are computed in an attempt to invert for the source characteristics. The seismic source is treated as a moving dislocation along a fault and seismograms are calculated from a Green's function representation of the displacements. The process involves obtaining a best fit between the synthetics and observed seismograms by varying the parameters of the source. Singh *et al.*[12] have computed synthetic seismograms to perform a moment-tensor inversion of band-pass filtered (0.05–0.02 Hz) displacement seismograms of the 1997 Jabalpur earthquake. The inversion yields reliable focal mechanism and seismic moment, although the depth resolution is poor. Mandal *et al.*[25] and Rastogi *et al.*[26] studied the Koyna seismicity in detail, making use of the digital data generated by a local network. The fault plane solutions and focal depths were determined for several Koyna earthquakes using CMT inversions.

Estimation of attenuation relations to predict ground motions during future earthquakes forms an important element in the seismic hazard assessment of any region. Similarly, the near source recordings play a very important role not only in detailed estimation of source parameters but also in the evaluation of attenuation characteristics. The excellent recordings produced by the modern digital accelerographs (velocity and displacement traces can be obtained by integrating the accelerogram) offer a unique opportunity in this direction. Singh *et al.*[24] made spectral analysis of the 1997 Jabalpur earthquake to estimate a frequency-dependent Q of Lg waves. Making use of these estimates and assuming a ω^2-source model, they predicted peak acceleration and velocity as a function of distance, magnitude and stress parameters. These predictions are preliminary and need revalidation with more strong motion data in future.

4. Conclusions

Keeping pace with the technological developments, the seismic instrumentation and data interpretation in India have grown by leaps and bounds over the years. Under a World Bank-assisted project for seismic instrumentation upgradation in the Peninsular shield region, 24 seismological observatories under the national network of IMD have been upgraded with state-of-the-art digital seismograph systems having broad frequency response, large dynamic range and accurate time keeping using GPS synchronization. The data generated at some of these observatories of IMD are presently available in near real time at CRS, New Delhi of IMD. Also, a number of new observatories have been set-up with similar systems by various state and central government agencies. These digital broadband systems have generated very useful, high resolution data sets for several significant earthquakes, including Jabalpur (1997) and Chamoli (1999). This has greatly improved not only the hypocentral location capabilities in the operational mode but also the estimation of detailed source parameters, crust and upper mantle structure, etc. in the research mode. A similar upgradation programme for the extra-peninsular shield region together with matching communication facilities, will be useful for a near real time seismic monitoring covering the whole country.

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