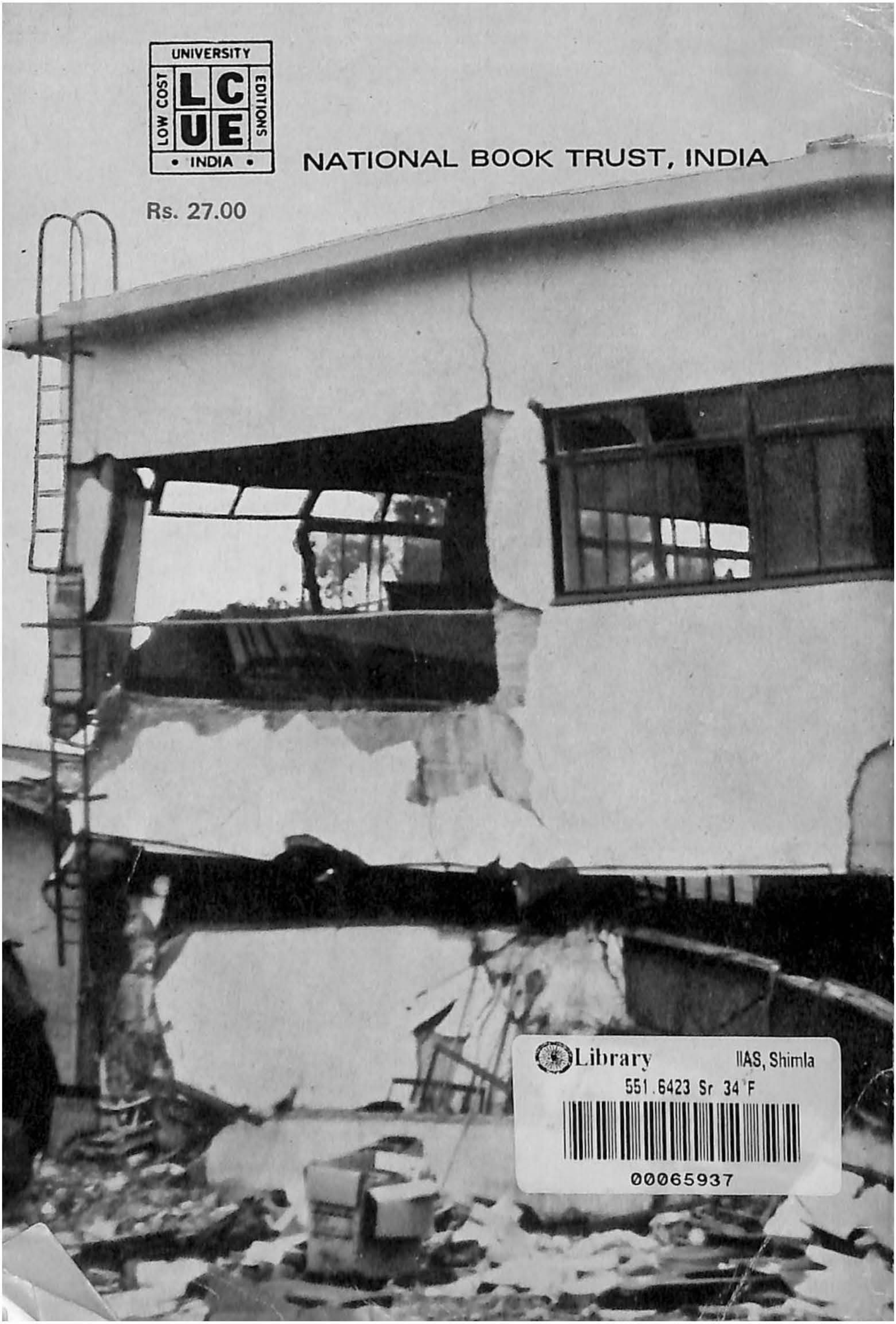

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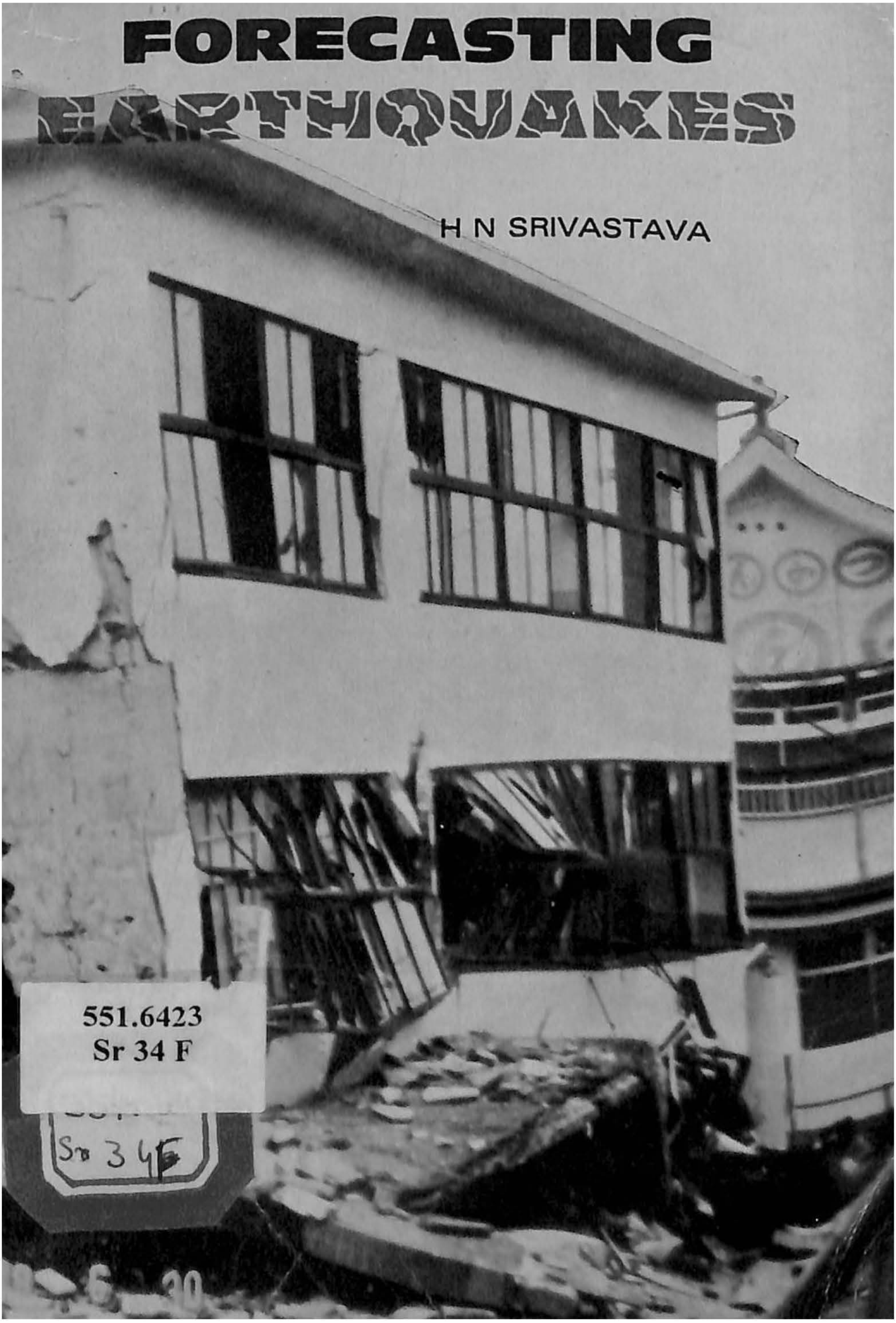
FORECASTING EARTHQUAKES

H N SRIVASTAVA



FORECASTING
EARTHQUAKES

This book describes the scientific and socio-economic aspects of earthquake prediction. Starting with the fundamentals of seismology and instrumentation, the book discusses in detail the techniques of and the progress made in long, medium and short range earthquake forecasting. The geoscientific community should find in this book ample material of use to them. Dam designers and earthquake engineers will find details about the seismological data input needed for the computation of design seismic coefficients and the international recommendations for seismic instrumentation around river valley projects and reservoir induced seismicity. The general public and the administrators may also find the book useful in planning for disaster mitigation.

Hari Narain Srivastava (b. 1936) joined the Indian Meteorological Service in 1959. He was awarded the Ph.D. degree in Physics from Lucknow University in 1963.
Dr. Srivastava has made pioneering contributions in the fields of seismology, meteorology and microwave physics. He has published about 100 research papers in reputed international and Indian journals. His researches pertaining to earthquake mechanism and plate tectonics, seismicity and earthquake catalogues and the prediction of earthquakes have been widely acknowledged. His book in Hindi entitled 'Bhookump' has been given a special award by U. P. Hindi Sansthan.
Dr. Srivastava is a member of the Governing Council of the International Seismological Centre, U.K. and extends consultancy services to a number of seismological and earthquake engineering organisations in the country. He is presently the Director of Seismology, responsible for the National Network and River Valley Projects, Seismological Stations and Research.

FORECASTING EARTHQUAKES

H. N. Srivastava

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Preface

EARTHQUAKES ARE ONE OF THE WORST NATURAL CALAMITIES WHICH cause instantaneous destruction of property and loss of life. The growing demand on seismologists to predict earthquakes is, therefore, not unjustified. It is easy to achieve better success in forecasting those disciplines of science which are directly accessible to observations, such as atmosphere. In the case of solid earth, however, difficulties of digging even a few kilometres to reach the focal zone of earthquakes for in situ observations are well known. Thus most of the information about the mechanism of earthquakes has to be obtained indirectly through seismic and other geophysical techniques, which monitor changes in the physical properties of rocks at the earth's surface, generally far removed from the focal region. Nevertheless, a beginning has been made to evolve methods of forecasting earthquakes and limited success has been achieved.

This book presents unified concepts from scientific as well as social angles relating to the forecasting of earthquakes. It discusses short, medium and long range techniques of forecasting, instrumentation, physical basis of prediction, triggering and control, economic and social impact of prediction and disaster management through its twelve chapters. The involvement of common man in earthquake prediction programme makes it desirable to educate the general public about different aspects presented in the book. Although some portions may appear to be rather difficult for the non-specialist, the book, should by and large, prove its utility in the hands of geologists, geographers, geophysicists, engineers, town planners, administrators and general public.

It is a pleasure to thank Dr. A. N. Tandon, former Deputy Director General and Shri H. M. Chaudhury, Additional Director General, India Meteorological Department whose close association has enabled me to develop some of the ideas presented in the book. I am grateful to Dr. P. K. Das, Director General of Meteorology (now a WMO Expert) for encouragement and kind permission to bring out this book. My sincere thanks are due to Shri S. K. Das, Director General and Dr. R. P. Sarcar, Additional Director General for their interest and help.

I am also indebted to Dr. Hari Narain, former Director (presently UNDP expert) and Dr. V. K. Gaur, Director of the National Geophysical Research Institute, Hyderabad for valuable discussions pertaining to the subject from time to time. I am grateful to the National Book Trust, India for publishing this book under their Subsidy Scheme. Grateful acknowledgements are due to my wife, Smt. Om Srivastava whose continued inspiration though at the expense of social obligations has enabled me to concentrate on this work outside office hours.

New Delhi H. N. Srivastava

Contents

CHAPTER 1

Earthquake Hazards, Lights and Sounds

EARTHQUAKES PRESENT A FRIGHTENING EXPERIENCE IN THE LIVES OF men. The disaster strikes suddenly, similar to that of lightening, tornadoes or nuclear explosions. It is estimated that, on an average, about 15,000 human lives are lost every year, while in a single year of 1976 about 2 lakhs were killed by earthquakes in China, Guatemala, Philippines and in other parts of the world. The damage to property runs into billions of rupees. In India, where 55% of the land area falls under active seismic zones, considerable destruction was caused by the earthquakes of Kutch (1819), Shillong (1897), Kangra (1905), Dhubri (1930), Bihar-Nepal (1934), Assam (1950) and Koyna (1967). With a growing population, damage to life and property is likely to increase, unless success in earthquake prediction is achieved.

Destructive earthquakes have also provided valuable scientific information. To the geologist and seismologist, instrumental data recorded during earthquakes as well as field surveys near the epicentral areas furnish evidence about the processes of faulting and enable to improve prediction techniques. The affected zone is the natural region for the earthquake engineer to study the pattern of damage to structures. This provides a basis for earthquake resistant designs. Administrators and town planners learn a good deal from the data collected during past earthquakes about disaster prevention.

Earthquakes and seismic waves

Earthquakes generate a variety of effects. Some are temporary, such as the shaking ground, swinging objects, rattling windows and oscillating trees. Permanent effects include damage to buildings, transportation and water supply systems and the landslides. Earthquakes are often attributed to different types of seismic waves generated at the earthquake focus (Fig. 1). The waves that arrive at a station first are called *P* or primary waves with velocities of the order

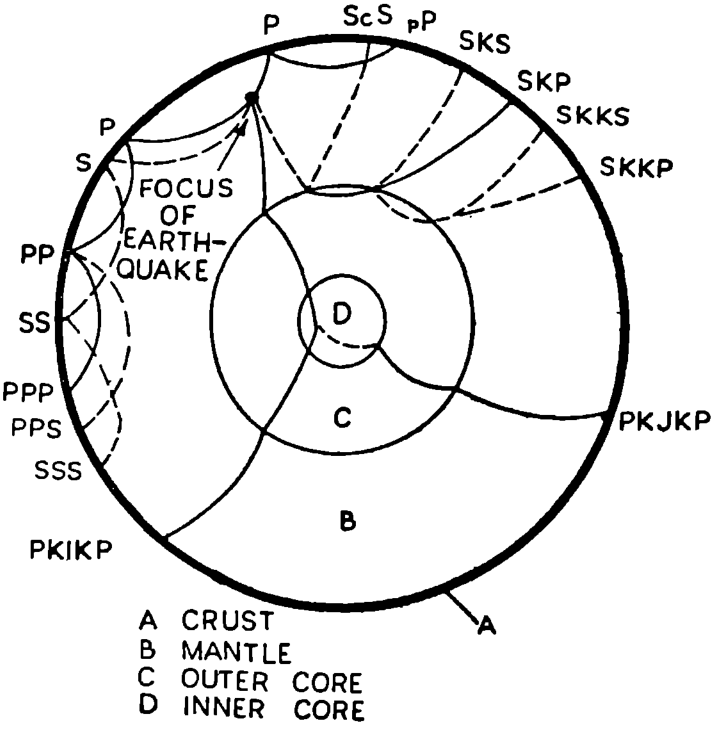


Fig. 1. Seismic waves emnating from the focus of an earthquake. A, B, C and D denote the internal structure of the earth (the main layers being crust, mantle and outer and inner core). The principal wave types being P and S get reflected from the earth's surface, mantle and core generating several types of waves. Reflections from crustal surface are indicated as PP, PPP, PPS, etc., while that from outer core as ScS. Symbol K indicates that the wave has been transmitted through the outer core while I and J denote penetration of waves through inner core. For reflection inside the core boundary, KK is used like SKKS. The time interval between P and near the reflected phase pP at a station gives information about the depth of focus of earthquake.

of 5·5 to 8 km/sec. The primary waves are similar in nature to sound waves with zones of compression and rarefaction (Fig. 2). Their vibration is longitudinal to the direction of propagation and velocity increases with depth, except in a low velocity layer. The next to follow are *S* or secondary waves, in which the vibration of particles is to the right of the direction of propagation of waves (Fig. 2). They are shear or transverse waves. Their velocities are of the order 3·3 to 4·8 km/sec. Both these waves propagate radially in all directions from the focus of earthquake. Surface waves are the slowest to arrive.

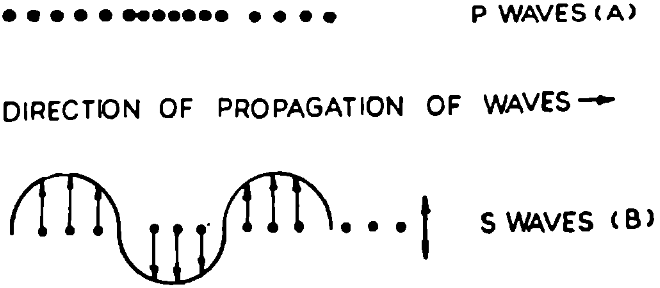


Fig. 2. Particle motions in P waves (longitudinal) and S waves (transverse).

They propagate only in the vicinity of earth's surface. These are of two types; for Love waves the particle motion is horizontal, transverse to the direction of propagation, while Rayleigh waves have elliptical particle motion, retrograde (moving backwards) at the surface in the vertical plane containing the direction of propagation (Fig. 3). The velocity depends upon the period of the waves.

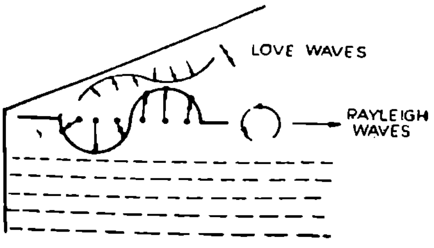


Fig. 3. Difference between Rayleigh and Love waves; particle motions as seen from one side.

Consequently, the surface waves are dispersive (Fig. 4a). The depth of penetration decreases with the period of the wave. The laws of propagation of seismic waves follow principles of optics, sound and theory of elasticity (Fig. 4b).

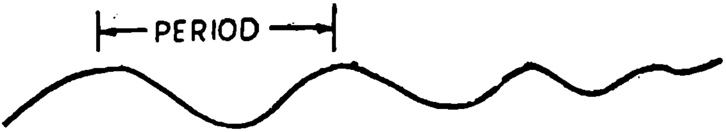


Fig. 4. (a) Dispersion phenomenon in surface waves; the period of waves decreases towards left and depends upon group velocity.

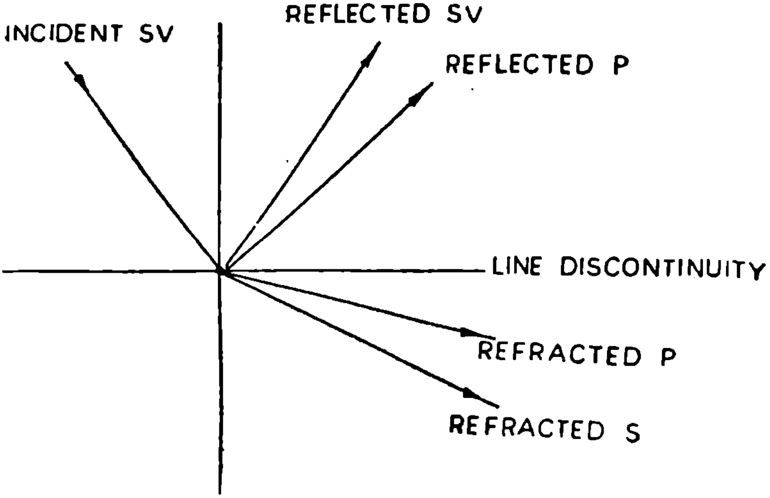


Fig. 4. (b) Phenomenon of reflection and refraction of seismic waves.

Earthquake effects due to body and surface waves are distinctly different and depend upon the type of structure and local geology. For example, shaking of a tall building in Delhi due to an earthquake with its epicentre about 900 km away in Hindukush region is attributed to the resonance between the longer period surface waves and the natural period of the building. (Surface waves require a distance of the order of the focal depth of the earthquake to build up in amplitude and are therefore effective at larger epicentral distances.) In such case, extent of damage is generally negligible. On the other hand, body waves from an earthquake with its epicentre near Delhi can shake more violently smaller houses. Such effects are used to develop intensity scales representing the severity of damage. These scales are used in risk assessment and disaster management.

Topographical changes

The primary effects of earthquakes over terrain are manifested in the form of offsets along known faults, fissures, scarps, elevation and depression of coasts which may occasionally be observed on the surface of the earth. Repeated opening and closure of ground fissures during severe earthquakes have been reported. Over hilly terrain, landslides are more common. Due to earthquake vibrations, the looser material at or near its maximum static stable angle may become unstable and move along the slope of the hill. The manner of movement depends upon the nature of the material. Large masses of dry earth and rock may slide over considerable distances, and they are named *earth avalanches*. If wet soil slips down the hill side, a 'slump' occurs. In rainy season, the soil and loose rock are sufficiently wet to be unstable. A slump may also occur during rainy season without an earthquake, but a large shock accelerates its formation. Both these effects depend largely on the steepness of the slope. Another phenomenon, known as *earthflows* is basically restricted to ground water. The earthquake is either accompanied or succeeded by a sudden burst of water from a locality where it normally appears in springs. The mud and sand are carried along with the water in a colloidal flow which could be destructive to buildings or fences coming in its path.

Liquefaction

The term *liquefaction* denotes a state in which solid deposits of sand inside the ground are transformed into a state of suspension, so that they behave as a viscous liquid. Under this condition, the foundation soil loses much of its strength, and consequently the structures on it are badly damaged or tilted.

Such consequences of earthquakes are often seen in alluvial deposits. Vast tracts of the plains of Uttar Pradesh and Bihar where the soil is generally soft and the water table is high, offer favourable conditions for such effects. The great Bihar-Nepal earthquake of 1934 produced a belt of slumping, extending from Bettiah in the north-west to Purnea in the south-east (a distance of nearly 320 km), surrounding the epicentral tract, in which all buildings were either tilted or sank in the soft alluvium. Subsidence of land was widespread over the region; there were innumerable fissures through which large quantities of sand and water were thrown up to the surface, thereby destroying the standing crop. The soil became totally unfit for cultivation.

The physical reasons for this phenomenon were only fully understood after the Nigata earthquake of June 16, 1964 in Japan (Fig. 5).

If dry sand is subjected to a shearing stress, its volume undergoes change. The extent of change depends on its density. If the sand is loose, it contracts, but if it is densely packed, its volume increases. If loose sand is saturated with water and subjected to the same amount of shear stress as in the dry case, no change in volume takes place. Under such a condition, the soil skeleton with a tendency towards contraction transfers some of its load to the water.The water pressure thus produced reacts, in turn, to prevent the change in volume. During an earthquake, the shear stresses generated affect the soil, and the excess pore pressure develops in undrained soil elements. Thus, the net or effective confining stress decreases and may become equal to the developed pore pressure. In this state, without an effective confining stress, the sand loses all its strength. Each sand particle is separated and thrown into the surrounding waters. In this manner, the sand mass is changed into a state of suspension and behaves as though it was fluid, thereby affecting the foundations of structures.

Tsunamis

Tsunami is derived from a Japanese word '*tu*' meaning a port and '*nami*' a long wave. Some tsunamis are caused by cyclonic storms over the sea but our main interest is in tsunamis generated by submarine earthquakes. These waves are often reported as 'tidal waves' which is a misnomer, because although they are recorded by the tide gauges, their generation is not related to tides. The velocity of waves is $\sqrt{gh}$ where g is the acceleration due to gravity and h is the depth of the sea. The periods of tsunamis range from 10 to

Fig. 5. Tilting of a multistoreyed building due to liquefaction of soil during Niigata earthquake (1964) in Japan. *Courtesy* : Shri S.K. Nag

Fig. 7. Damage to buildings due to November 23, 1980 earthquake (magnitude 6·9) in Italy. *Courtesy* : Mr. E.L. Krinitzsky, U.S.A.

40 minutes. Consequently, waves whose wavelength exceeds 100 km cannot be noticed on the open sea. However, as they approach a coast line, the depth and consequently the velocity decrease, so that the waves increase in height as the wavelength decreases. They thus become most destructive upon reaching narrow part of a V-shaped harbour, where the increasing height of the wave breaks it, flooding the low lying ground in the vicinity. Tsunamis may also be caused by the sudden subsidence or ascent of large areas of the sea floor associated with destructive earthquakes. The hydrographic survey in Japan after the great Kwanto earthquake of September 1, 1923 showed that vertical displacements of the order of 100 metres had occurred over a large area of sea floor.

Tsunamis are very common over the Pacific Ocean because it is surrounded on all sides by a seismically active belt. In the Hawaian islands, tsunamis approach from all directions, namely, from Japan, the Aleutian islands and from south America. On the other hand, the Indian coastal belt does not offer a favourable location for the generation of tsunamis. However, waves accompanying earthquake activity have been reported over the north Bay of Bengal. During an earthquake in 1881, which had its epicentre near the centre of the Bay of Bengal, tsunamis were reported. This was unusual because most tsunamis are generated by shocks which occur at or near the flanks of continental slopes. During the earthquakes of 1819 and 1845 near the Rann of Kutch, there was rapid movement of water into the sea. There is no mention of waves resulting from these earthquakes along the coast adjacent to the Arabian sea, and it is unlikely that tsunamis were generated. Further west, in the Persian Gulf, the 1945 Mekran earthquake generated tsunamis of 12 to 15 metres height. This caused a huge deluge, with considerable loss of life and property at Ormara and Pasi. The estimated height of waves was about 2 metres at Bombay, where boats were taken away from their moorings and casualties occurred. Fig. 6 shows the tsunamis warning system used by U.S. Geological Survey.

Pattern and causes of damage

Buildings

Buildings are often damaged during earthquakes (Fig. 7), particularly if they are constructed with brick, mud or timber, Reinforced

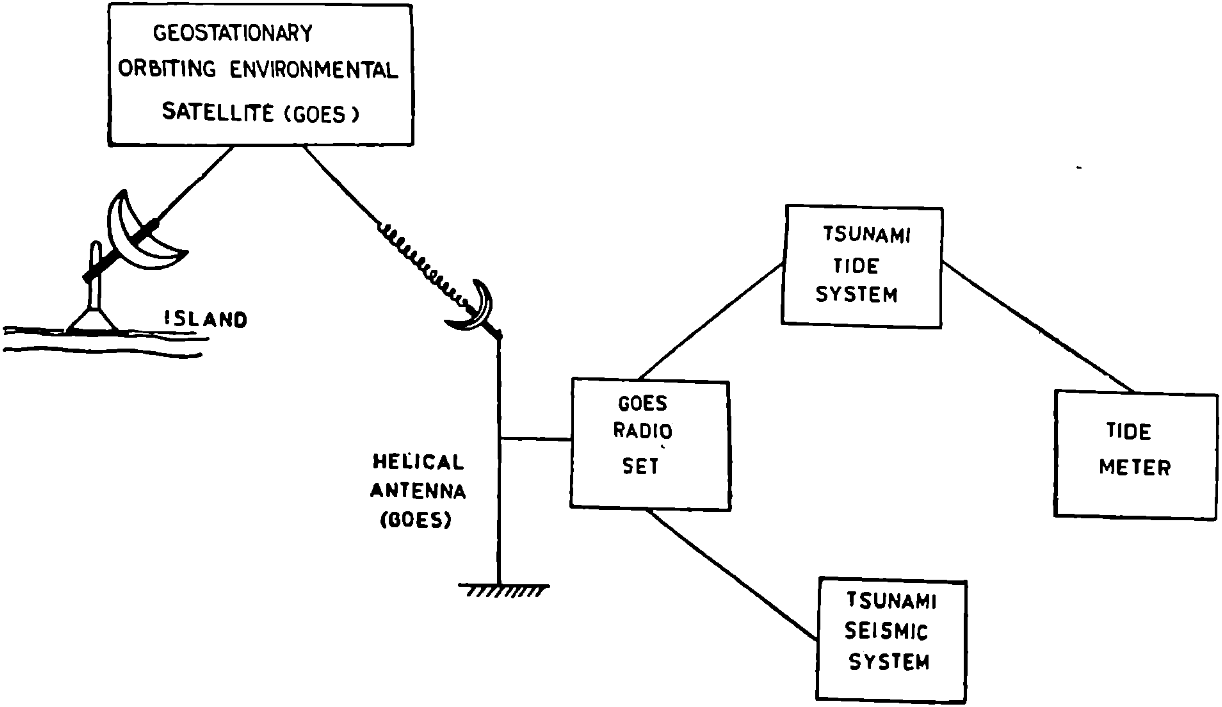


Fig. 6. Tsunami warning system through satellite.

concrete buildings suffer the least damage, while effected abodes and unreinforced brick buildings have been severely damaged during earthquakes in different parts of the world. Projecting cornices, balconies, towers and arcades render the building more vulnerable.

The reason why buildings are damaged by earthquakes is easy to understand. An earthquake sets up an oscillating (backward and forward) motion of the ground. Close to the epicentre, there is also a vertical movement. Due to the earthquake, the foundations of a building move with the ground, but the inertia of the rest of the building prevents it from moving instantaneously, and there is a slight delay before the upper portions start moving. This delay leads to differential stresses and subsequent cracking because the roof tends to separate from its support and the walls tend to be torn apart. The force exerted on a building due to earthquake depends upon the weight of the building as well as the movement of the ground. It is more if the building is heavier. Consequently, in earthquake prone regions it is essential to have light weight buildings with lighter roofs. The effects of foundation like liquefaction or closeness to fault add additional earthquake risk (see Chapter 5). Rapid progress in earthquake engineering has standardised techniques for earthquake resistant design of buildings in different seismic zones. In general, well-burnt bricks, specified proportion of mortar, lintel band in concrete over the windows and doors at the same level in walls of appropriate thickness, better workmanship in reinforced concrete buildings are the measures for preventing structures from collapse during an earthquake.

Damage to transportation system

Damage to transportation systems includes highways, railways, airports, marine and river systems, water supply and sewage, fuel and oil, energy transmission and communication systems. The facilities of transportation include those built on surface and those built underground. The effects of earthquake on these two types of structures are different. The underground structures, like petroleum pipes, are mainly governed by the strain in the surrounding ground caused by the propagation of earthquake waves, while the surface structures like the bridges are governed by the vibrating response of the structure to earthquake ground motion. The second category of damage arises due to the blocking of roads by jammed cars, fire, uprooted electric poles and collapsed buildings. Blocking of highway systems may stop various activities needed for post earthquake relief and rescue . Some detailed effects of earthquake damage on important transportation systems are given below.

Bridges : Damage to bridges can be subdivided into three parts, namely, damages to superstructures, substructures and approach portions. The damage to superstructures consists of collapse of girders, local buckling and breaking of girders, uprooting of anchor bolts, disjointing of hand rails and girders, permanent displacement and cracking of each part of the superstructures. The damage to substructures consists of sinking, overturning, tilting, cracking and breaking of piers and abutments, deformation of supports, buckling of piers and spalling of concrete. The damage to approaches consists of settlements, sinking, cracks of embankment, permanent settlement, deformation, cracking and spalling of retaining walls.

Tunnels : Earthquake damage to tunnels is significant if it passes through an active fault or a weak rock zone where dislocation of tunnel alignment and breaking of its lining may take place due either to the fault slipping or by partial pressure in the weak zones where a tunnel passes through a debris zone. Deformation and cracking of tunnel linings is caused by displacement and settlement of debris due to ground shaking.

Railway system : Damages to railway systems include rail tracks such as rails sleepers and sub-base, rail line structures such as bridges, tunnels, retaining walls, slopes and shore protection works, station structures, office and workshop buildings, electric power transmission lines and engines. Changes in horizontal and vertical alignment of tracks have a severe effect on railway transportation, thereby causing derailments.

Water supply system : The water supply system includes the intake and filtration plants and distribution pipe system. Destruction may occur in reservoirs causing failure of pumps by the shearing of anchor bolts induced by ground shaking, cracking or destruction of reinforced concrete tanks and basin. Dislocation of pipes and leakage of chlorine gas may occur in the chlorination plant and buckling of cylindrical walls of steel tanks. Even more damage is caused to the pipe systems in which there may be disconnection of joints, breaking of valves and buckling of pipes.

The extent of damage to water supply systems also impairs the fire fighting capability.

Earthquake lights

Different kinds of earthquake lights have been reported before, during and after severe earthquakes. Some observers have seen red, blue or white glows, while others have described them as balls of fire or flashes towards the sky. Such observations have been assigned different causes. Some attribute them to the lightning from a thunder cloud, some to sparks in the electric power lines, while others to the generation of static electricity in the vicinity of focal zone of earthquakes where relative movements of rocks may produce heat and light. Over the sea, such light could arise from luminous marine organism excited by the vibrations produced by the earthquakes.

Earthquake lights have been reported before Matsushiro swarms during the years 1965 to 1967 and before some recent earthquakes in China. During the Pattan earthquake (Pakistan) of December 1974, earthquake lights rising towards sky were observed by reliable forest officers and doctors far away from the earthquake epicentre. Experiments have been conducted at the University of Western Ontario, London (Canada) to understand the possible mechanism of earthquake lights. It has been suggested that adsorption or condensation of water could be thought of an energy source for the release of light from solid particles suspended in a cooling column of air above ground.

Earthquake sounds

Audible sounds associated with local earthquakes have been reported at several places in the world. The description of such sounds heard in the open air far away from man made structures has been described like the rumble of a distant thunder or the rushing of a wind. In the vicinity of man-made structures, the characteristics of sounds are often complicated by the falling objects and mechanical effects like resonance. In peninsular India, rumbling type of sound associated with earthquake swarms have been reported during the year 1966 in Tambaran (near Madras) due to local crustal adjustments. These occur in quick succession some of which are felt in the region but the associated sound creates more panic. However, important features of these swarms is that they die out after a period ranging from days to months without causing a big event or damage.

Some shocks like the San Francisco (USA) earthquake of 1906 and its after shocks, were reported to be preceded by sounds. Similarly, sounds were frequently heard during Matsushiro swarm in Japan during 1965-67. Scientific recording and investigation of such sounds have been reported for the first time for earthquake swarms during January 1975 near Brawley, California (USA) in Imperial valley. The recording system was a Sony TC-126 portable stereo cassette tape recorder with a flat frequency response from 50 Hz to 10 kHz (in the audible range). A microphone was fixed at one end of a stick 0·5 metre above the ground with its axis directly upward. The other end of the stick was firmly planted in the ground. The recording of seismic signal was done on the second tape channel. A short period (one second) seismometer (described later in this book) was buried close to the microphone and was connected to a preamplifier before connecting it to the tape recorder. Recordings were done only during the night time to minimise the effects of the ambient noise level.

The analysis of records showed that the audio signal begins about 0·06 second after the first earthquake wave motion called the *P* waves. It has been established that there is some delay, howsoever small, between the onset of *P* waves and the sound waves. The predominant frequencies in the audio signal lie between 40 to 70 Hz. It has been suggested that earthquake sounds are generated by seismic waves for local earthquakes which couple directly into the atmosphere through local ground motion at the earth's surface.

It may, however, be mentioned that although earthquake sounds are heard before shaking is felt (which may begin with the onset of slower moving *S* waves generated at the earthquake focus), the possibility remains that microfracturing in the source region of some earthquakes may produce premonitoring audible sounds hours to days before the earthquake. This was indeed the case for some earthquakes in Garm region of the USSR in 1966.

It may thus be summarised that earthquake sounds and lights may sometimes be of prognostic value which even lay persons can report, thus providing additional information than that gained through instrumental techniques for earthquake prediction.

CHAPTER 2

Instruments For Earthquake Forecasting

TECTONIC EARTHQUAKES ARE ATTRIBUTED TO RUPTURE IN THE ROCK masses which occurs following accumulation of strain. Earthquake prediction techniques, therefore, involve measurements of strains which are maximum in the neighbourhood of rupture or along the weakest rocks. Monitoring of earthquakes down to the smallest detectable level throws light on the development of cracks in these rocks and is of fundamental importance in earthquake forecasting. Also, changes in the physical properties of rocks in the focal zone preceding earthquakes bring out the need to measure geomagnetic and geoelectric properties in the region. Instruments have accordingly been developed which are briefly discussed here.

Seismographs

Seismographs are used to record earthquake motion and other seismic vibrations. They consist of a transducer which is basically an inverted pendulum with a device to damp motion (i.e. applying a force to oppose its motion) to write the movements of the pendulum on a photographic, heat sensitive, smoked or ink writing plain paper, a film or a magnetic tape recorder (Fig. 8). An accurate time marking, device usually a crystal clock, is used to impinge the time (hours and minutes) on the records which enable us to find the onset times of various seismic waves from which the epicentral distance of the earthquake, its origin time, magnitude and epicentre can be determined from the data of several stations through the help of electronic computers. With prior knowledge of seismic wave velocities in a region (or a velocity model with detailed crustal structure, etc. from earthquakes or better by calibration of the area

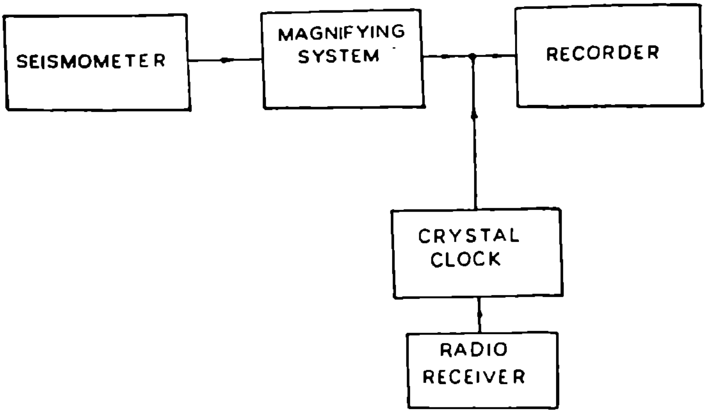


Fig. 8. A simple seismograph system (schematic).

with chemical explosions at specified locations, the monitoring of local earthquakes can be considerably improved if there are at least ten stations well distributed in azimuth. Theoretically, only three stations are needed to determine epicentre using elementary theorem of geometry that only one circle can pass through three points not on a straight line (Fig. 9). For focal depth determination, at least four stations are needed. For distant events, world-wide data are needed and Jeffreys Bullen Travel time tables are generally used. (Table I). Focal depth determinations still pose great

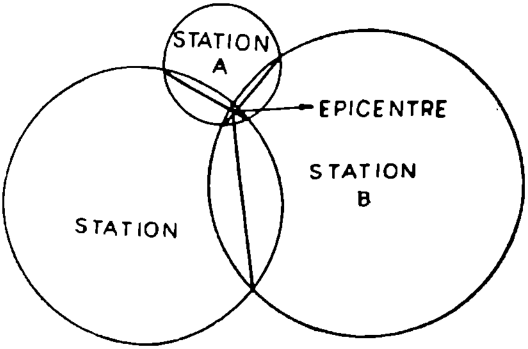


Fig. 9. Finding the epicentre of an earthquake from three stations A, B and C. The point of intersection of three circles is the epicentre.

TABLE 1. **Jeffreys Bullen (1948) travel time tables (abridged)**

	Time of P-wave				*Time of S-wave*			
Focal depth (km)	0.0	96	350	730	0.0	96	350	730
Distance △°	M-S	M-S	M-S	M-S	M-S	M-S	M-S	M-S
0.0	(6.8)	13.5	43.9	22.8	(10.7)	23.6	1-18.3	2-28.6
5.0	1-18.1	1-14.1	1-20.1	1-41.4	2-17.5	2-11.1	2-23.0	3-2.0
10.0	2-24-0	2-22.2	2-18.8	2-21.4	4-22.2	4-13.2	4-8.6	4-13.8
20.0	4-37.0	4-27.1	4-7.9	3-51.3	8-17.1	8-1.6	7-28.3	6-56.3
30.0	6-12.5	6-01.6	5-39.2	5-17.4	11-10.2	10-51.1	10-10.9	9-31.6
40.00	7-38.1	7-26.7	7-3.2	6-38.9	13-44.5	13-24.8	12-42.9	11-58.4
50.00	8-58.0	8-46.4	8-21.6	7-54.4	16-8.6	15-48.3	15-4.4	14-15.8
60.00	10-10.7	9-58.7	9-23.5	9-2.6	18-22.6	18-1.8	17-16.2	16-23.7
70.00	11-15.4	11-03.1	10-35.9	10-4.2	20-25.6	20-4.4	19-17.1	18-20.8
80.00	12-12.7	12-9.2	11-32.3	10-58.7	22-16.5	21-54.7	21-5.8	20-6.6
90.00	13-02.7	12-49.8	12-21.4	11-46.7	23-54.5	23-32.2	22-41.6	21-31.5
100.00	13-48.4	13-35.5	13-07.1	12-32.1	25-20.4	24-57.9	24-6.9	23-3.9
104.00	14-06.2	13-53.2	13-20.3	—	25-53.8	25-31.3	24-40.2	—

Note : The calculation of distances is done by changing angle in degrees using 1° = 111 km (M-S = Minute second) problems, though they can be fairly reliable for a large network of stations close to epicentre or if the depth phases (pP) can be identified on a seismogram.

Simple direct recording seismographs were widely used until 1930. Of these, the torsion seismometer developed by Wood Anderson which led to the definition of local magnitudes in Richter Scale is still helpful for deriving other magnitude scales. It consists of a metal fibre suspension held taut by a small weight attached to the side of a copper cylinder which can rotate about the fibre against the restoring force of torsion. The cylinder is kept in a permanent magnet through which eddy currents are induced in the copper when it moves due to seismic waves. A small mirror is fixed to the copper cylinder on which light falls from a distance. With the passage of seismic waves, there is a deflection of light spot due to twisting of the fibre which is recorded photographically.

The most widely used seismometer is the electromagnetic type which is based on the laws of electromagnetic induction. The electromotive force (or voltage) generated is generally proportional to the velocity of pendulum motion which determines the rate at which the lines of force (of a permanent magnet) are cut. The current so produced due to seismic disturbances is passed through a galvanometer with an attenuating network depending upon the ground noise to adjust overall gain, and finally recorded photographically from the mirror of the galvanometer (Fig. 10). Recent

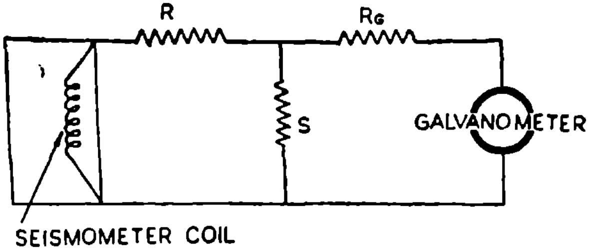


Fig. 10. Principle of an electromagnetic seismograph. R is the total resistance in the seismometer side (including internal resistance of coil). R_G is the total resistance in the galvanometer side of the circuit and S is the shunt resistance. These resistances forming a T-pad can be adjusted to the required gain depending upon the ground conditions and the sensitivity of the galvanometer and the seismometer.

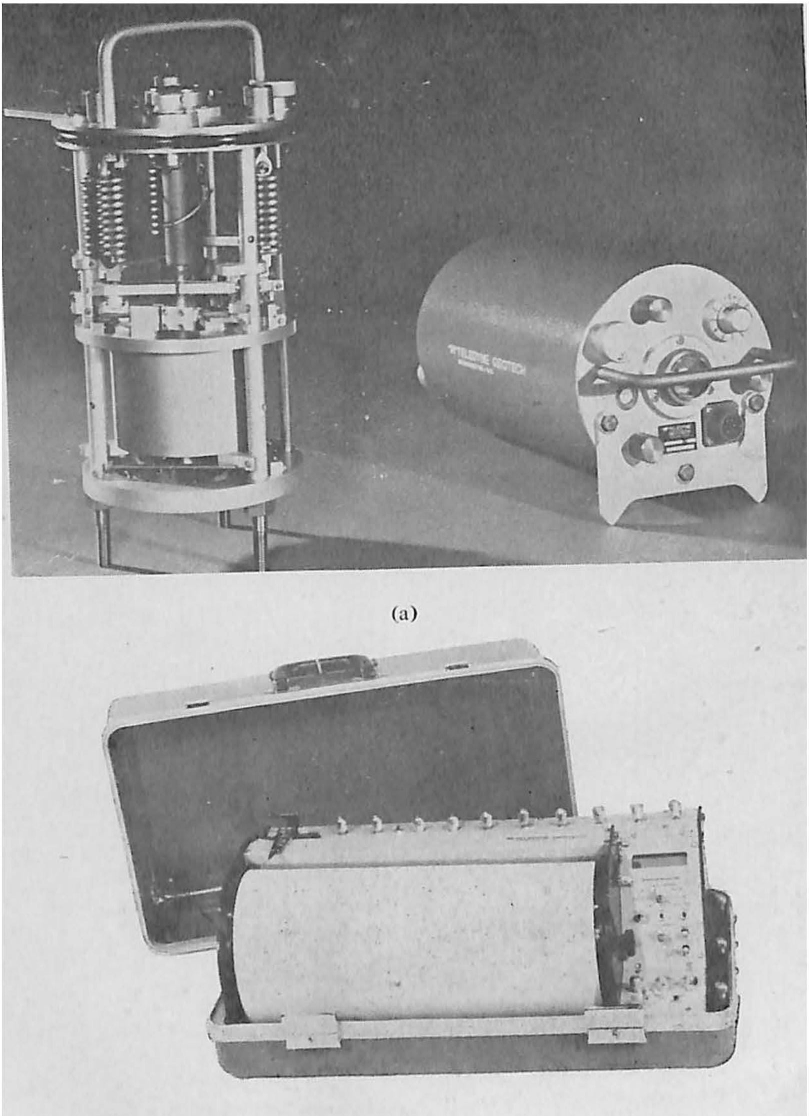


Fig. 11. Portacorder (Geotech) System. (a) Seismometer (b) Recorder. *Courtesy* : Geotech, U.S.A.

developments in electronics allow the use of high gain amplifier upto dynamic range of 120 dB with the electromagnetic seismometers which enables to record earthquakes down to magnitude—3.

The characteristics of ground motions in the entire field of seismology approximately range from about 0.00025 Hz (1 cycle per hour) to about 100 Hz with amplitudes of the order of a few millimicrons to a few millimetres (or rarely a few centimetres in case of surface waves from great earthquakes). Thus no single instrument can cover the entire range. We are now having seismographs designed for local earthquakes and teleseisms. For surface waves long period seismographs, called Press Ewing type, are used with seismometer period of 30 seconds combined with galvanometer period of 100 seconds in standardised instruments of US Geological Survey. In the shorter period range, Benioff seismograph which works on the principle of a telephone receiver of variable reluctance type is still in use. Some of these instruments are being made by the India Meteorological Department.

Figure 11 shows the seismograph system for recording microearthquakes made by Geotech Co., USA. The portable recording system is portacorder which has enabled us to operate at a magnification of a million at quiet sites on rocks.

Calibration techniques for seismographs are available like shaking table which determine the gain of the system at different frequencies from which the actual ground motion can be deduced. Figure 12 shows the response curves of some seismograph systems.

A standard seismological observatory consists of three components (one vertical and two horizontal seismometers) of short period, three similar instruments for long period, a pair of Wood Anderson Seismographs and an accelerograph (which actuates for a few seconds after the onset of a damaging earthquake and records ground acceleration on a film due to very short period pendulums). The cost of a seismological observatory along with instruments and buildings is of the order of Rs. 300,000 ($40,000 US).

Although the fundamental principles of all seismographs remain the same, a few systems have been developed for specific purposes.

Seismic arrays

If a number of seismometers are placed to form a pattern like the alphabet L or X and their outputs are combined, the resulting

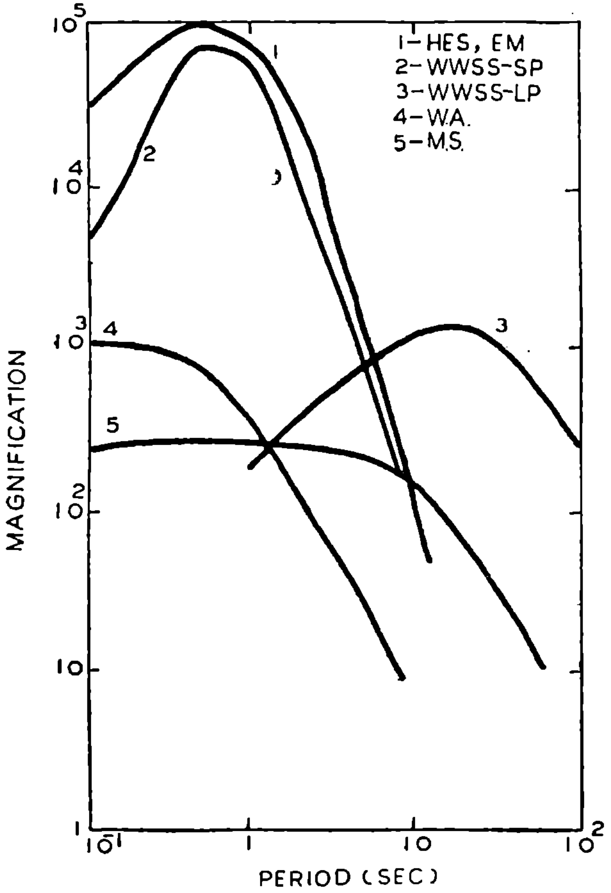


Fig. 12. (a) System response curves for (1) Hagiwara Electromagnetic Seismograph (HES); (2) World wide standardised Seismograph (WWSS) short period, Benioff type; (3) WWSS long period; (4) Wood Anderson (WA); (5) Milne Shaw (MS);

system is called a seismic array, which can operate at a very high gain. In its design, advantage is taken of the fact that seismic noise propagates with different speeds than the seismic signals that are

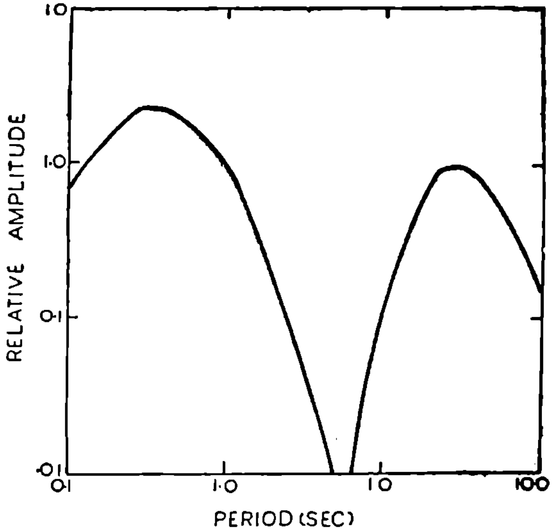


Fig. 12. (b) System response curves for Seismic Research Observatory System (Shillong). *Courtesy* : Geotech.

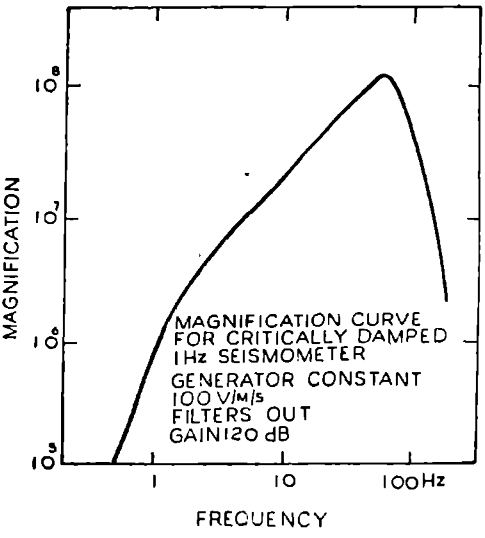


Fig. 12. (c) System response curve for Dyneer Sprengnether, MEQ-800. *Courtesy* : Dyneer, Inc. USA.

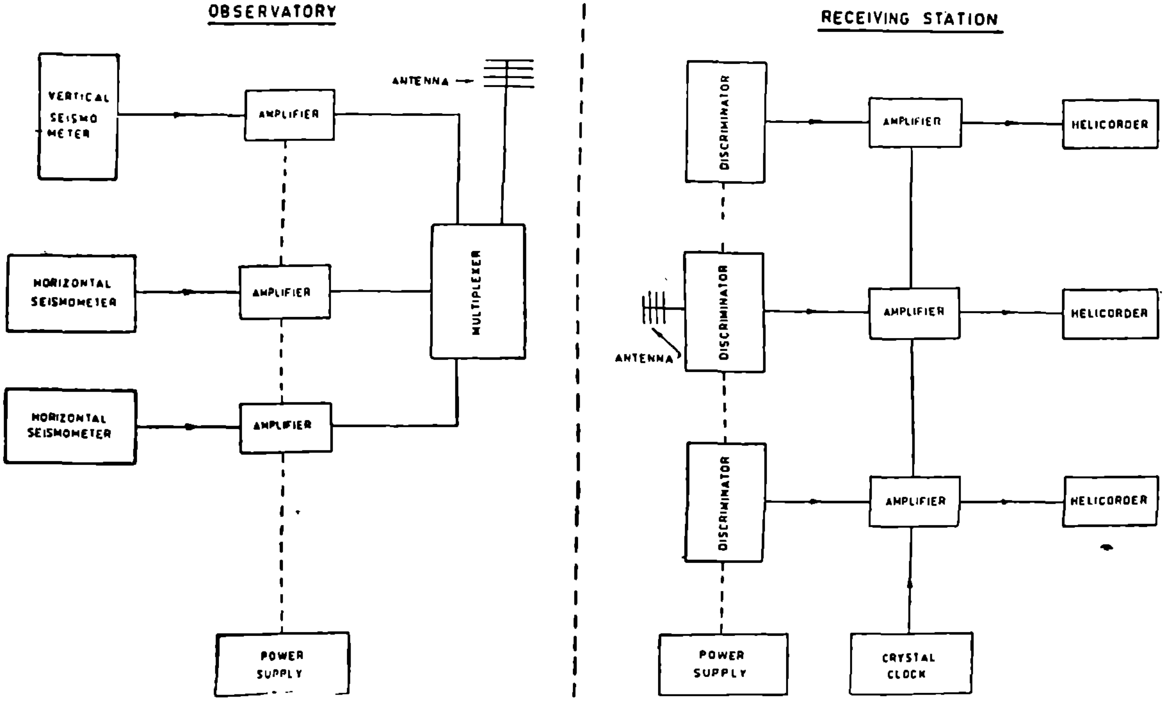


Fig. 13. Principle of a telerecording seismograph. Line of sight condition is essential between the seismological station and the central recording station in VHF range.

usually of interest. By time shifting the output of the various detectors by an amount corresponding to the surface velocity of the desired signal across the array, this signal is further enhanced over the straight summation process as compared to noise (which is random) giving considerable improvement in the signal to noise ratio. The direction of approach of the signal may be determined by comparing the time of arrival of an event at various elements of the array. From the apparent surface velocity and knowledge of the true velocity in the surface layer of the kind of body waves (P or S), the angle of incidence can be derived, providing an added tool for identification of phases, specially crustal phases from regional and local events. Although primarily meant to detect underground nuclear explosions, arrays have yielded valuable data to the seismologists for studying earth's interior down to its core. In India, one such L-shaped array with 20 short period and 5 long period seismometers operates at Gauribidanur under Bhabha Atomic Research Centre, Bombay.

Telerecording seismographs

A set of electromagnetic seismographs called array with a central recording system with multichannel tape recorder is generally used for monitoring micro-earthquakes in difficult terrains such as mountains. Line of sight condition between the seismographs which have a transmitter operating in VHF range and the central recording system is essential. Seismometers are of electromagnetic type with associated high gain amplifiers. Frequency modulation is used for transmission after which seismic signals are demodulated, amplified, filtered and recorded on ink writing or heat sensitive paper. (Fig. 13). A Digital Data Acquisition system receives data from the telemetry discriminator, converts to digital form and stores them on computers compatible tape. Triggering arrangements have been incorporated in the system to start the data recorder according to a certain criterion. Solar batteries are used in the system which overcome the problem of charging conventional batteries in remote areas. Solar panel, antenna and transmitter can be mounted on a metal mast which can be tied to the trunk of a trimmed tree. Complete system is commercially available from Kinemetric or Geo Tech Co. USA, but can be designed locally. The main advantage of this system is that the time base is common for all the stations. Thus the errors in the comparison of clocks at different stations can be eliminated.

Ocean bottom seismographs (OBS)

The use of ocean bottom seismographs is meant to secure an improved global coverage of seismic waves, thus providing new information on oceanic regions. Such instruments have been developed in USA, Japan and UK.

One type of ocean bottom seismograph contains three gimbal mounted, moving coil seismometers of 1 second period or less, a pressure transducer, a crystal clock, amplifiers, slow speed tape recorder and batteries. These are housed in a hollow, pressure resistant aluminium sphere which has an outer diameter of 1 metre with 2·54 cm thick walls. The assembly is dropped to the ocean bottom with no connections to the land or even to the surface. At the end of a predetermined time interval, the instrument package is broken loose from the base plate and pops up to the surface. A radio beacon and a flashing light are activated to make recovery possible. Data can be recorded for a period of 30 days on magnetic tape recorders.

In another type, the instrument is connected by cable to shore upto distances of 100 km from the coastal stations. The technique is more expensive but offers a more or less permanent recording site and has shown promise in revealing the seismicity along continental margins or important island arcs. Alongwith seismometers, a wide variety of other sensors like gravimeters, tiltmeters, hydrophones, etc. is housed in three pressure tight hemispheres that are mounted on a triangular base which rests on three large circular feet.

Seismic Research Observatory (SRO)

Seismic Research Observatory system combines a newly developed broad band bore hole seismometer and a computerized recording system. (Peterson et al, 1976) In order to reduce wind generated noise in the long period band, the seismometers are installed in bore holes at a depth of 100 metres. The characteristics of these seismometers are such that their output is flat in acceleration between 1 and 50 seconds periods which are used to produce both short and long period data and are recorded in analog (on heat

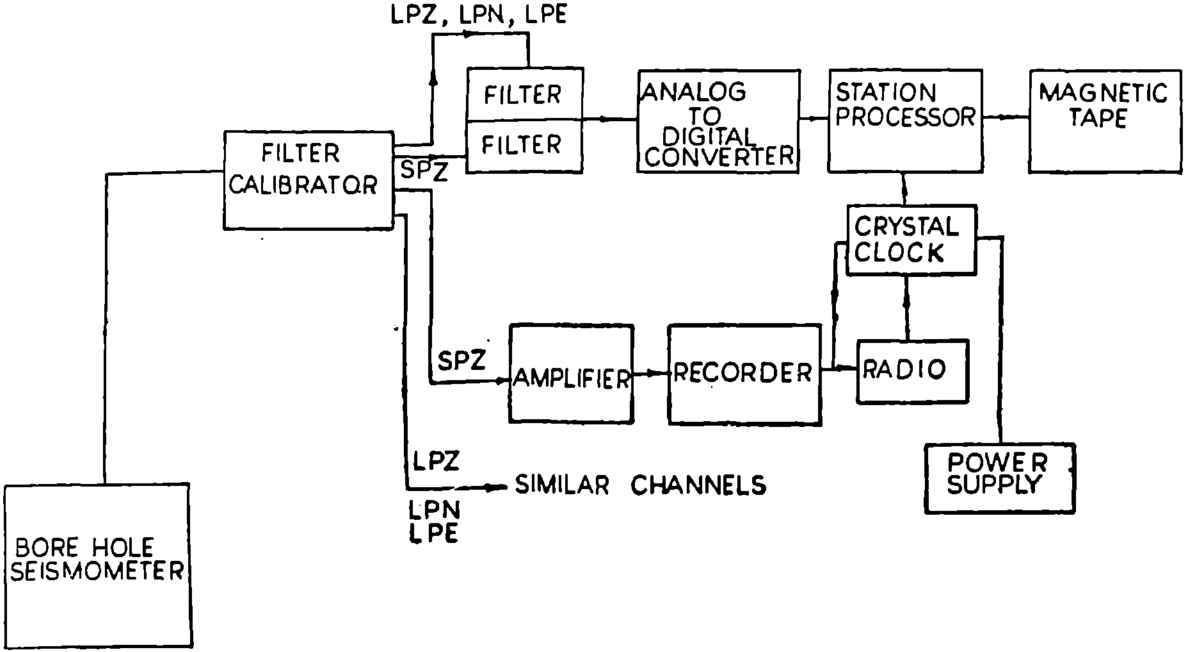


Fig. 14. Principle of digital and analog systems of Seismic Research Observatory.

sensitive papers) as well as in digital form (using magnetic tapes) (Fig. 14). The sensors are force balance type with capacitive transducers. The seismometer is designed for installation in 18 cm oil well casing. The digital recording system consists of filters, analog to digital converter, a station processor, two magnetic tape transports, a digital to analong monitor, a digital clock and a teletype writer. The station processor is a 16 bit mini computer with 16 K of core memory. The analog to digital converter samples the long period channel once each second and the short period channel 20 times per second. Long period digital data are recorded continuously on magnetic tape while short period data are recorded only when an event occurs. There are at present 13 such observatories in the world including one at Shillong, which provide valuable data for research in seismicity and source parameters of earthquakes. The data are specially suited for studies requiring filtering operations or spectral computations and can be directly used on computer. In addition to detecting small yield nuclear explosions which has been made possible by increasing gain in longer periods, the SRO is providing volumes of data for research in seismology (Fig. 15).

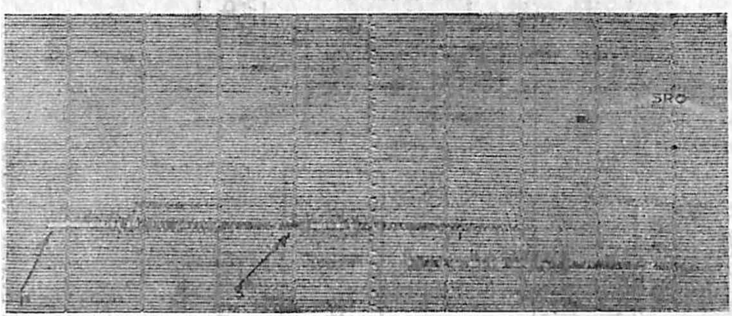


Fig. 15. Seismogram of near earthquake showing P and S phases recorded at Seismic Research Observatory, Shillong. The onset has been marked by arrows. *Courtesy* : India Meteorological Department.

Crustal deformation measurements

Crustal deformation is attributed to the accumulation of tectonic strain which may precede earthquakes. It is expected that for verti-

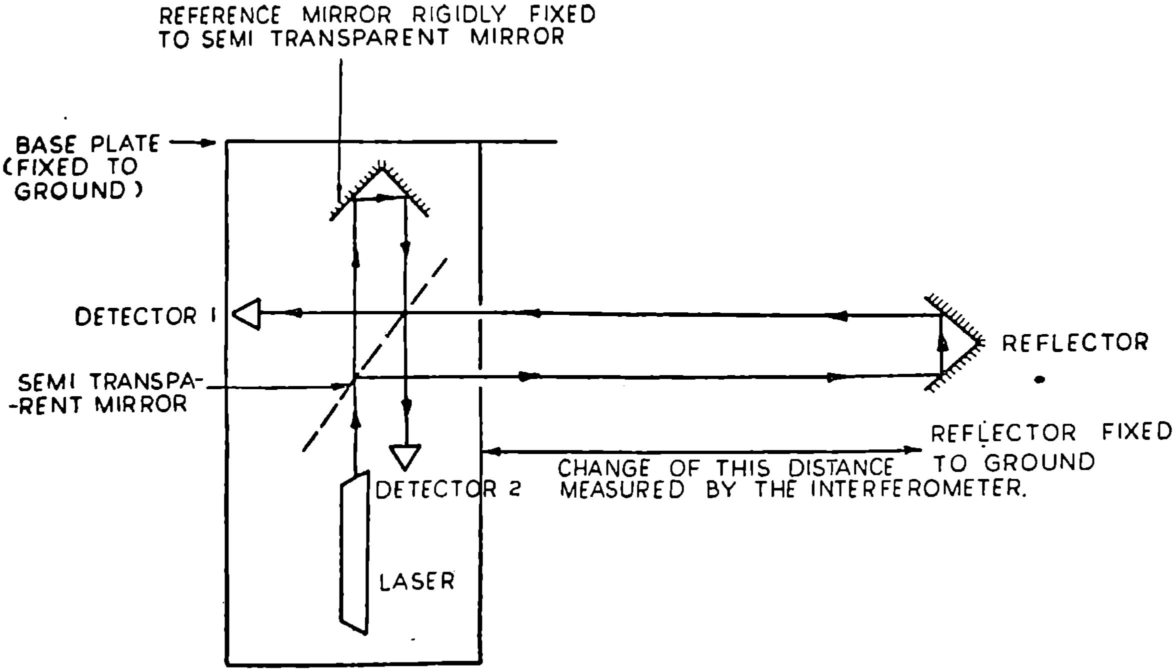


Fig. 16. Principle of laser strain interferometer (Michelson type).

cal, horizontal or oblique shears, if the surface becomes strained through an angle of about 1/2000, we could expect a strong earthquake. Instruments can therefore be used at periodical intervals through triangulation survey or geodimeter survey which reveal strains along the lines joining successive piers in the fault zones. The distances between two points embedded on either side of fault zone can also be measured continuously with the help of instruments called strainmeters or extensometers. On the other hand, tiltmeters are used to measure the tilting of the ground. Land uplift or subsidence relative to sea level can be detected through tide gauges.

Strainmeters consist of some standard length like a tube rod made of quartz or silica or laser beam which extends between two points on the earth's surface. One end of the standard of length is kept fixed anchored to the basement rock and the other end which is kept free, is used to measure relative displacement. Recording system may employ optical lever, a capacitance or inductance transducer. The signal to noise ratio of a strainmeter for tectonic studies is proportional to its length. Lengths as great as 100 metres have been used at Matsushiro Observatory in Japan. Location of strainmeters in a deep site, such as a mine, provides a more reliable coupling to the bed rock, eliminates diurual and seasonal heating and cooling and provides an extremely stable atmospheric environment for the instruments and, therefore, better signal to noise ratio can be obtained. However, it does not allow a freer choice of sites. Nowadays, special vaults are built underground a metre or two below the earth's surface which is quite insulated and helps in eliminating local strain noise near the surface.

The development of laser as a coherent light source and the principles of optical interferometry enabled the design of laser strain interferometer (Fig. 16). In its simple form, it consists of a Michelson interferometer consisting of a source, beam splitter and the fixed arm on one pier and the long arm mirror on another pier at a known distance. The light returning from the far end is mixed with the light from the local mirror to produce the classic fringe pattern. The long arm path is generally evacuated to reduce the effects of refraction corrections. The change in distance is detected in terms of integral number of half wavel ngth. For the helium neon laser and one kilometre interferometer, the least

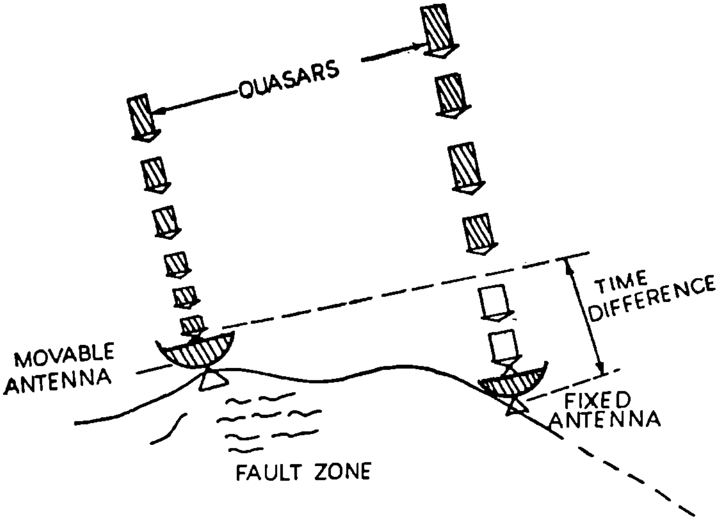


Fig. 17. Vertical deformation of earth's crust measured through quasars.

count strain is 3×10^{-10}. Another model is called Febry Perot interferometer.

The latest technique in crustal deformation measurements makes use of quasars which are radio emissions from quasi stellar objects billions of light years away (Fig. 17). In view of their extreme distance from the earth, their positions relative to one another within the framework of the sky remain unchanged. The random radio signals from a quasar may be compared with the sounds of a distant gunfight and the arrival time of each gunshot can be monitored at two antennas.The lag in the arrival time at one antenna (kept in a fault zone) relative to the other (away from the fault zone) with the help of an accurate clock would indicate the distance from quasar like gunfight. Deformation of earth's crust prior to an earthquake would cause a change in this, thus indicating an impending earthquake.

Tiltmeters

A horizontal pendulum (where a pendulum weight oscillates almost in horizontal plane) type of seismograph such as Milne Shaw instrument has been used as a tilmeter whose period of oscillation is large. If the axis of a horizontal pendulum undergoes slight tilting, the weight tends to rotate with a fairly large angle and enables one to measure ground displacement. The movement of the pendulum weight is amplified by an optical lever and recorded on a photographic paper. Simple mechanical tiltmeters are now considered out of date as they are effected by meteorological and other factors. The instruments should be capable of monitoring tilts as small as 10^{-8} to 10^{-9} radians.

Water tube tiltmeter

If two water pots are placed on the ground at a distance of several metres and connected with a pipe, changes in the difference in height of water surface are proportional to the tilting of the ground where the system is installed (Fig. 18). For this purpose, long underground vault are necessary to reduce atmospheric and other effects.

In India, portable water tube tiltmeters using the above principle designed by Agarwal and Gaur (1968) are being used at some places which permit resolution of relative vertical displacements up to $\pm 10\mu$ using a micrometer spindle.

Bore hole tiltmeters

These have been developed to monitor free surface tilts for placement in bore holes to achieve temperature stability required for operation at high sensitivity. The instrument is cheap and does not require special vaults.

Bore hole tiltmeter consists of a 50 cm vertical pendulum which in combination with a pair of closely spaced capacitor plates constitutes a differential capacitance bridge. A signal is recorded electronically depending on the direction of tilting of the pendulum from the vertical.

Tide gauge

Tide gauge employs the principle of recording the vertical motion of a buoy floating on the surface of sea water which is taken to a well where waves of short period are damped out.

The interpretation of tide guage observations is sometimes rendered difficult due to anomalous descent of the sea level associated with abnormal state of the oceanic current or changes in

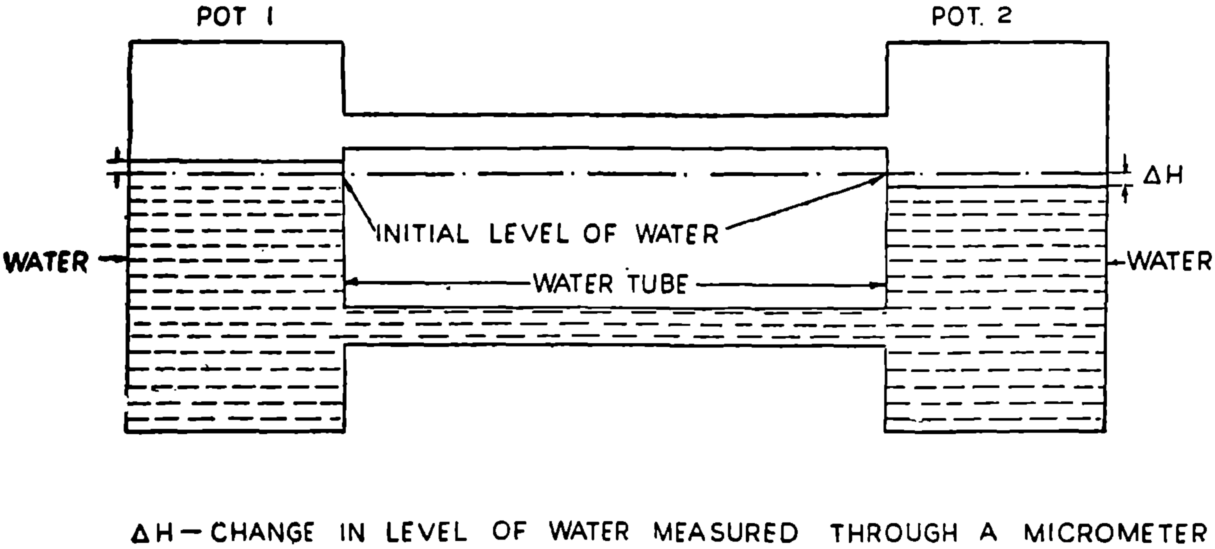


Fig. 18. Principle of a water tube tiltmeter.

atmospheric pressure, water temperature, wind, etc. In order to reduce these effects, the observed height of sea level at one tide gauge station is compared with neighbouring stations. In general, the results of levelling surveys over land massess should agree with tide gauge observations near the coast.

Resistivity measurements

Variometers

Variometers which record ground resistivity continuously consist of four electrodes buried in the ground several metres apart in a straight line. An alternating current is put into the ground with the outer two electrodes. The apparent ground resistivity is proportional to the voltage across the two inner electrodes. This method is used in Japan where small variations in resistivity before and during earthquakes have been detected.

Dipole-dipole method

The method basically consists of two pairs of electrodes—the transmitting dipole and the receiving dipole. The transmitting dipole (the source) is usually several kilometres away from the receiving dipole. Direct current is passed to the ground via the source dipole. At the receiving dipole, a record is made of the corresponding voltage change, which is proportional to the current input at the source dipole, the apparent resistivity between the transmitting and the receiving dipoles, and to some factor determined by the geometry of the arrangement. For a given geometry, the ratio of voltage differences to the known magnitude of input current is proportional to the apparent resistivity. The arrays of electrodes are laid in the seismic zones.

Proton precession magnetometers

Within the outermost kilometres of the earth, minerals with ferromagnetic properties are found. The local distortions of the magnetic field are related to the earth's crust in which magnetic properties of rocks like susceptibility and permanent magnetisation play an important role. The second application is to analyse the past history of earth's magnetic field making use of permanent magnetisation alone. Of the various type of magnetometers, proton precession magnetometer is widely used for these measurements (Fig. 19).

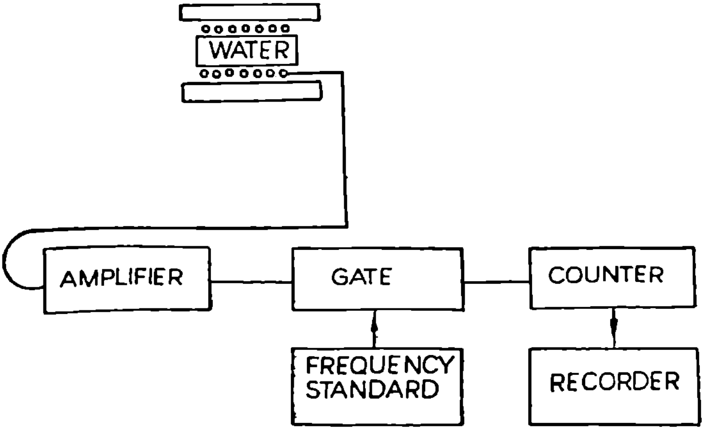


Fig. 19. Principle of Proton precession magnetometer.

Its principle is based on the precession of nuclei (protons) around a magnetic field direction by passing an electric current through a coil which induces a magnetic field along which the magnetic elements of protons arrange themselves. Measurement of magnetic fields depends upon the precise measurement of the frequency of this precession around a conical axis of the geomagnetic field. The instrument consists of a sample container (water filled cylinder) surrounded by a coil, with electronic switching to permit the coil to be connected in turn to a d.c. supply or to a high gain audio amplifier and frequency counter. The frequency is counted during the few seconds that the signal persists. After the signal has decayed exponentially towards zero, the sample may be repolarized. The total magnetic field is measured with prior calibration based on laboratory results.

The frequency f is related to the strength of the geomagnetic field F by

$f=k.\mathrm{F}/2\pi$, where $k=26751\cdot 3$

Gravimeters

It is simply a mass suspended on a spring arranged in such a way that detectable changes in the system will occur when it is set up at places where the acceleration due to gravity is different. Modified systems are used with moving ships.

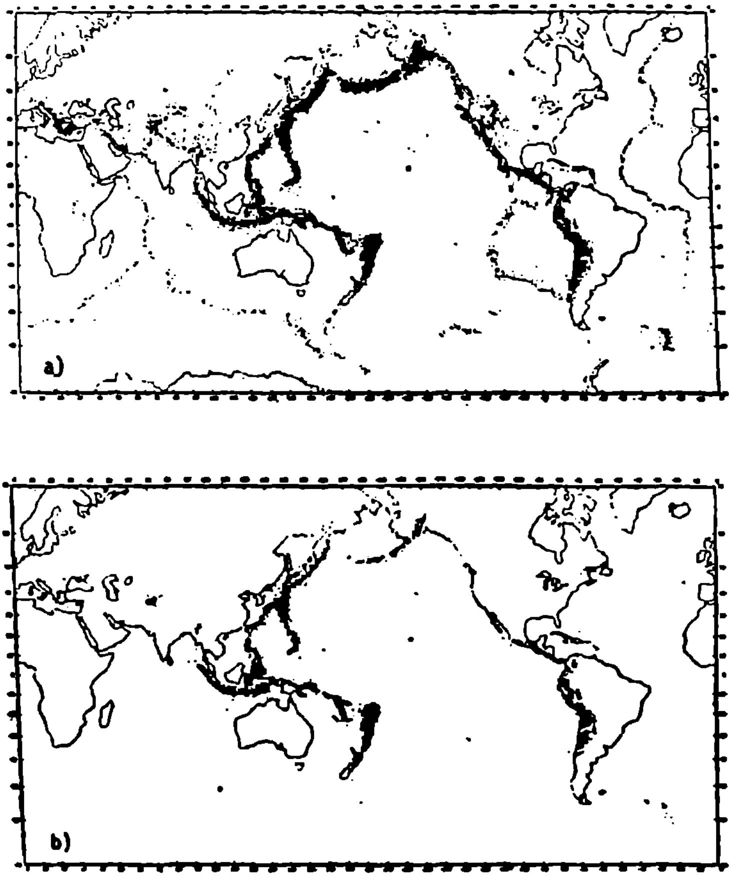


Fig. 20. (a) Epicentral belts over earth's surface. (a) Shallow focus ($<$ 100 km). (b) Deep focus ($>$ 100 km), (M. Barazangi and J. Dorman, 1969). *Courtesy* : Bulletin Seismological Society of America.

CHAPTER 3

Earthquake Prediction Climatology

Global seismic belts

CLIMATOLOGY MEANS THE NORMAL OR LONG-TERM AVERAGES OF weather elements such as atmospheric temperature, pressure and rainfall. Earthquake climatology is generally used to identify the pattern of distribution of earthquakes over long periods and is prerequisite for evolving forecasting techniques.

Instruments to detect earthquakes were developed towards end of the nineteenth century (more precisely around 1888-1890) which made it possible to locate some earthquakes. Many earthquakes, however, went undetected because of low magnification of seismographs and their sparse locations. With the design of more sensitive instruments, particularly those based on laws of electromagnetic induction, the accuracy of epicentral parameters increased, but still the global coverage remained poor. Since 1963, however, a worldwide programme undertaken by United States Coast and Geodetic Survey (now under US Geological Survey) established about 120 stations throughout the world (excluding USSR and China) which enabled us to locate almost all earthquakes of magnitude 4·5 and above with an accuracy of ±0·1 degree (about 10 km) in the epicentre.

Figure 20 a and b shows the epicentres of shallow (less than 100 km) and deep focus earthquakes for the period 1961 to 1967. It may be noticed that there are some well defined seismic belts. The most spectacular is the 'ring of fire' all round the Pacific Ocean called the *Circum-Pacific Belt*. About 75% of the energy is released through shallow earthquakes in this belt. The second well marked belt called Alpide belt extends from Indonesia through the Himalayas to the Mediterranean where about 20% of the energy release takes place. Seismic belts of minor earthquake activity passing through the oceans generally confined to ridges in the Mid-Atlantic and Indian Oceans are now recognised as centres of ocean floor spreading which will be discussed later. Deep focus earthquakes are fewer and mostly confined to the Pacific region. The deepest known shock has been reported to have occurred at 720 km which implies that the earthquake activity is confined to crust and mantle of the earth. Comparison of Figs. 20 a and b shows that the shallow and narrow seismic belt in the mid-Atlantic Ocean completely disappears in Fig 20b due to absence of earthquakes deeper than 100 km in the region. Along the trenches, the foci of earthquakes deepen towards the continental side. All such earthquakes are tectonic and are caused due to gradual accumulation of stress energy of the orders of $10^{20}-10^{25}$ ergs in the earth's crust which is essential for the earthquakes to occur due to slippage of rock masses across the zones of weakness called faults. These results have given seismological support to the theory of plate tectonics which enables us to explain systematically the narrow earthquake belts and their peculiar characteristics on a global scale. In addition, it enables identification of the zones of damaging earthquakes in future on long term basis, thus providing basis for earthquake prediction climatology.

It is, therefore, essential to understand the concepts of the plate tectonics which have been evolved on the basis of the 'drifting continents' and 'the spreading of the ocean floor' hypotheses. However, before discussing these, it will be better to know the underlying cause of earthquake called the 'elastic rebound theory' which is more widely accepted.

Elastic rebound theory

A large, shallow earthquake is usually accompanied by substantial deformation of the ground over hundreds of kilometres and this is indicative of the volume of rock from which the elastic strain is released. Comparison of geodetic observations in California before and after the San Francisco earthquake of 1906 was responsible for the evolution of the elastic rebound theory of earthquakes first postulated by Ried (1911) as follows:

(*a*) The fracture of the rock which causes a tectonic earthquake, is the result of elastic strains, greater than the strength the rock can withstand, produced by the relative displacements of neighbouring portions of the earth's crust.

(*b*) These relative displacements are not produced suddenly at the time of fracture, but attain their maximum amounts gradually during a more or less long period of time.

(*c*) The only mass movements that occur at the time of the earthquake are the sudden elastic rebound of the fracture towards positions of no elastic strain, and these movements extend to distances of only a few kilometres from the fracture.

(*d*) The earthquake vibrations originate in the surface of fracture; the surface from which they start has at first a very small area, which may quickly become very large, but at a rate not greater than the velocity of compressional elastic waves in the rock.

(*e*) The energy liberated at the time of an earthquake was, immediately before the rupture, in the form of energy of elastic strain of the rock.

The sequence of events of the elastic rebound theory of an earthquake is shown in Fig. 21. Due to shearing motion, elastic strain is

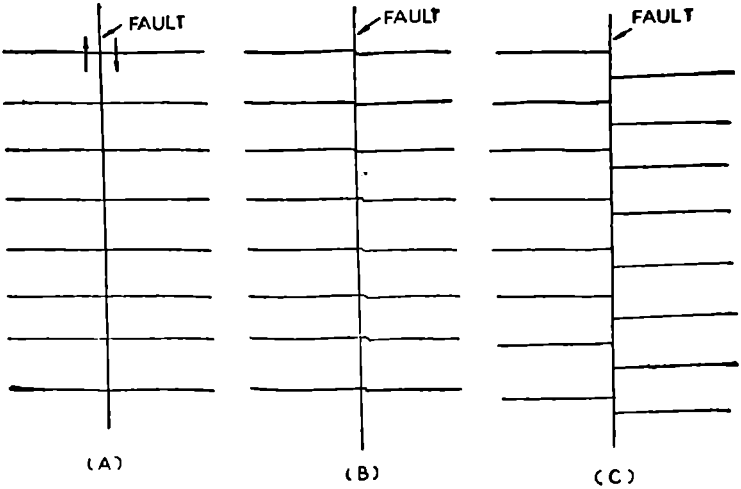


Fig. 21. Mechanism of faulting. Horizontal lines in (A) become curved across the zone as shown in (B) under the differential stresses across the fault and then take up new positions as in (C), causing earthquakes.

slowly built up from the unstrained state (a) to state (c) when the energy is released suddenly producing displacements across the fault generating earthquakes. Thus faulting or zones of weakness cause earthquakes when energy of the order of 10^{20}–10^{25} ergs is gradually stored before exceeding the bearing capacity of the rock masses. The temporary interlocking of 'two plates' across their common boundaries allows tremendous amounts of strain energy to be stored. Earthquakes occur as soon as the stress exceeds a limiting value for the rock masses. The concept of frictional sliding is generally valid for shallow earthquakes. However, the elastic rebound theory can also be extended to deeper earthquakes by assuming a fluid pore pressure across the fault which has lubricating effect, thus allowing sliding to occur at greater depths.

Drifting continents

In 1912, a German meteorologist Wegener proposed that originally all the continents were joined together which drifted apart with the passage of time spread over millions of years. His 'continental drift theory' was based on the fact that coast lines of east Africa and of west coast of south America are quite similar in shapes (Fig. 22) even though they have been separated by more than 5000 km across the Atlantic Ocean. There is a remarkable continuity of geological strata, flora and fauna in the two continents.

This theory, however, was not widely accepted because it was difficult to explain as to how such heavy continents could have moved over the rigid ocean floor. This was explained satisfactorily around the 1950s based on interesting observed evidence that the ocean floor itself is moving. The continents are merely passengers in a moving train. The revival of the drift theory was achieved by discoveries in the field of palaeomagnetism (fossil magnetism) by the English scientists in 1954 through the studies of the directions of remnant magnetism in several samples of rocks of different geological ages. In the red sand stones of the Triassic period (about 200 million years ago) and the present time, it was noted that there is a distinct difference in the directions of the geomagnetic field. This difference was attributed to the rotation of England by about 30° clockwise which explained the deflection of the angle of declination. It could, alternately, be attributed to the change of geomagnetic field direction from the Triassic to the present but the

Fig. 22. Continents drifting apart. Note the close fit of the American coast with the African coast.

observations of the angle of inclination, namely, about 30° in the Triassic and now 65° suggested that England must have been situated at a lower latitude during the Triassic. Similar observations on rock samples from other countries gave definite evidence that the continents must have moved considerable distances in past geologic times. Thus, by using various geologic criteria and palaeomagnetic data, reliable reconstructions of the continents suggest two theories:

(*a*) A single super continent (Pangea) was formed initially and started breaking after palaeozoic era.

(*b*) Two primeval continents, namely, Lauresea (north America plus Eurasia) and Gondwana land (all southern continents plus sub-continents of India) formed separately in the northern and southern hemispheres and broke up at the end of the palaeozoic period.

Of these, the first theory is favoured more. It is suggested that Pangea was fragmented during Triassic era by the generation of the North Atlantic rift and the Afro-Indian rift. India continued remarkable drift bordered by the ninety east ridge and Maldive Laccadive islands since Jurassic era and was being reabsorbed along the northern boundary by the Tethyan Oceanic trench. It encountered and underthrust the Southern margin of Asia in Neogene, resulting in the formation of Himalayas in the zone of collision which is a fairly wide earthquake belt. About 65 million years ago, India crossed the equator and passed over a mantle thermal centre at latitude 7°S and longitude 72°E. The magma from the hot spot spread out as Deccan Plateau basalts. Further northerly movement of India across the hot spot created Laccadive ridge. India is stlil moving in a northeasterly direction.

Spreading ocean floor

The surface of ocean floor is not uniform but consists of 'sea mountains' called ridges (at some places as high as 2 to 3 km), trenches and valleys. As early as 1873, the British oceanologists in their topographical survey in north Atlantic Ocean floor had described the existence of ridges in the middle of the ocean. About 50 years later, it was discovered that the sea ridges are characterised by several steep and large valleys remaining parallel to the ridge axis (except in East Pacific Rise) and are of very long continuation (total length over the oceans is roughly 8000 km). They possess large amount of heat, 2-8 times larger than the average value flowing out along the ridge. Also the seismic wave velocity (*Pn*) over the ridges is remarkably low. This may imply that hot and therefore soft material is rising up just beneath the oceanic ridge and spreading on both sides of the axis. Surprisingly, it was discovered from the geomagnetic observations that the strength of the geomagnetic field printed on the ocean floor was distributed in stripe patterns symmetrically spreading out on both sides of the axis of the mid-Atlantic Ocean (Fig. 23). Similar geomagnetic patterns were subsequently discovered in various oceanic floors around other ridges. However, the rate of spreading of the ocean floor could differ in different regions. The reason as to why the geomagnetic field leaves an imprint on the ridge like voice in a magnetic tape recorder is easy to understand. Hot magma gets cooled by the time

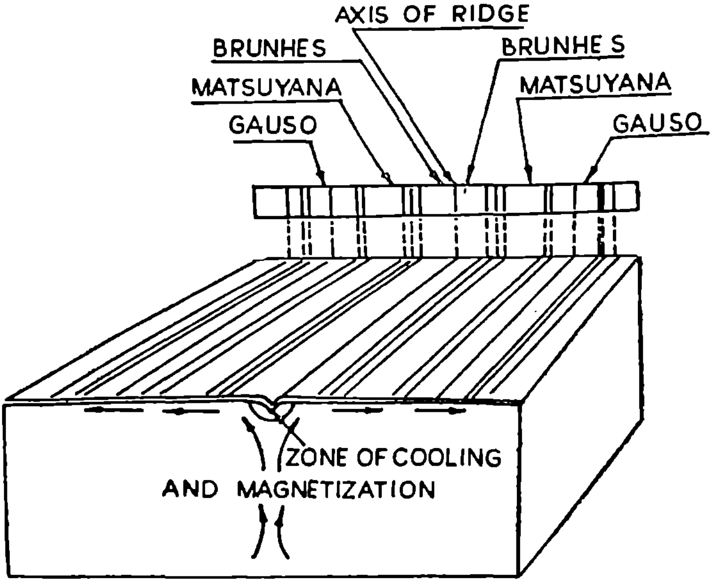


Fig. 23. Symmetrical spreading of lava and magnetic reversals across mid oceanic ridge.

it reaches the earth's surface. Beyond the Curie temperature, the magnetic elements in the material are magnetised by the prevailing geomagnetic field at that time. This 'residual magnetism' is very stable and the magnetic field is firmly printed in the rock. Spreading of this 'magnetic fossil' on both sides of the oceanic ridge, as mentioned earlier, shows a symmetrical pattern.

Geomagnetic field is presently decreasing by 5% in 70 0 years in its strength. This implies that the magnetic field of the earth will become zero after about 2000 years and will gradually enter into the reversed magnetic field epoch. On average, reversals appear to have occurred once every 2000 years. By using an instrument called the proton geomagnetometer, the geomagnetic field in a volcanic rock can be determined. After applying the correction due to the present geomagnetic field, the true geomagnetic pattern was revealed which showed alternate distribution of normal and reverse bands all parallel and symmetrical to the ridge axis. The distances of these alternate strips to the ridge axis were proportional to the geological history of the periodical alternation of geomagnetic field. The history of geomagnetic reversals could be studied by extrapolating backwards upto 80 million years ago from the rock data through Deep Sea Drilling Project in USA (1969) which has supported the spreading of the ocean floor. Assuming that the width of the magnetic anomalies is 20 km and the average interval between the reversals of the magnetic field is found as 5×10^5 years, the spreading rate comes out as 4 cm per year. This is roughly the order of spreading rates around the Atlantic, Pacific and Indian oceans.

Studies on the age of the rocks in various chains of Islands as a function of distance from the ridge axis in the Atlantic Ocean and elsewhere also supports the movements of the ocean floor. Similarly, the ages of sea mounts (extinct submarine volcanoes) increased with their distances from the nearest ridges, which also suggested that they were merely ridge volcanoes displaced by spreading of the sea floors away from the ridges.

Plate tectonics

It is well known that the earth's interior consists of three main divisions called the crust, mantle and the core (Fig. 1). The crust may consist of two or three layers called granitic rocks (layer) over the basaltic rocks (layer) with an overburden of sediments over the top layer. The crust is thickest under the mountains and thinnest over the oceans (where the granitic layer may be absent). The mantle has been divided into two portions called the lower and the upper mantle. The core is also divided into outer and inner cores (Fig. 1). A slightly different classification is followed in the newly developed theory called 'the plate tectonics'. The top layer, known as the *lithosphere*, generally includes the crust and upper part of the mantle which has considerable strength. The next layer is known as asthenosphere which extends from the base of the lithosphere to a depth of several hundred kilometres and is weaker. Beyond this lies the mesophere which extends to the remaining portion of the mantle and possesses strength.

The word 'Plate' is used to infer the outermost portion of the earth's surface, comprising of the earth's crust and the upper mantle having 50-100 km thickness. The plate is supposed to be rigid without undergoing buckling except at its end where it may suffer deformation. It is thinner under the ocean as compared to conti-

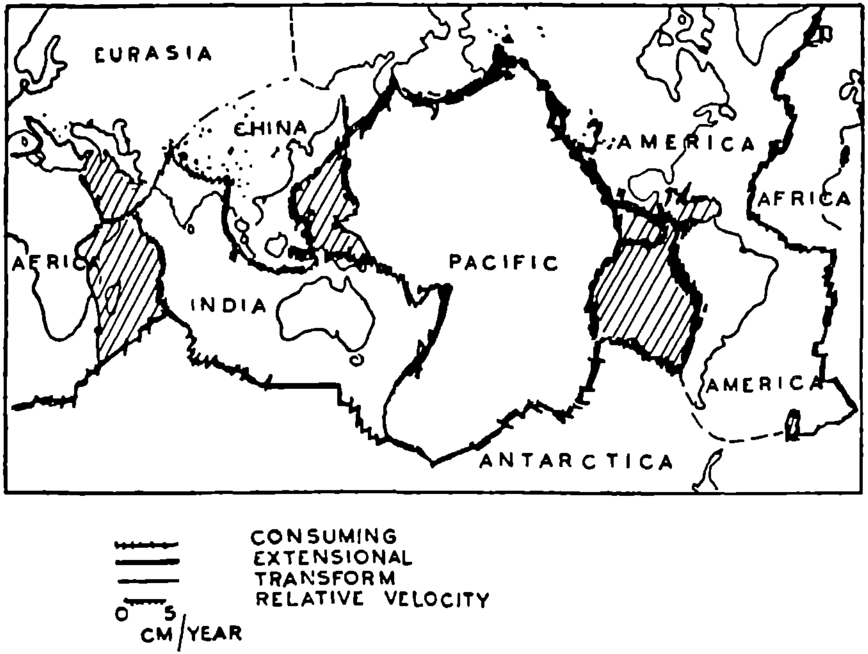
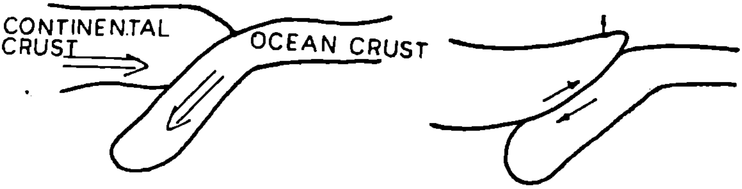


Fig. 24. Main plate boundaries on the earth's surface. Vectors of differential motions at selected points are also shown (simplified after Le Picheon et al, 1970) (Copyright American Geophysical Union, Jr of Geo-physical Research).

nents. Originally the earth's surface was divided into six large plates called Pacific, Atlantic, Eurasian, Antarctic, Indian and American Plates (Fig. 24). Subsequently, six smaller plates have been added as more and more geophysical evidence became available. These plates are constantly in motion relative to each other moving over denser but less rigid parts of the earth's mantle. There can be three types of plate boundaries. First type of plate boundary can be considered as the separation of the plates through the force of magma across the ridge axis. This is the region where the plates are created by adding the material on both sides. Age determinations of rocks near the ridges confirm it. The oldest age of the rock discovered on the ocean floor does not exceed 300×10^6 years, which is much younger than the continents ($3{,}800 \times 10^6$ years). As mentioned earlier the rate of spreading of the main plates at the creating margins can be measured from the distances of the axis of adjacent normal and reverse magnetised strips divided by the age of difference between them.

The other type of plate boundary is where the two plates collide or thrust below the other. These are the destructive plate margins across the regions known as trenches (Fig. 25). The rate of movement of the plates can be inferred across the boundaries by the total displacement produced by all the past earthquakes over a particular time span of say fifty years. Other methods for determining the velocity of plates are based on paleomagnetic data. Laser reflectors placed on the surface of moon give a better estimate of plate movements.



(A) *Trench type* (B) *Under thrusting type*

Fig. 25. Mechanism of earthquakes near trench and under thrusting type of earthquakes.

A third type of plate boundary occurs along what are known as transform faults (Fig. 26) named by a British seismologist Wilson

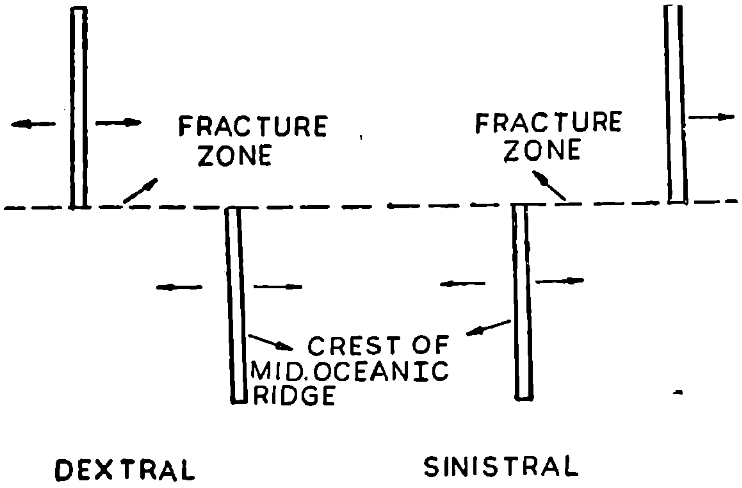


Fig. 26. Transform faults. The mid oceanic ridge is not continuous but gets displaced at right angles creating fracture zone between two portions of the same ridge. The mechanism of earthquakes on these portions is distinctly different.

in 1965. Here the plates move laterally relative to each other and the crust is neither produced nor destroyed. The lateral displacement on one side of the fault is taken up either by formation of new crust along a terminated segment of ocean ridge or by crustal shortening along a terminated segment of the mountain range or the ocean trench. Thus transform fault link the mobile belts of the earthquakes into an interconnected network subdividing the earth's surface into a series of rigid plates.

It may be mentioned that the concept of rigid plate tectonics is based on Euler's fixed axis theorem, according to which any conceivable displacement of a plate on a spherical surface can be produced by rotation about an appropriate axis passing through the centre of the sphere. Any given displacement can be completely specified by one of the two poles where the axis of rotation cuts the surface and by the angular rotation about the axis needed to cause the displacement (Fig. 27). The relative movements of the two plates is defined by the pole of rotation and the angular velocity of

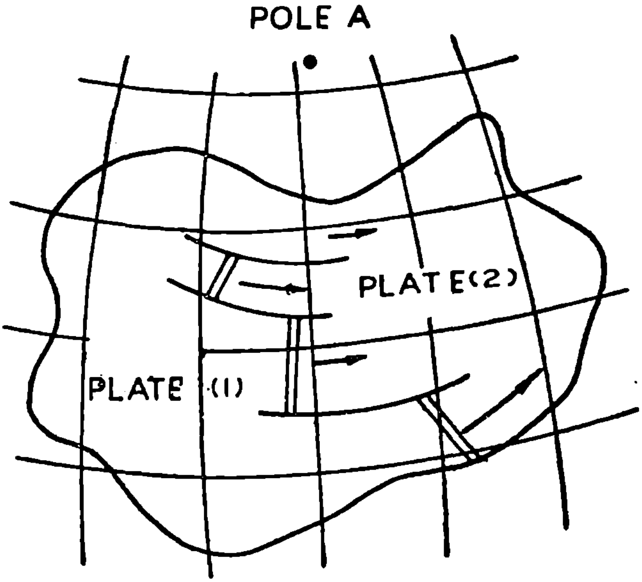


Fig. 27. Rotation or movement of plates on a rigid sphere (schematic).

rotation. It may be noticed that the pole of rotation for two adjacent portions of spreading ocean floor on opposite sides of an oceanic ridge can be estimated from the geometry of the fracture zone which are active transform faults. In fact the criteria for dividing the earth surface into main plates was based on fixing the pole of rotation and angular separation associated with each pair of plates using fracture zones and spreading rates.

Driving mechanism of plates

The driving force for movement of such large and heavy plates presents a major problem. On the assumption of the upper mantle as a viscous fluid, convection currents are generated due to the heating from below resulting in free thermal convection. In the lower mantle, convection may be inhibited by the high viscosity. The plates can be passively dragged along the top of the mantle wide convection cells provided horizontal dimension of these cells would be very large, almost of the order of the width of an ocean. This appears to be physically impossible and therefore alternatives have been suggested.

Two concepts of convection in the upper mantle have been proposed. In Fig. 28a the long cellular convection cells exert a drag on the overlying lithosphere. Maximum tension would be produced over the upwelling current at ocean ridges and maximum compression above the downsinking current and between them. Figure 28b shows Orowan Elasser type of convection model in which the lithosphere of the oceans is fast cooling part of the system which has spread horizontally (laterally) from the ocean ridges.

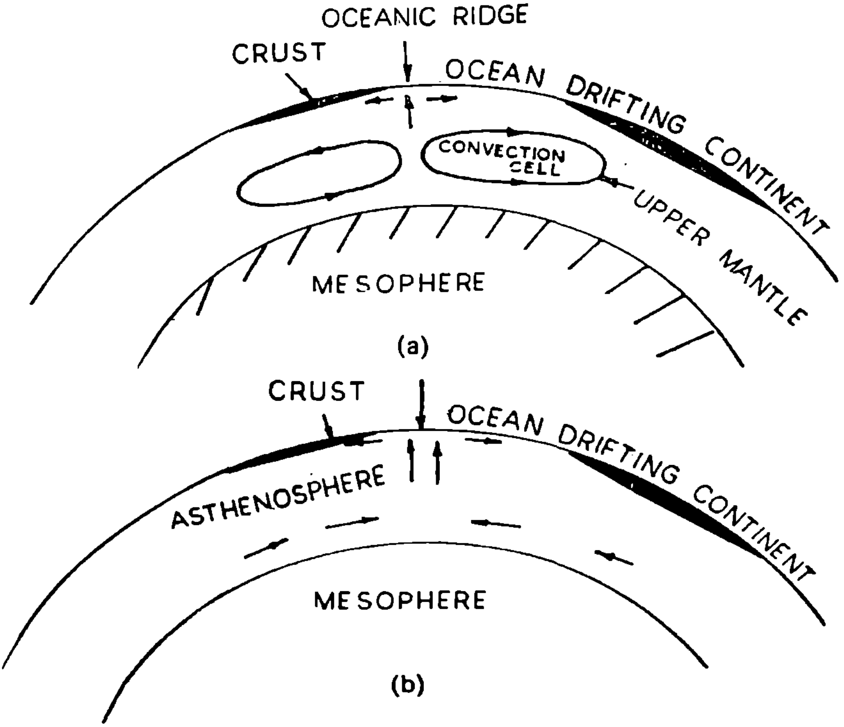


Fig. 28. Two types of convection mechanism near the oceanic ridges driving the plates (a) long cellular and (b) Orowan Elasser type.

The reverse current is a relatively slow migration of material back towards the ridges in the upper mantle. Thus the overlying plates move but the asthenosphere remains nearly stationary. The plates are forced to move apart due to pressure of magma which is exerted on the boundaries of the adjacent plates of lithosphere. However the differences between the oceanic and continental regions of the upper mantle are not fully understood and the problem of upper mantle convection is still being investigated.

Characteristics of earthquakes along plate margins

It may be noticed from Figs. 20 and 24 that the boundaries of the plates are the main regions across which the seismic belts pass. The reliable studies on the nature of faulting and accurate determination of epicentral parameters enable us to understand the mechanism of earthquakes at various kinds of plate boundaries.

Earthquakes along the oceanic ridge

From Fig. 20 it may be noticed that earthquakes are taking place all along the axis of the ridge. Detailed examination, however, shows that the ridge is not continuous but broken along fracture zones which shifts the ridge transversely. Along the ridge axis, the earthquakes are of 'swarm' type and are associated with volcanic activity. On the other hand, the earthquakes along the fracture zones between the ridge segments are not followed by after shocks, swarms or volcanic activity.

Distinct difference in the source mechanism of earthquakes at these two zones was reported by L.R. Sykes of Lamont Geological Observatory, USA. The earthquakes near the ridge had normal faulting while those near the fracture zones had transform faulting. This is because, along the ridge the plate is pulled apart in opposite directions, due to which a force of tension perpendicular to the axis of the ridge appears creating a normal fault. Along the fracture zone between the shifted ridge segments, a strike slip type of fault is generated due to the movements in opposite directions (Fig. 26). The longest transform fault is San Andreas Fault about 5000 km in USA along which earthquakes take place due to right lateral horizontal motion. Another example of transform fault is Alpine fault in New Zealand with a right lateral shift for a distance of 450 km.

Earthquakes near the trench including deeper ones

A trench is formed due to the penetration of a plate into the mantle. Thus a plate may be considered to bend down just in front of a trench (Fig 29). The focal mechanism of earthquakes near the bending portion of the plate shows normal faulting (Fig. 30a) and the foci are aligned along a plane at an inclination of about 45°. Earthquakes are generated due to tension which acts near the surface of bending of underthrust oceanic plates. Further ahead, inside the arc-trench gap, the earthquake foci are aligned along the boundary between the descending oceanic plate and the continental plate above. The mechanism of faulting is thrust type (Fig. 30b) in this zone of more active seismicity, which is interpreted as the relative motion of two converging plates of lithosphere.

The usefulness of the concepts of plate tectonics lies in explaining the cause of the deep focus earthquakes. The earlier hypothesis that they are due to explosive change in volume was ruled out from the quadrantal distribution of the sense of first motion of P waves (Fig. 31). The recent finding that deep focus earthquakes occur in downgoing slabs of lithosphere is now supported by reliable data of focal mechanisms. Thus the deep focus earthquakes involving dip slip mechanism are caused by the release of stress within the sinking plate of lithosphere and extends to great depths into the aestheno-sphere depending upon its temperature and resistance offered to it in the mantle.

Continental earthquakes

The interaction of plates of lithosphere appears to be complex when all the plates involved are continents or pieces of continents than when at least one plate is an oceanic plate. This is attributed to the breaking of the continental crust into many blocks as a result of geological evolutions in its long history. These blocks may move in different directions along the boundary or zones of weakness. As such, the distribution of epicentres and the mechanism of earthquakes do not coincide well with the plate motions. The seismicity is diffuse and shallow (Fig. 32). The mechanism of earthquakes near the plate boundaries are generally of thrust type, but the relative movements of the plate cannot be deduced with greater confidence from the orientation of slip vector which is so reliable when the plate boundary is continental island arc type.

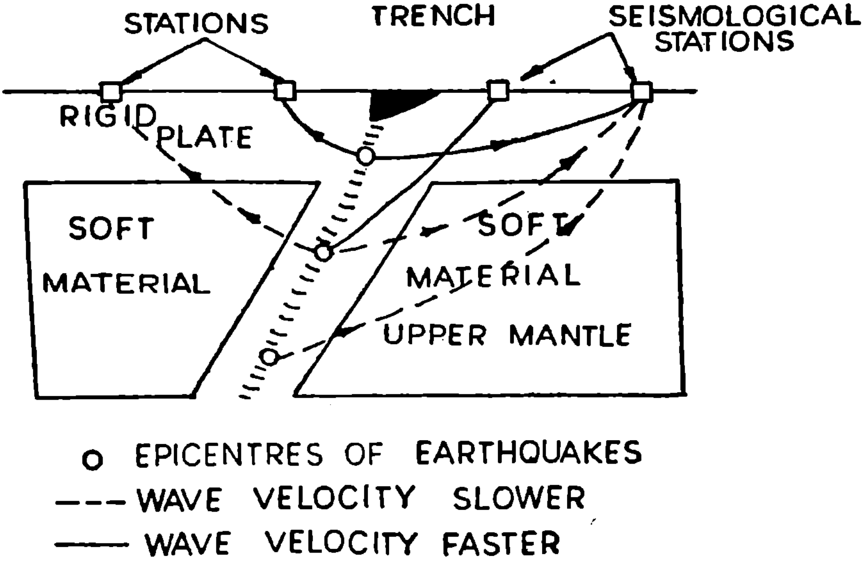


Fig. 29. Bending of a rigid plate through Island arc. Deep earthquakes occur so far as the plate bends below the softer material of the upper mantle.

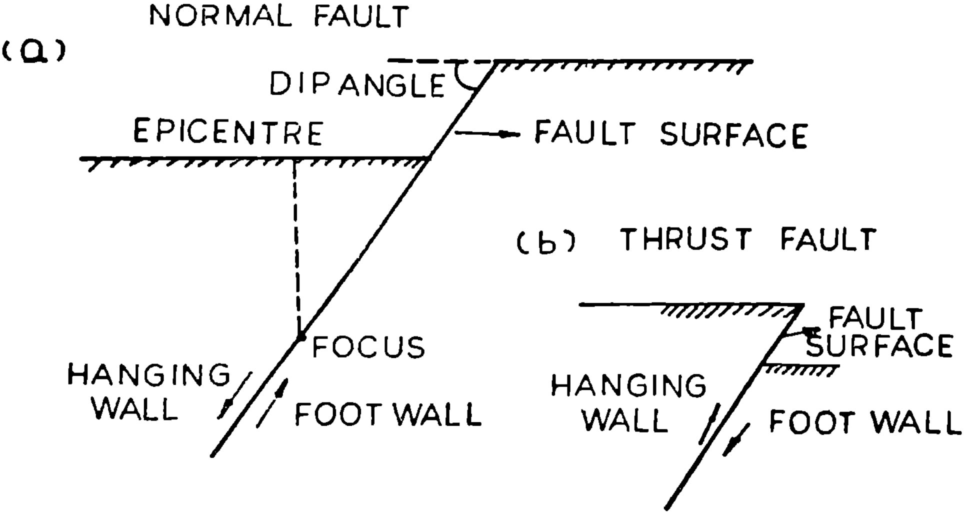
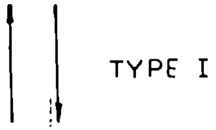
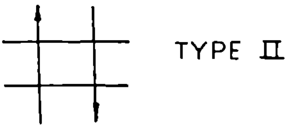


Fig. 30. (a) Normal and (b) thrust faults.



(a) SINGLE COUPLE FORCE WITH MOMENT



(b) DOUBLE COUPLE WITHOUT MOMENT

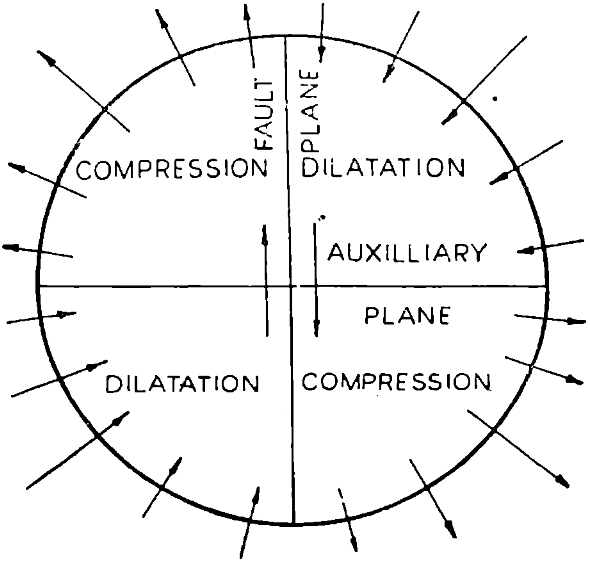


Fig. 31. The forces at the earthquake focus.

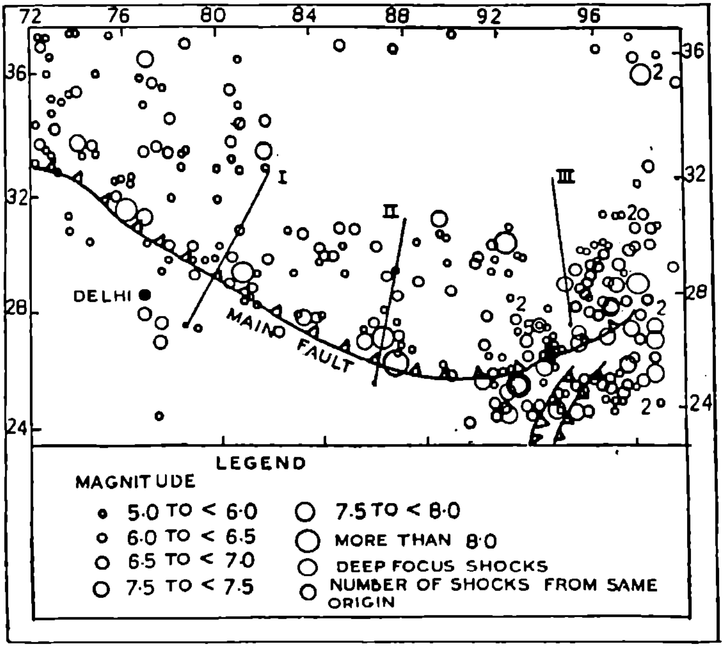


Fig. 32. Earthquakes in the Himalayas. *Conrtsey* : India Meteorological Department.

It may be summarised that most destructive earthquakes around magnitude 8 can occur across the consuming plate boundaries while the maximum magnitude may be about 6 near the oceanic ridge. The magnitude of earthquakes depends upon the thickness of plates, the length of the fracture zone and the extent of the under thrusting in island arcs.

Indian Plate and its future movements

The whole of India lies on the Indian Plate whose relative motion is generally towards the north-northeast at a velocity of about 5 cm per year. It encounters the adjacent plates in the Burma-Andaman Sumatra region in the east, the Himalayan foothills in the north and the Suleman ranges of Pakistan in the west. Great earthquakes in Shillong (1897), Kangra (1905), Bihar Nepal (1934) and Assam (1950) have occurred on the northern boundary of the Indian plate

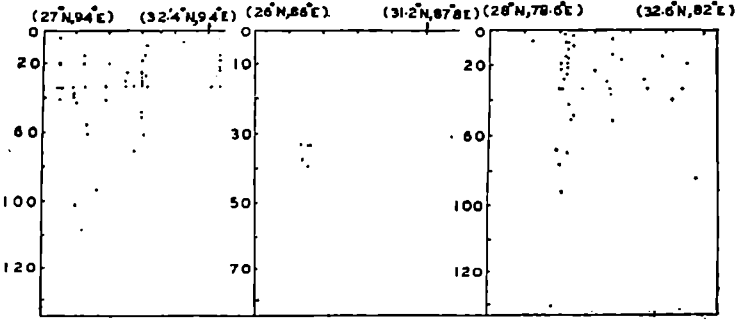


Fig. 33. Depth-wise (vertical) cross sections of earthquakes near Himalayas foothills (boundary of Indian and Eurasian plates).

which is underthrusting the Eurasian plate. Kaila and Narain (1976) have proposed the northern boundaries of the Indian plate north of Himalayas. Considering the arcuate structure of the Himalayan chain, four radial cross sections across the foothills were drawn with the earthquakes projected depth-wise which did not reflect dipping of the Indian plate (Fig. 33). On the other hand, the dipping of the plate towards east is clearly reflected in Burmese to Andaman sectors through similar cross sections where the focal depths of earthquakes generally increase as we move towards the east (Fig. 34). In the Hindukush region, a cluster of epicentres forms more or less V-shaped region having foci at depths upto 200 to 250 km which is attributed to the underthrusting of the Indian plate into the remnants of Tethys ocean. The focal mechanism of several earthquakes determined by the author and his coworkers show thrust faulting along the Himalayan foothills (Fig. 35). The pressures are generally acting at right angles to the faults. Thrusting is also indicated along the eastern boundary. A few earthquakes with normal faulting and with different amounts of strike slip movements all along the boundary from north to east call for improvements in regional plate tectonics model (Srivastava and Chaudhury, 1979).

Plausible motion of the Indian Plate in future

During late cretaceous time, approximately 75 million years, direction of sea floor spreading changed to become approximately

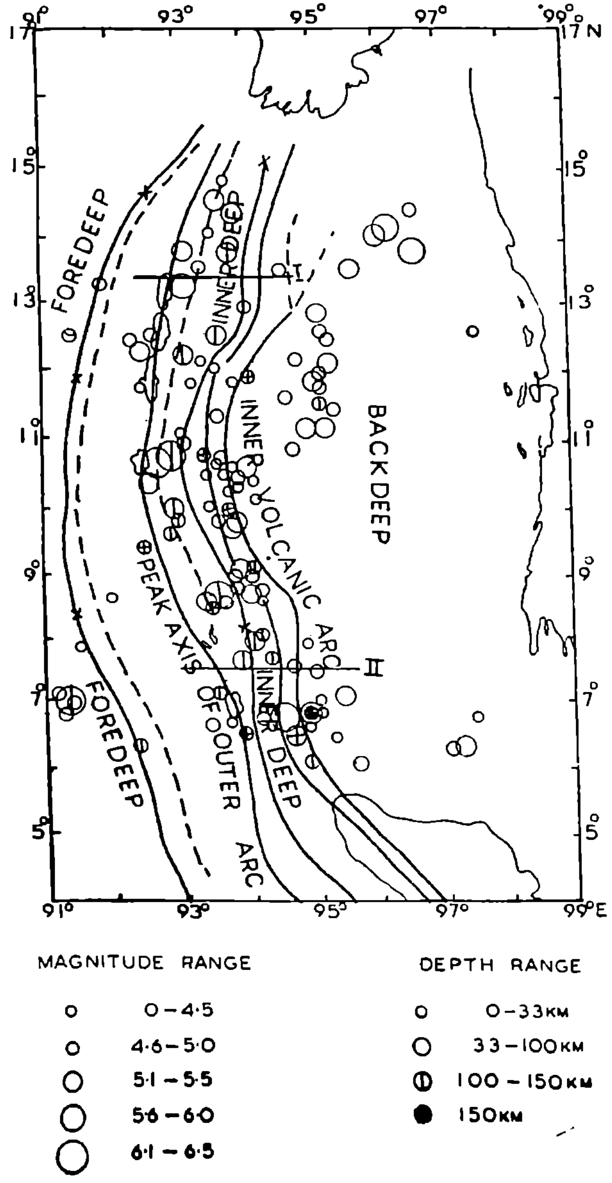


Fig. 34. (a) Earthquake in Andaman Island. I and II denote the cross sections across which the epicentres have been plotted depth-wise

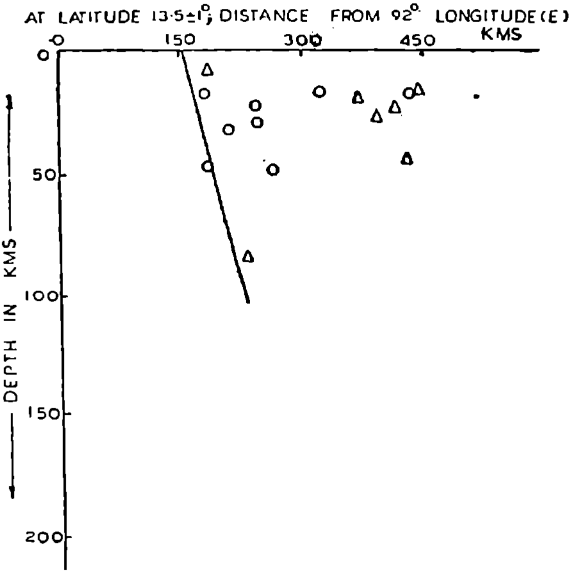


Fig. 34. (b) Depth-wise cross section of curve i

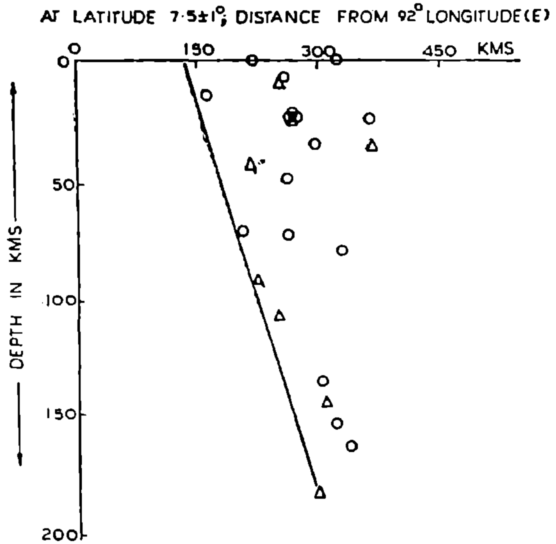


Fig. 34. (c) Depth-wise cross section of curve II

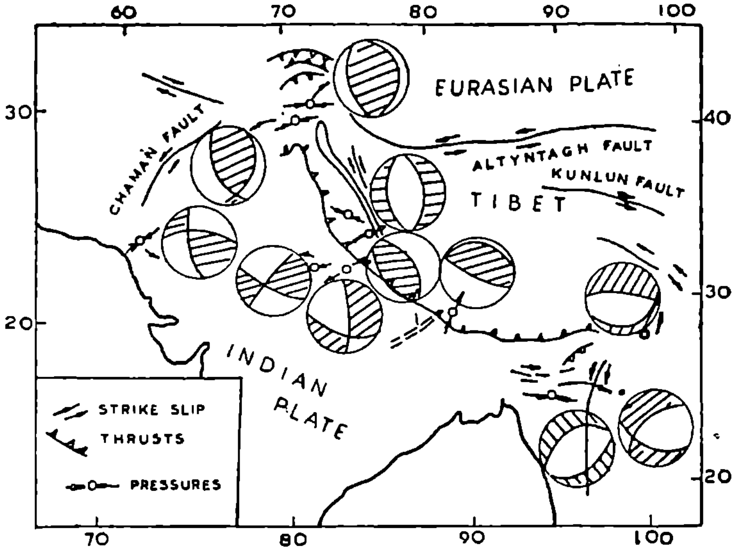


Fig. 35. Focal mechanism of earthquakes around Indian plate. Lower half of equal area projection. Blank area denotes dilatation. Hatched area denotes compression. Double arrows indicate orientation of pressures.

north south, parallel to the present Ninety East Ridge. This northerly movement of the Indian plate changed to northeasterly about 35 million years ago. As discussed earlier, the resistance to the Indian Plate in Himalayas coupled with relative easier subduction from Burma to Andaman Islands as revealed by the epicentral cross sections plotted depth-wise may eventually allow a more easterly movement of the Indian plate than what is existing at present resulting in increased strike slip movements near the northeastern boundary of the Indian Plate. Because of this trend coupled with the thrusting in the Himalayan-Burmese sector, the northeastern region will continue to be the source of damaging earthquakes.

It has been shown with cartographic precision that after 135 million years, quite a large portion of northern India will shrink in size due to the thrusting of the Indian Plate below the Eurasian Plate.

Intraplate tectonics

Seismicity of the Indian Plate assumed more importance after the occurrence of recent earthquakes in the Peninsula (Koyna, 1967, 1973; Bhadrachelam, 1969; Broach 1970; Bay of Bengal 1972, 1973). But Plate tectonics does not offer a satisfactory explanation for earthquake occurring within the plate itself. Prior to this, the great Rann of Kutch (1819) located far away from the boundary of the Indian Plate could also not be accounted for by the plate tectonics model.

It is remarkable to note that the tear faults in the foothills of Himalayas, namely Moradabad, Lucknow, Patna and Dhubri faults, are oriented roughly along the direction of movement of the Indian Plate. Valdiya (1973) has also found a number of transverse lineaments in the Himalayan foothills.

The focal mechanism of two recent earthquakes in the Bay of Bengal has given evidence of a new thrust fault oriented along the motion of the plate with left lateral strike slip movement (Chaudhury and Srivastava, 1974). Subsequently Chandra (1977) has suggested that orientation of the zones of weakness with respect to the ambient stress field may be an important factor in determining the faults along which future earthquakes are likely to occur. Another interesting intraplate result is discussed by Sykes (1970) who suggested that a nascent island area may be developing in Indian Ocean between Ceylon and Australia based on seismicity data. The author has found that the junctions of thrust faults and transverse lineaments near the plate boundary are more likely to be affected by damaging earthquakes.

CHAPTER 4

Physical Models for Earthquake Forecasting

Early laboratory results

EARTHQUAKE OCCURRENCE IS PRIMARILY A PHENOMENON OF fracturing of rocks inside the upper layers of the earth called crust and mantle. Premonitory trends in the physical properties of the source region of earthquakes may therefore be comparable to the experimental results on rock specimen in the laboratory under high temperatures and pressures corresponding to the conditions of actual earthquake occurrence. Movements across faults, whether stable or jerky are being studied in the laboratory to understand the role of friction through well designed experiments on rocks. Attempts are being made to develop realistic models for earthquake mechanism on which forecast can be based. Lots of experiments on different kinds of rocks have been conducted in Japan, USA, USSR and China.

Laboratory techniques started since 1962 in Japan consist of cutting the specimens of rocks into rectangular shape and then applying increasing pressure over it till it breaks (Mogi, 1962). A small pick up microphone attached to the rock sample detects the development of microfractures in it. It has been observed that if the rock is very uniform, no microfractures are observed and the rock breaks almost suddenly. For heterogeneous (non-uniform) samples, microcracks occur with a constant stress rate (stress is defined as force applied per unit area) before the main rupture occurs. In extremely heterogeneous type of rocks, microcracks occur but without any main rupture (Fig. 36). In the second category those earthquakes come which are preceded by foreshocks while in the first type, foreshocks do not occur and the earthquake strikes suddenly.

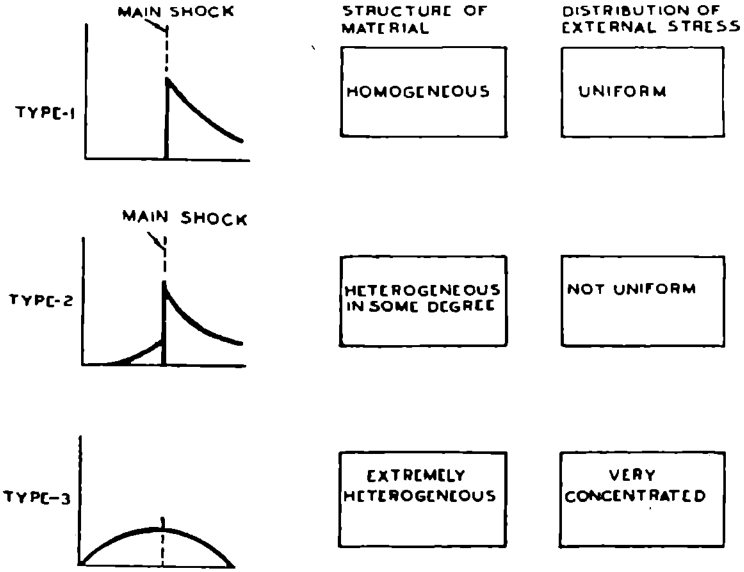


Fig. 36. Patterns of Earthquakes.
Top : Homogeneous material, without foreshocks.
Middle : Slightly heterogeneous material, with foreshocks,
Bottom : Extremely heterogeneous, swarms (no bigger event).

Earthquake swarms are the examples in the third category where no big event takes place just as often happens in peninsular India (Vizianagaram 1953-54; Dhavelji-Bijapur district, 1955; Sehore, 1956, 1959; Bidar district Mysore, 1956; Kerala, 1960; Kozikode, 1961; Tambaram, 1966; Hospet, 1980).

Stable and stick slip sliding

Sliding on faults may occur in two ways. It may take place by a series of discrete, rapid slips with a period of little motion between slips. This is called *stick slip* and is considered to be the mechanism of generation of earthquakes on natural faults. Alternately, the motion may be more uniform which is called *stable sliding* and is defined as continuous displacement along a frictional surface without abrupt changes in the applied force. It corresponds to the fault creep observed on natural faults. The character of sliding depends in a complex manner on pressure or normal stress, temperature, mineralogy, amount of gouge, pressure of water or other fluids, surface geometry and other factors. It is found that stick slip is increased by high pressures or normal stress, low temperatures, the presence of strong, brittle minerals like quartz, feldspar, absence of gouge, lower surface roughness or presence of water in sliding zone. In general, low level of seismic activity was observed to accompany stable sliding in granite. It has been found that the transition from one type of sliding to the other is a function of experimental technique and rock type as well as the variation of external parameters. Experiments have been carried out to study the time dependence of frictional strength of rock showing three stages of creep during frictional sliding. At low pressure, the frictional strength increases with the time of stationary contact provided faults surfaces are separated by fault gouge. It was found that the initial application of shear stress between surfaces of granite at low pressure produced a displacement which continued at a decaying rate until sliding ceased to occur. By increasing the stress, the same thing recurs. At higher stress, the creep rate decays but continues at a very slow rate. Finally the movement accelerates until catastrophic stick slip occurs. Similar phenomenon occurs in earthquakes.

Some discrepancies between laboratory results and natural earthquakes remain unresolved. The experimental results have shown that under crustal conditions, the stress required to cause the sliding of one rock over another is several kilobars while the stress drop during even large earthquakes is rarely greater than 100 bars, which represents only a small fraction of the total shear stress. Higher shear stress implies that a very large amount of energy would be released even during very small earthquakes. It is surmised, therefore, that there are other modes of dissipation of energy.

Volume changes

Volume changes due to deformation of rocks occur due to elastic changes in the minerals, compaction (elimination of pore space) and dilatancy (defined as inelastic increase in volume) or increase of pore space.

Volume changes can be measured by:

(*a*) Surface straingauges using electric resistances measurements.
(*b*) Cantilever displacement gauges.
(*c*) Observation of changes in pore volume.
(*d*) Changes in the total volume of the sample.

In low porosity rocks, dilatancy increases initial porosity by a factor of 2 or more while in porous rocks or granular aggregates, the increase is only 20 to 50%. In rocks of high initial porosity, actual pore volume increase is larger. Applied to field observations, earthquake precursors which depend on the magnitude of dilatancy are expected to be more pronounced in porous rocks like sandstones or fault gouge. On the contrary, precursors which depend on fractional changes in some porosity related property (i.e. relative change in pore volume) may be more pronounced in rocks of low initial porosity such as dunite, quartzite or anorthosite.

It has also been reported (Nur et al., 1973) that extensive dilatancy sufficient for undersaturation can develop around thrust faults while strike slip or normal faults may not. This is because the direction of least compressive force and dilatant extension is vertical in thrust fault. After the dilatant force exceeds the overburden pressure, dilatancy can develop without restraint.

Area of contact

The real area of contact during sliding is the most fundamental element in the frictional behaviour of fractures and faults because temperature, local state of stress, seismic energy released and gouge generation are area dependent. This has been determined during frictional sliding along pre-cut surfaces in tennessee sandstones using thermodyes. The dyes are applied as a lacquer to the sliding surface before the test and undergo a phase transformation accompanied by a colour and textural change at a specific temperature. Maximum temperatures are reached when two surfaces are in actual contact (i.e. the real area of contact). By mapping the areas of maximum temperature at a specific time in the displacement history, we can calculate the real area of contact at that time. Observations of surfaces after sliding has shown that the dyed areas are elongated or smeared out in the direction of sliding. The amount of displacement can be measured from the maximum lengths of these areas It is found from experiments that as the nominal displacement rate decreases from 10^{-2} to 10^{-3} cm/sec, there is a transition in mode from stable sliding to stick slip. With a further decrease in this rate, the magnitude of the stick-slip events increases. Further, time dependent behaviour of the real contact area may offer some explanation of post earthquake creep, fore and aftershocks and stuck patches along fault zones as discussed later.

Premonitory slip

Premonitory slip prior to stick slip has been widely observed in laboratory experiments on sawcuts or prefractured specimens of rock. The mechanisms for this precursory displacement are not fully understood although brittle fracture, thermal softening and time dependent flow have been suggested. Physical changes accompanying premonitory slip have received very little laboratory attention but changes in pore pressure reflecting changes in dilatancy and resistivity have been observed. No noticeable changes in the velocities of seismic waves have been found prior to stick slip event or during major displacement on the specimens of Cocooino and tennesse sandstones and granite containing a sawcut. However, 30% decrease in the P-wave velocities was found in Berea sandstones samples prior to stick slip phenomenon.

Laboratory experiments have shown that under some conditions the shear wave (S wave) splits into the components (called SH and SV waves) at right angles to each other. The velocity of the component along the axis of the compressive stress has higher velocity than the other one. The effects of these velocity changes even though small, cause differences in arrival times of the two components depending upon stress conditions and show some promise in predicting earthquakes (Gupta, 1973). A model has also been suggested to explain the occurrence of pre-seismic creep, stick and foreshocks before the main earthquake. It is generally accepted that an actual fault motion initiates at a point or over a small segment of length surrounded by locked sections as also found in the laboratory. The rupture quickly propagates to the extremities of the specimen which may take a considerable time for a large specimen. The stiffness vary inversely with the fault length implying gradual development of instability through fault extension. It is noticed that bigger earthquakes are associated with longer fault length with attendant large amount of instability.

Dilatancy models

American model : In USA Scholz, Sykes and Agarwal (1973) have carried out laboratory experiments on the rock samples. The influence of effective stress (total pressure minus pore pressure) on the velocities of seismic waves shows interesting results. The velocities have been measured in directions parallel and perpendicular to the compressional force applied to a rock specimen. Marked changes in velocities of P waves occur (if the rock is saturated with water) before the rock breaks. Similar to sound waves, velocities of P waves are less in dry rock as compared with wet rocks and depend upon the elastic constants of rocks like density and rigidity. For S waves which are torsional in nature, the formation of cracks with increase of effective pressure has hardly any effect. Thus, the experimental results lead to abnormal change of ratio of velocities of the two types of waves called Vp/Vs before the occurrence of main events. Similar results have been observed before occurrence of several earthquakes (Chapter 6) in different countries. This has led to the development of a model for earthquake forecasting called *dilatancy water diffusion model.* When the stress reaches about half of the breaking strength the rocks *dilate.* In other words, small open spaces called voids are created due to cracks in the rock resulting in increase of its volume. Dilatant volume changes can be traced to micro cracks which have been observed under electron microscope.

In Fig. 37, three phases in the change of P wave velocities of rocks are marked as I, II and III. Assuming the rock saturated with water, increasing external pressure leads to development of small cracks inside, making it dilatant. Due to this, the water content of rocks begins to decrease because some time is required for the surrounding water to fill these voids. Due to decrease of water content, P wave velocity decreases and shifts almost to the value corresponding to the dry rocks. This occurs in Phase II. Since S waves are not appreciably effected, the ratio of velocities Vp/Vs decreases in this phase. Gradually diffusion of surrounding water starts into the open spaces (cracks) and the rock again becomes saturated with water, leading to recovery of the velocity ratio Vp/Vs corresponding to Phase III. Further increase of pore pressure decreases the effective pressure reducing the strength of the rock and breaking it (causing earthquakes in field). Larger the dilatant zone,

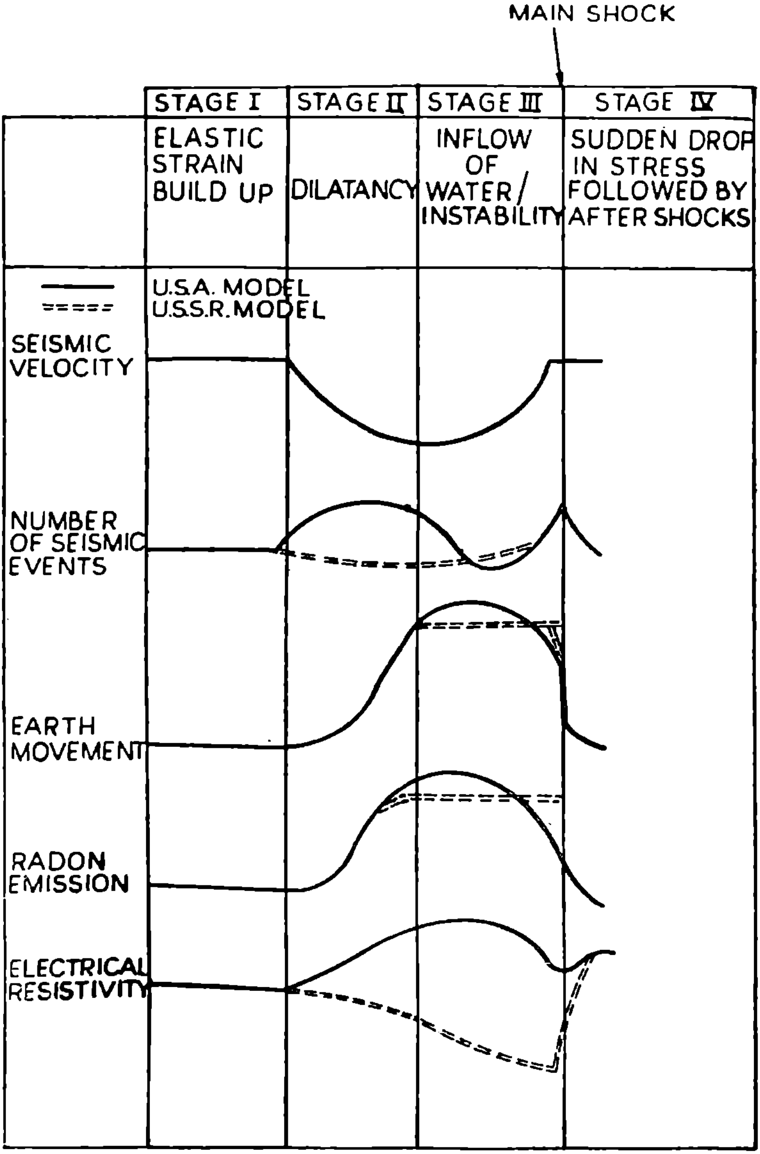


Fig. 37. Dilatancy models; difference between USSR and USA models may be noticed through changes in electrical resistivity, radon emission, earth movements and number of tremors.

longer is the time needed for the process to be completed and greater will be the earthquake.

In laboratory, anomalous changes in velocities of seismic waves of the order of 0 to 30% have been observed. The magnitude of the velocity change depends upon the following parameters:

(*a*) Crack porosity.
(*b*) Amount of volatile material in the rock.
(*c*) Strain rate.
(*d*) Magnitude of stress change.
(*e*) Elastic constants of the rocks.
(*f*) Volume of dilatant zone relative to the total volume measured.
(*g*) Direction of wave propagation and polarization (applicable only in the case of shear waves) relative to the orientation of the principal stresses.

The ultrasonic velocity (P wave) measurements on granite samples have shown that rocks may become extremely anisotropic with respect to propagation of seismic waves when fractured under biaxial compression. P wave velocity increases continuously in the direction of maximum compression in the pre peak region while it decreases markedly in the directions of the medium and minimum principal stresses after fracturing is initiated. In the postfailure region P wave velocity decreases in the direction of maximum of compression. The dilatancy water diffusion model also suggests the following precursory phenomena to be observed in addition to changes in the velocity ratio

(*a*) Electric resistivity of the rock which depends upon the water contents of rocks decreases due to the dilatancy.
(*b*) Seismicity will decrease in the stage of dilatancy.
(*c*) Vertical changes in the surface of the earth should take place.
(*d*) Rate of flow of water in the rocks of dilatant zone will increase resulting in the increase of radioactive 'radon' gas.

Laboratory studies in USA have been carried out to find relationship between the surface area and release of radon gas in Henderson Gneiss (a kind of rock). It was found that the amount of radon released from the rock is proportional to the surface area due to cracking. Further experiments on various kind of rocks show that the volume or quantity of occluded gases like hydrogen, carbon monoxide, carbon dioxide, nitrogen and oxygen increases with the increase of stress on the rock. The largest rate of gas release occurred as the rock failed by crushing. Similarly, experiments have suggested that observations of magnetic field may be suitable for detecting earthquake precursors because rate of magnetisation increases with creep rate.

USSR model : In the USSR model, which is sometimes called dilatancy water diffusionless model water does not play any role. During the second stage when dilatancy becomes a dominant factor, innumerable cracks called 'avalanche' develop in the rock, causing a fall in the seismic wave velocity due to the open spaces inside it. Further increase of stress across the faults leads to instability in the cracked rocks which is finally deformed. There is a partial relaxation of stress and cracks close to some extent causing the rocks to recover some of the original properties like increase in seismic wave velocity, decrease in volume and others. Main event takes place due to faulting caused by instability, after which the stress is released along with the recovery of most of the original properties of rocks associated with drop in stress.

Some conspicuous differences in the changes of electric resistivity of rocks in the US and USSR models may be noticed (Fig. 37). During the deformation of water saturated rocks, the new cracks fill with water and the resistivity decreases (American model). However, the deformation of dry rock increases the resistivity as it becomes dilatant in the USSR model.

Scale invariant properties of failure

Brady (1977) reported interesting laboratory results of tilt and seismicity anomalies before failure in rocks. Specimens of granite were cut and ground to a length of 13·5 cm and deformed to failure under a confining pressure of 150 bars, in a servo controlled material testing system. Bending moments corresponding to tilt measurements in seismic regions were measured about two perpendicular axes intersecting at the centre of the transducer and normal to the load axis. Changes in load were also measured. A small piezoelectric transducer was used to detect seismic emission as acoustic noise from the test sample. Moments, load and seismicity were recorded on two digital memory scope with 20 to 100 microsecond interval per sample point. A noticeable increase in seismicity (noise count rate) followed by its decrease prior to rupture was observed. Tilting in the direction of fault growth was observed with a tilt reversal that resulted in specimen failure. The decrease in acoustic emission rate of seismicity occurred during the tilt reversal prior to each rupture. These results enabled Brady to develop a theory of failure called *inclusion theory*. According to this theory, intense concentrations called *primary inclusion zones* develop within a localised region in rock near failure (Fig. 38). Each primary inclusion zone has the following effect in the focal region:

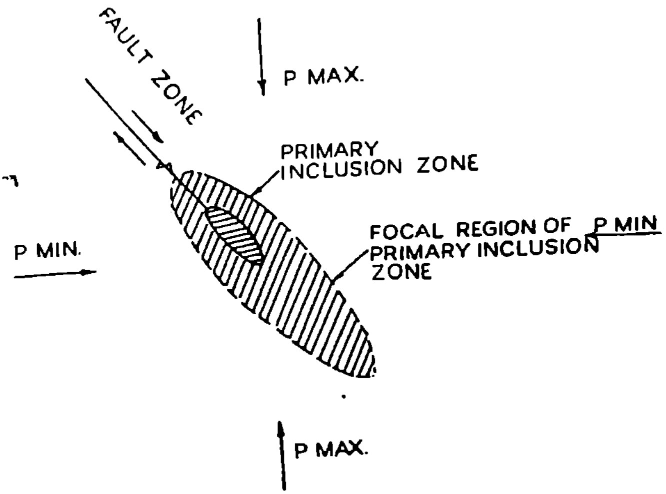


Fig. 38. Development of Primary Inclusion Zone (Brady's model).

(*a*) The local principal axes that produce the primary inclusion zone are rotated from their normal orientation.

(*b*) Within the primary inclusion zone, a tensional stress (pulling force) is induced normal to the major axis of the primary inclusion zone.

(*c*) The magnitude of the least principal stress increases in the 'focal region of the primary inclusion' where the primary inclusion and its associated fault will grow. Due to the increase of least principal stress, cracks in the focal region begin to close when the focal region begins to store strain energy. The theory assumes that failure occurs if all the cracks in the focal region are closed. The tension axis within the primary inclusion and the strain energy throughout the focal region reach a maximum just before the initiation of failure. In this hypothesis also, presence of water in the fault zone is not an essential requirement and therefore may be considered to be similar to USSR model.

The outstanding feature of the inclusion theory is that the process of initiation and growth of faulting in rocks is scale invariant. In other words, same physical processes occur on the small scale (laboratory conditions), intermediate scale (mine failure) and large scale (earthquakes). For example, anomalous seismic activity precedes failure of rock on the laboratory scale, and rock burst in mines and earthquakes. Further, the time interval (precursor time) during which anomalous seismic activity appears, increases with the magnitude or the size of the impending failure. The time interval corresponding to the three types of events may be of the order of milliseconds (laboratory), a few minutes to a few hours (mine failures) and a few days to some years (earthquakes). These observations have direct bearing for predicting the time of occurrence of earthquakes on the basis of seismicity anomalies which depend upon the length of faulting involved.

Insitu stress and velocity measurements

Earthquake occurrence is attributed to stress accumulation and subsequent release. Therefore, direct tectonic stress measurements in a region would be valuable for predicting earthquakes. In Japan, measurements of crustal stress by 'hydrofracturing method' has been carried out in two bore holes (100 metres deep) separated by about 4 km in the central part of Honshu, facing the Pacific Ocean close of the city of Shizuoka (Tsukahara et al., 1979). The method is based on the computation of horizontal principal stresses from the pressure records of 'hydrofractured new cracks'. Four measurements at depth between 57 and 90 metres were conducted. A hydrophone was placed in the borehole for observing acoustic emissions during the hydrofracturing. It was found that the frequency of the emissions is closely related to the pressure variation and thus fracture pressure can be identified. The direction of the maximum horizontal stress was obtained from the azimuth of the hydrofractured plane using a 'bore-hole televiewer'.

It was found that the stresses increase with the depth. Also, the direction of the least principal stress was indicated as vertical while that of the maximum pressure as inclined at an angle of 40° with the true north. The direction of regional strain field (determined by Geodetic Survey), however, did not agree with this observation. Although detailed investigations are in progress, it is surmised that hydrofracturing method can be successfully applied to complicated orogenic regions.

In Fenoscandia, *insitu* measurements of stresses in deep mines have shown high value which could not be explained on the basis of overlying rock loads alone. It is possible that the regional tectonic stresses have also contributed to increasing the *insitu* values.

Insitu measurements of P wave velocity in a bore hole in granite gave a value of 4 to 4·5 km/sec while a velocity of 5 to 5·5 km/sec was measured in intact granite samples from the same bore holes in the laboratory. These lower *insitu* values have been attributed to the presence of joints in the earth which behave in a different manner than the microcracks in the laboratory. It is felt that better understanding of earthquake mechanism may be achieved through *insitu* measurements of stresses and other parameters on rocks under different tectonic regime.

CHAPTER 5

Long Range Earthquake Forecasting

Objectives

LONG RANGE FORECASTING USUALLY DEALS WITH TRENDS IN SEISMIC activity of a region in a probabilistic manner. This is based on the study of long term seismic activity, including the periodicity of large earthquakes (if any) and the accumulation of tectonic strain (defined later). Measurements of crustal strain through repeated geodetic surveys and seismic gap are also sometimes considered as additional observations although the author would prefer to classify them under medium range precursors. Another useful method called *pattern recognition technique* is based on geomorphological data which has shown that strong earthquakes occur at disjunctive knots, namely, zones of intersection of major faults in Central Asia.

Long range forecasting of earthquakes has two objectives. Since no exact estimate of time of occurrence of future earthquakes can be possible, the results are more useful to identify regions where observations can be intensified for medium and short term forecast. Secondly, considering higher probability of future earthquakes, earthquake risk for engineering designs can be estimated.

Risk evaluation techniques

Techniques of risk evaluation are fairly involved using geological, seismological and engineering concepts. Plate tectonics hypothesis (Chapter 3) and earthquake statistics provide the basis for long range forecasting and risk evaluation.

Faults identification

Deep seismic sounding techniques are used to find the location of faults by recording the seismic waves produced by chemical explosions at a number of seismological stations (Fig. 39).

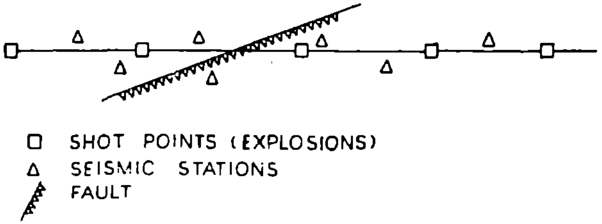
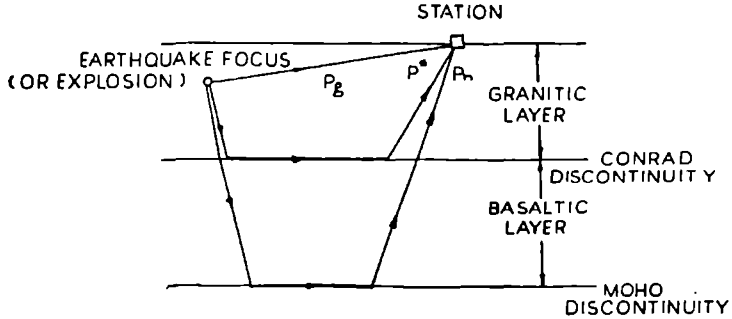


Fig. 39. (a) Recording seismic waves from chemical explosions (Deep Seismic Sounding Experiment).



Fig, 39. (b) The types of waves generated close to earthquake focus or explosion, Pg is the phase directly recorded, P^* through the Conrad discontinuity and P_n through the Moho. Similar notation holds good for S-phase.

Seismological data for risk assessment

Seismological techniques and observations provide basic data for risk evaluation as discussed below.

Earthquake catalogues

The first requirement for the evaluation of seismic risk is the preparation of an uptodate catalogue of earthquakes containing not only microseismic data but also information about the location and magnitude of earthquakes. For some countries, such as China, detailed information about important earthquakes is available for

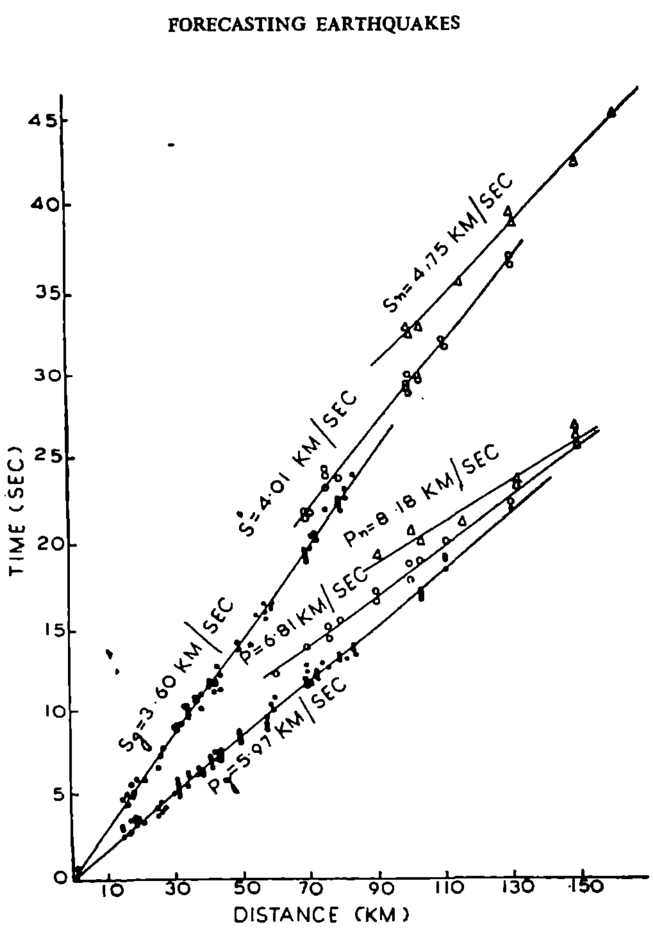


Fig. 39. (c) Time distance plot of seismic waves recorded through DSS explosions in Koyna area. The velocities of P and S waves can be found by the slope of the straight lines. Substitution of these wave velocities into equations (appendix III) enables us to find the thickness of earth crust (granitic and basaltic layers) giving the velocity model after neglecting the sedimentary layer.

the last 3000 years. In the case of India, such information is available only for the past 200 years. Dr. T. Oldham, a former Director of the Geological Survey of India, has prepared a catalogue of earthquakes occurring in and near India from the earliest time to the year 1869. This catalogue though very useful is somewhat incomplete, specially for the earlier period because the felt reports were mostly confined to populated areas only. The seismological division of the India Meteorological Department has compiled an uptodate catalogue of Indian earthquakes with magnitude 5 and above, occurring in and near India (Tandon and Srivastava, 1974). This compilation is based on the following sources:

(*a*) Bulletins of International Seismological Centre.
(*b*) Report of the British Association for the Advancement of Science.
(*c*) Monthly listing of US Geological Survey.
(*d*) Bulletins of International Seismological Summary upto 1964.
(*e*) Publications entitled 'Meteorology in India' and 'Monthly Weather Review' and Seismological Bulletins of India Meteorological Department.
(*f*) Seismicity of the Earth by Gutenberg and Richter.

This catalogue contains fairly reliable information at least for the last 70 years and is available as a magnetic tape file after updating it till 1976. Through computer programme, the data in the required form are extracted and supplied to users on request.

It may be pointed out that more information about historical earthquakes in the Indian region is urgently called for. The example of Koyna earthquake of December, 1967 illustrates the necessity as this earthquake took place in an area where severe earthquakes were not expected. After the occurrence of the damaging earthquake, Professor Kelkar of Poona University reported in a Marathi newspaper on the basis of original records of the time of Peshwas that an earthquake of similar intensity as that of December 1967 had occurred in 1764. If this information were available earlier our understanding regarding the seismic potential of Koyna region would have been different. Serious efforts have been made by Dr. N.N. Ambreysis of Imperial Science College, London to prepare earthquake records since historical times in Iran and Afghanistan through the help of historian, linguist and other literary persons of different languages, and similar assistance of these persons for the Indian region is to be welcomed.

Isoseismal maps

Intensity is measured on a 12 numbered scale (I to XII) on the Modified Mercalli Scale (MM) and describes the effects of earthquakes at different places (Appendix I). It depends upon the magnitude of earthquake, focal depth, the distance from the epicentre and soil conditions. Damage to structures starts with intensity VI MM. A number of empirical relations between the maximum intensity, magnitude and focal depth of earthquakes have been published, but none is entirely satisfactory.

The lines joining the places of same seismic intensity are called isoseismals (Fig. 40) and are generally elliptical (at least a few inner lines) for an earthquake source which can be represented as a line. Such maps have enabled us to estimate the epicentres of historical earthquakes fairly accurately. They also define the orientation of faults except in complex tectonics zones.

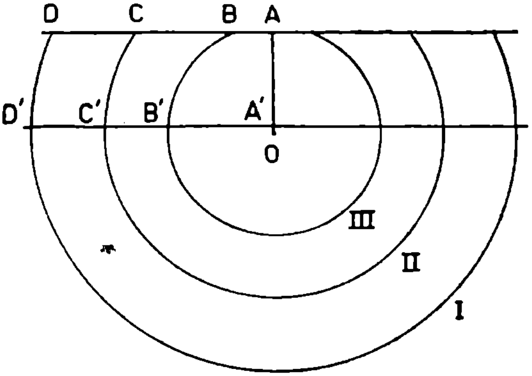


Fig. 40. Difference between the seismic intensity due to a shallow focus and a deeper focus (OA) earthquake, assuming earthquake as a point. For earthquake represented by line source, isoseismals are elliptical in shape.

It may be clarified that intensity is assigned based on field survey which is undertaken by geologists, engineers and seismologists soon after a damaging earthquake (Fig. 41). Intensity has, however, one limitation in conveying the effect of earthquakes. Earthquakes can be assigned same seismic intensity due to local moderate earthquake

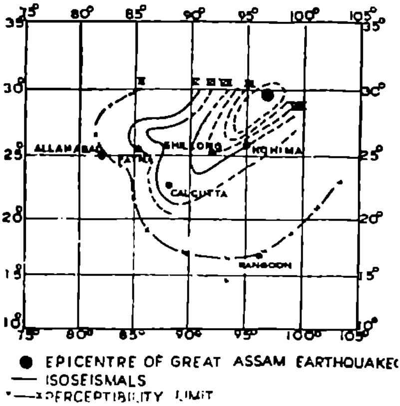


Fig. 41. Isoseismals of the great Assam Earthquake of 1950. (Tandon, 1954). (*Courtesy*: India Meteorological Department).

or a great earthquake at larger distances. The near earthquake has much higher frequency vibrations and for a shorter time than the larger one which will produce lower frequency and prolonged vibrations. Thus the effects would be different on structures which need be studied by engineers in detail with reference to the source parameters. Measurements of actual acceleration through strong motion instruments are, therefore, recommended during damaging earthquakes which is useful for design purposes.

Magnitudes

The magnitude of an earthquake is an instrumentally determined quantity and is related to the amount of energy released at the earthquake source. It is generally measured in Richter Scale which is defined as the logarithm of the maximum amplitude recorded by a standard Wood Anderson Seismometer kept at a distance of 100 km from the epicentre. For other distances, the amplitudes are corrected. This scale is valid upto 600 km epicentral radius. Since the scale is logarithmic, each unit of change represents ten times increase in the amplitude of vibration or 30 times increase in energy. The smallest earthquake detected so far had a magnitude of —3 while the largest had a magnitude of 8·9. Damage to structures generally starts with earthquake of magnitude 5.

Different magnitude scales are now in use and mathematical formulae have been evolved to convert one scale into the other. The amplitudes and periods of P and S waves are included into 'body wave magnitudes' while the slower moving surface waves of 18 to 22 seconds give rise to 'surface wave magnitude'. The total duration of vibration on a seismogram is also used to assign magnitude but is generally limited to microearthquakes.

It becomes difficult to have a complete catalogue of earthquakes based on only one scale of magnitude. Conversions introduce errors not only in assessments of intensity but also in the computation of return periods of earthquakes as will be described later.

Depth of focus

The focal depths of earthquakes expected at a site plays a vital role as seismic intensity is dependent upon this factor. Deeper earthquakes are felt over a larger area and cause destruction over a limited area as compared to shallow ones whose effects are more damaging over a wider region. In general, the focal depth cannot be determined accurately unless depth phases on the seismograms are identified or 8 to 10 close seismic stations well distributed in azimuth are opened in the project area.

Fault length

Fault length is an important parameter in the assessment of earthquake risk. It can be estimated by geologist but its activity (whether it is seismogenic or dormant) can be assessed by seismologists on the basis of monitoring small earthquakes with the help of 8 to 10 portable seismographs (Fig. 42). Faults, concealed below the earth can also be detected by this method. Fault length can also be estimated from the aftershock areas of past earthquakes. (Srivastava, 1981). The maximum magnitude of expected earthquake can be assigned on the basis of these considerations.

Fault displacement

Although vibrations produced by the earthquakes affect a much larger area and produce considerably more seismic risk, the length of expected surface breakage for damaging earthquakes directly

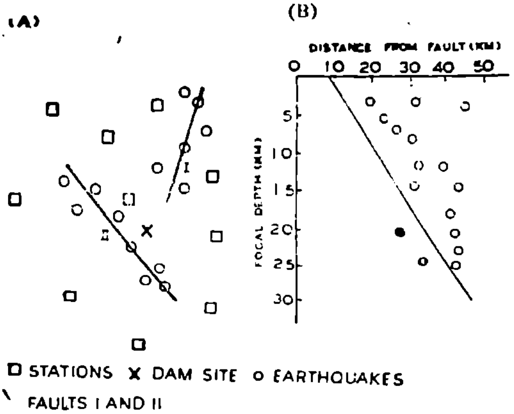


Fig. 42. Fault detection through seismological stations, (left) Note that the orientation of the faults (I) and (II) can be revealed through the spread of epicentres. Dipping of faults can be studied by vertical cross sections across faults I or II as shown on the right.

affects the structures located over it. Fault displacement can be predominantly horizontal, for example, with a maximum displacement of 5 metres near San Francisco or can be of thrust type like that associated with San Fernando earthquake of 1971. Thus the length of surface breakage of earthquakes of given magnitude depends upon the mechanism of earthquakes. It may also depend upon the velocity of rupture in the fault zone. It may however be clarified that no amount of precautions in design can save a structure, if it is located directly on a fault and suffers displacement.

Mechanism of source and its characteristics

More reliable information about faults are obtained through first motion P wave and the polarisation angle of S waves. Surface waves are also sometimes used. These enable us to find the strike of the fault, dip angle and direction, the nature of faulting, the orientation of stresses and several other parameters (Fig. 43). They supplement the observations of geologists and others who generally give their finding by only observing the geomorphological features.

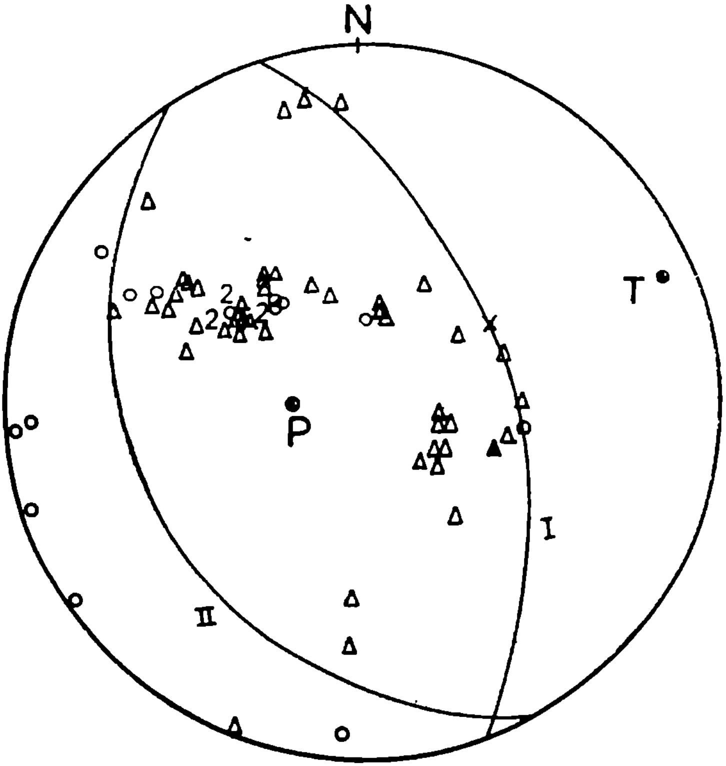


Fig. 43. Fault parameters determined from P wave first motion data of Kinnaur earthquake (1975). Nodal planes are shown by I and II. Plane I dipping towards ENE was chosen on the basis of aftershocks as the fault plane P and T denote the orientations of pressures and tensions.

The nature of faulting has a direct bearing on the type of vibration produced by the earthquakes and their effects on structures. These differences, their field effects and different characteristics of records on instruments are explained, in terms of a newly developed 'spectral theory of earthquake dislocation'. According to this theory, the displacement spectrum of the radiated energy of shear waves has a simple shape, being flat at the low frequencies, and falling off as the square of frequency at high frequencies. In this theory, a circular area of rupture is considered on a fault plane over which a uniform dislocation occurs resulting in drop of stress and release of seismic energy. An important source parameter is defined as seismic moment as a product of fault area, the rigidity of rocks and the dislocation. Seismic moment is one of the most reliable seismological parameters that represents the 'size' of an earthquake. It has been shown to be related to seismic energy and can be more accurately calculated than the magnitude scales, particularly for great earthquakes. In general moment and magnitude are the same for earthquakes of radius greater than 0·5 km (corresponding to magnitude of about 3 on Richter scale). For sources greater than this, the source radius is a function of the difference between moment and magnitude. The peak or corner frequency is defined as one where the spectral amplitude is maximum. Figure 44 shows the

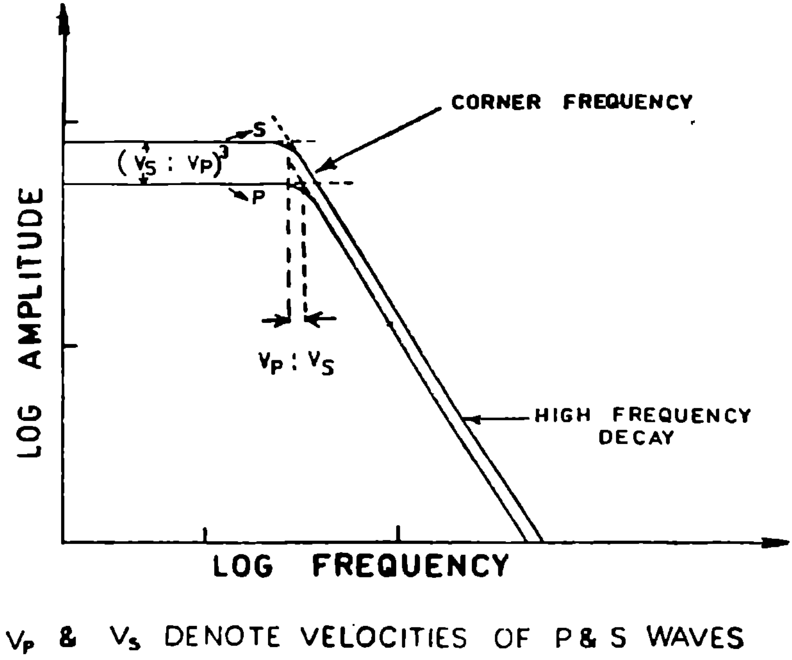


Fig. 44. Source spectra (displacement spectrum versus frequency) for P and S waves. V_p and V_s denote their velocities.

idealised source spectra for displacement plotted as the ordinate and the frequencies as abscissa on logarithmic scale. It is found that the seismic moment determines the low frequency level of the displacement spectrum and that the source becomes deficient in high frequencies above the corner frequency. For the acceleration spectrum, the high frequency level is determined by the magnitude, and accelerations fall off at frequencies lower than the corner frequency.

From the point of view of earthquake risk analysis and engineering applications, it has been found that areas of large displacement indicate small, compact, high stress drop sources in strong rock, whereas those of low displacement indicate large, low stress drop sources in weak or fractured rock. The former earthquake sources will have a greater proportion of long period energy and can excite taller and more flexible structures. On the other hand, earthquakes in areas of large displacement will be deficient in long period energy or will be richer in high frequency energy and thus would affect small stiff structures. Thus regional differences in source characteristics give a better insight in assessment of earthquake risk.

The practical method of spectrum analysis is to digitize the seismograms and then find the amplitude spectra using fast Fourier transform through a computer (Bath, 1974). Manual digitization from records of conventional seismograms introduces several errors and, therefore, trend is fast developing to install direct digitizing seismographs. As mentioned in Chapter 3, the Seismic Research Observatory at Shillong provides volumes of data on source mechanism of earthquakes which may help in better assessment of earthquake risk in northeast India.

Earthquake recurrence

We are familiar that the number of bigger stars in the sky is considerably less than the smaller ones. Similar is the case with earthquakes which led the seismologists Gutenberg and Richter to express the relationship between the size (magnitude M) and the frequency N (number) of earthquakes over an area during a given period as

$$\log N = a - b\, M$$

where a and b are constants. The value of a depends upon the period of observation and on the level of seismicity of the observed region while the constant *b* depends upon the tectonic characteristics of each region. Figure 45 shows this relationship for Andaman Island region.

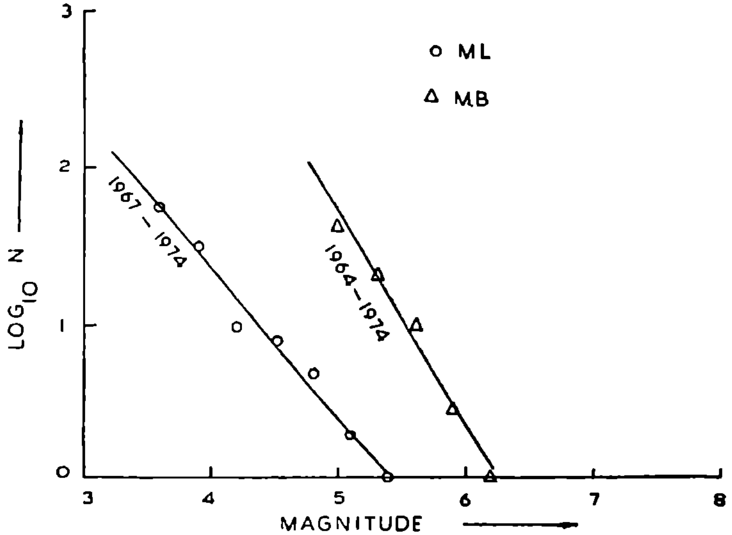


Fig. 45. Frequency magnitude relationship of earthquakes in Andaman Island region for (a) 1964-1974 (b) 1967-1974. The slope of the straight line and the intercept on *Y*-axis gives constants *b* and *a* respectively (Srivastava and Chaudhury 1979). (*Courtesy*: India Meteorological Department).

Table 2 gives the maximum magnitudes of earthquakes expected for some Indian regions. The results have limitations when the data sample is small and available for a short span of time. Still they give fairly reliable information for assessment of earthquake risk versus the life of a project or structure. It may, however, be remembered that the above method gives statistical inference to the extent that the periodicity of earthquakes may considerably vary in practice. For example, if statistical analysis has shown that in Delhi, an earthquake of magnitude 6 is expected once in 40 years; in actual practice, two such earthquakes may occur in quick

TABLE 2. **Statistical forecasts of damaging earthquakes in India***

Region	*Return period of earthquakes (years)*				*Maximum magnitude of earthquake expected*
Magnitude (Richter Scale)	8.0	7.0	6.0	5.0	
Northeast India	50	25	8	—	8.0-8.5
Andaman Islands	75	40	10	—	8.0-8.5
Himachal Pradesh	100	60	15	1.0	8.0-8.5
Nepal-Sikkim border	—	40	20	1.5	7.0-7.5
Rann of Kutch region	Insufficient data to compute return period				6.5-7.0
Nepal-India border	—	50	15	2	6.5-7.0
Delhi	—	—	40	5	6.0
Himalayas	40	4	0.5	—	8.0-8.5

*Based on Gutenberg-Richter frequency magnitude relations, Gumbel's statistics and strain release pattern (author's interpretation, unpublished). Extrapolation to maximum magnitude earthquake restricted to 8.0 due to paucity of data.

succession or there may be a considerable lapse of time between them. The use of different magnitude scales also sets a limitation in the computation of return period. If data are available for a fairly long period but are deficient in high magnitude events, statistical techniques developed by Gumbel and others (Fig. 46) can be employed to obtain a more reliable estimate of return period of earthquakes of different magnitudes.

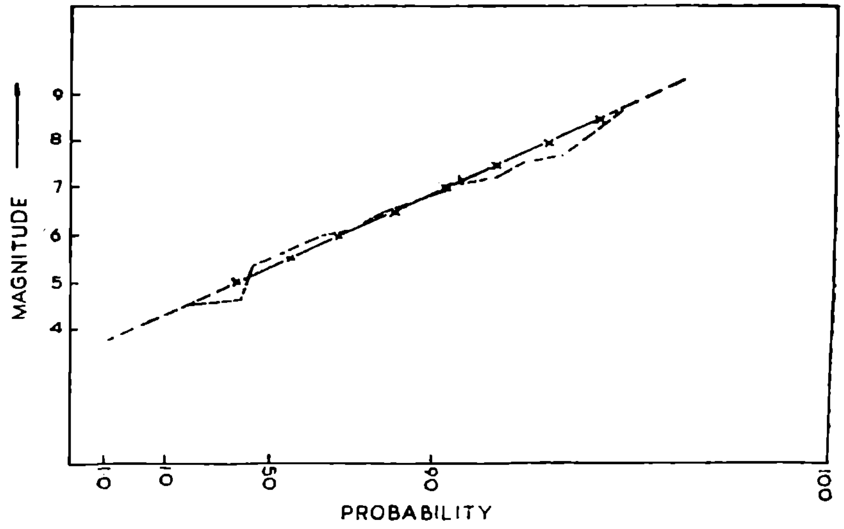


Fig. 46. Estimation of return period of earthquakes using Gumbel's Extreme Value Theorem; area 23°N-29°N and 90°E-95°E.

A number of other empirical relations between magnitude and the energy released in an earthquake, such as the strain (equal to square root of the energy released), or cumulative strain over a fault (sum total of the strain due to all earthquakes) are sometimes used to classify the peculiarities of earthquake source.

Strain release patterns

Strain release characteristics of Kashmir, Bihar-Nepal, Assam and Kutch regions in India have been studied by Chouhan (1979). These curves (Fig. 47) may be used to estimate the amount of

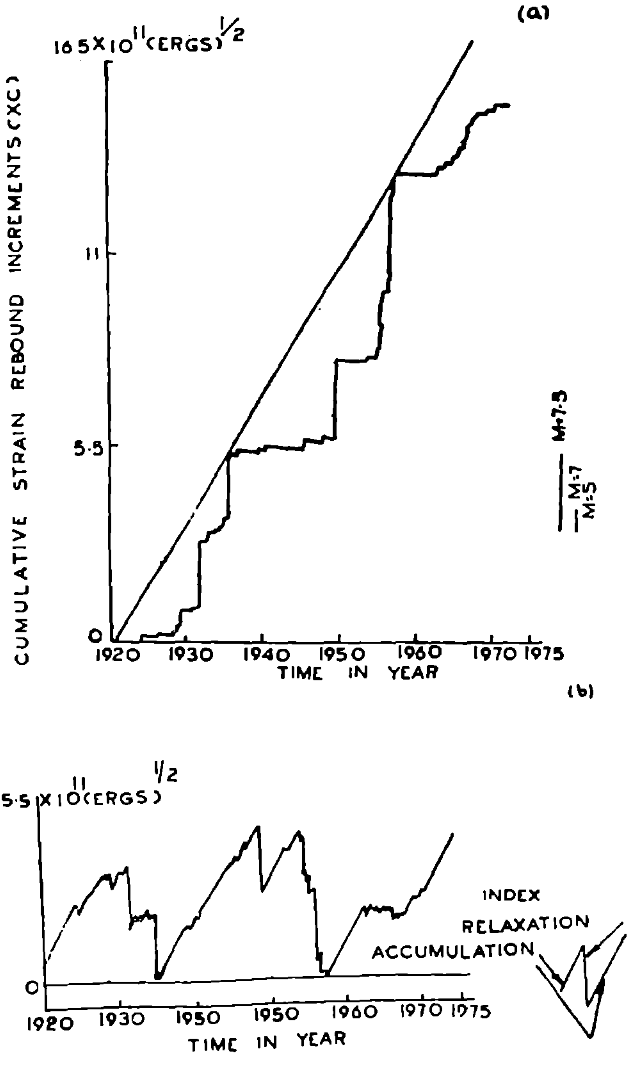


Fig. 47. Strain release curves for Kashmir region. Strain is computed by taking square root of earthquake energy, (Chouhan, 1979). (*Courtesy*: India Meteorological Department).

stored strain and the maximum magnitude of an earthquake, if all the accumulated strain is released simultaneously. Accordingly, the maximum possible magnitudes in Assam, Kashmir and Kutch region have been assessed as 8·3, 7·5 and 6·4 respectively. Similar studies can be extended to smaller faults.

In Nepal-India border region, there has been a considerable decrease in the strain energy release due to low level of seismic activity after the earthquake of 1966 in the region. On these considerations, the author predicted a damaging earthquake at the 3rd Seminar on Himalayan Geology (Wadia Institute) in December, 1973. Indeed an earthquake occurred on 29th July, 1980 causing heavy loss of life and property in Nepal and the adjoining hills of west Uttar Pradesh.

Pattern recognition technique

This technique was first developed by Gelfand et al. (1976) for forecasting the sites of future earthquakes in California as part of the joint USA-USSR programme on earthquake prediction. This enables us to delineate dangerous and non-dangerous zones based on statistical decision rules and past earthquakes data.

Varunoday, Gaur and Wason (1979) applied this technique in the Kumaon Himalayan region. It was found that the main central thrust is one of the most seismically active regions. Most of the dangerous points on curved segments appear on the concave side of the bends while the non-dangerous zones appear on the bend convex towards the Indian plate.

Seismic zoning and risk maps

Seismic zoning maps should give us a fairly accurate idea of the seismicity (geography of earthquakes) of the various areas and the probability of occurrence of future earthquakes of various intensities in the region. Since sufficient instrumental data are available only from the beginning of the present century, they are not enough for estimation of earthquake risk because strong and destructive earthquakes often take place in areas with no previous history of damaging earthquakes during 100 to 500 years. In the past, the seismic zoning maps were based only on historical data with the assumption that the same pattern of seismicity repeats in future. This method has been found essentially inadequate as can be understood from the occurrence of Koyna earthquakes of 1967 which led to revision of seismic zoning map under the auspices of Indian Standards Institution prepared by seismologists, engineers and geologists (ISI-1893 : 1962). More emphasis has, therefore, to be laid on the geological history of the area and identification of faults and thrusts along which movements have taken place during geologically recent times. This technique gives a better estimate of earthquake risk since it has enabled prediction of earthquakes For example, a detailed seismotectonics map prepared by Professor Gubin of USSR for the peninsular India in 1968 correctly predicted the Broach earthquake of 1970. According to Gubin, seismic zoning maps should include the following:

(*a*) Seismogenic area which should contain areas where strong earthquakes are expected to occur.
(*b*) The maximum possible magnitude and intensity of earthquakes in each zone.
(*c*) Frequency of shocks of different magnitudes in every zone.
(*d*) The attenuation of seismic intensity with distance from the epicentre.

India has been divided into five seismic zones. The highest danger from earthquakes lies (IS-1893 : 1975) in zone V which includes parts of Kashmir, Himachal Pradesh, East U.P. and Bihar hills, Northeast India, Andaman Islands and Rann of Kutch. Rest of northern India foothills and adjoining plains including Delhi lie in zone IV. Parts of Rajasthan, Madhya Pradesh and southern peninsula are relatively free from earthquakes and have been placed in zone I. The map serves as a rough guide only and the proper safety factor particularly for projects lying at the border of the two seismic zones can be assigned by seismologists on the basis of additional data.

Seismic coefficient

Proper risk evaluation is important from economic as well as safety point of view. The force of earthquakes on structures acts predominantly in the horizontal direction and therefore it is computed through horizontal seismic acceleration which in turn is based on seismic intensity. The *seismic coefficient* to be adopted in the design of structures is a product of horizontal seismic acceleration, soil foundation factor, recurrence period of earthquakes and the acceptable risk factor. An alternative method called *response spectrum method* applies corrections based on the average acceleration spectra, appropriate natural period and damping of the structure. The latest seismic zoning map prepared by the Indian Standards Institution (IS-1893 : 1975) has also incorporated importance factor; the highest value of 6 has been assigned to atomic power reactors. This coefficient has to be chosen very carefully as a compromise between economic and safety consideration. Higher values of seismic coefficient adopted may prove very costly for the project while lower values increase the chance of damage during earthquakes.

A simpler procedure outlined below is sometimes adopted in practice to compute the horizontal seismic acceleration:

(*a*) Catalogue of earthquake for the region is scanned. The maximum intensity due to the largest earthquake which occurred in the region is assessed.

(*b*) The location of the site is referred to in the seismic zoning map prepared by the Indian Standards Institution and the maximum intensity expected is noted.

(*c*) The recurrence of earthquakes of various magnitudes and their probabilities are computed and allowance given for the importance of the structure and the type of the soil. Maximum magnitude expected is assessed considering the activity of faults in the vicinity. This is then converted into forecast intensity using empirical relations.

(*d*) The discrepancies between the actually experienced intensity due to past earthquakes and the maximum expected according to ISI seismic zoning map are resolved and the forecast intensity is assigned as a compromise between the economic considerations and reasonable amount of safety.

(*e*) The intensity forecast is then converted into the horizontal acceleration by empirical relations or equations.

For important projects like dams and nuclear plants, special seismic observations have to be collected at least 3 to 5 years before the construction stage. Through commercially available more sensitive seismographs, the microearthquake data can be collected in a relatively small period from which the return periods of the earthquakes of bigger magnitudes can be extrapolated (though with lesser degree of accuracy). The activity of faults, if any, in the region can also be assessed. In addition microtremor measurements have also to be recommended to determine the type of soil strata (as discussed later).

In India, shallow underground chemical explosions have been used to estimate the predominant period of the ground using Wood Anderson Seismograph at Bhakra, Pong and Thien dams. The seismographs show fast decaying wave trains called coda after the body waves whose predominant periods are measured for classifying the type of ground. The data were then used to compute the seismic coefficient. The Earthquake Engineering Department of the Roorkee University prepares models of bridges, dams and important structures and tests under dynamic conditions similar to those experienced during earthquakes motions. Thus, the extra cost involved is worth, as it provides greater confidence in the design of earthquakes resistant structures.

Table 3 gives the seismic intensity and the horizontal acceleration based on the strong motion observations in California, USA (average as well as range of values, being higher on soft ground as compared to hard strata). In general, these values have to be suitably modified for seismic zones IV and V, otherwise the cost of construction becomes exhorbitant.

In this country, there is a standing committee for the assessment of seismic coefficient to be adopted in the design of various river valley projects. The committee consists of seismologists, earthquake engineers, geologists and dam designers.

Microzoning

We have seen earlier that within the same locality damage to structures may be different depending upon the soil conditions. Figure 48 shows the variation in seismic intensities observed during the great Assam earthquake of 1950 at different distances from the epicentre. The lower envelope represents the intensities on rock while the upper envelope for the overburden. Similarly, during the San Francisco earthquake of 1906 in USA, the structures built on loose water soaked areas suffered nearly ten times more damage

TABLE 3. **Accelerations recorded for various degrees of earthquake intensity**

[Data from US Coast and Geodetic Survey accelerograph records 1930-41]

Intensity MM scale of 1931	2	3	4	5	6	7	8	9
Average maximum acceleration on one component cm/sec²	2.3	3.1	9.3	13.3	40	67	172	250
Range of acceleration cm/sec²	1-5	1-8	2-46	2-75	5-175	18-140	51-350	250

Seismic Zone I corresponds to intensity V MM scale.
II corresponds to intensity VI MM scale.
III corresponds to intensity VII MM scale.
IV corresponds to intensity VIII MM scale.
V corresponds to intensity IX MM scale.

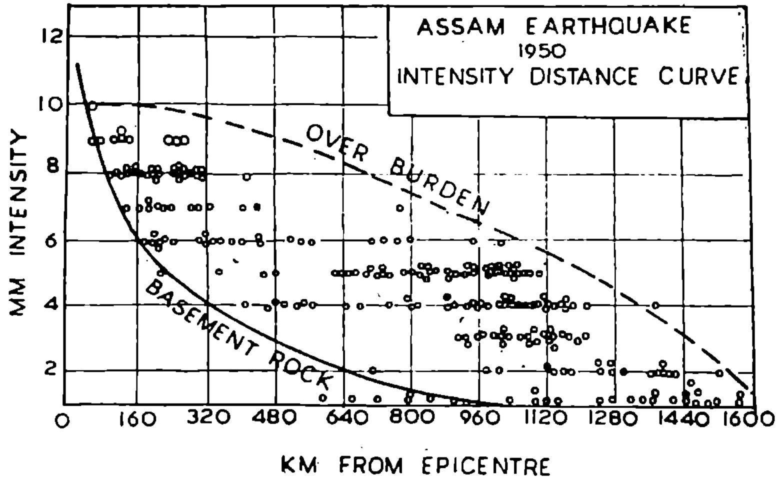


Fig. 48. Variation of seismic intensity with epicentral distance (a) over burden (b) bed rock due to great Assam earthquake of 1950 (Tandon, 1962). (*Courtesy*: Indian Society of Earthquake Technology.)

than those built on rocky foundations. Thus, the intensity in a given locality may vary by 3 to 4 stages on MM scale due to the effect of geological conditions. The amplification of vibration is attributed to the less dense, less rigid soil near the ground surface which causes the wave to travel at a lesser velocity, with a corresponding increase in the amplitude of vibration, provided the layers are at least 10 metres deep. Resonance and interference phenomena in low velocity layers of appropriate depth also cause further amplification or increase of intensity. The phenomenon of liquefaction may occur with loose, uniform, fine sands due to intense earthquake vibration, causing almost complete loss of support to any structure. Loose sand and gravel may also compact leading to differential settlement.

Steeper slopes near hills are of doubtful stability. The loose material becomes unstable under earthquake vibration and may move as a rock fall or slump along the slope. Moisture contents play a vital role; the greater area of ground may be effected in wet weather due to landslides.

The last consideration causing variation of earthquake risk is the direct displacement and damage to the structure associated with faulting. Thus microzoning maps are more detailed as compared to seismic zoning maps which give only an average idea of the earthquake risk.

Microzoning maps for urban areas are prepared after geological, geophysical and soil surveys. These are supplemented through strong motion instruments data if available as they reveal the actual accelerations experienced during the past earthquakes. The measurement of ground noise (also called microtremor measurements in Japan) enables us to classify the soil type by observing the predominant periods, and give clear information on the characteristic nature of underground strata. In the Building Code of Japan, the ground has been classified as follows:

Kind-I : Hard ground composed of rocks of the tertiary or older geological formation, covered by very thin surface layer less than 2 metres, if any.

Kind-II : Ground covered by relatively thin surface layer such as diluvium less than 15 metres or alluvium less than 10 metres.

Kind-III : Ground covered by fairly thick surface layer such that diluvium of more than 15 metres thick or alluvium of thickness 10-25 metres.

Kind-IV : Ground covered by extremely soft layer or covered by very thick alluvium more than 25 metres.

In the Indian Standards Institution Criteria (IS-1893 : 1975) only three types of soil (rocky, medium and soft) have been considered.

The method of finding the type of soil is based on recording the natural vibrations (horizontal component) called microtremors at the site with the help of a very sensitive seismograph for a few minutes (Fig. 49, a). The period of wave with maximum number of occurrence is called the predominant period of the site (Fig. 49, b). Microtremor observations at the surface and in a bore hole enable us to assess the effect of foundations versus structure.

Microzoning maps have been published for Wellington city, New Zealand (Taylor et al, 1974). For disaster preparations and assessment of insurance risks, microzoning maps need to be prepared for Indian cities as early as possible.

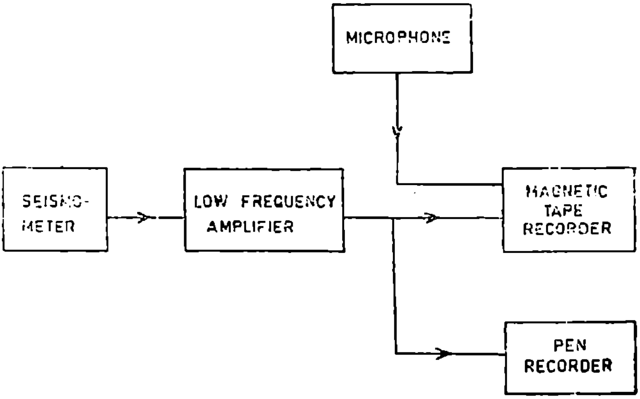


Fig. 49. (a) Recording system for microtremors at a site.

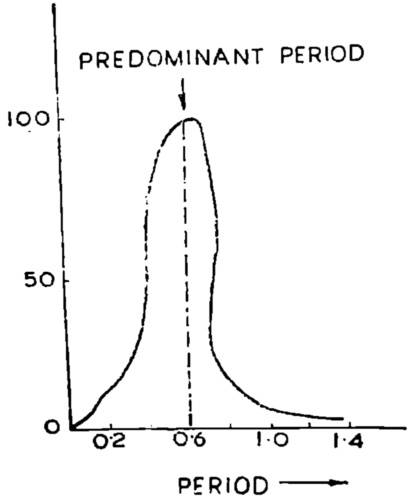


Fig. 49. (b) Finding the predominant period of waves. Number of waves of specified period are shown along the ordinate of the figure.

The instruments recommended for microzoning or risk evaluation for a dam or any important project consist of 8 to 10 microearthquake seismographs well distributed in azimuth with a spacing of about 20 to 30 kilometres operated for a period of five years for epicentral location, one or two accelerographs for recording actual acceleration of the ground and one set of Wood Anderson Seismographs for magnitude calibration.

CHAPTER 6

Medium and Short Range Earthquake Forecasting

Medium and short term prediction

MEDIUM TERM PREDICTION MEANS FORECAST OF AN EARTHQUAKE A FEW months to a year or more ahead, while short term prediction implies forecast ranging from few hours to some days in advance. Some times *imminent prediction* is included as the fourth stage, though keeping an analogy with the classification of weather forecasts, the author considers only three stages, namely, long, medium and short range predictions sufficient in view of the present day development in the science of earthquake forecasting. Of these, the medium and short range stages in earthquake prediction are concerned with forecasting the occurrence of an earthquake of a particular intensity over a specified locality within a particular time limit. Satisfying this criterion, a few earthquakes have been successfully predicted in Japan, USA, USSR and China. It is actually these two stages of earthquake prediction which save the largest population from disaster in terms of life or property, and is more often demanded by public as well as Government. Even though the medium and short range prediction techniques are broadly similar using several disciplines of geophysics, some simple observations like earthquake lights or sounds, unusual behaviour of animals, changes in the level and colours of well water, hydrochemical changes and foreshocks can be of great assistance from the point of view of short range prediction of large earthquakes, if general public can be properly educated to report them.

We shall discuss in this chapter these unusual phenomena which can help in medium and short range earthquake forecasting.

Unusual animal behaviour

Unusual behaviour of animals prior to earthquakes received wide publicity after the Haichang earthquake of February 4, 1975 was successfully predicted in China. The official report was presented by the Chinese delegation at the Inter-Governmental meeting convened at UNESCO, Paris, in February 1976 which stimulated considerable scientific interest. Prior to this, however, several instances of abnormal animal behaviour were noticed before occurrence of some of the damaging earthquakes in different parts of the world, but they were considered more as historical legend. In Japan, innumerable rats were seen every day in a restaurant in Nagoya city, which suddenly disappeared on the evening prior to the Nobi earthquake of 1891. Similar observations about rats have been reported before two other damaging earthquakes, namely, the Kanto earthquake of 1923 and the Sankriku earthquake of 1933. In recent times, unusual behaviour of rats was reported in China before the 1966 Hsingtai earthquake in Hopei Province (300 km away from Beijing).

As early as 1886, a seismologist named Milne had mentioned that dogs escaped from the city of Talcahuano in Chile before an earthquake (1835). Flocks of birds flew inland before the Chilean earthquakes of 1822 and 1835. Monkeys were reported to have become restless a few hours before the Managua earthquake (1972) in Nicargua. In the Tientsin region of China, chickens refused to enter their dens, tigers became restless, yaks declined to eat and horses and sheep started running restlessly a few hours before the earthquake of July 18, 1969. Hens and cocks were reported restless about an hour prior to the 1896 Ryukyu earthquake in Japan. In Yugoslavia, birds in a zoo started crying before the 1963 earthquake. Deer gathered and cats disappeared from villages in northern Italy two or three hours before a damaging earthquake occurred in 1976. Such observations have also been noticed among animals who live underground, like snakes, insects and worms, and those living in water (fishes). In Japan, fish were reported to have disappeared before the Kanto earthquakes of 1923. Just before the 1855 Edo earthquake on November 11, many grass snakes were reported to have come out of the ground near the epicentral area, despite the severe cold. Other instances involving fishes have been reported in Japan near northwestern coast before the 1896 earthquake and the

Tango earthquake of 1927 when abundant fishes were caught near the coasts. Some experiments have also been conducted on Cat Fish which is considered as a more reliable earthquake precursor in Japan (Rikitake 1976).

An interesting instance of unusual behaviour of dogs (but not of other animals) has been reported before the destructive earthquake on November 24, 1976 in Turkey (Toksoz, 1979).

The Group of Earthquake Research of the Institute of Biophysics, China (1979) has carried extensive survey of the animal behaviour before damaging earthquakes occur. Its results are summarised below.

1. Most animals show increased restlessness before an earthquake.
2. The precursor time varies from a few minutes to several days, with increased restlessness at 11 hours which becomes still more marked about 2 to 3 hours before the earthquake. In general, the precursor times of various animals are mostly within 24 hours before the earthquake.
3. These observations have been noticed predominantly in the high intensity or epicentral regions close to active faults.
4. Changes in animal behaviour are observed during earthquakes of magnitude 5 or more.
5. More intense responses can be noticed with the increase of intensity of earthquakes.

A detailed statistical study of animal behaviour has been reported by Rikitake of Japan at the UNESCO symposium on earthquake prediction, Paris (1979). After the devastating earthquake of January 14, 1978 near the Izu Peninsula and Izu Oshima Islands, questionnaire cards were sent to townhalls, schools, zoos, etc. in the meizo-seismal area. It has been found that the mean precursor time is estimated 0·56 day. Rikitake analysed 157 cases of animal behaviour and found two peaks of precursor times centred at about 2 hours and 0·4 days. Thus, if this type of animal behaviour can be observed in future earthquakes, it might give a positive sign for imminent prediction.

Impressed by the Chinese survey of unusual behaviour of animals, about 300 qualified volunteer observers have been recruited along seismically active region of California in USA (Otis and Kautz, 1979). These volunteers have been provided with forms on which they rate the behaviour of animals on a scale of 0 to 4. Zero denotes typical behaviour, 1 slightly atypical behaviour, 2 clearly atypical, 3 very atypical and 4 behaviour never observed before. Only those volunteers are selected who have daily contact with the animals either by virtue of employment or hobby. Volunteers have been instructed to call on a toll-free hot line to the Central Institute in California on a fixed day once a week to keep proper liaison. They can also use the line at any time if unusual animal behaviour is observed. It is hoped that such a study will provide a more scientific basis for using biological precursors.

The question arises as to how animals get premonitory indications due to earthquakes. It is possible that just as a dog is over-sensitive to smell and can trace a culprit, the skins of most of these animals may be so sensitive that they may feel minor tremors or foreshocks. The other explanation could be that in the tectonic regions of high content of radon gas which is radioactive, the emission of the gas (even though in extremely small quantities) from well water or through frictional sliding of rocks in the epicentral zone could make them uncomfortable. It is also possible that changes in geoelectric properties or earth current in the focal zone may be responsible for unusual animal behaviour. It is, however, more probable that animals living underground like snakes, etc. can be more easily affected due to changes in heat flow content in the focal zone. However, any scientific explanation at present does not appear to be acceptable unless laboratory experiments can be carried out on animals or the phenomena observed almost universally.

Although several destructive earthquakes have occurred in the Himalayan region and elsewhere, only one authentic observation of unusual animal behaviour has been reported in India. In the Govindpur, Manbhoom district (formerly in Bihar) on February 19, 1892, animals were noticed to sniff the ground and exhibit nervousness such as a dog shows in the presence of an unaccustomed object, while the air had distinctly sulphurous smell an hour before the shock. Frequent references to earthquake prediction in newspapers and magazines through unusual animal behaviour in China have stimulated much interest in the minds of Indian public and therefore such observations on a large scale prior to an earthquake are not likely to go unnoticed.

Hydrochemical precursors

Regular observations of the chemical composition of underground water were taken during 1977 in seismically active regions of Tadzhik, SSR and Uzbekistan (Sultankhodjaev, 1979; Sadovsky et al., 1979). The water samples were analysed in following two ways :

1. The concentration levels of dissolved mineral components like sodium and calcium ions, bicarbonate and chloride ions were measured before, during and after the earthquakes.
2. The gaseous components of water like helium and hydrogen sulphide were analysed at different intervals of time.

The following encouraging results have been obtained:

1. During seismically inactive period, the concentration levels of dissolved minerals and gaseous components remain almost constant (which may equal their average long term values).
2. About 2 to 8 days before an earthquake, appreciable increase in the concentration for dissolved minerals is noticed. Also, the maximum volume of helium gas in thermal water tends to occur 3 to 5 days before the increase in seismic activity.

During this phase, variations are noticed in the level of underground water, the pressure of artesian water, the discharge of water sources and the temperature of underground water. The extent of these variations depends upon the magnitude of the earthquake, the depth of the water source and its distance from the observatory. Greater anomalies are observed if the earthquake is large and close to the observation point.

3. In the last phase, that is, after the occurrence of earthquake, anomalies in the concentrations of the gaseous and mineral components disappear until they slowly return to their original values.

The mechanism of the behaviour of these hydrogeochemical precursors is attributed to the upsetting of balance in the rock/interstatial solution/underground water system prior to earthquake. This is due to the increase of stress and the consequent appearance of permeable fissures through which an increased inflow of underground fluid from the subsurface zones of the earth's crust takes place. The anomalous variation may also be controlled by the faults.

Some specific instances of the changes in the temperature and levels of underground water before a few earthquakes are described below.

Temperature changes

A rise of temperature by 10 and 15°C has been reported before earthquakes in Lunglin, China (1976; epicentre, 24·4°N, 98·6°E) and Przhevalsk, USSR (1970; epicentre 45·5°N, 78·4°E). The epicentral distances for these earthquakes where observations were taken in hot spring/well were 10 and 30 km and the precursory periods were 42 and 72 days respectively.

Water level

Unusually muddy and fall in the level of water was reported in several wells a few days before the great Nankai earthquake (1946) in Japan. However, rise of water level by 3 and 15 cm was also reported before the Lunglin (China) and Przhevalsk (USSR) earthquakes. Similarly, water level rose by 3 cm a few hours before the earthquake in Meckering, Australia (1968) at an epicentral distance of 110 km (Gordon, 1970).

In Kurile islands, variations of the water levels in wells drilled to a depth of 410-670 metres are used to predict earthquakes of magnitude 4 and more at epicentral distances up to 700 km. This technique is considered an effective but simple instrument for observing the deformation of the earth's crust. The model on which the forecast of earthquakes in this region is based shows that 3 to 10 days before an earthquake, the water level begins to fall. After a short period, it starts rising when earthquake takes place.

More complicated variations of water level in deep wells have been reported before and after the 1976 Tangshan earthquake in China. Within the epicentral region, the water level fell continuously for 3 to 4 years before the earthquake. The rate of fall increased sharply 3 to 4 months before the earthquake, but there was a sudden rise in the water level a few days before its occurrence. Subsequently, the water level almost recovered to its normal value. In China the upwelling and rise of level in water wells has been observed before several other earthquakes (Liu-quiao and Shanyin, 1979) including the Haicheng earthquake (1975) where successful prediction and evacuation of public was reported by the Chinese delegation to the Inter-Governmental meeting at UNESCO in February, 1976. It may be mentioned that well water level variations have to be very carefully interpreted as they can be affected by rainfall, floods or prolonged droughts in the region.

Radon gas

Radon is a radioactive gas with a half-life of about 2·5 days. It is discharged from rock masses prior to an earthquake and dissolves in the well water which shows increase in its concentration. For this purpose, water samples are taken from a bore hole or artesian well. The radon concentration measurement can be done using an 'aqua radon meter' which consists of a ZnS(Ag) scintillation detector and counting system. The counting rate of alpha particles from radon (Rn–222) and its daughter nuclides (Po–218 and Po–214) in the detector chamber are recorded.

A number of cases of anomalous increase in radon content prior to an earthquake have been reported in Tashkent region (Sadovsky et al., 1972). Increase in concentration varying from 15 to 200% was found about 3 to 13 days prior to an earthquake. Similarly, two to three months before the Izu-Oshima, Japan (magnitude 7·0) earthquake of January 14, 1978, radon concentration began to decrease and then fluctuated. On January 9, there was a sudden drop in radon concentration but recovered quickly to the normal level (Wakita, 1979). In China, 50% and 70% increase in radon concentration was reported 18 and 6 days respectively before the earthquakes of Tangshan (1976) and Luhuo (1973) at Langfang and Guzan stations which were located 130 and 200 km epicentral distances for the two cases.

Oil wells

Some cases of sharp fluctuations in the oil flow prior to earthquakes have been reported for wells in Israel, northern Caucasus and China. These earthquakes which occurred in 1969, 1971 and 1972 (epicentre 27·5°N, 33·9°E) gave rise to increased flow of oil 330, 120 and 150 days respectively before their occurrence at an epicentral distance of 100 km (Arieh and Merzer, 1974).

It is argued that when the tectonic stress accumulates to a certain level, the pore pressure within a deep oil bearing strata may reach its breaking strength causing oil to spout along the oil wells.

Foreshocks

Foreshocks provide potential clues to the occurrence of a stronger earthquake and are sometimes placed under the 'imminent' stage of prediction. Successful prediction of Haichang earthquake of February 4, 1975 is attributed to the increased seismicity in December and in February immediately before the earthquake. Similar success was reported before the Oaxaca, Mexico earthquake of November 1978 based on foreshock observations.

Figure 50 shows the time interval in hours between the first reported foreshock and the main shock (in logarithmic scale)

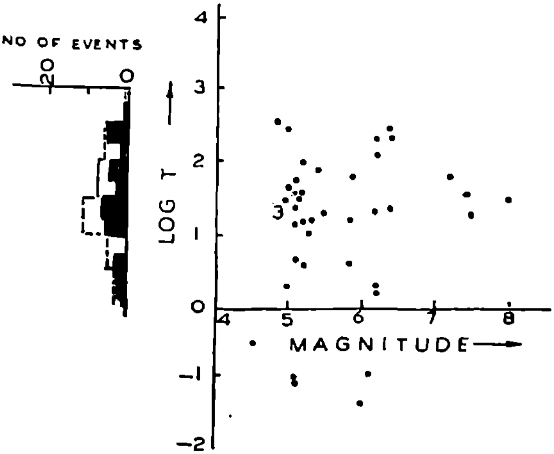


Fig. 50. Time interval in hours between the foreshock and main shock versus magnitude of the main shock in Indian region. (Srivastava, H.N and Chaudhury, H.M., 1979). *Courtesy* : India Meteorological Department.

versus the magnitude of the main shock based on past earthquakes since 1900 in the Indian region (Srivastava and Chaudhury, 1979). The frequency distribution of the events versus the time of occurrence is also given in the same figure. It may be noticed that although there is a preponderance of events about ten hours before the main shock, no relationship between the precursor time and the magnitude of the main shock could be found even in the statistical sense. Foreshocks have been detected a few days to months in advance with the help of closely located seismic stations in Himachal Pradesh for several earthquakes like Anantnag (1967), Dharamsala (1968), Kashmir (1973), Kinnaur (1975) and a few others. On the other hand, there have been many earthquakes in India and other places which were not preceded by foreshocks. In Japan, earthquakes of September 9, 1969 and January 21, 1970 which had magnitudes of about 6 had just one foreshock each which was detected by microearthquake net. In such situations, prediction of main earthquake is rather difficult. On the other hand, sudden increase of activity of the swarm type may sometime raise false alarm without being connected with any principal event. Nevertheless, Himalayan region which is moderately fractured, can generate a foreshock-shock-aftershock sequence more often (Chapter 4) and therefore increasing seismic stations may enable us to bring out a foreshock pattern of premonitory value as found in adjacent Chinese region for Lungling (1976) and Yenyuen (1976) earthquakes of damaging magnitudes which were preceded by foreshocks of magnitude 5·3 and 4·0 respectively a few hours to 2 days before the main events.

Seismicity patterns

In general, there are five important patterns of seismicity as follows :

(*a*) Preseismic quiescence in the epicentral area.
(*b*) A precursory swarm (not immediate foreshocks).
(*c*) Change in seismicity in the surrounding area, i.e. decrease or increase.
(*d*) Seismicity 'calm' surrounded by a seismically active region called doughnut pattern.
(*e*) Clustering of activity before the main shock.

Temporal variations of microseismicity

Experimental observations on rocks suggest that seismicity increase followed by a decrease should be observed before the main earthquakes. Thus, in China, microearthquake activity began to increase around the Haicheng area on February 1, 1975. It increased further during the next two days when two earthquakes of magnitudes 4·2 and 4·7 were reported. The activity suddenly quietened down on the morning of February 4 when evacuation order was issued to the public by the local authorities. The main shock of magnitude 7·3 occurred towards the evening of the same day, thus saving most of the precious lives. Similarly, the earthquake swarm activity weakened considerably a few hours before January 14, 1978 earthquake of magnitude 7·0 near the Izu Peninsula and Izu-Oshima Island in Japan.

Temporal variations of seismic activity before earthquakes have been studied in India in Himachal Pradesh and Andaman Islands region. In both these regions, the number of earthquakes increased a few months earlier followed by a decrease before the main events. Figure 51(a) shows earthquake occurrence within 45 km of Dharamsala observatory which confirms the pattern of activity before the earthquakes of September 16, 1975 and June 14, 1978. The decline in seismic activity before the earthquakes of September, 1975 has been brought out more clearly in the lower part of Fig. 51(b).

Anomalous seismicity

Typical patterns of anomalous' seismicity often precede a large earthquake. It is found that a swarm type of seismic activity takes place in an area where a major earthquake is likely to occur in the near future. The larger the magnitude of the main shock, the longer is the lead time of the anomalous activity.

In USA, anomalous seismicity was observed 934 and 1029 days before the two earthquakes (magnitudes 6·3 and 6·4) in the Gulf of California during 1966 and 1968 respectively. Earlier, for an earthquake (1960) of magnitude 6·2 in Mendocino Ridge, off California anomalous seismicity was observed only 404 days prior to the event. In New Zealand, more instances of anomalous seismicity have been reported for 8 earthquakes during 1966 to 1976; the precursory times ranging from 183 days for a magnitude 4·9 earth-

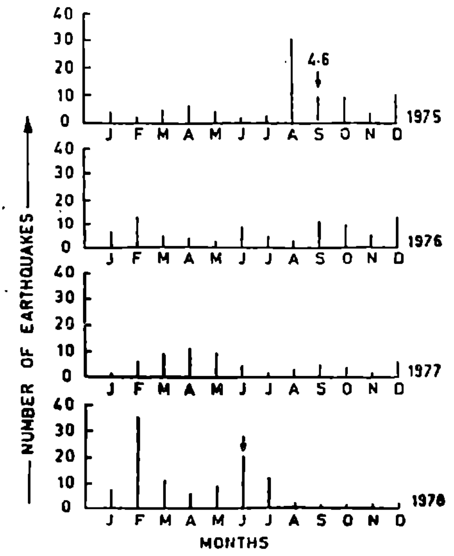


Fig. 51. (a) Increase of tremors due to earthquakes near Dharamsala (H.P.).

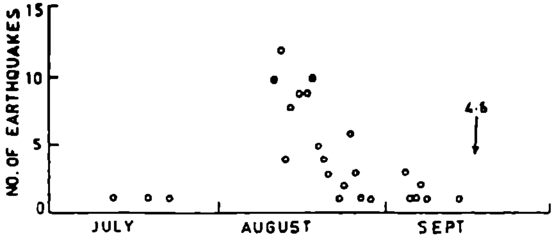


Fig 51. (b) Increase followed by decrease in the number of tremors prior to September 16, 1975 earthquake near Dharamsala.

quake to 2995 days for an earthquake of magnitude 7·0.

In China, seismicity has been studied before the major earthquakes of magnitude 7. In general, a narrow band of seismic activity was detected about one month to two years before the earthquake. The shape of the band changed slowly with time and its linear dimension was much larger than that of the focal area. The formation of the linear band is attributed to the inelastic deformation in the focal region and the tectonic movements in the surrounding region.

In USA and USSR anomalous increase in seismicity has been observed in the off-shore Aleutian and Peru Islands and Garm region. In India, anomalous seismicity was noticed before August 23, 1980 earthquake near Jammu (Fig. 52).

Microseismicity through bore holes

In Tokyo which is under intensified observations as a result of Japanese national programme of earthquake prediction, microearthquakes are being recorded in two deep wells drilled to depth of 3510 metres and 2330 metres. A third station at a depth of 2750 metres will also be started to form a triangle around the metropolitan area with side length of 30 to 50 km. (Takahashi et al., 1979). It is found that microearthquake swarms are followed by felt earthquakes in or near Tokyo one to two weeks earlier, which point out the utility of bore holes observations in regions covered with thick sedimentary layer, thereby reducing the background noise at depths.

Velocity changes

Changes in seismic wave velocity

We have seen in Chapter 4 how the ratio of seismic compressional wave (V_p) to shear wave (V_s) velocity undergoes conspicuous changes in the focal region of a rock before the main earthquake occurs. The duration of V_p/V_s anomaly depends upon the size of the dilatant zone, which is estimated from the length of the fault or dimensions of the aftershock area. Earthquakes occurring far away from the epicentral zones are used to compute these velocities. The alignment of source and stations should be such that the seismic waves pass through the dilatant zones in different directions. Field obser-

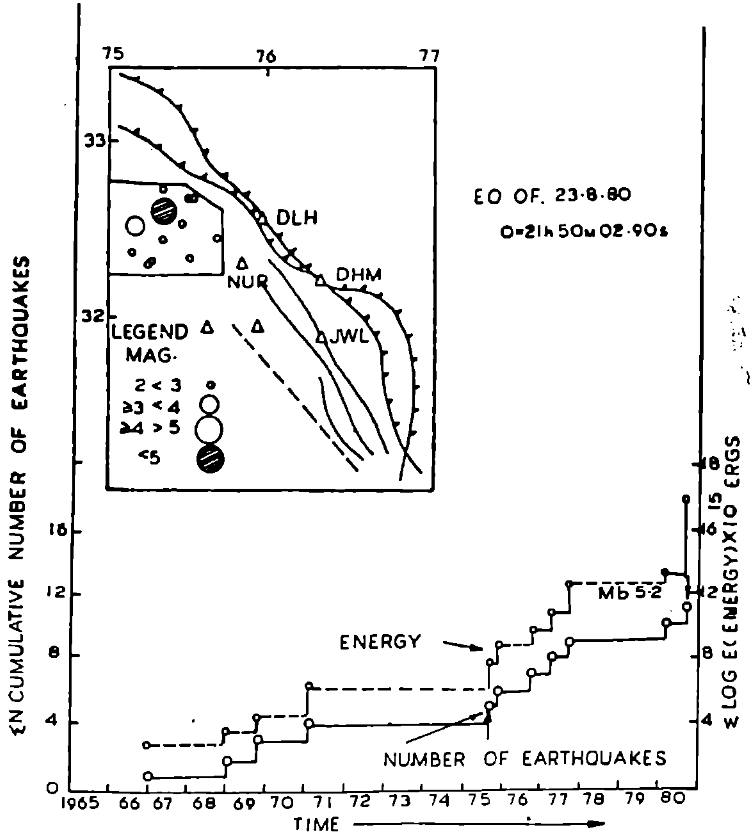


Fig. 52. Anomalous seismicity preceding Jammu earthquake of 1980 (shown by downward pointing arrow). Vertically pointing arrow indicates the onset of anomalous seismicity. (Srivastava, H.N. and Dube, R.K., unpublished.)

vations showing unusual decrease of V_p/V_s were first reported in the Garm region of USSR. In the USA Aggarwal et al. (1973) reported similar observations before Blue Mountain Lake earthquake in 1973 [Figs. 53 (a) and 53 (b)]. The velocity anomaly period for this earthquake was about 5 days and the decrease in velocity ratio was about 12%. Similar decrease in the velocity ratio has been reported before the damaging Haichang (February 4, 1975), Songpan-Pingwu

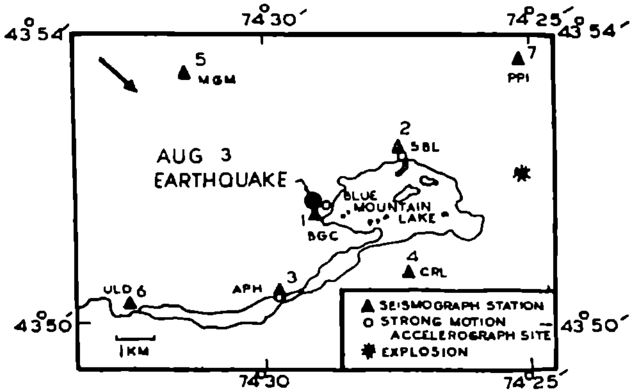


Fig. 53 (a) Seismograph sites and the epicentre of August 3, 1973 in Blue Mountain Area, USA.

(August 16, 1966) and Lungling (1976) earthquakes in China. In Japan 7 to 40% decrease in the velocity ratio ranging from 50 to 700 days before the main earthquakes have been found. Precursor time before an earthquake (1965) of magnitude 6·1 in Shizuoka prefecture (Japan) was reported as 1800 days with a 15% decrease in the velocity ratio. In Teheran, 14% decrease in velocity has been reported 1 to 3 days before three earthquakes in 1974 which had a magnitude of 2·5.

Teleseismic P-wave residuals

Another method of finding the change in P-wave velocity is to monitor 'residual' by subtracting observed P-wave travel time from the travel time computed for a standard earth model (Appendix 3) between the source and the station. In order to ensure that the changes in residuals are caused by the velocity changes near the seismic station, the effects of the rest of the path and sources are removed by averaging the residuals at one station from several sources located in a particular azimuth. Thus, the effect of the residual caused by velocity change near the dilatant zone would be common to all residuals and can be detected. This method has been widely used for earthquakes in Japan, New Zealand, California and India. In all such cases, the mean residual averaged for monthly, 3 monthly or 6 monthly interval shows an increase a few months

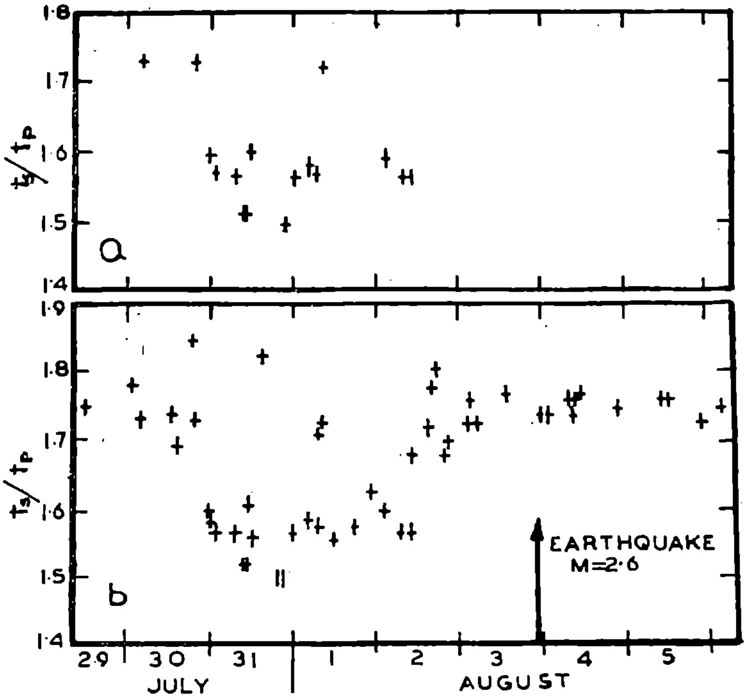


Fig. 53 (b) *Above* : Data reduced in the field to predict the event. *Below* : Data of above combined with the data reduction after the actual earthquake. Travel time ratio t_s/t_p as a function of time before and after the occurrence of the predicted earthquake of August 3, 1973. Arrow indicates the occurrence of the earthquake. Anomalously low t_s/t_p values (1·5-1·6) were observed on July 31 and August 1 as precursor to impending earthquake (Copyright : American Geophysical Union, Aggarwal, Y. P. et al., 1973.)

before the main earthquake. Greater confidence in technique is observed if the residual difference is computed between the station located inside the dilatant zone with that away from it. For the event of June 1969 about 20 km from Shillong, P-wave residual differences between Shillong and Delhi (Fig. 54) increased from March to May by 0·5 seconds which became normal in the month of May (Srivastava and Chaudhury, 1979). Similar result has also been reported by Gupta et al. (1979) who have used six monthly averages

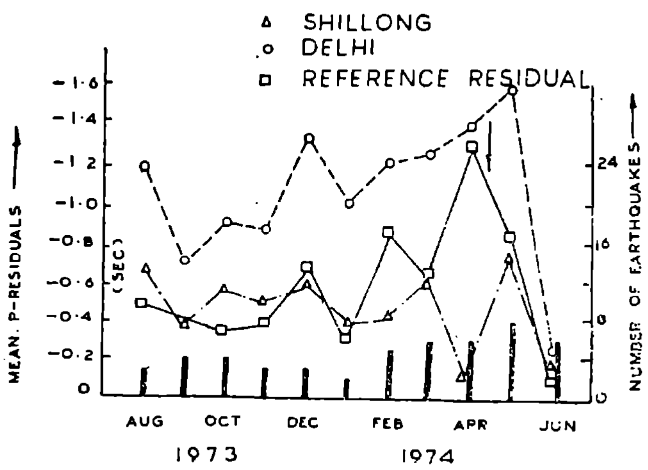


Fig. 54. Seismic wave velocity anomaly near Shillong as revealed through mean monthly P-wave residuals. (Srivastava and Chaudhury, 1979). (*Courtesy*) : India Meteorological Department.)

of residuals. According to them, the earthquake of 1969 occurred approximately three months after the residual had returned to normal. Since 1970, teleseismic P-wave residuals at Shillong have become positive which till now show the same trend. The author has noticed increase of micro-earthquakes within 50 km around Shillong since 1980. It is surmised that the region may be experiencing a precursory dilatancy stage. Seismic monitoring has since been intensified through a few highly sensitive mobile stations.

A few ambiguous or even negative results about velocity changes or residuals have been reported from observations in western United States and elsewhere. It is possible that in such cases, the seismic waves may miss the dilatant zone if it is located at a larger depth (Fig. 55). Sometimes, the data is biased due to scarcity of observations or reading late P-wave arrival, particularly if their onset is emergent (gradual) and magnitude of the earthquake is small or events from different tectonic zones are taken to find the average of velocities. Known chemical explosions, even though expensive, may enable to detect such anomalous velocity changes with greater confidence.

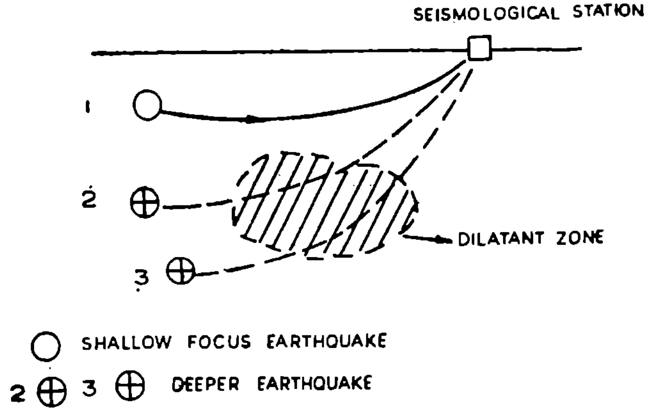


Fig. 55. Seismic waves from shallow and deeper earthquakes. Wavss form earthquake focus at (1) will miss the dilatant zone.

Chemical explosions

Since the exact locations and origin times of earthquakes used to detect changes in seismic wave velocity are not known, small yield chemical explosions can be detonated once a month to monitor such changes, if any. So far, no result of prognostic value has been reported, although experiments have been conducted in Japan and other countries.

Nuclear explosions

Some countries like USA and USSR are periodically carrying out underground nuclear tests at specified locations. In Kazakh region of USSR, the frequency of such tests appears to be about once a month. Although the locations and origin times of these explosions are not known. the epicentral parameters can be more reliably determined than earthquakes whose focal depth introduces uncertainty. Further the wave path between the source and station is the same. Srivastava (1979) has studied the changes in the travel times observed at closely spaced seismic stations in Himachal Pradesh from the Kazakh explosions (Fig. 56). It was found that long term changes as may accompany great earthquakes in Himachal Pradesh could be monitored through these explosions.

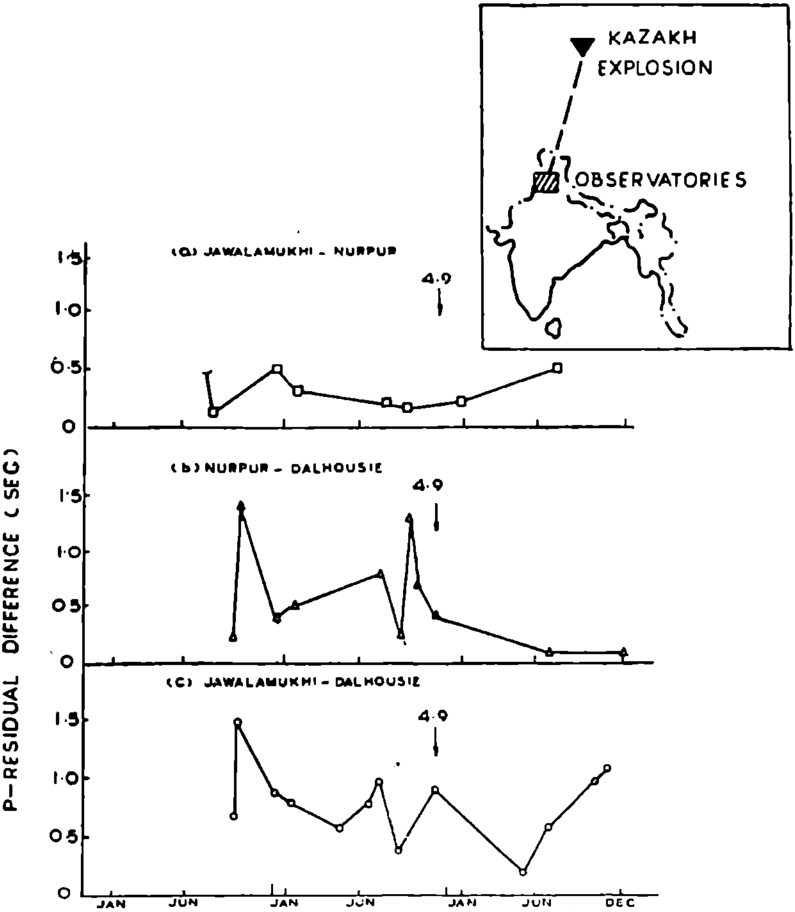


Fig. 56. P-wave residual difference due to Kazakh nuclear explosions recorded at Jawalamukhi, Nurpur and Dalhousie. The seismic wave anomaly is less marked prior to November 1968 earthquake near Dharamsala. (Srivastava, H.N., 1979), (*Courtesy* : India Meteorological Department).

From explosions in Nevada, USA (where the exact locations and times of nuclear explosions have been announced) and Noya Zemlaya, USSR results of precursory value could not be found so far.

Insitu measurements

Insitu measurements of seismic wave velocities are carried out by 'controlled source method'. A hydraulically activated vibrator (Vibroseis) shakes the ground with a controlled sinusoidal force upto 6 ton weight. The base plate is held to the ground by the 7-ton weight of the vehicle. While the plate is on the ground, a force of upto 6 ton is exerted on it by a hydraulic system that jumps one ton mass up and down from the base plate with precisely controlled frequency and phase. The truck merely holds the base plate on the ground; its weight is not involved in the vibrating system.

The vibrator produces a P-wave signal that can reach down to the depths of 20 to 25 km in the region. The seismic wave generated travels downward in a nearly vertical direction from the source, which is reflected back to the surface whenever it meets any discontinuity in the crust, for example, the zone of transition from sedimentary rocks to granitic or from the crust to the Mantle at the Mohorovicic discontinuity. This technique enables us to accurately monitor the time taken by P-wave to travel down to the discontinuity and its return. Similarly, the travel times of P-waves travelling directly (unreflected) between any two sites can be measured accurately. By repeating such measurements at an interval of a few months, it is possible to identify any changes in P-wave velocities with time which may be related to change in stress in the earthquake prone area prior to moderate events. The return of seismic waves from the Vibroseis to the surface is recorded on an array of up to 100 seismometers which are kept at intervals of 10 metres apart. This technique allows us to detect changes of the order of 1 part in 10,000 in the travel time of P-waves in the crust. The geophones should be embedded beneath the water table at both the source and receiver sites so that seasonal variations of soil moisture are reduced.

The technique is being used in San Andreas fault, USA where greater than normal variations in travel times have been identified with the nucleation process preceding some earthquakes.

Stress axis rotation in focal region

The radiation pattern of seismic waves allows us to compute the orientation and inclination of stress, namely, the compressional stress, the tensional stress (minimum stress) and the intermediate stress as determined from the fault plane solutions of P-waves. In the Garm region of USSR, it was found that the stress pattern, which is generally random, starts getting well organised 2 to 3 months before the main earthquake. In general, there was a rotation of the stress axis by 90° in the focal region. The compressional stresses became aligned in the same direction as that of the impending event.

Although this aspect is quite interesting from the point of view of earthquake prediction, it is often difficult to find reliable focal mechanism (fault plane) solutions from P-wave data due to lesser number of observations available for microearthquakes whose sense of first motion often gets obliterated with the background noise.

Seismic wave spectra

The spectra of seismic waves provide information about the earthquake source characteristics. In Japan, characteristic differences in the P-wave spectra were reported before and after the Matsushiro earthquake swarm of 1965. With the installation of digital bore hole high gain seismograph at Shillong, India, regional variation of P-wave spectra for earthquakes in northeast India has been studied by the author. Constant monitoring of such spectra for earthquakes from a given location may reveal premonitory trends.

Seismicity gap

A region where earthquake activity is less compared with its neighbourhood along plate boundaries is called *a seismic gap*. This approach to earthquake prediction which falls under the category of medium to short range precursors, assumes that the area under consideration is seismic due to its proximity to the plate boundary but the strains are being temporarily accumulated along the faults, thereby increasing the chances of occurrence of a large earthquake. This assumption is supported by the history of earthquakes which shows that severe earthquakes rarely recur along the same segments of a fault in a time less than a few decades needed for accumulation of strain. Thus along the plate boundaries such locked sections with negligible seismic activity may appear from time to time due to frictional resistance. Assuming that the average movement of one plate relative to the other is estimated as 5 cm per year along the San Andreas fault but no movement could be observed for a century, the strains corresponding to 5 × 100 cm movement would have accumulated which becomes a potential zone for a future damaging earthquake. In the neighbouring seismically active regions along the plate boundary strain is being relieved through smaller events and are therefore relatively less hazardous.

The identification of seismic gaps around the margin of the Pacific Ocean has been successfully used in forecasting the locations of several large earthquakes, for example, Sitka, Alaska (1972) and Oaxaca, Mexico (1978). In Japan, a large earthquake of July, 1972 off the coast of Nemaro, Hokkaido also occurred in a region which had been an open area for nearly 20 years.

In USA, three seismic gaps have been identified as precursory regions:

(*a*) Between rupture zones of the 1964 and 1957 earthquakes along the Aleutian arc.

(*b*) Between the aftershock zones of the 1964 and 1958 earthquakes in Alaska.

(*c*) Section of San Andreas fault which was ruptured in 1857.

In the first two seismic gaps, the seismic potential remains uncertain due to inadequate seismic history, while in the last case, the average recurrence interval is about 160 years and therefore may not be a region of immediate threat. However, further studies are being undertaken in these gaps.

In the Indian region, two seismic gaps (Figs. 57 and 58) have been identified—one in Himachal Pradesh (Srivastava and Chaudhury, 1978) which lies along the plate boundary between the earthquakes of Kangra (1905) and Kinnaur (1977) and the second one called 'Assam Gap' in northeast India between the great earthquakes of 1897 and 1950 (Khattri and Wyss, 1975). Of these, the seismic gap in Himachal Pradesh will be discussed in detail. It may however be mentioned that seismic surveillance in Assam gap has also been increased through the efforts of several geophysical institutions in the country.

Possibility of a large earthquake in Himachal Pradesh

A reliable knowledge of the history of earthquakes is useful

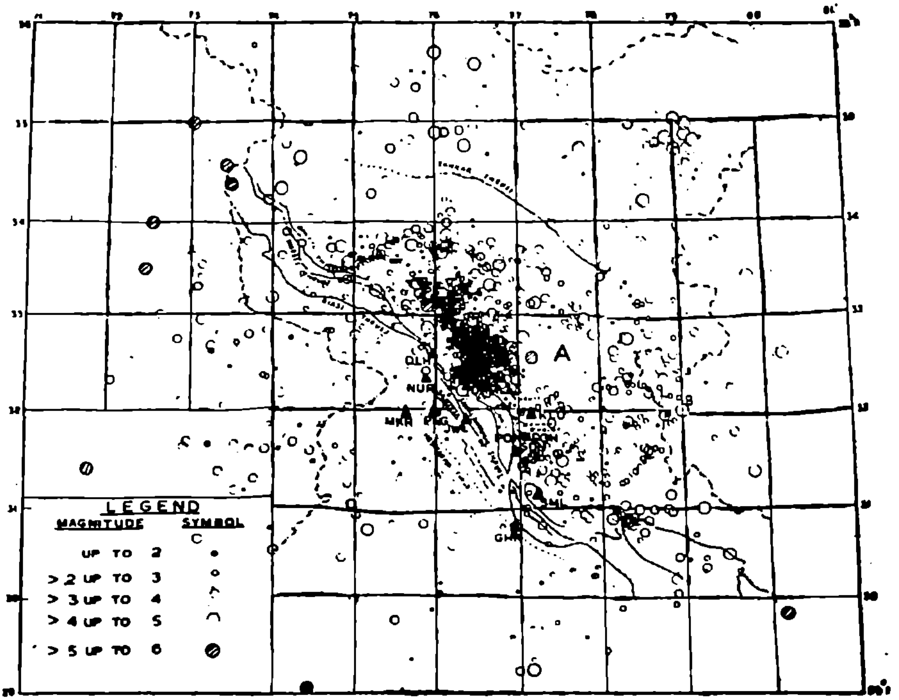


Fig. 57 (a). Seismic gap 'A' in Himachal Pradesh (1965-1974). The cluster of epicentres is seen in the zone of great Kangra earthquake of 1905.

to assess the possibility of the occurrence of a destructive earthquake in the vicinity of a seismicity gap. In the Himachal Pradesh, however, the history of damaging earthquakes is available for the last one hundred years only.

The most destructive earthquake in Himachal Pradesh occurred in April 1905 when 20,000 people are reported to have been killed. The area of maximum intensity of X on modified Mercalli scale included the important town of Kangra where heavy destruction was caused. The earthquake whose magnitude exceeded 8 on Richter scale was felt over an area of 416,000 km. Another significant earthquake occurred in Himachal Pradesh on June 22, 1945 with its epicentre in Chamba district. The recent earthquake of January 19,

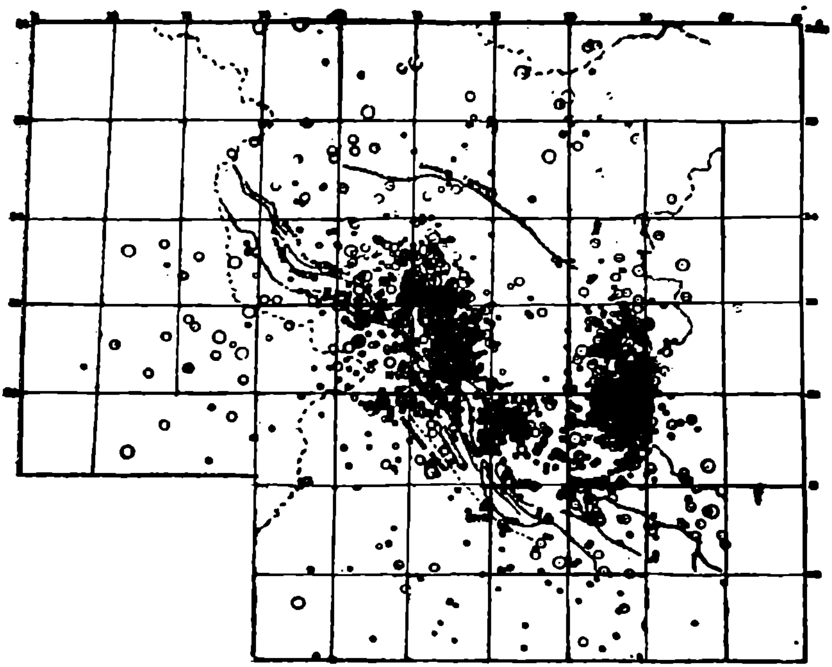


Fig. 57 (b). Same features as in (a) during 1974-1980 except that the region east of 'A' is filled with aftershocks of Kinnaur earthquake of 1975. (*Courtesy* : India Meteorological Department).

1975 occurred in Kinnaur which took a toll of 42 lives besides causing major destruction to property. The aftershocks of this earthquake have been numerous and are continuing even after 5 years.

Himachal Pradesh has been referred to by geologists as the Punjab Himalayas which contains a complete sequence of marine Palaeozoic and Mesozoic rocks in the Inner Himalayas while the Tertiary development is seen in the outer Himalayas. The northern margin of the Punjab Himalayas is characterised by upper Cretaceous flysch-like deposits with basic and ultra basic rocks. The tectonic sequence in the region consists of precambrian basement overlain by upper tertiary rocks and covered by the alluvium of

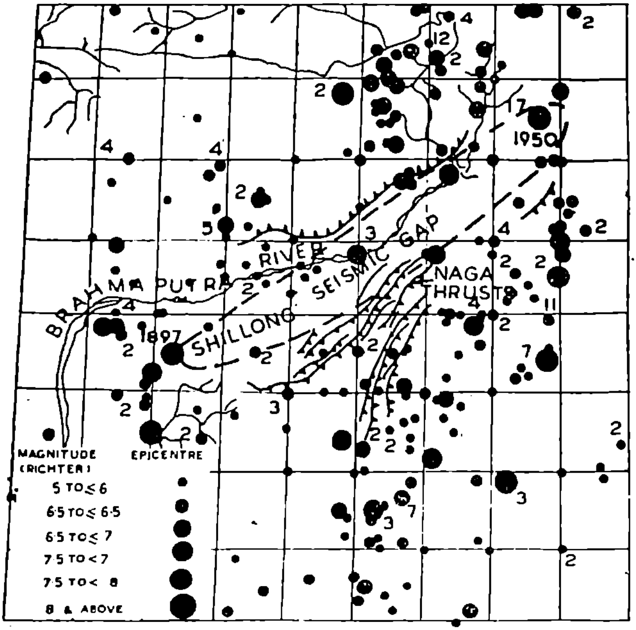


Fig. 58. Earthquake epicentres (1897 to 1971) in northeast India and neighbourhood. The 'Assam gap' has been enclosed by dashed line.

the plains followed by the younger tertiaries (Siwaliks), older tertiaries, Punjab volcanics, krols, granite, gneiss and chail. The region is characterised by the presence of thrust sheets, folds and nappes. Figure 59 shows the important faults called the main boundary fault, the Jawalamukhi thrust, the Hoshiarpur thrust, the Nahan and Krol thrusts. The Chamba and Rupar tears in the Ravi and Sutlej rivers also contribute to the seismicity of the region.

According to the regional plate tectonics model, tremendous amount of strain is accumulating in the region due to the relative movements of Indian and Eurasian plates which is occasionally released through destructive earthquakes all along the foothills.

Significant features of the newly prepared microseismicity map (Fig. 57) are as follows:

1. There is well marked concentration of minor earthquakes

in the grid marked by the latitudes 32° to 33°N and longitudes 76° to 77°E. The great Kangra earthquake of magnitude more than 8 occurred in April 1905, in this region.

2. A well marked seismicity gap called 'A' can be demarcated within the grid bounded by the latitudes 32° to 33°N and longitudes 77° to 78°E. It may be pointed out that the area of seismicity gap will not change significantly even if the errors in the epicentral parameters are combined in the most adverse manner.

3. Diffuse seismicity is observed at other places. However in the eastern zone of hitherto low seismicity, an earthquake in the Kinnaur region occurred on January 19, 1975 whose aftershocks were spread over a wide area.

The focal mechanisms of four earthquakes in Himachal Pradesh were of thrust type with the exception of Kinnaur earthquake which showed normal faulting (Fig. 59). The great Kangra earthquake of 1905 was also associated with displacements taking place along a low angle fault of the thrust type. Focal mechanisms of a large number of earthquakes in neighbouring Himalayan foothills also show thrust faulting. The directions of the pressures are generally acting at right angles to the mountain front and are shallow dipping. Considering all these factors and the history of earthquakes in the neighbouring regions in Kangra (1905) and Kinnaur (1975), there is a possibility of a strong earthquake in the seismic gap marked by letter 'A'. Although it is difficult to surmise about the mechanism of faulting for this earthquake, but considering the proximity of the main boundary fault where the major earthquakes are of thrust type, the impending earthquake may also be of similar nature.

A question arises whether the seismic gap A could be a stable block inside the seismically active zone. The catalogues of past earthquakes in this area do not show any earthquake; but the past data were restricted to the higher magnitude events. Even if smaller tremors occurred they could not be detected. It is also not unusual that gaps in activity are often quiet for moderate size earthquakes and even shocks as small as microearthquakes. The confirmation of the thrusts and faults in the region, however, indicates that the area covered by the seismicity gap is unlikely to be different tectonically from the adjoining areas.

Plate tectonics model requires that relative motion must occur at least sporadically along major plate boundaries and an important

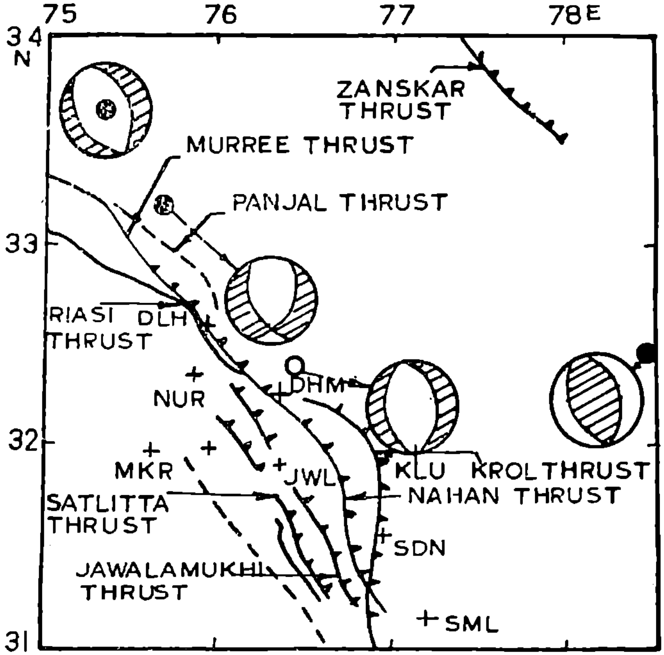


Fig. 59. Main faults and focal mechanism of earthquakes in Himachal Pradesh. Shaded area shows first motion dilatations and open area compressions. (Srivastava, H.N. et al., 1979; UNESCO Conference on Earthquake Prediction, Paris.)

part of the motion is associated with very shallow earthquakes. Laboratory experiments on rock specimens have suggested that moderately fractured samples have a foreshock aftershock sequence while homogeneous rocks break almost suddenly. The seismicity gap which is under strain due to the proximity of the boundary of the Indian and Eurasian plates cannot remain stable without being fractured. The maximum area of this seismicity gap is 10^4 km^2 approximately. Tandon and Srivastava (1975) have found the following relationship for the Himalayan Region between the aftershock area A and the magnitude M_L of the main earthquake:

$$\log A = 0{\cdot}89\ M_L - 2{\cdot}67 \qquad (1)$$

In the event of an impending destructive earthquake, the entire seismic gap being homogeneous may be fractured giving rise to aftershocks spread all over the region. Taking 10^4 km^2 as the area of the aftershocks, the magnitude of the impending earthquake from equation (1) comes out to be 7·5.

Possibility of an earthquake on the basis of seismicity gap does not enable us to infer about its time of occurrence. The magnitude-precursor time relation by Rikitake (1976) gives an idea about the time of occurrence since an anomaly is observed in seismic wave velocity/crustal deformation. However, it varies greatly in different regions. Nur et al. (1972) suggest that thrust faults are capable of large dilatancy and the dilatant volume can be similar in size of the aftershock zone. Considering the proximity of thrust faults close to the seismicity gap *A* it is expected that precursory changes on the basis of dilatancy model could occur. Thus the region calls for integrated programme of earthquake prediction.

Changes in the 'slope' of frequency magnitude relation

We have seen that the of earthquakes generally becomes less prior to the main event. If such shocks are continuously monitored and a running graph of frequency magnitude is kept under surveillance, the curve shows a significant change of slope *b* prior to the occurrence of a major event as reported for earthqukes in India and elsewhere.

Figure 60 shows six monthly *b* value in Himachal Pradesh during the years 1967-1970. From July to December 1967, the value of *b* was found as 1·09 which decreased to 0·73 during the next six months. An earthquake of magnitude 5·0 occurred in the region in October 1968 about two and half months later. During the subsequent six months, the value of *b* rose to 1·08 which again fell to 0·87 during the period from June to December 1969. An earthquake of magnitude 4·5 occurred in the region on January 17, 1970 followed by another shock in March 1970. During the first six months of 1970, a low value of *b* was obtained which was attributed to contamination of population through foreshocks and aftershocks of the main event. During the remaining six months of 1970, the value of *b* was almost restored again. Thus the *b* value decrease had been observed before two earthquakes in Himachal Pradesh.

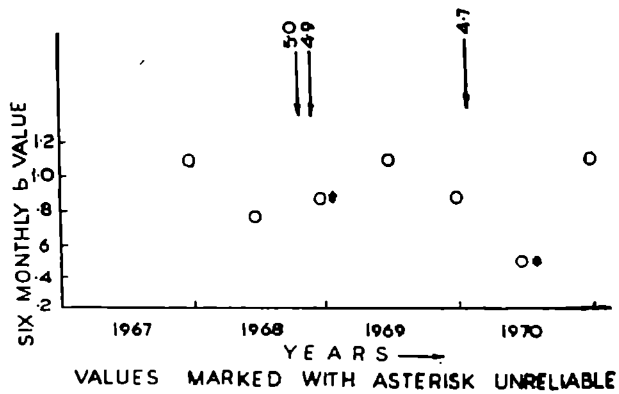


Fig. 60. Decrease of *b* value preceding earthquakes in Himachal Pradesh (Kangra region). (Srivastava H.N. and Chaudhury, H.M., 1979). (*Courtesy* : India Meteorological Department).

In the Koyna region, *b* values were found to decrease consistently for about three and a half years before the main earthquake of December, 1967.

Decrease of *b* values has also been observed in China before Haichang (February 4, 1975) and Song pan Pingwu (August 16, 1976) earthquakes and also in the Hollister (USA, 1971) and several other cases.

Comparison of 'b' value between foreshocks and aftershocks

Suyehiro (1966) reported for the first time that the value of *b* was lower for foreshocks as compared to aftershocks in a few earthquake sequences. In the Indian region, similar results have been observed before the Ladakh earthquake of February 11, 1968 and the Himachal Pradesh earthquake of November 5, 1968. The results are attributed to higher tectonic stress for foreshocks than aftershocks as interpreted by Wyss (1973).

Comparison of 'b' value of foreshock with general seismicity

The value of *b* found from foreshocks is often less than that determined from long period seismicity data as found by author for Himachal Pradesh grid bounded by latitudes 32-33° N. Longitudes 76-77° E. The limitation of this method is that unless the data sample is quite large, reliable value of *b* and consequently their prognostic applications cannot be ensured.

Prediction of aftershocks

Many shallow focus earthquakes are followed by aftershocks. These are attributed to delayed adjustments of the stresses to reach equilibrium in the focal zone after the main earthquake. Their mechanism can be understood by Kelvin-Voigt mechanical model involving a dash pot with viscous fluid.

Aftershocks are also considered under prediction because they may cause further damage to the structures already weakened by the main earthquakes. These create more panic in population if they continue for a longer period, say months or years which occasionally happens with damaging earthquakes. In general, the magnitude of the largest aftershock is 0·5 to 1·5 less than the main shock and their number decreases rapidly with time following a semi empirical hyperbolic law. In the Indian region, Chaudhury and Srivastava (1972) have found that the largest aftershock generally occurs within two or three hours of the mainshock. Also the area confined by the aftershocks increases with time, perhaps covering the entire weaker zones. Sometimes even before the sequence has ceased, a bigger event occurs with its own sequence called secondary aftershock.

Figure 61 (a) shows the decay of aftershock activity at Delhi Observatory due to Kinnaur earthquake of January, 1975. Similar pattern which is called hyperbolic law of aftershocks is noticed in most of the shallow focus earthquakes accompanied by the aftershocks. However deeper earthquakes are rarely followed by aftershocks.

Aftershocks also define the length and area of the faulting involved and their trend can be predicted using statistical relationship (Tandon and Srivastava, 1975, Srivastava, 1981) Figure 61 (b) shows the extent of these parameters monitored by a set of sensitive instruments after the earthquake of July 29, 1980 near India Nepal Border.

Crustal deformation

Crustal deformation measurements include following two types of observations.

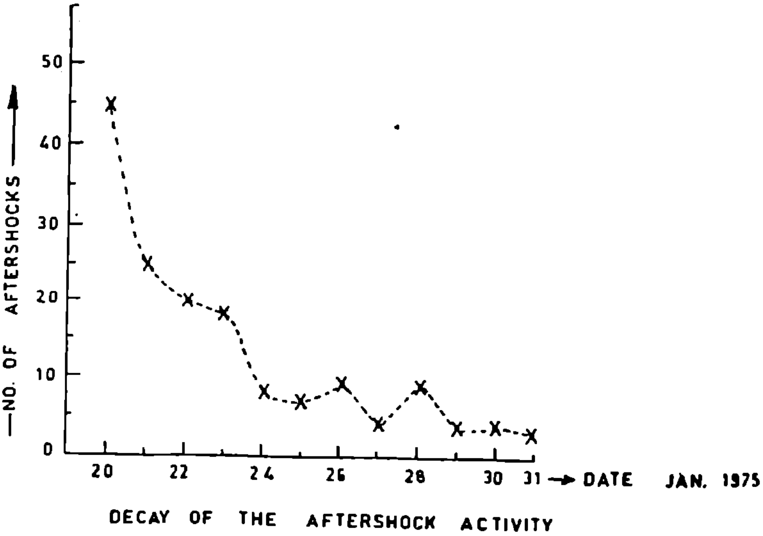


Fig. 61 (a) Decay of the aftershock activity due to Kinnaur earthquake (January, 1975) recorded at Delhi.

1. On the spot or sporadic observations through repeated levelling surveys or repetition of triangulation or using geodimeters which measure distances between two fixed points at periodical intervals.
2. Continuous measurements of crustal deformation through strainmeters, tiltmeters, tidegauges and gravimeters.

In order to get greater confidence in the interpretation of data the results using both these independent measurements are compared.

Geodetic surveys and other observations

Several cases have been reported in Japan when land deformations were witnessed by people before the following great earthquakes:

1. Ajigawa (1793) and Sato (1802) earthquakes when land rose by one metre about 4 hours before the earthquakes.

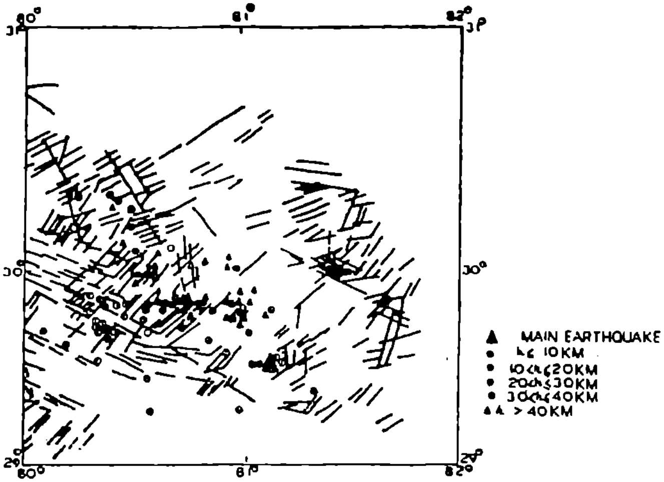


Fig 61 (b) Spatial distribution of the aftershocks recorded through microearthquake stations. The epicentres have been plotted on Land Sat Imagery of the region. Relatively deeper events occur on northeastern side of the main central thrust dipping in NE direction. The strike of the fault oriented northwestwards is defined by the longer dimension of the spread of the epicentres. (After Chaudhury, H.M., Srivastava, H.N. and Chatterjee, S.N., unpublished.)

2. Hamada earthquake (1872, magnitude 7·1) when land rose 2 metres about 30 minutes before the earthquake.
3. Tango earthquake (1927, magnitude 7·5) when land rose by 1·5 metres two and a half hours before the earthquake.

Through precise levelling, crustal deformation was detected before the earthquakes of Sakihara (1927), Futatsvi (1955) and Nagaoka (1961) in Japan (Tsuboi, 1933, Kaminuna et al., 1973) and Garm region in USSR (Sadovsky and Nersesov, 1974). Geodimeters revealed strain changes of the order of 4×10^{-6} shortly before the Hollister earthquake (1960, magnitude 5·0) in USA (Hoffman, 1968). Anomalous uplift of earth was observed for about ten years prior to destructive Niigata earthquake in Japan (Dambara, 1973).

More interesting results of two anomalous land lifts have been reported by levelling surveys on either side of the Pacific Ocean.

An extensive uplift by 45 cm was found along a segment of the famous San Andreas fault, California, USA originally centred on Palmadale, about 70 km north of Los Angeles. By the middle of 1977, the uplift appeared to have extended to the California Arizona border. The second uplift of the order of 15 cm has been found in the Izu peninsula about 100 km southwest of Tokyo, Japan. Both these uplifts are now areas of intensified observations although the uplift need not necessarily be connected with impending earthquakes.

Strain meters

Strain changes by 10^{-6} to 10^{-8} have been reported 4 to 300 days before earthquakes in Japan, USSR and USA.

Changes in volume strain associated with an earthquake (magnitude 7·0) on January 14, 1978 under the sea between the Izu peninsula and Izu Oshima Island in Japan were detected at a station located at the southernmost tip of the peninsula. It was noticed that although the trend changed its sign about 4 days before the mainshock, an anomalous compression appeared to have been occurring since December 3, 1977.

Tilt anomalies

Anomalous tilt observations have been reported before several earthquakes in the world. The changes of the order of $1{\cdot}5\times 10^{-5}$ were noticed 3,000 days before the Niigata earthquake of 1964 at epicentral distance of 80 km (Kasahara, 1973). Tilt changes of lesser magnitudes (10^{-7}) were observed before the earthquakes in Matsushiro (1966) in Japan (Yamada, 1973) and Danville in USA (Wood and Allen, 1971). In the south eastern Akita earthquake of 1970 (magnitude 6·2) which occurred at the northeastern part of the Japan Island, the tilt change at Nibetsu, about 80 km northwest of the epicentre showed an anomalous behaviour which continued until two to three months before the main shock. It was interpreted that the dilatant area had already spread out to Nibetsu at the initial time of the anomalous period and the strength of the dilatancy increased gradually with time. The size of the dilatant zone possibly associated with the main shock could be about ten times as large as that from the aftershock area in linear dimension. Significant correlations of tilt have been reported prior to two earthquakes in New Zealand (1975, 1977) after the results were corrected for rainfall and other meteorological elements. It was found that the tilt directions were roughly away from the future epicentre and each earthquake occurred about a month after the tilt anomaly began to return to normal. However no such anomaly could be noticed before a deep earthquake of magnitude 5·9 in the same region. Sudden changes in the tilt direction were reported (Fig. 62) a few days before several small earthquakes in Hollister area in USA during 1973-1974 using borehole tiltmeter (Johnston and Martensen, 1974). In Koyna region, a plot of the weekly means of tilt measured with torsion pendulum type tiltmeters in the dam showed a systematic change (Fig. 63). It reversed abruptly by 180° in its direction about two weeks prior to the main earthquake of December, 1967 which could be considered as a precursor (Sitapathi Rao et al., 1979).

Tide observations

Use of tide gauge for recording sudden vertical deformation of land at the time of earthquakes is considered promising. Its use for Aburatsubo in Japan showed that the place subsided at a rate of 5 mm per year before 1917 to 1918 and after that the rate changed to zero or rather upward. About 5 years later, the great Kanto earthquake occurred. Similar trends were reported from mareograms (records) at Kushimoto before the earthquakes (magnitudes 8) of Nowakai (1944), Nankai (1946) and Niigata (1964). Subsidence to the extent of 2 cm was observed 360 days in advance at the epicentral distance of 40 km before the Niigata earthquake of 1964 which supported the results from repeated land surveys (Tsubokawa et al., 1964). Wyss (1976) has reported interesting local changes of sea level before large earthquakes in South America (1961) and Hyuganada, Japan (1968). Detailed analysis of hourly data of tide gauges at Hosojima and Tosashimizu stations in Japan suggested a conspicuous change in sea level 1·5 days prior to the Nankai earthquake (1946, magnitude 8·1). The sea level at the latter station located about 230 km away from the epicentre shows an anomalous land upheaval amounting to 50 cm.

Gravity measurements

The gravity variation caused by the density changes associated with crustal strain preceding earthquakes is so small that it can hardly be measured. However, since crustal deformation occurs in

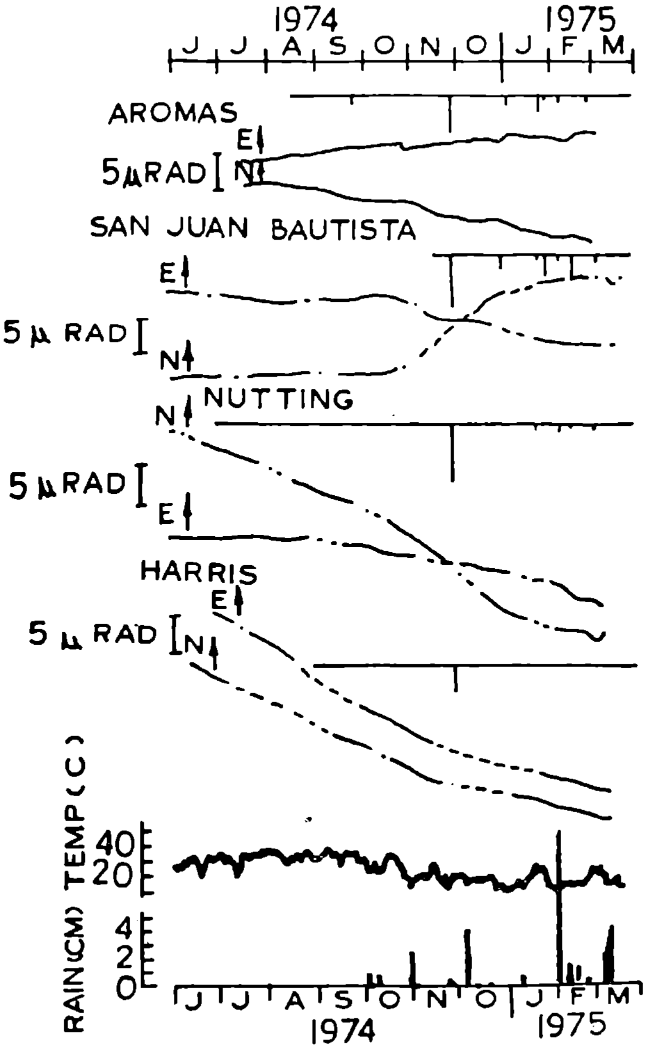


Fig. 62. Raw records from the four operational tilt sites nearest the Thanks Giving Day earthquake epicentre. Rainfall and temperature in the area of the tilt array are shown in the bottom plot. Dashed lines connect record sections where on site recorders failed but instruments zero was not lost. (Copyright : American Geophysical Union.)

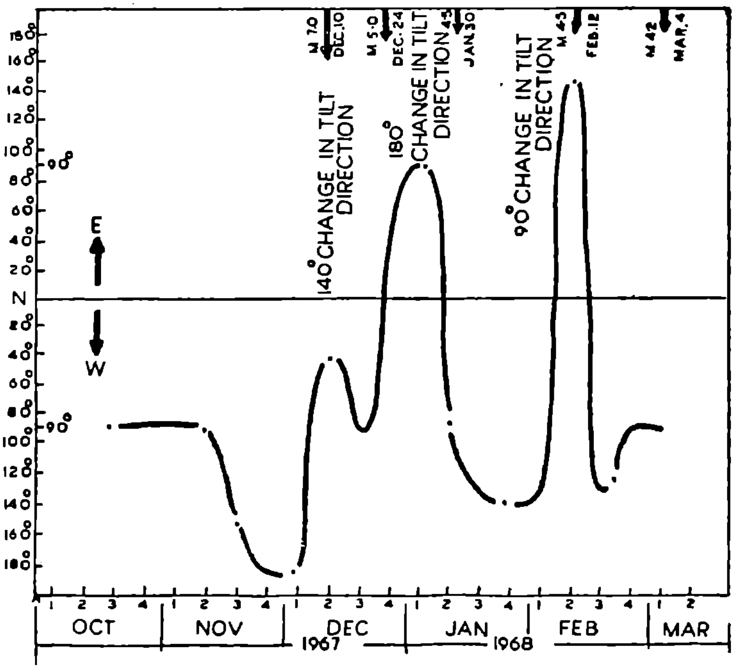


Fig. 63. Ground tilting in the Koyna region. Sitapathy Rao et al., 1979. (*Courtesy* : India Meteorological Department).

wide areas before any great earthquakes, it should be possible to detect gravity changes with improved type of modern gravimeters. In Japan, gravity measurements have been included under intensified observations which reveal that gravity value is increasing at a rate of 0·02 mgal/year in Miura and the southern part of Boso Peninsula. Satisfactory explanation of such large observed rate of gravity is yet to be found. In the Tangshan area, also significant variations of gravity have been observed before the damaging earthquake of July 28, 1976 (Seismological Bureau, Hopei, 1979). Before the earthquake, a slow continuous long term gravity increase of 0·13 mgal and a short term increase of 0·19 mgal were observed at Tangshan. Away from this region at Tientsin, increase of gravity by 0·350 mgal was found associated with crustal sinking due to exploitation of underground water.

Geomagnetic changes

The most reliable geomagnetic precursor has been reported two months prior to the earthquake of November 28, 1974 near Hollister, California in USA. The anomaly was detected with the help of a proton precession magnetometer array of seven stations along San Andreas fault. Decrease in the horizontal intensity of the geomagnetic field by 20 gammas (1 gamma$=10^{-5}$ gauss) was reported 7·5 years before the Sitka, Alaska earthquake in 1972 (magnitude 7·1) which returned to normal after the event in the same year. In Japan, an anomalous change in the geomagnetic field amounting from 15 to 20 gammas was reported during a ten year period preceding the Niigata earthquake of 1964 (Fujita, 1965). In USSR, an anomalous decrease in total intensity of 15 gammas started four hours preceding an earthquake (1967) in Garm region at epicentral distance of 24 km. The geomagnetic field returned to normal several hours after the shock. In China, the difference in vertical intensity between Peking and Hongshan near Hsingtai occasionally decreased by 2 gammas 4 to 5 days before an earthquake of magnitude 3 or more near Hongshan. The value appeared to recover two days prior to the earthquake. The vertical component of the geomagnetic field in the epicentral area decreased a few years before the Tangshan earthquake of 1976. In the Koyna region, precursory geomagnetic effects in the total magnetic field intensity have been noticed from the records of Alibag Observatory (Bombay) at a distance of about 170 km from the region (Arora and Singh, 1979). Anomalously large secular change in the horizontal component of magnetic intensity was reported at Tanabe on Kii peninsula of central Japan. It was noticed that the change in horizontal intensity at Tanabe is anomalous compared to that at neighbouring stations, which are tens of kilometres away from Tanabe. The anomalous change took place after the occurrence of two earthquakes of magnitudes 6·1 and 6·4 near Tanabe during the years 1960 and 1961 (Tazima, 1968).

It may be clarified that interpretation of geomagnetic changes associated with earthquakes is often rendered difficult due to relatively larger changes in the geomagnetic field associated with ionospheric and magnetospheric effects.

Electrical resistivity changes

Using dipole-dipole method (Chapter 2), marked electrical resistivity changes in the Garm region of USSR have been reported (Baruskosv, 1974). The resistivity decreased by 7 to 18% prior to the occurrence of several earthquakes and the minimum of resistivity coincided with the occurrence of earthquakes. Marked variations in resistivity have also been reported in Kamchatka region before an earthquake. In California, USA 24% variation of resistivity has been reported about 60 days before an earthquake in June, 1973 which after increasing to a maximum almost recovered to the initial value just before the occurrence of the earthquake (Mazzella and Morrison, 1974). In Japan step-wise changes in ground resistivity were reported before 11 earthquakes with magnitudes between 4·8 and 8·0 at distances from 66 to 1094 km from the recording station. In China, 15 to 20% decrease in resistivity was found 5 to 120 days before the Tangshan earthquake of 1976 at stations 10 to 80 km away from the epicentral region. Similar results were reported for Sungpan and Lunglin earthquakes of magnitude around 7. It was found that for all the three strong earthquakes in China, there is a characteristic decrease of resistivity before an earthquake, then a step-wise variation, recovery after the earthquake and dependence of the variation upon the seismic activity of the region and the local ground conditions at the measuring station (Jiadong et al., 1979). Figure 64 shows the resistivity changes prior to Izu Hanto-Oki earthquake (1974). The results are attributed to gradual increase of stress in the source region of earthquakes which extends to the earth's surface under the influence of the regional stress field.

Earth currents

Changes in earth currents ranging from 30 millivolts to 150 millivolts per kilometre have been reported a few hours to 22 days before several earthquakes at various epicentral distances in Kamchatka region of USSR during the years 1959 to 1971 (Sobolev, 1973).

Classification of precursors

We have seen in Chapter 4 that the duration of anomaly in the precursory observations is generally related to the magnitude of

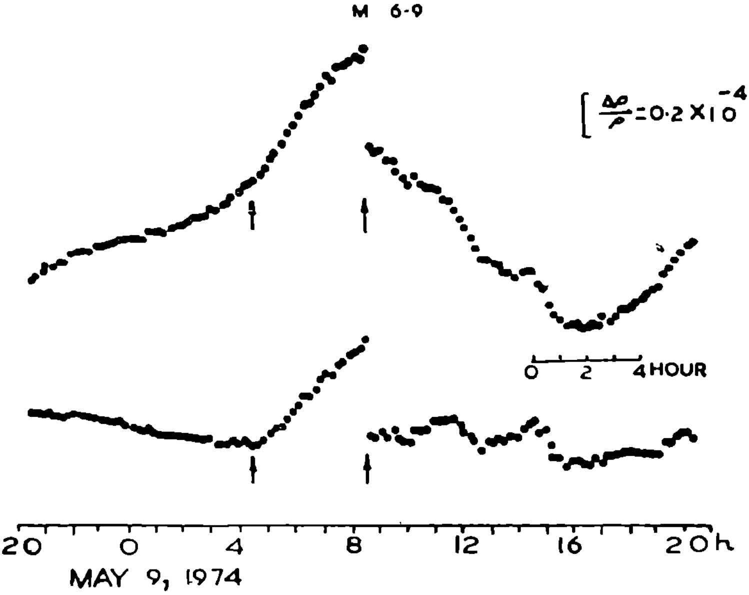


Fig. 64. Resistivity changes prior to 1974, Izu Hanto-Oki earthquake. The onset of precursory effect is indicated by the first arrow while the main shock by the second arrow. (After Rikitake and Yamazaki, 1978.)

the earthquakes. Larger the earthquake, earlier the anomaly can be observed which is supported by the dilatancy models. For example, an earthquake of magnitude 7 may start showing anomalous changes about 10 to 20 years in advance which is extremely advantageous for the preparation of earthquake disaster prevention plans. For smaller events, anomalies ranging from a few hours to several days have been reported. It is however noticed that there are a few events whose precursor times do not depend upon the magnitude. Rikitake (1978) has, therefore, classified three kinds of precursors depending upon its precursory time.

Precursors of the first kind: Under this category, those precursors are included whose duration of anomaly is dependent upon the magnitude.

Precursors of the second kind : The precursors can be grouped around log $T= -1$ which are independent of the magnitude (T is the precursor time).

Precursors of the third kind : Considering only precursor times of foreshocks, tilt and strain anomalies for earthquakes of magnitudes 6 or more, another kind of precursor is indicated whose mean precursor time is about 4·5 days. These are also independent of magnitude.

Rikitake (1979) has summarised 391 cases of precursors in different parts of the world as given in Table 4. Since then several other interesting results have been noticed particularly in India. It may, however, be mentioned that majority of them have been associated with past earthquakes and only a few denote precursory

TABLE 4. **Number of precursors (Rikitake 1979)**

S. No.	*Discipline*	*Number of cases*
1.	Land deformation	30
2.	Tilt and strain	89
3.	Tidal strain	2
4.	Foreshock	83
5	Anomalous seismicity	14
6	Slope changes in frequency magnitude relationship	12
7.	Micro seismicity	4
8.	Source mechanism	7
9.	Hypocentral migration	4
10.	Fault creep anomaly	2
11.	Ratio of P- to S-wave velocity	50
12.	V_p and V_s	19
13.	Geomagnetism	6
14.	Earth currents	17
15.	Resistivity	32
16.	Conductivity anomaly	3
17.	Underground water	2
18.	Radon	12
19.	Oil flow	3
	Total	391

trends on which reliable forecast was issued or can be issued. A few results are also of doubtful significance.

The procedure for choosing areas for operational earthquake forecasts consists in identifying regions using techniques of long term prediction like trends in seismic activity, the periodicity of earthquakes, tectonic features and accumulation of tectonic strain. During the next phase (medium term prediction) intensified observations may be started using integrated geophysical approach as is being done in Tokyo, Japan. In some cases, it may be possible to get an idea during this stage about the magnitude, M of the impending event depending upon the spatial extent of the precursors. Using this, the approximate occurrence time T, of the future earthquake may be estimated from the following relation (Rikitake, 1976)

$$\log T = 0{\cdot}76M - 1{\cdot}83 \qquad (2)$$

In China, the time duration of precursors is shorter for the same magnitude of earthquakes (greater than 4). This relation is given by

$$\log T = 0{\cdot}38M - 0{\cdot}34 \qquad (3)$$

In the last phase (short range prediction), the observations should be further intensified when precursors (whose duration is rather uncertain and may widely differ for different earthquakes) may be detected. It may be clarified that more research is urgently needed in different parts of the world before earthquake forecasting can be assigned an operational role.

CHAPTER 7

Earthquake Triggering and Control

Experiments on 'man made earthquakes'

EARTHQUAKE OCCURRENCE IS ATTRIBUTED TO THE TECTONIC CAUSES implying slippage of huge rock masses along the zones of fracture called faults when the accumulation of the strain energy exceeds the bearing capacity of the rocks. When such causative factors already exist, earthquakes occur due to slight increase in stresses in the region under the influence of some external forces which disturb the equilibrium. Such earthquakes are called *triggered earthquakes*. The triggering forces may be considered like catalytic agents in chemical reactions which in minute quantities accelerate the rate of reaction. Similarly, the term 'earthquake modification' is widely used by seismologists which implies that a region which has been generally non-seismic starts showing increased seismic activity due to some external 'man made' or natural factors. 'Control of earthquake' implies controlling the earthquake occurrence in such a way that damaging earthquakes can be either prevented or tamed according to our plans. In order to study the role of external factors, experiments have been conducted in USA and Japan in wells and oil fields to study the mechanism of artificial earthquakes generated.

Water injection in wells

Interesting observations of artificial earthquakes were obtained when in 1962, waste water was injected in a deep well at the Rocky Mountains near Denver, Colorado, USA (Evans, 1966). No significant earthquakes were reported from the region prior to 1962. A month or so after the commencement of injection of water at the rate of 2×10^4 m^3 per month, earthquakes were reported from the area. It was noticed that whenever the injection of water was totally stopped or suspended, the earthquakes also stopped in the region. During September 1969, the injection of water was totally stopped but this time earthquakes continued to occur for nearly ten years. A few of these earthquakes were comparatively large. It was noticed that ten to twenty microearthquakes were observed every day with magnitudes ranging from 0 to 3·7 on the Richter scale. Their focal depths varied from 4·5 to 5·5 km. The epicentres were distributed in an elliptic area having length of 8 km and width of 3 km. The depth of the well was about 3800 m which was rather close to focal depth of the earthquakes. A significant correlation was found between the earthquakes and fluid injection. The samples of cores taken out from the bore hole showed that there was a fractured zone close to the bottom of the well where many cracks existed. Due to the increased pore pressure of water column and the reduction of the friction, slippage of the rocks started occurring giving rise to earthquakes.

Somewhat similar results were also obtained at Matsushiro in central Japan (Ohtake, 1971). At this place, a sudden spurt in the number of earthquakes occurred during the years 1965 and 1966. Towards the end of the most violent stage of this seismic activity, about $10^7 m^3$ of mineral water started gushing out from the ground. In order to test the theory, a hole of 1800 metre depth was drilled close to the foot of Minakami mountain where the activity was located in its early stage. During January and February, 1970, water was injected in the well. The total volume of water injected was 2880 m^3 at the pumping pressure varying from 14 to 50 bars. The daily frequency of microearthquakes suddenly increased ten times within 5-10 days after the injection of water. The epicentres of these earthquakes were located about 4 km from the well which coincided with the trend of the fault. The focal depths of the microearthquakes were shallow in the beginning but increased with time. It was concluded that the earthquakes were related to the water injection.

Oil fields

Further experiments on earthquakes triggering were conducted at an oil field at Rangely, Western Colorado in USA during 1969-1973 (Healy et al, 1972). At this place, water was injected in an experimental well of 2000 metres in depth. Earthquakes occurred when the impounding pressure exceeded a threshold value.

Triggering factors

Tidal forces

The influence of forces of attraction of the sun and moon results in change of load on the earth's surface which causes earthtides. These have been correlated by some seismologists with past earthquakes. Studies made in USSR have reported that practically all the strong earthquakes in Kamchatka, the Kuril Islands and in northeast Japan occurred during certain phases of lunar tides having a cycle of 18·6 years. Forecast of earthquakes using tidal forces as trigger was however found to yield negative results on verification at other places.

According to the tidal force theory earth's fragile solid crust is under strain created by the pressure of rotation and gravitational attraction associated with the extra mass at the equator. Thus the regions which can be subjected to sudden shearing have been identified as the main earthquake belts, namely, Alpide and Circum-Pacific regions. Similar to ocean tides, the large crustal tides may act as trigger during new or full moon when the sun and moon are in conjunction and in opposition respectively. Using a computer programme incorporating the past data, earthquakes associated with the new moon of July 9, 1975 were predicted in Bonin Island, Burma, Nicobar, Bay of Bengal, New Ireland, Solomon Island, South California, Mexico, Southwest Atlantic and Spain. Of these 6 earthquakes (66%) were expected to have occurred between July 6 and 12 and the rest up to four to six weeks later. Only one earthquake actually occurred on July 8 in Burma which was felt widely in northeast India. Thus the overall percentage of earthquakes attributed to tidal forces is small. Whether the event of Burma occurred just by chance cannot be ruled out. Damaging earthquakes were expected in India during solar eclipse of February 16, 1980 and March 10, 1982 due to planetary alignment (Jupiter Effect), but no significant earthquake occurred. In general, the correlation of earthquakes to planetary configurations is considered doubtful by many seismologists because the order of stresses generated through this process is extremely small to disturb tectonic set up. What may perhaps be anticipated at best is increase in minor tremors called microearthquakes.

Connection between earthquake on one plate boundary to other ends

The earthquake belts in the seismic region have been nicely explained with the help of recent theory called *Plate Tectonics* according to which rigid layers of the earth called plates (50 to 100 km thick) move over denser but less rigid material and the earthquakes generally occur at the boundary of these plates. The question arises whether large earthquakes occurring at one end of the plate boundary could trigger earthquakes at the other plate boundaries. This may be possible considering that the plates are rigid and do not undergo buckling or any other type of deformation except at the ends. Thus big earthquakes at one boundary could possibly transmit stresses at other weaker zones. Study of earthquakes in the western and eastern boundaries of the Indian plate does not show any remarkable correlation. After considering the Indian Eurasian plate boundary north of Himalayas (instead of across the foothills as generally believed) and extending it close to Beijing (China), Kaila (1974) at the National Geophysical Research Institute, Hyderabad found that on 66% of the occasions, earthquakes at the eastern boundiary of the Indian Eurasian plates triggered earthquakes occurring in the Pacific region which is the boundary of the Pacific Eurasan plate. If, however, mini Philippine plate in the Pacific Ocean is considered, the results become less encouraging.

Rainfall

Increase in frequency of tremors has sometimes been reported after rainy season which is considered to act as a trigger. Such results have been noted in some years in Delhi, Himachal Pradesh and elsewhere. However, such earthquakes are of slight intensity.

In southern California, seasonal rainfall data for the last 90 years have been correlated with the occurrence of large (magnitude$\geqslant$6) earthquakes along the arid region of the San Andreas fault. It was found that most large earthquakes were preceded by a pattern consisting of a few years of below normal precipitation (drought conditions) and followed by one or more consecutive seasons of heavy (above normal) rainfall. It is surmised that this new precursor when combined with other premonitory signals may help in earthquake prediction in arid regions.

Role of smaller earthquakes

A probabilistic model of earthquake occurrence has been based on the triggering of large earthquakes by smaller ones which in turn are triggered by unobservably small and localised strain changes. The model is suggested by the fact that several damaging earthquakes appear to be multiple events in which the initial tremors are small compared with the later event as found for the great Alaska earthquake of 1964. Similarly, distant triggering of small fault slips by moderate earthquakes have been reported for the Borrego mountain earthquake of 1968 and the point Mugu earthquake of 1973.

Nuclear explosions

Nuclear explosions are sometimes considered as the triggering forces. Their influence on seismic activity has been studied in detail in Nevada Test site (USA). The underground nuclear explosions called Benham, Purse, Jorum and Handley initiated earthquake sequences lasting approximately 70, 10, 20 and 60 days respectively. The number of earthquakes of magnitude 2·0 or larger in these sequences were 2012, 24, 159 and 231 respectively with the maximum magnitude less than 5 on the Richter scale. The frequency magnitude relations following these explosions were similar to earthquakes in other regions. The spatial distribution of earthquakes appeared to be largely controlled by geological structure. Of these, even the largest explosion did not affect the rate of earthquake occurrence in the region.

Following Gnome explosion in Nevada region, about 10,000 aftershocks, were recorded in December, 1968 but their magnitudes were quite small and did not change the general level of seismicity. The largest nuclear explosion in the world so far was Cannikin on November 6, 1971 in Aleutian Islands which had a magnitude of 6·8. Its aftershock activity was also less significant in increasing the general seismicity in Aleutian Islands which is a zone of frequent earthquakes. The question arises as to why such big nuclear explosions have not triggered large earthquakes or changed seismicity. We know that earthquakes occur generally from 5 to 700 km below the earth's surface. Although it is mainly the crustal earthquakes (up to 40 km depth) which are most damaging, the depth at which Cannikin was detonated was less than 2 km and its influence even on triggering deeper tectonic earthquakes can be only casual. If useful results on the triggering of earthquakes are to be obtained the explosions should be detonated close to the focal region of earthquakes which is indeed a difficult task.

The Indian nuclear explosion in Pokhran on May 18, 1976 was detonated in seismically quiet region in Rajasthan and, therefore, its impact on triggering earthquakes could not be assessed. If, however, a few high yield nuclear explosions could be conducted in tectonically active regions, the mechanism of triggering of earthquakes may perhaps be better understood.

A question has been raised whether the unusual seismic activity during the year 1976 in different parts of the world was related in any way to the increase of underground nuclear explosions conducted by USSR, USA and China. It may be mentioned that seismological methods enable us to locate the sites of these explosions even though they are not announced. Such sites have been identified in Nevada, Aleutian Islands, Kazakh, Noya Zemalaya, Ural Mountains, Lop Nor, etc. As mentioned earlier, the biggest nuclear explosion in the world so far was Cannikin on November 6, 1971 which had a magnitude of 6·8. This is roughly two units less than the largest earthquake reported in the world. In terms of energy, therefore, the explosion was about 100 times smaller than the most damaging earthquake. All other explosions in the past few years were not only relatively smaller but generally located far away from the main faults. Thus, any influence of Cannikin in triggering earthquakes even in Pacific after lapse of 4 years may be ruled out. The only influence of this big nuclear explosion in Aleutian Islands was a small aftershock activity which is not unlikely in the highly seismic zone.

Dams inducing seismicity

Dams are considered to have triggered earthquakes in 20 cases, where seismicity coincided with lake filling in different parts of the world. The percentage of induced seismicity is about 0·1% for dams of 100 metre height or more. At some of these artificial lakes, the earthquakes of damaging magnitudes have occurred following the impounding of the dam with water. The cause of the reservoir associated seismicity has been attributed to the rising pore pressure and consequent decreasing rock strength. According to this theory earthquakes are triggered when pore pressures reduce the effective normal stresses on the pre-existing fractures or faults implying reduction in the shear strength of the rock. If the tectonic stress on the fracture or fault approaches the strength of the rock, a small reduction in effective normal stress can trigger slip causing earthquakes. In other words, the height of the water table in the reservoir may raise the pore pressure (by 15 to 20 bars) in the rock which weakens it lowering the tectonic stress that it is capable of sustaining. The excess stress is relieved by a temporary increase in the fault movement, causing earthquakes. It is generally assumed that stresses are released depending upon tectonic stress build up rather than changes in pore pressure due to fluctuating lake level. In brief deep injection of water into the crust may induce earthquakes similar to injecting water into a deep well.

Seismicity features and dams

Induced seismicity associated with the lake filling shows appreciable increase in the frequency of tremors with their epicentres located mostly within a distance of 25 to 50 km from the dams. The frequency is dependent upon the rate of increase of water level, the maximum level, duration of loading and the duration of retention of water at the highest level in the lakes. The local geology also plays a prominent role in inducing earthquakes. In general, rocks with evidences of volcanism in the past which are easily affected by water are considered more favourable. It has been however found that a well built dam on a firm foundation can withstand moderate earthquake shaking with maximum accelerations of the order of 0·2 g without detrimental effects.

Significant increase in regional seismicity was observed following the impounding of the world's largest artificial reservoir, Lake Kariba in Central Africa. At Kremasta, in Greece, an earthquake of magnitude 6 occurred three months after filling the lake. Detailed investigations were undertaken recently at Lake Oroville, California. At this place no significant increase in local seismicity was observed till the end of 1967, but a sudden increase occurred in June 1974. On August 1, 1975 an earthquake of magnitude 5·7 was reported.

Although no direct relationship between the main earthquake and the water load stress could be found, the small earthquakes of 1974 were attributed to the pressure of 200 metre of water (20 bars) at the reservoir which could have diffused to the focal region through some permeable zone along the fault. At another place in USA, Lake Mead has been seismically active for the last 40 years which showed significant increase in the number of felt earthquakes after the reservoir was filled. The majority of events occur at depths of less than 8 km. However, neither the number of events nor energy release showed any relation with the increase in lake level. Detailed investigations have shown that the weight of the lake and resulting loading (subsidence) was not responsible for these earthquakes. The Nurek dam on the Vaksh river in Soviet Tadzhikistan has also reported (Simpson and Negmatullaev, 1981) appreciable increase in seismic activity following the filling of the dam which is 300 metres high. The two most intense periods of activity were related to rapid increases in water level during the first two stages of filling in 1972 (water level 105 m) and 1976 (water level 205 m). It was found that extremely small changes in filling rate can trigger the onset of seismic activity (Fig. 65). Close collaboration between USSR and USA scientists is being maintained through an exchange programme to interpret the seismological data for this dam using a telemetred network. In Japan, a clear correlation to the seismic activity with height of water has been reported in Kurobe dam of more than 100 metres height. In China, a major shock of magnitude 6·1 occurred 2½ years after impounding in March 1962 in Hseien Fenkiang dam, which suffered some damage.

Aswan lake in the southern parts of Egypt and adjoining Sudan lies in the region which was considered to be aseismic like Koyna region. It was gradually filled since 1964 and reached a maximum water level of 177·48 metres in November 1978. An earthquake of magnitude 5·6 occurred on November 14, 1981. It caused minor damage to old buildings in Aswan. This shock was preceded by three foreshocks and followed by a large number of aftershocks. The lake effect in triggering this earthquake could not be ruled out due to the possibility of water penetration in the fractured near surface rocks and increased pore pressure through east-west extendings sets of faults.

It may, however, be mentioned that in a few cases decrease in

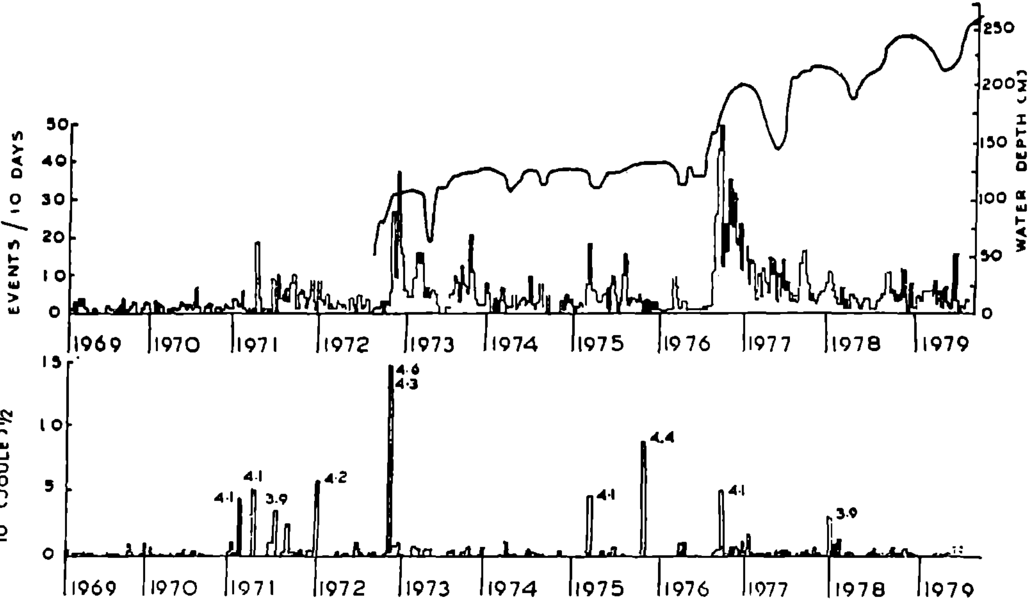


Fig. 65. Seismic activity associated with Nurek Dam. *Courtesy* : Bulletin Seismological Society of America.

seismic activity has also been reported like in case of Tarbela Dam in Pakistan. Similarly, Mangla Dam in Pakistan located in a highly seismic zone of Himalayas has not shown a positive increase in seismicity.

Reservoirs in India

In India, the occurrence of Koyna earthquake in 1967 attracted the attention of seismologists and engineers throughout the world. Earthquakes of slight intensity have been felt at Nagarjun Sagar and Hirakud Dams. Some dams have shown temporary increase in tremors located on the margins of peninsula like Ukai, Idduki and Mula Dams. On the other hand, artificial lakes like Bhakra, Pong, Pandoh (Fig. 66 a, b) and Ram Ganga in seismically active region have so far not indicated any increase in seismic activity. The damaging earthquake on December 11, 1967 occurred about 3 km to the south of Koyna Dam. Its epicentre was near latitude 17° 22·4° N and longitude 73°44·1° E with depth of focus about 8 km. In this region earthquakes of this magnitude were rare. A large number of houses in Koyna Nagar, a small township close to the dam either collapsed or suffered heavy damage, and 177 persons lost their lives. Cracks also appeared in the body of the dam at a few places. An old arched road bridge 3 km away from the epicentre (across the Koyna river) collapsed. However, another bridge built in 1954-56 with a RCC beam and slab deck supporting on rubble masonry piers (16m spans) stood undamaged though it was within a kilometre of the epicentre and with debris all round. Although the damage was mostly confined to a narrow belt about 8 km long and aligned approximately north-south, the shock was widely felt up to places like Surat and Ujjain in the north, Nagpur and Hyderabad in the east and Bangalore in the South. This created an impression that the focus was rather deep seated. It is now surmised that there were two shocks; the one having its focus near the surface was responsible for local damage while the other a deep seated one (about 60-80 km) was felt widely.

The Koyna area began to experience minor earth tremors with the filling up of the reservoir in 1964. To study these, a network of observatories was established around the Koyna dam and accelerographs were also installed within the dam. The maximum accelerations recorded during the earthquake were as follows:

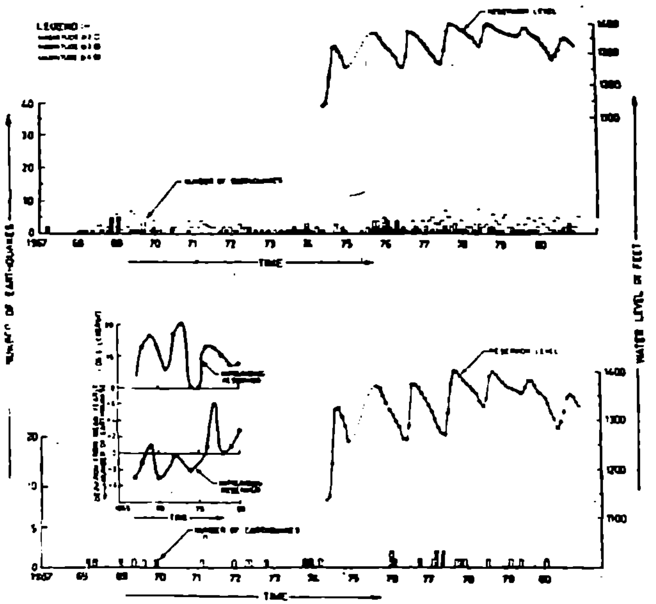


Fig 66 (a). Seismic activity in the vicinity of Pong Dam.

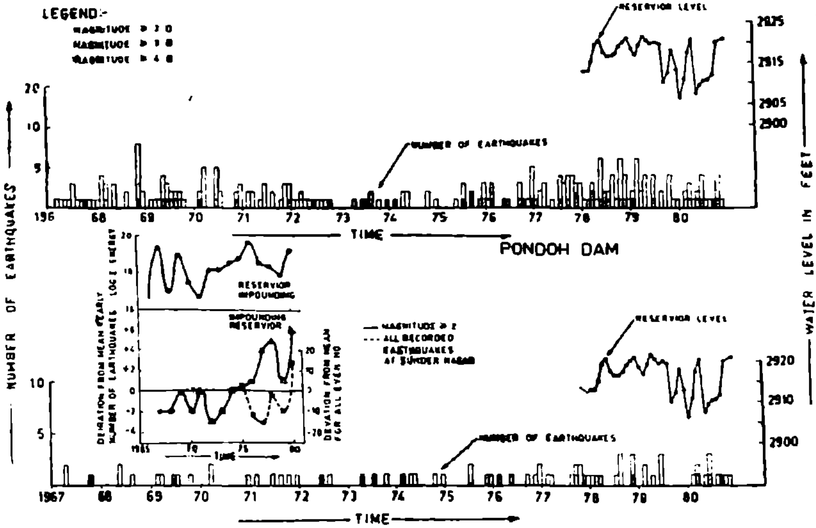


Fig. 66 (b). Seismic activity in the vicinity of Pondoh Dam.
In both the figures top portion shows earthquakes within 100 km. and bottom within 50 km.

Horizontal (transverse direction)	510 cm/sec/sec
Horizontal (longitudinal)	660 cm/sec/sec
Vertical	260 cm/sec/sec

The Indian Government set up a Koyna Tremors Committee in 1968 which includes scientists from several central Government Departments as well as from the State of Maharashtra. Through the help of UNESCO, three scientists, namely, Professor S. Okamoto, Professor I.E. Gubin and Dr. J.B. Auden were invited in 1969 who published detailed results about the causes of Koyna earthquake. In their report they have not mentioned any direct correlation between the filling up of the reservoir and the dams.

As mentioned earlier, the number of shocks against time at Koyna suggested a decaying event with observed aftershocks between 20 and 30 per week up to April 1972. From mid-May 1972, however, there was an increase in seismic activity. There was a lull in activity between June and September 1973. Suddenly, their number increased when on October 17, 1973 another moderate earthquake of magnitude 5·2 occurred. This earthquake occurred about almost simultaneously with the raising of the water level to the 2100 elevation which had not been reached since 1967. Since this earthquake had a close similarity with the earthquake of September 13, 1967 which took place three months before the damaging earthquake of December 1967, a doubt arose whether another damaging earthquake was likely. ,However no such event happened although about 10 years have elapsed. The aftershocks have already started showing a decreasing trend soon after the event. Since this shock raised an alarm even among the widely differing scientists, the same UNESCO experts were again invited in 1975. Of the three scientists, only Dr. J.B. Auden came to India (February-March, 1975) to study the problem in detail. Meanwhile, the data were also examined by India Meteorological Department which found that there was a fault aligned in north north-easterly direction in the region based on the distribution of aftershocks.

Dr. Auden re-examined the reservoir mechanism (UNESCO report, 1975). As is well known, the Koyna region is overlain with Deccan volcanics due to deposition of lava. These are transversed by a series of fractures, along some of which fault displacements have occurred. The majority of these fractures are gouge filled through which reservoir water cannot percolate to great depths, i.e. below about one kilometre which is the estimated thickness of the column of volcanics. On the other hand, the focal depths of aftershocks was 2 to 15 km. The north north-easterly fault is thought to be responsible for the Koyna seismicity which supported the results of Tandon and Chaudhury (1968) on the basis of focal mechanism data. However, recently deep seismic sounding experiments in the Koyna region reported by Kaila (1979) of National Geophysical Research Institute suggest that the orientation of the fault is north north-west dipping in easterly direction and the seismicity could be attributed to this tectonic feature.

Earthquakes are still being felt from Koyna region. The recent one occurred in September, 1980 which had its epicentre south of the dam. Prior to this, increased seismic activity has been reported from the region during October, 1976 and October, 1977 in addition to the events in 1967 and 1973. It is generally agreed that increase of minor tremors during the post monsoon months could be attributed to the release of stress (with time lag) due to water loading across pre-existing faults. However since earthquake of December, 1967 occurred after a period of 200 years and energy is being released periodically through the occurrence of smaller tremors in the region, another earthquake of damaging intensity is less likely in future.

International recommendations

Two symposia were held on induced seismicity in UK during 1973 and in Canada during September 1975. The second intergovernmental conference on the assessment and mitigation of earthquake risk was held at Paris during February 1976 where it was agreed that earthquakes induced by reservoirs are triggered either by the increase of pore pressure or more rarely, incremental load stress. It was therefore emphasised that a knowledge of the state of stress in the neighbourhood of the reservoir prior to impounding is a prerequisite for an assessment of the possibility of induced seismicity. The following resolution was adopted at this conference.

> "Member States in which large reservoirs are planned, detailed seismic surveillance be carried out to obtain good hypo-

> central control and source parameters of the earthquakes in the reservoir area from two years or more prior to the beginning of the construction. Furthermore it is recorded that measurement of initial stress near the deepest point of the future reservoir be carried out by the available techniques such as hydraulic fracturing and over core strain resettles as a means of understanding the mechanism of induced seismicity after filling. Large reservoir means that the maximum depth of water is more than 100 metre and its volume is greater than 10^9 m^3 at operational level."

Some more details about the time frame and the type of instrumentation were recommended as follows :

Two years before impounding any reservoir, at least three seismometers should be installed. Later their numbers should be increased to eight or ten. At least one three component strong motion accellerograph should also be located.

The basic requirement of the seismograph will be as follows :

1. Electromagnetic seismometer, free period 5Hz.
2. Low noise high gain amplifier.
3. Recorder with thin stylus to record on smoked paper.
4. Crystal clock with accuracy one part in 10^7.
5. Radio capable of receiving time signal.

Telerecording seismographs may be employed in more difficult terrains. In order to apply computerised methods for analysis and intepretation of data, digital recording seismographs (Chapter 2) are preferred.

It is expected that with the above type of instrumentation well distributed in azimuth around the dam with interstation distances of 20 to 30 km will enable us to determine the epicentres correct to ±1 km and the focal depth to ±5 km, provided there are in all ten observatories.

The International Commission on Large Dams (ICOLD) founded in 1928 is a non-governmental organisation which aims at global sharing of information and expertise in planning, design, construction, maintenance and operation of large dams. Under its perview, dams over 15 metres in height or of esser height but storing more than 100,CC0 m^3 of water are categorised as 'large dams' and thus differ from the definition of 'large reservoirs' as adopted by UNESCO.

In India, there are at present over 1,550 large dams, masonry and concrete gravity dams, concrete arc dams, earth and rockfill dams. Of these dams like Koyna, Pong, Pondoh, Bhakra, Ram Ganga, Idduki are well equipped with seismological instruments. It is well known that local population has resisted the construction of Tehri dam in UP where a few seismological observatories are functioning for over a decade. The argument that dams should not be built in highly seismic zone is not only unsound from the view point of national economy, but also not supported by the trends of seismic activity as observed in the case of high dams already built in similar regions elsewhere. Even though the subject of reservoir associated is still controversial, the phenomenon can be better understood with the help of modern instruments around dams of height 100 m or more. This may help in prediction of earthquakes, thereby saving major disaster due to sudden flooding and power breakdown in the eventuality of damage to the reservoir. The trends of seismic activity during the construction stage or later may also enable engineers to strengthen the dams well in time.

Migration of seismic activity

Some seismologists have reported migration of seismic activity from one region to the other. If they tend to occur on the same faults they can be better understood because of their unidirectional behaviour in similar tectonic set up. Northward migrations have been reported in Chile between 35° S and 10° S in the years 1957 and 1960, the speed of migration increasing from 7·6 km per day in the first cycle to 41·3 km per day in the fourth. Southward migration of earthquakes was noticed from California to Chile in 1951-1958. Active seismic areas were reported to migrate systematically from Japan to Alaska in three decades. Eastward migration of seismic activity has been observed along the Anatolian-Alpide belt during the year 1962 with a velocity of 12 km/hour. In the Mediterranean region, a west to east migration had been indicated with a migration velocity of 1·41 degrees of longitude per day. In Kashmir moderate earthquakes occurred during the years 1963, 1967 and 1973 located along the Punjal thrust which could perhaps indicate eastward migration.

Wandering of seismic activity has also been reported as oscillation patterns mostly found in aftershock areas with more or less periodic shift of the highest seismic activity between the two extremes of the area. It was exceptionally well developed in the Aleutian aftershock sequences in 1957, the oscillation period increasing with time from a few hours just after the main earthquake and approaching about 300 days three years later.

It may, however, be mentioned that the results of migration or oscillation of seismic activity are less acceptable to many seismologists in the world.

Controlling earthquakes

Let us consider some way of controlling earthquakes which are attributed to tectonic causes. If the slow accumulation of energy across the faults is periodically released through nuclear explosions, the tectonic energy would not be able to accumulate to such an extent that damaging earthquakes would occur. An earthquake of magnitude 5 or above is taken as a damaging earthquake which is a measure of its energy.

An earthquake of magnitude 6 has an energy about 20 times more than an earthquake of magnitude 5. In order to control an earthquake of magnitude 6, we will have to explode 20 nuclear explosions of magnitude 5 to release all the energy which is expensive. On the other hand, the most destructive earthquake of 8·5 magnitude has almost same energy as one lakh earthquakes of magnitude 5. Thus exploding such large number of explosions of energy equivalent to magnitude 5 is indeed a fabulous task. If we succeed only in exploding 20,000 earthquakes, then the energy equivalent to the remaining 80,000 earthquakes will yield an earthquake of magnitude 8·4 which will be almost equally disastrous as an earthquake of magnitude 8·5 and, therefore, no advantage would be gained.

Other means of controlling earthquakes could be through the construction of large dams in seismically active regions which may release energy periodically through smaller earthquakes thereby possibly preventing large earthquakes.

CHAPTER 8

Programmes and Seminars on Earthquake Forecasting

National programmes

EARTHQUAKE PREDICTION EFFORTS CAN BE MORE FRUITFUL IF systematic researches are carried out involving integrated geophysical techniques. The differences in the tectonics of various regions clearly bring out that no technique can be of universal application. Keeping this in view national programmes on earthquake prediction have been prepared and implemented in Japan, USA, USSR and China.

Japan

The field of seismology has made rapid progress in Japan where frequency of occurrence of damaging earthquakes is high. This led to the formation of a Study Group of Planning on Earthquake Prediction in April 1961. The following year this group published the blueprint entitled "Prediction of earthquakes—progress to date and plans for further development". This blueprint proposed the following disciplines for practical observations and research:

(*a*) Crustal deformation revealed by geodetic measurements—repetition of observations at 5 or 10 year intervals.

(*b*) Tide gauge stations for detecting crustal deformation—establishment of 26 new tide gauge stations.

(*c*) Continuous observation of crustal deformation—establishment of 100 new stations.

(*d*) Seismic activity—modernisation of observation system of Japan Meteorological Agency and establishment of 200 observation points for microearthquakes and 6 stations for ultra microearthquakes.

(*e*) Determination of seismic wave velocity by means of explosion seismology.

(*f*) Geomagnetism and earth currents—specialised research to relate changes in geomagnetism and earth currents to earthquakes.

(*g*) Active faults—survey and comparison of geological and seismological data.

It was unanimously expressed that "measurements needed would be of such a large scale that no single institution could adequately afford to operate and moreover, a thorough consideration is needed regarding existing scheme of seismic research for the effective practice of such a nationwide-project as required for earthquake prediction."

The above blueprint led to a long term Government supported plan of earthquake prediction which was launched in April, 1965. Soon after the start of the project, innumerable tremors, called swarms, were felt at Matsushiro about 200 km north-west of Tokyo. Scientists were successful in issuing warnings for future seismic activity. Inspite of the initial success, the Tokachu-oki earthquake of May 16, 1968 in north-eastern Japan which caused widespread damage compelled the seismologists to re-examine the earthquake prediction plan. During the second phase of the project, the following additional lines of research were included in the blueprint:

(*h*) Study and measurement of rock fracture—experiment on the fracture of rocks and direct measurement of stress in rocks.

(*i*) Ocean bottom seismograph system—development of seismograph system and observations thereof.

(*j*) Observation centre—data gathering and study of data processing.

(*k*) Observation in Tokyo metropolitan area—seismic observation in deep well (3500 metres); the deepest observation point in the world.

(*l*) Intensified observations—for the practice of earthquake prediction, various kinds of observations in dangerous areas are intensified.

The total budget allocated by the Government for the project during the years 1965 to 1973 was fifteen million dollars. Inspite of such challenging efforts, methodology for earthquake prediction on routine basis has not been accomplished. During the later plan for the years 1973 to 1977, special efforts have been taken to construct six bases for the prevention of disasters in the Kyoto area of Tokyo where food and water arrangements for 5 million refugees can be made.

The Coordinating Committee for Earthquake Prediction has been set up with its headquarters at Geographical Survey Institute, Ministry of Construction, Tokyo. National universities, the Japan Meteorological Agency, the Geological Survey and the National Centre for Disaster Prevention are also participating in the programme.

USA

After the US-Japan Conference on Earthquake Prediction in 1964, ten year well defined programme was proposed in September 1965. This included various kinds of field studies, specialised instruments, theoretical and laboratory studies, earthquake engineering and earthquake modification. Due to financial difficulties, however, the programme could not be implemented which would have cost about $137 million in a ten year period. However, researches into earthquake prediction techniques were intensified in Government as well as academic institutions. Subsequently a unified national programme on earthquake prediction called the Earthquake Hazards Reduction Programme (EHRP) has been started since 1973 with the support of the US Government. The following studies are included in this programme:

(*a*) Geodetic survey for monitoring crustal deformation at major faults.
(*b*) Creep measurements.
(*c*) Tiltmeters for monitoring slow deformations as well as rapidly monitoring changes.

(*d*) Telemetering microearthquake observations for looking into precursory changes.
(*e*) Geological mapping near active faults.
(*f*) Portable seismographs for studying crustal structure and aftershock characteristics.
(*g*) Deep drilling for instrumentation and direct examination of fault zones at depth.
(*h*) Global plate tectonics studies.
(*i*) Geological and tectonic studies of active faults.
(*j*) Measurements of physical properties of rocks in laboratory under realistic conditions inside the earth's crust.
(*k*) Measurements of strain using strainmeters at shallow depth.
(*l*) Laser ranging instrument for high precision distance measurements.
(*m*) High sensitivity magnetometers for geomagnetic anomalies as premonitory indicators.
(*n*) Computer modelling of deformation and faulting in realistic earth model.
(*o*) Radon measurements in water.
(*p*) Testing techniques of earthquake prediction developed in Japan, USSR and other countries.

At present, earthquake prediction research is being carried out extensively in California, Nevada, Aleutian Islands, Missouri and Utah Mountain regions. More efforts are, however, being concentrated along San Andreas fault in California where movements are being monitored very precisely through the use of quasars. Joint programmes with USSR scientists in both the countries have also been undertaken.

In USA the Geological Survey is the principal agency which runs an extensive programme in California. A number of universities including California Institute of Technology participate in earthquake prediction research. According to Frank Press (1975), a noted seismologist, and the Scientific Adviser to the Minister of Defence, the US programme is not sufficiently supported to make prediction a reality within the next decade.

USSR

Systematic earthquake prediction research is being carried out in USSR in Tadzhikistan, Uzbekistan, Kamchatka and Sakhalin. In each region, the lines on which work is being carried out are different. In Tadzhikistan, an integrated earthquake prediction programme is based on seismological, deformation, electromagnetic and geochemical methods. In Uzbekistan, more emphasis has been placed on tilt measurements and geochemical methods. In Kamchatka region, predictions of strong earthquakes have been carried out since 1972 using seismic wave velocity, electrical resistivity and crustal deformation measurements. A great deal of attention is devoted to theoretical and laboratory experiments on the physics of earthquake sources.

Earthquake prediction programme of the USSR is primarily carried out by the Institute of Physics of the Earth, Moscow, and by the science academies of the Kazakh, Kirghiz, Uzbek, Tadzhik and Turkman Republics of the Soviet Union. In view of the environmental treaty between US and USSR, there has been frequent exchange of ideas in the field of earthquake prediction and earthquake engineering through exchange of scientific delegations. Thus both countries are kept informed by the latest unpublished researches.

China

China has adopted an earthquake prediction programme after the earthquakes of March 8 and 22, 1966 in Hopeh province. Tilt and strain measurements, frequent levelling and triangulation surveys and seismological observations are included in the programme in several provinces. Sophisticated instruments like laser beam geodimeters, proton precision magnetometers indigenously developed are being employed. General public, students and peasants are associated with the programme who play an important role in detecting precursory anomalies like animal behaviour and changes in colours of well water. More data are thus available to the seismologists who are able to combine their scientific results for a more reliable assessment of earthquake occurrence. Involvement of the public in earthquake prediction programme also helps them to take some simple but relatively effective measures to resist earthquake hazards. In the event of an earthquake warning well informed public can act more constructively which reduces the casualties and losses. It is surmised that Chinese will be able to gather more data than any other country due to the size of their programme and the frequency of damaging earthquakes.

Earthquake prediction conferences

US-Japan Conferences on Earthquake Prediction

Two US-Japan Conferences on Earthquake Prediction held in 1962 and 1964 discussed developments in the subject. The topics on which papers were presented included crustal deformations, seismic activity including aftershocks, geomagnetism and earth currents, tectonic movements through aerial and satellite photographs, So far five conferences have been held on the subject.

ESSA Symposium on Earthquake Prediction

In USA Environmental Space Science Administration also arranged a symposium on earthquake prediction in February 1966. Physical basis of rocks involving the rock mechanics, focal mechanism, microearthquake survey, crustal, and strain measurements, role of deep hole and underwater seismographs were discussed in detail.

Symposium on Earthquake Prediction in India

The first symposium on earthquake prediction in India was sponsored by the India Meteorological Department and the Indian Meteorological Society at New Delhi from March 6 to 8, 1978. It was attended by about 200 delegates from different geophysical and other institutions in the country and discussed the following aspects through 45 papers presented:

(*a*) Geology, tectonics and earthquake occurrence.
(*b*) Space and time variations of seismicity and instrumentation.
(*c*) Statistical methods of earthquake prediction.
(*d*) Precursory changes.
(*e*) Theoretical studies (computational techniques, source mechanism and wave propagation).

Some of the interesting results of precursory value pertained to Himachal Pradesh, Assam and Koyna regions.

During the panel discussions it was brought out that a committee consisting of representatives from different organisations in the country should be formed to plan earthquake prediction research. It was also recommended that a group should be appointed to publicise earthquake forecasts whenever feasible. The proceedings of the symposium have been published in the journal *Mausam* (1979).

Natural Disaster Mitigation Research

An Indo-US Workshop on Natural Disaster (earthquakes and wind effects) Mitigation Resaerch was sponsored by the Department of Science and Technology, Government of India and the National Science Foundation, USA which was held at New Delhi from December 13 to 16, 1978. Among six projects identified for collaboration research, highest priority (Project No. 1) was given to the establishment of a strong motion earthquake instrument array in the Shillong area and analysis of strong motion data recorded. This area was identified earlier as the most potential zone for a damaging earthquake in future as a result of a workshop on Strong Motion Instrument Arrays held at Honolulu in Hawai, USA from May 2-5, 1978. A total of 200 analog and 50 digital strong motion accelerographs were recommended for the region to study source mechanism of earthquakes. Mobile, local extended and local laboratory arrays have also been planned to collect data of engineering importance under different geological, topographical and soil conditions.

South Asia Disaster Preparedness Seminar

This Seminar was held at New Delhi from January 23 to Febrary 1, 1979 in which specialists from 13 countries participated. It was sponsored by the US Foreign Disaster Assistance Agency for International Development, the League of Red Cross Societies, Switzerland and UNDRO. Detailed discussions were held for meteorological, geological and environmental hazards like cyclones, storm surges, droughts, floods, deforestation, landslides and earthquakes. Disaster preparedness plans and procedures in countries like Afghanistan, Burma, India, Nepal, Pakistan, Sri Lanka and Philippines were discussed. Some of the important recommendations were setting up an office for disaster preparedness on national level, regional coordination cell, mutual assistance agreements and working arrangements on regional basis, and financial and technical assistance including opening of more seismological stations for earthquake prediction research through international cooperation agencies like UNDP, USAID, the World Bank and the UNDRO.

International Symposium on Earthquake Prediction (UNESCO)

The first International Symposium on Earthquake Prediction organised by UNESCO was held at Paris, France, from April 2 to 6, 1979. About 240 participants from 40 different countries discussed through the following sessions :

(*a*) Earthquake precursors.
(*b*) Experimental and theoretical aspects of physical processes.
(*c*) Methods of earthquake prediction.
(*d*) Individual and group response.
(*e*) Economics of earthquake predictions.
(*f*) Role of institutions.
(*g*) Communication of predictions and warnings.

The observations of individual precursors effective in long, medium and short term predictions were (*i*) seismological including foreshocks, seismicity gaps and anomalous seismic velocities; (*ii*) hydrodynamic phenomena observed in shallow and deep well and (*iii*) crustal deformations, including tilt. In addition, magnetic and electric resistivity anomalies would also be used. Biological precursors were discussed for short term prediction. The papers presented in the symposium suggested that the reliability of earthquake prediction is gradually increasing, although several problems in issue of routine forecasts still remain and their solution may not be possible in near future. It was also noticed that forecasts based on only one type of precursor are in general less reliable than those based on a combination of precursors.

The panel of experts discussed the scientific, social and economic aspects of earthquake prediction from April 9 to 12, 1979 at UNESCO Headquarters in Paris. Twelve recommendations for member states of UNESCO along with its own involvement were made on the following aspects :

(*a*) Prediction research.
(*b*) International experimental sites.

(*c*) International meetings.
(*d*) Education.
(*e*) Prediction evaluation.
(*f*) International advisory committee on earthquake risk.
(*g*) Working group on earthquake preparedness and public policy.
(*h*) Earthquake warning announcements.
(*i*) Role of international agencies in developing preparedness for earthquake prediction.
(*j*) Communication of prediction information.
(*k*) Regional projects.
(*l*) Future international symposium on earthquake prediction.

The following prediction oriented conferences have also been held through UNESCO :

(*i*) Regional Seminar on Earthquake Prediction and Seismic Risk, San Juan, Argentina, October 1980.
(*ii*) International Symposium on Continental Seismicity and Earthquake Prediction, China, September, 1982.
(*iii*) UNSECO Seminar on Earthquake Prediction case histories, Geneva, October 1982.

Other conferences

UNESCO has also arranged the following conferences with the idea of mitigation of earthquake risk:

1. Inter–governmental meeting on Seismology and Earthquake Engineering, Paris, 1964.

   As a result of this meeting, a handbook of seismological observatory practice was published in 1970 by the International Seismological Centre, UK through the financial support of UNESCO.
2. Inter-governmental Conference on the Assessment and Mitigation of Earthquake Risk, Paris 1976.

   This conference identified the following interdisciplinary problems of the highest priority in programmes on earthquake risk:

(*a*) Choice of design earthquake ground motions.
(*b*) Specification of engineering design criteria.

(*c*) Induced seismicity and its social impact.
(*d*) The interpretation of historic and archaeological records of earthquakes.
(*e*) Consequences of earthquake prediction.
(*f*) Interdisciplinary research for the improvement of the earthquake resistance of non-engineering indigenous dwellings and buildings.
(*g*) Economic and social implications and insurance relating to the mitigation of earthquake disasters.
(*h*) Evaluation of seismic risk.

Some aspects of the earthquake damage, risk assessment, disaster prevention and earthquake resistant design of structures are discussed once every four years at the World Conference on Earthquake Engineering. These conferences have been held at Berkeley (USA) in 1956, Tokyo (Japan) in 1960, Wellington (New Zealand) in 1965, Santiago (Chile) in 1969, Rome (Italy) in 1973, New Delhi, (India) in 1977 and Istanbul (Turkey) in 1980. Six conferences on earthquake engineering have been held at the University of Roorkee. These precede the World Conferences while similar earthquake engineering conferences in Tokyo (Japan) follow them. The proceedings of all these conferences have been published.

Organisations connected with earthquakes prediction

The following organisations,' besides UNESCO, render valuable support directly or indirectly to any earthquake prediction programme and disaster mitigation:

(*a*) International Seismological Centre (ISC), Newbury, UK. It brings out a monthly seismological bulletin based on world wide data which is of great use in earthquake risk assessment and prediction research.
(*b*) US Geological Survey, USA. It publishes epicentral parameters of world wide earthquakes in a shorter time than ISC but with lesser data. Within a few hours, it is able to announce the parameters of an earthquake of magnitude 6 or more occurring anywhere in the world.
(*c*) Regional Centre for Seismology for South America (Peru).
(*d*) International Association of Earthquake Engineering.

(*e*) International Council of Scientific Unions.

(*f*) International Union of Geodesy and Geophysics (IUGG). Its affiliate called International Association of Seismology and Physics of the Earth's Interior (IASPEI) has a permanent commission on earthquake prediction.

(*g*) International Centre for Theoretical Physics.

(*h*) Inter Association Committee on Mathematical Geophysics.

(*i*) The League of Red Cross Societies.

(*j*) United Nations Disaster Relief Office (UNDRO).

(*k*) United Nations Environment Programme.

(*l*) European Seismological Commission. It organised a symposium on the analysis of seismicity and on seismic risk from October 17 to 22, 1977 at Prague, Czechoslovakia.

International projects

So far the following three international projects have been completed which have improved our understanding about earthquakes.

1. *International Geophysical Year*: This project started in 1957 laid more emphasis on studies about the internal structure of the earth.
2. *Upper Mantle Project*: In this project which commenced in 1964, more emphasis was laid on the upper mantle structure. Through this project, significant results pertaining to plate tectonics, volcanoes and earthquake prediction were obtained.
3. *International Geodynamics Project*: This project which started in 1973 has concentrated on more detailed investigation about plate tectonics and earthquake mechanism. It has involved several other multi-disciplinary approaches like gravity, heat flow, geology and tectonics coupled with horizontal movements and earth's plates.

It is now proposed to take up a new project called 'crustal dynamics' on world wide basis which may further improve our understanding of earthquakes through vertical motions in the earth's crust.

CHAPTER 9

Implications of Earthquake Forecasting

Accuracy in earthquake prediction

EARTHQUAKE PREDICTION ENABLES US TO TAKE TIMELY PROTECTIVE measures. Long term prediction presents an opportunity to reinforce building and other structures, prepare emergency shelters and move to safer areas vital industries, records, art works and other non-replaceable materials. Short term prediction enables us to save valuable human lives and mitigate physical injuries by evacuation of unsafe buildings, shutting off gas and oil pipelines, closing down atomic power plants and properly storing radioactive and toxic material, restricting traffic on dangerous roads and bridges, and alerting fire fighting and rescue teams. In order to prevent disruption in social life, the prediction should be reliable to the extent of 100%. However, science has its limitations and prediction with the present state of knowledge can at best be qualified by probability. For example, the probability that an earthquake with magnitude more than M will hit an area X within the next m months is $L\%$. This nature of prediction capability has not been appreciated by the public in general with the result that social demands for earthquake prediction are increasing day by day. Thus there are immense administrative and socio-economic problems which arise once an earthquake forecast is issued.

Political consequences of prediction

Earthquake prediction may trigger a chain reaction on the political life of a country. Once scientists have issued a forecast even with lesser confidence (probability), the members of parliament or state legislature may demand of the Government to place before them action proposed to face the disaster. Even though the limitations in the forecast may be brought out by the scientists, the Government is faced with dilemma whether to completely ignore the forecast or start planning emergency rescue. If the forecast by chance materialises without taking protective measures the opposition parties in the country may take the Government to task. In the event of a major disaster, the tales may be carried to the next general elections. On the other hand, if the forecast fails, there could be innumerable socio-economic and legal problems as will be discussed later.

In this respect, the line of action adopted by the state governments appears to be more compromising for north-east India where a damaging earthquake has been forecast during the next few years on long term basis. The administrative machinery has been geared to face the emergency with the help of civil defence, police, border security force, army and social organisations. Public is being educated by the government which includes distribution of literature on how to face an earthquake, what to do during and after it has occurred. Scientists have been associated along with the administration to assess the earthquake risk from time to time. However whether short range prediction can be achieved is still debatable. Lots of funds involving billions of rupees are needed for research before the problem can be reliably tackled.

On the international front an earthquake prediction may have serious repercussions, particularly when an earthquake has been predicted along a border region between two countries. Closer cooperation between the governments and scientists of the neighbouring countries is necessary to meet the danger. If only exchange of data is envisaged, there is no immediate problem. However, for extracting more information, the original records may have to be exchanged which may contain information, say, about movement of vehicular traffic or artillery fire in a sensitive area (in addition to earthquake data) which can be recorded automatically on the seismograms. Such a situation may create ill feelings between them causing failure of the collaboration programme on prediction. Similarly, if the triggering of earthquakes is also included in prediction technology, and a nuclear explosion is detonated underground near the border of a country, the occurrence of a future damaging earthquake in the neighbouring country could be associated with the explosion creating political problems.

Rapid progress in earthquake prediction research has however to be gained through international cooperation. The panel of experts after the first International Conference on Earthquake Prediction, Paris (April 1979) recommended that "in order to accelerate the collection of the high quality observational field data required for progress in earthquake prediction, UNESCO develop a mechanism whereby countries can offer highly seismic areas of their territory for long term study as international experimental sites. Following designation of each site, other countries could apply to install instrumentation and perform investigations at the site in collaboration with the host country and other participating countries. Such experimental sites should be located in regions where large earthquakes are expected within the next ten to twenty years. Sites should preferably include locations in different tectonic provinces such as subduction zones and intra-continental seismic zones." How many countries actually respond to such international cooperation particulary because of sensitive installations in the seismic regions has yet to be watched. In short, prediction oriented collaboration on prediction research may create embarrassing situations for some countries.

Legal implications

Earthquake prediction may also present serious legal problems to the government. For long term prediction, the legislative measures for land use and zoning may be summarised as follows:

(*a*) Taxation measures to steer development away from hazard areas.
(*b*) Legal measures for the enforcement of zoning and other regulations for controlling density of population and pace of development.
(*c*) Government action to acquire land by compulsory purchase and to alter existing land use.

In other words, the earthquake disaster preparedness legislation should outline the powers and responsibilities to be placed upon the Government. Viewed from the point of view of individual, such measures constitute significant infringements of vested property rights particularly if there is no provision for adequate compensation. In the early years of earthquake prediction therefore, there may be 'writ petitions' or constitutional challenge in courts of law based on unreasonable justification to acquire the land or forcible demolition of 'hazardous' houses on the grounds of lack of data or uncertainties of the forecast. Similarly, after a short range prediction is issued advising the people to evacuate, the public may have to be shifted to some other 'safe place', but if during this short period, the unsocial elements become active resulting in largescale thefts and the forecast fails, legal action against government could be initiated by organisations and individuals.

Apart from physical dislocation, the other legal issues may arise due to depreciation in property value, increased insurance premium and personal mental stress. .

In southern California, USA, attempts have been made thrice to implement seismic safety legislation aimed at reducing the loss of life and property associated with damaging earthquake but had to be stalled due to the resistance of local community. Young and Nigg (1979) have inferred that this resistance has developed because of varying assessment of acceptable risk in the constructional work.

A study conducted by Driscoll (1979) at the Faculty of Law, Edinburgh University, UK has observed that "the dearth of legal studies on almost all aspects of disaster prevention and mitigation supports the conclusion that research into all these areas of law is urgently required." It will then be possible to promote disaster preparedness legislation which would outline the powers and responsibilities to be placed upon governmental and non-governmental agencies and upon individuals.

Effects on insurance

Earthquake prediction has direct impact on insurance. Insurance contracts covering earthquake risk may be seriously affected as soon as an earthquake is forecast. It would be necessary to amend the clauses after defining the rights and responsibilities of each party. For example, it should include the right of the parties to cancel a contract, renewal provisions, reinsurance, long term agreements, new policies and the effect of insurance on property values. Study conducted in USA suggests that once a reliable prediction has been issued, the Commissioner of Insurance in California may not permit the sale of new earthquake policies. There are, however, several advantages that will be gained from earthquake prediction. The insurers may take appropriate action well in time for financial planning, pre-earthquake inspections of insured property, assessment of losses and settlement of claims (Gill, 1979). In India too some insurance companies have started taking interest in the subject. Earthquake risk maps specifically for the purpose of insurance policies have been prepared in consultation with specialists by an insurance company. These are broadly based on the 'seismic zoning map' prepared by the Indian Standards Institution. A better estimate of earthquake risk as discussed in Chapter 5 using the concept of microzoning should be developed for insurance purpose. For example, even in the same city the effects of a damaging earthquake will be more on houses located on soft ground than those on rocks. Thus, even if the type of construction is similar, the houses in Lodi Colony in New Delhi may suffer more than those located in Chittaranjan Park or Kalkaji. This is borne out by studies of pattern of damages of past earthquakes in different countries.

In New Zealand, about 900 claims amounting to over $ 100,000 were made on the Earthquake and War Damage Commission in Wellington area after the earthquake of November 1, 1968. The distribution of damage claims due to this earthquake showed remarkable correlation with the soil pattern; the frequency of damage claims was much higher in filled up areas as compared to the houses located on bed rock (Grand Taylor et al., 1974). Another interesting observation was that the frequency of damage claims in the sand areas was a little less than average, despite the chance of liquefaction which of course did not occur due to insufficient intensity. Under this condition, therefore, sands behave better than fine grained alluvium. However, if the liquefaction would have taken place, the damage claims could have been many times more. Attempts were also made to study the importance of the age factor of the dwellings on the damage pattern. In general, the relative average claim density was 1 to 3 times higher in older houses (pre-1914) as compared to the new (post-1950) houses in similar topography. ·Such a detailed insurance study was possible because a computer analysis had been carried out by the Valuation Department in the year 1965 of assessments classified unit residential, industrial and commercial buildings. Although it may appear unpalatable to the public, the insurance charges similar to varying health conditions have to be prepared after microzoning in cities has been completed. Similarly, weaker and old houses can be charged higher premium than a newly constructed one. This subject is, however, fairly involved and needs more intensive study.

Damaging earthquake in the next few years has been forecast for northeast India. It is understood that no significant effect has yet come to light on the sale of insurance policies in the region.

Economic implications

Earthquake prediction is being analysed by economists from the cost-benefit point of view. The benefits of earthquake prediction are well known in reducing risk to life and property. The cost of warning system arises due to research and development, evacuation, decline in property values or effect of erroneous prediction. It can have serious effect on the life of a community due to the need for shifting the business out of hazardous region, which can result in unemployment, decline in tourism, shift of sources of essential supplies to safer regions at increased prices (Munroe, 1979). According to a study conducted in the University of Colorado, USA the local enonomic loss due to prediction might be as great as that caused by the earthquake itself. Another opinion that has been expressed is that "*only added losses* are admissible as debits against prediction" (Cochrane, 1979). On the other hand, there is some evidence from Japan, Mexico and USA that while most predictions of damaging earthquakes had no significant economic effect, the more credible ones for threatened area did carry some impact (Hass, 1979). Credibility is based on the reputation of the source of prediction, the extent of consensus among the seismologists regarding the prediction and to a lesser extent the probability with which the forecast has been made about the place, time of occurrence and magnitude.

Financial institutions like commercial banks may also be constantly under threat due to non-availability of earthquake insurance for life, fire and casualty after a 'prediction' and stoppage of outside pre-disaster financial assistance. The role that such institution may play in situationsinvolving predictions of varying probability and time duration (imminent, short, medium or long range) however needs to be studied in detail.

Using benefit-cost analysis and decision analysis, economists are studying the economics of earthquake prediction (Panel of Experts, UNESCO Conference on Earthquake Prediction, 1979) by

(*a*) Focussing attention on the importance of obtaining specific data on the nature of the prediction (i.e. magnitude, location and time) and the credibility of the forecast. These data are considered as essential inputs to an analysis of the consequences of different programmes such as developing insurance premiums for specific towns, specifying building codes and safety standards,

(*b*) Evaluating the relative merits of different earthquake hazard reduction measures, such as building codes and land use regulation, as a function of the prediction. For example, it is possible to compare the impact of short-term, medium term predictions in evaluating the capacity of building codes to reduce economic losses from a future earthquake.

(*c*) Evaluating the trade offs and possible integration of different prescriptive measures such as investment in better earthquake prediction techniques, insurance programmes.

We have seen that the hazards associated with earthquakes may be of different nature depending upon whether the locality effected lies in a rural area or is in an industrial town or a city with skyscrapers. The problems of prediction of economic losses due to earthquakes in agricultural Georgian regions of USSR have been studied in detail (Koridze, 1979). Since the maximum damage occurs due to rural dwellings which do not take proper safeguards in their construction and there are wide differences in the mode of construction of individual houses due to use of local building material, a map was prepared for this region dividing it into geographical zones according to major building types and the percentages of the different types to be found in each zone. An estimate of loss expected to be suffered corresponding to earthquakes of different magnitude was expressed as the ratio of cost of hypothetical repair to total building cost. The probability of degree of loss in buildings during such time during earthquakes of varying force was worked out. A damaging earthquake of magnitude 8 which occurred in Georgia on January 2, 1978 enabled to check the accuracy of predictions regarding the losses suffered by rural dwellings. Each building was classified according to the degree of its damage and an estimate of repairs was prepared which confirmed the economic loss actually predicted on the basis of pre-earthquake data. But a similar exercise for a modern city is quite expensive. Nevertheless, disaster preparedness plan has been drawn for four main cities in Japan and may possibly be tried at a few places in India.

In order to assess the economic implications of earthquake prediction, closer collaboration between earth scientists, engineers and economists is called for, which may bring out the adjustment of extra cost of prediction through mutual adjustments between private and public sectors.

In view of the high input costs and other implications for earthquake prediction as discussed above the question arises whether earthquakes should be predicted or not. It may be worthwhile to recall the criticism in weather forecasting whenever it fails. Inspite of this, weather forecasts play an important role for agriculturists, aviators and coastal people threatened by the onslaught of furious cyclones. While there is tremendous technological advancement in the field of weather forecasting due to direct observational techniques like satellites, radars and numerical models, some aspects of forecasting still need improvement. Inspite of their limitations, weather forecasts are welcomed. It may also be borne in mind that no amount of money can equal a human life. The other view that comparatively more people die from several other natural causes and accidents, is unhealthy for scientific advancement and needs to be discouraged. Earthquake forecasting is the need of the hour through increased research and a beginning must be made.

CHAPTER 10

Response to Earthquake Forecasting

Reactions to earthquake forecasts

WITH THE RAPID ADVANCE IN THE EARTHQUAKE PREDICTION RESEARCH, our ability to forecast earthquakes is increasing day by day. This necessitates a thorough examination of the responses of organisations and individuals vis-a-vis warnings of the earthquake hazard. Social scientists have, therefore, started taking an active interest in the subject through field studies in several countries. The sample surveys undertaken so far are far from being satisfactory except in the southern California. The method of such surveys includes personal interviews, telephonic interviews or through questionnaires. The data collected are analysed using the well-known statistical methods and are presented either graphically or in tabular form. The information so collected enables concrete steps to be initiated for disaster mitigation by government officials, seismologists, publicity media and other agencies involved. Thus, earthquake hazard reduction can be better achieved through appropriate combined responses of individuals, families or groups and the government. Such response of individuals or groups to earthquake prediction in some countries is discussed here.

Southern California, USA

The observations made by scientists during 1975-76 in southern California that the earth's surface was uplifted by more than 40 cm over a vast area centred near Palmdale, Los Angeles along the famous San Andreas fault in USA led to a widespread speculation whether an earthquake is indeed likely. The association of an 'uplift' with an impending earthquake is always questionable because the phenomenon may occur without any accompanying earthquake. However, the California Safety Commission declared that the uplift should be considered a threat to public safety and welfare in the Los Angeles metropolitan area. This was based on the following considerations :

1. An uplift of this nature sometimes actually precedes earthquakes.
2. The extent along which the uplift has been observed across the San Andreas fault could generate an earthquake of magnitude 8 which would cause huge deaths, injuries and loss of property.
3. An earthquake is overdue in the southern parts of San Andreas fault which is seismically active.

The US Geological Survey increased observational network in the region, which might enable scientists to issue timely warnings. Meanwhile an interesting study on the human response to earthquake threat in southern California was conducted by Turner et al. at the Institute of Social Science Research, University of California (USA). This report was based on a sample survey of 1450 adult residents of Los Angeles Country from mid-January to mid-March 1977. In order to assess awareness of the uplift among the public it was found that 72·7% of the people who have heard of the uplift understood that it could indeed be an earthquake precursor.

Success in disaster prevention plan depends upon identifying groups of people who are out of the mainstream of public communication. It is then convenient for the administration and other agencies to devise means so that these people can also be provided with equal opportunity to protect themselves against such hazards as other population. The survey brought out very clearly that special efforts are called for young adults, people having school-aged children, the less educated and members of lower income group, non-whites and non-anglo groups so that they may be made aware of any future earthquake prediction.

It was found that most southern Californians have heard some announcements about an impending earthquake in the region through newspapers, radio, television, magazines, a bestselling fiction or a prophecy. Out of these television news programme was the principal source of information about earthquakes in California. It was, however, revealed that less than one-third of the viewers had taken such programme seriously because people generally do not expect the earthquake to be unusually severe. Among the different sources of earthquake forecasts, the scientific announcements are taken more seriously than the non-scientific ones.

At the time when the survey was conducted in southern California about 43% people expected that an earthquake would occur within a year from February 1978. Since no earthquake has taken place during the period, it remains to be studied whether the confidence of public in future warnings will be diminished.

Of the various natural disasters, facing southern California, only 6·6% of the entire sample mentioned earthquakes as the most serious one. Thus, the public mind is more preoccupied with such problems as crime, cost of living, taxes, unemployment, smog (mixture of fog and smoke in early mornings), pollution, transportation, education and high population density. Some people also mentioned that earthquake threat is less severe than danger from tornadoes, hurricanes, winter storms and floods. However fear and concern about earthquake have been found among the population. Of the 63% who were reported frightened, only 49% said that they were substantially worried. In the event of a definite earthquake forecast with time and place, it was observed that many people preferred to find a relatively safe location within the earthquake zone itself. There is no indication that many people would pack up their belongings and move away from southern California because of earthquake forecasts or warnings issued in the year 1976.

The question whether earthquake prediction should be released or not is still debatable and will be discussed in detail in Chapter 11. However, many Californians want to be forewarned only if the scientists are relatively confident about a prediction. They feel that a few weeks to six months is sufficient time to know about an earthquake forecast. Many of them are of the opinion that it is the responsibility of the government to release such a vital information to the public.

Most people in southern California have given some thought about the suggestions which they expect for government action. More than 35% people expected structural improvements through building codes, reinforcing or destroying unsafe buildings, making dams, while 'educating' people to face the disaster was next important suggestion. Plans for emergency care and relief also got almost equal response (25·7%) so that adequate shelters and supplies, medical care, evacuation plans and good communication systems may be adequately assured to the public.

The citizens' confidence in California officials dealing with the earthquake preparedness was not very high. The people who are well informed about the uplift have the least favourable view of the government efforts in earthquake mitigation. Nevertheless, they do expect official action to reduce earthquake hazards.

The question that arises next is to find out the extent to which the citizens have prepared themselves against earthquake hazards. There are several ways for the people to meet such an eventuality. For example, flash lights, battery operated radios and first aid kits are generally kept in the house whether there is an earthquake threat or not. In California, more than a quarter of the population do not have emergency lights while about 45% are without first aid supplies. Not many have battery radios so that they would be unable to hear radio broadcasts due to power failure during an earthquake. Further, people should make arrangements to store emergency supplies of water and canned or dehydrated food as supply of these items can be interrupted during severe earthquakes. It was found that very few people have taken any steps in this direction.

The life of inhabitants is further endangered from falling objects such as almirahs, which can injure people. The contents of cupboards should be rearranged so as to reduce the risk of breakage and their doors should be locked. Few people have given thought to this aspect.

It is felt that joint responsibility plans involving neighbours should be set up to discuss earthquake preparedness which may include calling meetings at regular intervals. In southern California, only one person in fifty-nine had attended a neighbourhood meeting about earthquakes. It was thus concluded that most people are not prepared for an earthquake emergency inspite of its possibility being widely publicised. It was noticed that whites who are more aware of of the uplift are better prepared than blacks or Mexican Americans.

For communicating earthquake forecasts to the public, television and radio sets have been considered as reliable media. However, greater reliance is placed when the forecasts are published in magazines and books. In America, group meetings, for example in a club, school, church, neighbourhood blocks are considered as important means for stimulating interest in public about natural hazards. In spite of this, very few Californians have actually attended such meetings.

The much publicised Chinese programme of earthquake prediction based on unusual animal behaviour is now considered by 67% of the total Californian samples as a sign in daily life which is useful for prediction. More than two-fifths of their population believes in unusual weather, and, more than a third accept human instinct to forecast earthquakes. Unusual aches, small tremors and changes in water levels were also considered as other signs in daily life for prediction.

Constraints on organisational and household response to earthquake prediction were also studied at three United States west coast urban areas. This was conducted by National Hazards Warning System, University of Minnesota through extensive interviews with 200 randomly selected households in each research site. Many aspects of household responses were similar to that in California as the interviews covered (*a*) sources of information about earthquake prediction, (*b*) past experience with earthquakes, (*c*) exposure to neighbourhood and mass media communication channels, (*d*) preparedness levels for earthquakes. Another study conducted in USA relates to the social factors affecting the response of groups to earthquake prediction. Spread over a two year period, a variety of groups were involved in the study in the state of California, USA. This has helped to reveal why different types of responses are likely after a prediction. The factors which will play a vital role in determining the course of action for hazard reduction were (*a*) image of damage, (*b*) exposure to risk (insurance), (*c*) exposure to risk (other factors), (*d*) access to information, (*e*) commitments to target area and (*f*) resources. These factors have suggested ways in which prediction warning group response can be managed through policies designed to induce constructive response and minimise undesirable responses.

Japan

The Science and Technology Agency in Tokyo, Japan conducted a survey through interview of 1177 persons to ascertain individual responses by a hypothetical earthquake warning supposed to occur at 11 O'clock in the morning of a week day (Simizu, 1979). The survey was carried out in three cities and one town in Shizuoka prefecture where a great Tokai earthquake is expected in the near future. It is reported that after the issue of the warning, most people at home will first of all take care to prevent a fire and then switch on television. More than 30% people working in the offices will rush home within half an hour. About half the people at offices will ring up their families. Traffic jams and paralysis of telephone service will be unavoidable. Most people are however eager that such official information on earthquake prediction should be issued even if it does not come true.

The response of individuals to the warning just before the earthquake has been analysed through Nagoya University as well (Shimazu and Hiramatau, 1979). The study has considered several alternatives but probable cases for the timing of warnings, such as (*a*) earthquake occurs without warning, (*b*) issue of warning is too late to complete emergency actions, (*c*) earthquake occurs as predicted, (*d*) warning issued but no earthquake and (*e*) earthquake occurs after warning is cancelled. A distinction has been made between the systems panic due to collapse of service and administrative systems and mass panic caused by the behaviour of individuals under abnormal conditions. It is surmised that the prevention of systems panic is more important than the mass panic and therefore issue of warnings is oriented towards this aspect. Similar to the earlier study for Shimoga prefecture, it is found that the major sources of systems panic after the issue of warnings arise due to rupture in telephone lines and separation of family between residential and working areas. Comparison of the systems behaviour in day, at night, during weekends, holidays and rush hours has suggested that the day time urban system should be reorganised into the night time system to reduce panic. Also, the time duration from the issue of warning to the earthquake occurrence should not be longer than a day.

Italy

The Friuli earthquake of 1976 in Italy has provided an insight into the responses of the population through investigation of 142 households which experienced the shocks and are also exposed to damages from rock falls and floods from a river. Two-thirds of the people who were questioned could not give any explanation for the occurrence of earthquake while the rest gave slightly irrational than rational explanations. Of the three types of disasters mentioned above, rock falls and floods are considered to recur sooner than earthquakes. The public considers earthquake resistant design of structures as the safest method. Only about a quarter of the sample think of moving away from the damage zone if the warning is issued (Geipel, 1979). Most people expect the state to take protective measures rather than through their own initiative although only a few have full faith in government action.

India

A preliminary survey about the response of individuals has been made in northeast India, Kashmir, Himachal Pradesh and Delhi. The people interviewed were engaged in different types of professions like teaching, medicine, hotel management, household work, missions, manning teastalls, para military organisation, etc. It was revealed that there is quite good understanding among public in north-east India where some people expect damaging earthquake to take place soon. Others, however, are more curious to verify the authenticity of the forecast and the time of its occurrence. They have learnt about the hazard from radio, newspapers, friends and colleagues. The people in Kashmir, Himachal Pradesh and Delhi are aware of a few felt or damaging earthquakes in the past but do not consider this hazard to take place in the near future. There is great belief among the scientists about the earthquake forecasts in north-east India, but curiosity has been expressed by some in the Chinese method of unusual animal behaviour as a tool. In one or two houses maps showing escape routes in the event of an earthquake have been prominently displayed. No special precautions about storing any canned food or other articles like torches have been taken in general, but people have expressed faith in government actions. No direct contact could be made with tribes in the region but it is learnt that such people are apparently unconcerned about the impending earthquake. The main reason attributed to this type of attitude is that the tribal people are accustomed to face natural hazards such as floods, more frequently and some of them have also suffered in the past damaging earthquakes in the region or heard about them from their elders and accept it as a part of life.

Memories about earthquakes are often short lived. This is reflected through interviews of people in Srinagar. For example, even educated people do remember earthquakes of Badgam (1963), Anantnag (1967) and Kishtwar (1973), but expect earthquakes to recur only at these places. They do not consider any threat at Srinagar which was destroyed in the year 1828 and falls within the highest seismic zone. In Himachal Pradesh, the local uneducated population was frightened at some places as soon as they learnt about initiation of long term precautionary measures through homeguards. They got a feeling that an earthquake is round the corner with such actions. This is partly attributed to the occurrence of recent damaging earthquake in Kinnaur region in 1975 whose memories have not yet faded and partly because of numerous felt earthquakes in the region and a few others close to Dharamsala. In the capital, greater risk exists in the crowded colonies of the walled city where even escape routes may be jammed due to fire or falling debris but people are not enthusiastic to get their vulnerable houses demolished or even leave them in the event of an earthquake forecast due to fear of robbery/thefts. They want to be assured almost cent percent about the accuracy in the forecast before considering any action.

It may be mentioned that a more detailed survey in India on the human response to earthquake prediction is desired on the lines of southern California for planning better disaster measures in the seismically active areas.

CHAPTER 11

Publicity and Evaluation of Earthquake Forecasts

Publicity

EARTHQUAKE FORECASTS ARE BEING ANNOUNCED FROM TIME TO TIME by scientists as well as non-scientists like astrologers, psychics, etc. While there is an increasing awareness among public to give more credibility to scientific forecasts, there is an inherent ambiguity in them due to the limitations of our present state of knowledge making it difficult for a common man to understand the constraints under which the results are arrived at. For example, publication of the findings in a scientific journal with so called sensational captions like "Will there be an earthquake in Himachal Pradesh soon?" could, if given wide publicity through press, may imply to a common man that an earthquake is imminent, although authors of the scientific paper might have only examined the probability of its occurrence based on various facts and might have suggested more intensified observations for a meaningful short range forecast. It is true, however, that a few scientists may purposely wish to get publicity through the media of the press even before reporting their results in scientific journals or discussing them with other experts in seminars or symposia. Keeping in view the variety of socio-economic implications, such forecasts based either on vested interests or based on meagre data may have serious repercussions on the Government. If such a forecast comes true, scientists would be in the news again but if it fails, no harm would be done to them.

It may be interesting to examine in detail the impact of a few such forecasts which were published with so called sensational captions in scientific journals or got publicity through press media.

The occurrence of Koyna earthquake has attracted the attention of seismologists throughout the world. It may be recalled that an earthquake of magnitude 5·2 occurred at Koyna on October 17, 1973 roughly six years after the damaging earthquake of 1967. On the consideration of a foreshock of comparable magnitude on September 13, 1967 before the main Koyna earthquake in the same year, H.K. Gupta and B.K. Rastogi (1974) of National Geophysical Research Institute, Hyderabad (NGRI) published a paper in *Nature* about the possibility of another earthquake in Koyna region. To quote the authors, "The recent October 17 earthquake has a close similarity with the earthquake of September 13, 1967 which took place three months before the damaging earthquake of December 1967. The two earthquakes have comparable magnitudes, originated at the same spot, have a similar foreshock aftershock pattern and occurred following a rapid loading of the reservoir to peak levels. While it could not be said with surety that the current seismic activity is a forerunner to a relatively high magitude earthquake in the Koyna region, it may be mentioned that there is a definite enhancement in the seismic activity which correlates with the increased reservoir levels."

This publication received attention in the press and Koyna dam authorities through Maharashtra Government which requested UNESCO to send the same team of experts which was deputed to study various aspects connected with the main earthquake of 1967. Of the three scientists, only Dr. J.B. Auden, a geologist from UK could come to India in early 1975 to study the problem. Based on the data supplied to him, he concluded that since 20 months after the event of 1973 had already passed without the occurrence of more damaging earthquake, the slight increase of seismic activity could be considered to be subsiding gradually with time. Indeed no earthqauke has occurred so far even after a lapse of nine years. In this particular instance, a casual connection between the reservoir loading and the earthquake was not ruled out. Thus the interesting inference of NGRI scientists who considered the possibility of 1973 event as a foreshock of a damaging earthquake, attracted more attention of scientists and geologists. This forecast, however, did not create any large scale panic in the minds of public of the small township of Koyna who have got accustomed to the numerous felt earthquakes including damaging ones.

As mentioned earlier, publication of a news item in 1977 from Regional Research Laboratory, Jorhat that a very damaging earthquake would occur in northeast India during 1977-80 created an unprecedented commotion among the people of the region. The forecast was based on the extrapolation of past data, implying it to be essentially a long range type but specific time of its occurrence (1977-80) was mentioned in the newspapers. The forecast though scientifically limited in scope has been successful in attracting the attention of State Governments to initiate precautionary measures in the region which is highly seismic. Simultaneously, even though there is no certainty about the time of occurrence because of its statistical nature, it created panic in the region and had at one time in 1978 led to an increased demand and consequent rise in the prices of GI sheets for dwelling units.

In the year 1978 a paper entitled "Possibility of a large earthquake in seismic gap of Himachal Pradesh" by the author and H.M. Chaudhury was published in the Proceedings of Vth Earthquake Engineering Conference in Tokyo, Japan. This study is based on a very close network of seismic stations in the Himachal Pradesh and the seismic gap which has been delineated lies between the damaging earthquakes of Kangra (1905) and Kinnaur (1975). In the seismically active region of Himachal Pradesh, geophysical investigations from various disciplines have been suggested to draw any inferences about short range forecasting. In the views of the author, this region is scientifically better equipped for prediction studies than northeast India where detailed seismological observations of microearthquakes have yet to be collected. Further, the large area involved in northeast India even though criss-crossed by several faults may make it difficult to achieve success in prediction work. This is obvious from the seismic history during the past 150 years which shows that damaging earthquakes (Cachar 1869, Shillong 1897, Srimangal 1916, Dhubri 1930, Assam 1950) had occurred in widely different places in northeast India, thus making it difficult to choose a specific area for intensified observations. On the other hand, the area in Himachal Pradesh which may cover the seismic gap and its adjoining zone of great Kangra earthquake is of the order 200× 100 km (excluding Kinnaur and adjoining region where recurrence of earthquake so soon after 1975 earthquake is less likely and the population is very sparse). However, most of the scientists are apparently less concerned about this region at present.

Releasing earthquake prediction to the press had positive impact on the Governments in several other parts of the world as well. In Japan, a noted seismologist Dr. H. Kawasumi announced on the basis of Japanese history of earthquakes for the past 1200 years that a strong earthquake would hit the southern Kanto district including Tokyo with a periodicity of 69 years (with an uncertainty of 13 years). According to his view, the dangerous period of a possible strong earthquake has started from the year 1978. Kawasumi's periodicity theory was questioned by other seismologists. However, the prediction attracted the attention of Tokyo Metropolis to draw a detailed plan called 'Operation Tokyo' to start measures for mitigation of earthquake disaster. In June 1978, a special law for counter measures against great earthquakes was also passed by the Diet. The law provides for the issue of warnings and the administrative procedure against impending earthquakes. Before the enactment of this law, a notice on aftershocks issued after the damaging Izu Oshima Kinkai earthquake of January 14, 1978 caused unexpected confusion in Japan.

In USA, an abnormal uplift reported by scientists in southern California in 1975 aroused considerable interest. Even though nobody is as yet definite about the meaning of uplift or its possible association with an impending earthquake, the National Administration issued a prepared press release on February 13, 1976 because of the growing number of enquiries from press as well as public (Wesson, 1979). More funds were sanctioned to undertake programmes for experimentation and hazard assessments. The response of individuals and groups to the possibility of an earthquake in the region was studied by social scientists. Standard procedures were outlined to evaluate and communicate earthquake forecasts within the United States.

Thus the publicity of earthquake forecasts through the media of the press or with so called sensational captions in scientific journals (not necessarily intentional but with the prime objective of bringing them to the notice of other scientists) has attracted more attention of the public and the Government. While no restrictions are needed to be imposed upon the scientists to publish their results in scientific journals even under so called sensational captions, particularly when better quality and abundant data may reveal clearer precursory trends in future, the release of such results to the press has to be restrained. This is all the more important if false predictions (as discussed below) get reported in newspapers and other publicity media.

False alarms

False alarms about earthquakes can create lot of administrative problems for the civil authorities because the rumours connected with such forecasts spread fast. An interesting example of the effects of such rumours has been reported for Oaxaco, Southern Mexico (Ordous, 1979). In 1977, seismologists had indicated the possibility of a strong earthquake in the region after identifying a 'seismic gap' in its vicinity. This was a medium to long term precursor. In April 1978, a telegram was received from United States in Mexico country that a strong earthquake with huge quantity of water would occur at Pinotepa Nacional (Oaxaca) on April 23, 1978. It was also indicated that the probability of earthquake was based on scientific facts. The source of the telegram was not indicated, but the municipal authorities who received the telegram disclosed it to public. This gave rise to a spade of rumours which were supported by the Press. Some said that a tidal wave would sweep across Pinotepa Nacional extending as far as Petatlan to the north and Puerto Escondido to the south while electricity would be cut off from April 18 to 20 to prevent outbreaks of fire. Other rumours mentioned that the Government was going to establish an airlift to evacuate the population, the banks would be closed, the Government was going to evacuate the teachers and students as their training was a costly affair; some people disposed off their property like houses, land, cattle, etc. Such rumours spread more rapidly in small places through markets and schools. The town in Oaxaca with a population of only 20,000 has a very good programme of education through primary, secondary and preparatory schools besides an agriculture school and a market centre. All these helped to spread rumours quickly. Since the 'false alarm' could not be stopped soon after its receipt, it created great problems for the Government. In such situations, the expectations from earth scientists can be easily visualised. There are innumerable queries from various quarters to confirm the possibility of the event. The reply that the technique for forecasting is not yet fully developed or that there are no positive indications about a future earthquake neither satisfies the Government nor the public. It may be easy to blame the scientists if an earthquake does take place because post mortem is often easy. However, the limitations of the present state of earthquake forecasting should be constantly kept in mind. Obviously the press has to act with greater caution to prevent false alarms or giving more importance to the findings of scientists (who might have arrived at the forecast from limited data) reported in journals. It will be in the national interest if reliability of the forecast can be verified through Government agencies before publishing it in newspapers.

Somewhat different type of a false earthquake forecast was reported by T. Rikitake of Japan at a UNESCO seminar on earthquake prediction case histories held at Geneva (October, 12 to 15 1982). A false earthquake warning was issued through a wireless broadcasting system in Hiratsuka city which is about 60 km southwest of Tokyo in Japan. This happened because of an unexpected malfunction of the system on October 31, 1981 at 9·02 P.M. As the area falls under intensified measures against earthquakes, a tape which records the emergency announcement of earthquake warning by the Mayor in his own voice is always kept ready for use at the controlling centre. The contents of announcement were as follows:

(*a*) An earthquake warning statement has already been issued by the Prime Minister.
(*b*) The Mayor himself is speaking.
(*c*) The city office is on the alert according to the prescribed programme for preventing earthquake disaster.
(*d*) Each citizen is required to pay attention to later information coming through TV, radio, etc.
(*e*) Each household should extinguish fire, store water, prepare for evacuation and so on.

The announcement was cancelled about 20 minutes later through the same broadcasting system as well as public relations cars of city office, police and fire brigade. Two independent surveys were undertaken to find the public reaction to the false alarm due to the broadcast. The surveys showed that the announcement reached directly to 10 to 14% of the citizens only and they were not unduly disturbed after hearing it. No paralysis of telephone communication system was reported. This was because most of the people were at home with their families and the offices and banks were closed at that time. However, the incidence brought out the need of careful handling of earthquake warning information by the administrative officials.

Other unfulfilled predictions

Two significant cases of prediction of earthquakes in California and Peru which remained unfulfilled were discussed at the UNESCO seminar on Earthquake Prediction case histories at Geneva (1982) through C.R. Allen of California Institute of Seismology, USA and A.A. Giesecke, Director, Regional Centre for Seismology for South America (CERESIS).

(*a*) *Whitcomb prediction*

Dr. J.H. Whitcomb predicted an earthquake on April 15, 1976 at the annual meeting of the American Geophysical Union in Washington, D.C. based on the time dependence of the P-wave velocity and P and S wave velocity ratio in southern California where an earthquake of magnitude 5·5 to 6·5 within the next 12 months was indicated due to the return of the velocity anomaly to normal. This forecast was given publicity through a news conference at the California Institute on April 21 same year. Dr. Whitcomb later withdrew the prediction. Although no earthquake occurred in the specified area during the period, the scientific community seemed to come through the episode with reasonable credibility in the public eye. It was surprising that the prediction did not create great public concern possibly because the scientists and the news media treated the forecast in a relatively low key fashion. However, the procedures adopted by the Earthquake Prediction Evaluation Council of California to alleviate undue public concern could be debated due to hearing the young scientist in open which was reported as headlines like "Experts won't accept quake prediction" in Los Angeles Times.

(*b*) *Brady's prediction*

Dr. B.T. Brady of the US Bureau of Mines published the forecast about an earthquake in coast of Central Peru through the study of observed seismicity patterns and their interpretation in terms of the theoretical model of the failure preparation process in rocks in a journal, "Pure and Applied Geophysics" (vol. 114, 1976). The prediction was made more specific at a meeting in Golden on May 24, 1974 that a great earthquake would take place in Peru in July 1981 followed by another large shock in April 1982. This was widely publicised through news media after a seminar on earthquake prediction in Argentina in October 1980. The matter was discussed at the highest level including the President of Peru but he was not convinced that an emergency situation had developed. The forecast was also discussed by the US National Earthquake Prediction Evaluation Council (described in next section) whose members were also unconvinced about the scientific validity of the prediction. Although a few earthquakes with magnitude of the order of 5·0 occurred in Central Peru between October 1980 and May 1981 which were taken as the foreshocks for an impending earthquake, Dr. Brady later withdrew the prediction saying that the interpretation based on space-time seismicity patterns in Central Peru was not correct. The forecast had several social and economic impacts on the local population. It increased the awareness of the earthquake risk in schools where exercises like rapid and orderly evacuation drills were undertaken. During 1981, there was also an increase by about 35% in the number of insurance policies for residential houses. Two lawyers initiated legal action to sue Dr. Brady but the case was rejected by the Court due to insufficient evidence about the loss of revenue to Peru. The Government of Peru gave support for further seismological research through scientific collaboration with USA which provided lot of data to seismologists.

Responsibilities for issue of forecasts

As mentioned earlier, a heavy responsibility rests with scientists and Government before an earthquake forecast is released to the press. According to Dr. C.R. Allen, President of Seismological Society of America (1976), "great care and great caution in making predictions are certainly fully warranted." In order to extract full advantage and take suitable anti-disaster measures, "earthquake prediction should be a time, space and magnitude window. It must give some sort of indication of the chances of the earthquake occurring anyway, as a random event and author's confidence in the reliability of the forecast." The panel of experts which met in Paris from April 9-12, 1979 soon after the UNESCO Conference on Earthquake Prediction also recommended about earthquake warning announcements as follows:

"The issuance of an earthquake prediction or the announcement of the occurrence of possible precursors, is the responsibility of earth scientists. They alone possess the expertise to collect, synthesise and analyse large amounts of complex and often ambiguous data, and to reach appropriate conclusions. On the other hand, the issuance of a warning (i.e. a set of guidelines or orders to take protective actions that will alter the normal activities of a community) is the responsibility of civil authorities, who have substantial political, economic and social impact. It is recommended that UNESCO and UNDRO should encourage affected Member States to take legislative and administrative step to identify an agency for prediction evaluation, a clearly defined authority for the issuance of earthquake warnings, and channels for the dissemination of such a warning."

Earthquake Prediction Evaluation Council

Earthquake prediction is still in its infancy and therefore guidelines must be prepared to handle earthquake forecasts to prevent false alarms. In USA the Panel of the Public Policy, Implications of Earthquake Prediction (1975) expressed the view that in the event of scientific announcements of forecasts, public officials, the media and the general public would require advice from a disinterested group of scientists in distinguishing valid from invalid predictions. It was also felt that an individual scientist or institution might have highly relevant information but may not be in a position to evaluate the situation alone. Therefore, the responsibility for a prediction should be shared among a wider group of responsible scientists. The first step in this direction was taken in the State of California where damaging earthquakes can occur any time and predictions are more likely to be issued from time to time. For this purpose, California Earthquake Prediction Council was formed in 1974. Its main objective was to advise the Director of the Office of Emergency Services on the validity of predictions of earthquake capable of causing damage in California. The Council is expected to evaluate and provide the Director with professional opinion as to the reliability of the data and the scientific validity of the technique used to arrive at a specific prediction. It consists of a State Geologist as Ex-officio Chairman and eight earth scientists.

At the Federal level in the United States, the responsibility for the evaluation and communication of earthquake prediction has been assigned to the Director of the US Geological Survey. The council called USGS Earthquake Prediction Evaluation Council in 1975 is being modified as National Earthquake Prediction Evaluation Council. This council is composed of scientists working both within and outside the Federal Government.

On the International scale, UNESCO will extend help to the Member States by providing the services of qualified scientists for prediction evaluations at their request.

In India, too there is an urgent need to form a National Earthquake Prediction Council to assess the reliability of forecasts. It can be coordinated either through the Department of Science and Technology or the Geological Survey of India and may be composed of about a dozen earth scientists from the India Meteorological Department, National Geophysical Research . Institute, Bhabha Atomic Research Centre, Central Water and Power Research Station and universities. Once it is formed, the credibility of predictions can be judged better before advising Government for practical remedial measures.

CHAPTER 12

Earthquake Disaster Management

DISASTER PREVENTION AND PREPAREDNESS AGAINST ANY NATURAL hazard are included in disaster management. It consists of a wide range of measures, some long term and others short term, aimed at saving lives and restricting the amount of damage that might otherwise be caused. As suggested by United Nations Disaster Relief Organisation (UNDRO), the term "disaster prevention" may be described as measures to prevent natural phenomena from causing or resulting in disaster or other related emergency situations." It concerns formulation and implementation of long term policies and programmes to prevent or eliminate occurrence of disasters and includes legislation and regulatory measures, mainly in the fields of physical and urban planning, public works and building. The term disaster preparedness may be described as action designed to minimise loss of life and damage and to organise and facilitate timely and effective rescue, relief and rehabilitation in cases of disaster. Preparedness is supported by the necessary legislation and means readiness to cope with disaster situations or, similar emergencies which cannot be avoided. It is also concerned with forecasting and warning, the education and training of the population, organisation and management of disaster situations, including preparation of operational plans, training of relief groups, the stockpiling of supplies and earmarking of the necessary funds. These are briefly the lines on which action should be taken to face earthquake disaster. Keeping in view the limitations of short range earthquake prediction, disaster preparedness in India may be undertaken on priority basis in those areas for which better assessment of earthquake risk has been evaluated on the basis of past data or those regions which fall under zones IV and V in the Indian Seismic Zoning Map prepared by the Indian Standards Institution.

Earthquake disaster preparedness may be undertaken in cities, hills, districts and villages. Of these, maximum losses in life and property occur in crowded cities which require more careful planning. However, a damaging earthquake on a hilly highway may completely cut off a hill station and paralyse its life, if it is not connected by air. Thus the effects of landslides and associated problems in hills need also be examined under the disaster prevention plan. In Osaka, Japan a large mound 35 metres above the sea level and surrounded by tall buildings has been constructed with a view to protect the refugees from post earthquake inundation. Thus the coastal stations and the effects of Tsunamis should not be ignored in disaster preparedness.

Legislation for disaster preparedness

Legislation related to earthquake disaster is essential to establish responsibility for the required action, whether of a long term or short term. These can be of two types; legislation for long term construction and reconstruction for prevention purposes, and legislation for preparedness, emergency and short term recovery purposes.

Japan which has suffered the most from damaging earthquakes, is unique to enforce an "Earthquake Disaster Prevention Ordinance" through the Tokyo Metropolitan Government which was passed in September 1971 soon after the possibility of recurrence of a damaging earthquake in Tokyo was realised on scientific basis. This ordinance consists of eight paragraphs describing duties of firms, quake shelters, city planning, prevention on destruction of buildings, prevention of fires, refugees, the system of information and communication, and the citizens cooperation. According to the ordinance the Metropolitan Government is authorised to appoint a 'disaster danger district' where rebuilding of wooden houses is prohibited, removal of dangerous objects or enforcement of earthquake resistance is recommended and accommodations for explosive or toxic substances are restricted.

On June 15, 1978, the Japanese Government promulgated an act called "Large Scale Earthquake Countermeasures Act" as Law

No. 73 (Kins, 1979). It is intended to protect life and property of citizens by consolidating earthquake disaster prevention arrangements such as the designation of earthquake disaster prevention areas, the formulation of earthquake disaster preventive plans and the improvement of seismological observation systems, issue of early warning when earthquakes can be predicted, establishment of an Earthquake Disaster Control Headquarters, implementation of earthquake disaster preventive emergency and other measures.

In India, too there is a need to take legislative measures in view of the hazardous seismic zones in the country. The Indian Standards Institution Code on the subject (1976) should be made mandatory. Also, legislation may include preparedness for actual emergency, short and long term recovery including rehabilitation and reconstruction. In particular, contingency plans may be prepared to include following aspects for long term recovery.

1. Restoration of public services and utilities, including communication, transportation of all types, electric power, water supply and sanitation.
2. Repair or reconstruction of public buildings.
3. Repair or rebuilding of roads, bridges, dams, runways and harbours.
4. Replenishment of nationally owned stockpiles, such as food, seeds, medicines, etc.
5. Provide immediate needs of the private sector, including housing, employment financial assistance, etc.
6. Proper utilisation of credits and gifts from other countries.

Local disaster preparedness committee

The main objectives of this committee would be to keep the population constantly prepared for an emergency due to earthquake, to direct and control rescue and relief work and to organise programmes of public information and education.

The local disaster preparedness committee may work under the guidance of the state Government and should include representatives of the following bodies:

District magistrate or his representative
Civil defence

Police
Public works
Public health and medical services
Fire service
Utilities like transport, electricity, gas, water, posts and telegraphs
National Red Cross
Radio and Television.

Evaluation of future earthquake damages

Effective measures against damaging earthquakes can be taken if an idea of the extent of damage due to an impending earthquake can be visualised in advance. A rough knowledge of likely damage can be made depending upon the magnitude of the expected earthquake extrapolated from past data, possible intensity/intensities in various locations from the type of descriptions given in intensity scales giving allowances for type of foundations and the structures, communication or transportation systems. A more reasonable extent of damage can be predicted through the principles of operations research in mathematics by incorporating more details of vulnerable items like storage of inflammable materials, disruptions of traffic and means of communication, spread of fire for various possible wind speeds and number of deaths, etc. Surveys of the important buildings used for schools, hospitals, open spaces and density of population should be made before estimation of the damages can be undertaken as input data. In Japan, predictions of damages have been made for main cities of Tokyo, Yokohama, Nagoya and Osaka (Hisada, 1977). Of these the extent of damage for Tokyo Metropolis is illustrated below:

Population	about 8,600,0C0
Area	581 km^2
Houses	2,900,000 approximately
Intensity of future earthquake	IX to X on the Modified Mercali Scale

"About 20,0C0 wooden houses are expected to collapse killing about 2000 people. If earthquake occurs on a winter evening, fires would break out at 732 places and 16 km^2 of the urban area would be burnt by assuming a wind velocity of 3.5 m/sec. If wind is blowing at 8 m/sec, about 90,000 people would be burnt while with a wind velocity of 12 m/sec, the death toll would increase to 560,000 in Tokyo's eastside Koto delta area alone. The death is expected to be higher because of widespread use of oil heaters. There is a 90% probability that the houses will be burnt within 3 hours. There will be serious damage to embankments and 4,500 hectres of land would be inundated. Over the soft ground, water mains and gas pipings would be extensively destroyed. Some reinforced concrete buildings and bridges would be damaged heavily and elevators in multistoreyed tall buildings will get out of order. There would be interruption in electric power supply as well as traffic and communication means." These give an idea of the extent of disaster expected due to a great earthquake in Tokyo.

Disaster prevention through town planning

In order to make our overcrowded cities safe from damaging earthquakes, we need systematic city planning through reconstruction of urban structure. It may include two aspects—long term construction of a disaster proof city and comparatively short term renewal of the existing city which may be undertaken, if necessary, through legislation and cooperation of the residents. In Japan, efforts are underway to increase incombustible buildings and open spaces in big cities through redevelopment of the urban regions and construction of shelters for refugees.

The public buildings like police stations, fire stations, hospitals and schools play a vital role during an earthquake and should be made earthquake proof. They may use the criteria laid down in the Indian Standards Institution Code for earthquake resistant designs. Attention should also be paid to make the following facilities earthquake proof:

(*a*) *Transport*: Railway could be equipped with an emergency device to stop a train at the time of an earthquake.

(*b*) *Bridges*: Wooden and weaker bridges should be replaced with incombustible bridges. Pantoon bridges may be kept as an alternate.

(*c*) *Highways*: These are important means of transport and communication which can be used as emergency roads.

Elevated highways may be equipped with devices to prevent the fall of girders.

(*b*) *Water supply*: Water supply and distribution pipes may be made of steel tubes or ductile cast iron tubes to make them earthquake proof.

(*e*) *Communications and broadcasting facilities*: Electric power generators and storage batteries may be kept for emergency use with the above facilities. Mobile radio communication and wireless sets may be kept ready for emergency operations.

More attention should be paid to fire prevention and construction of shelter as discussed below.

Fire prevention

During earthquakes, many casualties occur due to fire. Measures should be taken to make gasoline, oil and gas storehouses more resistant to earthquakes. Along the evacuation routes, which have a higher degree of fire hazards due to these storehouses, more fire extinguishers, buckets, etc. should be distributed so that fires may be checked at an early stage. In order to prevent the fires from spreading, large sized water tanks and school pools should be constructed in the vicinity. Gas and oil heaters should be fitted with a safety device to reduce the fire hazard.

In Tokyo, the fire fighting services have been modernised with the addition of helicopters which are used to observe the spread and control of fires on the ground.

Earthquake shelters

It is almost impractical to make a city completely earthquake proof. The population can however be saved to a great extent by constructing safety zones in different localities called "earthquake shelters" so that people can take refuge in them within an hour or so after an earthquake. The shelter is planned for quick rehabilitation of refugees and as a first aid station.

Earthquake shelters are planned considering safety of shelters, relation between the shelters and adjacent places and extent of the sheltering zones of each shelter. It must have an area of 50 to 100 hectres to ensure safety of the people in the shelter. A number of wind tunnels and outdoor experiments have been carried out in Japan to assess the safety of shelters from fire for various wind speeds.

In normal times, the earthquake shelters should have sufficient sunlight and other facilities for dwellers inside it. The refugees in the shelter should be able to survive big fires which can be caused by short circuits, cooking gas and petrol after an earthquake. Arrangements should be made to supply clothes, food, dwelling, medical aid and some recreational facilities like radio and television for a few days to the refugees.

In Japan, it has been estimated that the shelters must be built within 1·2 km so that any one (aged or children) can reach them in half an hour. The open spaces in the shelters should be surrounded by tall fire proof belt of buildings which may be designed to fit to the geographic and economic conditions of the area. In the centre of a shetler a twenty storey tower can be planned so that it can be seen from a distance. During emergency, the tower works as landmark so that refugees can find their way. At the top of this tower, there will be an information control centre. The centre will gather information about the earthquake damage, fires and the movement of public. It will also control fire fighting activity, first aid and medical care.

There are a few other considerations in the design of these shelters like safe routes leading to the shelter and its ability to survive the greatest earthquake. The soil foundations of the shelters should also be considered since weak strata create additional safety problems during earthquakes. Considering various factors, flexible steel frame structures with fire proof concrete may be used to give sufficient resistance and fire proofing to the buildings. The foundations of buildings can be made of cast-in-place concrete piles with a large radius of 2·5 metres. The basement should be about 7 metres deep for the buildings which reduces the input earthquake force. The lower floors of the buildings should be reinforced with stiff footing beams. Every floor of the buildings should have a small sheltering place which can serve as a temporary shelter for the public in the case of earthquakes. The cost of such earthquake proof buildings will be about twice that of the more common types.

Alarm system near coastal stations

This system aims at undertaking anti-disaster measures within ten seconds of the occurrence of a damaging earthquake in sea. Thus it is considered effective at coastal stations where the effects of seaquakes can be felt. The scheme is being tested in Kanto area in Japan where it is expected that it will take more than 10 seconds for the seismic waves to arrive at the Tokyo Metropolitan area if an earthquake takes place in Pacific Ocean. Detection of earthquakes is done through the ocean bottom seismographs. The disastrous effect of damaging earthquakes will be considerably less if within 10 seconds, atomic furnaces can be turned off, gas supply and electricity to oil complexes can be cut off and trains are stopped. The judgement whether the earthquake is large enough to produce disastrous effects has to be taken in one or two seconds after its occurrence, thus necessitating the deployment of large computers. Warnings are issued through radio, if considered necessary.

Model example of renewal plan of Koto District

An interesting attempt, the first of its kind which has been adopted for renewal of the city has been made in Shirahige District, located near the east end of Tokyo between the Sumida and Arakawa rivers. This area is believed to be the most dangerous where wooden houses are overcrowded and only 3% of the people are estimated to be able to survive a great earthquake and the fires. In addition, continuing subsidence of the land is posing threat against floods from the surrounding rivers. Due to this reason, the banks, river walls and flood gates are becoming less resistant against earthquakes.

About 10% of the land in the district has been acquired by the Metropolitan Government for the purpose of renewal. In order to prevent fires from the surrounding areas, thirteen storeyed buildings are being built along the east side of the district, about 50 metres from the existing built up areas. The open space between the river and those buildings have been earmarked for parks and sports grounds which will provide a sheltering place in case of an earthquake. An information control centre will be located almost centrally. Perfect separation of pedestrians and vehicular traffic has been planned. Cars can approach houses and offices from outside the district without entering inside except fire engines, ambulances, etc. The street passing through the district will be covered with an artificial pedestrian deck to ensure the continuity of the shelter plaza which are proposed to give people a chance to get into from anywhere. Large factories have already been moved out and the remaining small factories are being shifted to northern and southern ends where industrial apartments are being planned. Participation of the citizens has been given top priority from the first stage of planning to its execution by inviting frank opinion of the citizens and keeping them informed about the developments.

Public information and education

Public information and education is an essential component of disaster preparedness. In contrast to weather, public memory fades away quickly after a damaging earthquake. It is, therefore, necessary that awareness among the public be kept alive in earthquake prone regions. Public education and provision of information should also meet local requirements as much as possible.

Suitable education programmes for adults and children should impart basic knowledge about the causes of earthquakes, the associated hazards and protective measures. These should be supplemented by campaigns through press, radio and television. In case of short range earthquake prediction, more intensive campaign should be launched through posters and pamphlets in local languages. A few films may also be shown in public places like community halls, parks or cinema halls as documentaries. Lectures may be arranged from specialists at periodic intervals. Through these media, it should be emphasised that public bears a large share and responsibility for disaster preparedness.

In Japan, education on disaster preparedness is compulsory in schools and courses are given on safety measures and on orderly disciplined evacuation of danger areas. Every year around September 1, information on disaster preparedness is conveyed to the public through study courses, mass communication media, newspapers and other publications. Copies of the pamphlet, "Hints to Earthquake Sufferers" are distributed to the people. In the Philippines also, much work has been done in providing education to the public on these aspects.

Public information on earthquakes is supposed to complement and consolidate the corresponding educational programmes. This is important because public memories are poor for this type of disaster and populations change when new residents may settle in a vulnerable area. Public information may be classified as follows:

(*a*) Before the disaster—maintaining public awareness and responsibility.
(*b*) The emergency period—from the issue of short range forecast (if any) to the time of earthquake disaster.
(*c*) After the disaster—relief, rehabilitation, further precautions, for example, against epidemics.

It is suggested that material published in other countries may be freely consulted. 'Earthquake safety rules' similar to the ones prepared for United States may be freely publicised. Using these guidelines have been prepared for northeast India for which pamphlets have been distributed through Civil Defence authorities.

In order to prevent rumours which spread fast, information centres should be established to correct them. Through these, it may be possible to inform the public about the extent of damage and the measures adopted by the Government to meet the emergency needs of the people. For less educated public, intensive use of loudspeakers is recommended. Also, provision of community radio sets continuously tuned to the station broadcasting such information should be kept for this purpose. Battery operated radios/loudspeakers should be preferred.

Disaster exercises

Exercises in disaster preparedness serve the object of putting the planning and organisational efforts on trial provided the programmes have been drawn up as practical as possible. It helps the public with operational tasks to perform during an earthquake.

Exercises called 'dry runs' or 'mock type' can be outlined in a similar scale as done by the Army and Air Force in peace times. Some destruction can be planned in a small locality so that the effectiveness of personnel and equipment may be tested in an operational environment. Such drills may cover various kinds of activities like fire fighting and rescue operations, guard duties, emergency summons, defence and protection of facilities. They may also include clearance of roads, repairs to embankments, evacuation of inhabitants from a locality. Exercises should be undertaken on the basis that certain communications would be disrupted during an emergency and the engineers and technicians should gain practical experience in making alternative arrangements and testing them.

After each exercise, a report should be prepared by experienced officials and widely circulated to the public for constructive suggestions and lessons to be learnt.

As mentioned earlier, the Japanese observe the 'Disaster Preparedness Day' on September 1 every year in memory of the great Kanto earthquake in Tokyo on September 1, 1923. Disaster exercises are carried out on this day with public support.

Emergency operations

By the time a damaging earthquake strikes any region, the different organisations and Government machinery should be in complete readiness to carry out relief operations on emergency basis. Most of the needs are common to every natural disaster and are briefly summarised as follows.

Disaster assessment: Survey of the effected areas should be undertaken by well trained staff and responsible persons to know the local requirements of relief. Seismologists and earthquake engineers should be invited to visit the effected areas to examine the possibility of aftershocks occurrence and examination of important structures likely to be damaged further due to aftershocks, if expected.

Rescue and evacuation: All means of transport like helicopters, boats, land transport should be requisitioned, if necessary through private owners. People should be advised about the escape routes so that they can safely move out. Maps showing escape routes should be displayed at different places in the city. Special efforts should be made to rescue people from falling debris or buried under collapsed houses.

Relief to families and individuals: The primary needs in any natural disaster are food, clothing, shelter and medical care. The requirements may be supervised through the district authorities and other voluntary organisations like Red Cross or Servants of the People Society, etc.

Disaster victims should be encouraged to seek shelter with their relatives or friends if there is no adequate space in 'Plaza' or other shelters opened temporarily in schools, places of worship, exhibition sites, stadia, etc.

A number of problems have to be tackled from health and sanitary points of view. The collection, identification and removal of dead bodies and treatment of injured are important items of work. The collection and donation of blood for disaster victims need to be encouraged.

National Red Cross and other voluntary organisations should be given full cooperation to trace the fate of individuals or families, trapped in disaster.

Communications: During earthquakes, normal communications are often disrupted and additional radio links and despatch riders may have to be provided. Intensive pre-earthquake training of engineers and technicians responsible for communications may become handy to deal with partial, major or complete breakdowns.

Supply and storage: Adequate arrangements should be made for supply and storage of relief requirements such as food, medical stores and other necessities from different sources. Goods should be received and distributed expeditiously in order to avoid congestion at any of the posts. Since most of the relief-supplies are intended for rapid consumption or utilisation, the administrative arrangements for receipt of goods, protection and distribution should be maintained at a high standard.

Public information: In order to reduce panic and rumours, public should receive all information and instructions through the press, radio and television. Interviews and press conferences with seismologists and high Government officials should be arranged at frequent intervals.

Earthquake disaster rehabilitation and resettlement

The main object of rehabilitation is to provide services and facilities which will restore to families and individuals their former living conditions as far as possible. While the morale of the population is to be kept at a high standard, welfare services should be so arranged that they do not become a permanent burden on the nation. In effect a feeling of self-reliance and a determination to participate in the social life of the community should be encouraged. For the victims, assistance may be given for the repair of houses, food and clothing. The rehabilitation of public services and amenities which are important include repair of roads, bridges and other means of transport, assistance to industry, commerce and agriculture.

In some countries like Japan and the USA disaster insurance plays a vital role in mitigating the effects of the disaster. One of the main advantages gained through insurance is that if people were covered by it, the cost of Government assistance to the victims would be reduced. In India more and more people are getting their houses insured against natural disasters like floods or earthquakes but it is mostly confined to the regions where such threat is more expected.

Resettlement on a regional or national scale is also considered as a disaster prevention measure. This may require some population to move to safer places in the vicinity or other part of the country. Care must be taken to include adequate social planning as well as economic planning while undertaking resettlement.

Disaster prevention efforts in India

Disaster preparedness is attracting the attention of Government and social organisations in India. In the northeast India where a damaging earthquake is expected during the next few years based on statistical probability, the Governors of the States are taking appropriate administrative action to face the emergency through Civil Defence, district authorities, Border Security Force, Army and Police. The northeastern council is the pivotal coordinating, agency. Regular meetings are being held at district levels throughout the states to prepare for the emergency. Pamphlets have been distributed to the public to take action before, during and after the earthquake. Hand-operated sirens or battery operated megaphones are being kept ready to warn and alert the public if timely forecast of earthquake has been made. Pantoon bridges are being requisitioned to maintain the transport system. Supply of eatables, petrol and lubricants is being planned in a systematic manner. Diesel sets are being kept as standby in case of power failure. Relief work is being planned through Red Cross, Catholic and Baptist churches and other local religious or social organisations. In the rural area relief work is being arranged through Block Development officers, Vokmas Laskers and local school teachers. Earthquake engineers are being called to examine the vulnerable structures as regards their safety to withstand shocks during damaging earthquakes. Seismological and other geophysical observations are being strengthened in the region and a data bank will soon be formed under northeastern council at Shillong. A high level committee of experienced seismologists from different organisations in the country has been formed which will examine the earthquake risk periodically in the region.

Civil defence is also concentrating on disaster preparations in Himachal Pradesh which is another area where damaging earthquakes are not ruled out. In fact, all along the Himalayan foothills ranging from Kashmir to northeast India disaster preparedness is of prime importance to face earthquake hazards. Damaging earthquakes may also be expected in Delhi and other regions of India where little attention to this has been paid so far.

Among the many social organisations engaged in disaster preparations, the Joint Assistance Centre, New Delhi deserves to be mentioned which has arranged a number of camps of about 10 days duration. Rescue operation, first aid, fire fighting, camping/tent pitching, rowing, rock climbing and naturopathy have been taught, besides arranging lectures on earthquakes, cyclones and floods. It would be really effective, if more such organisations start courses on disaster preparedness to assist the Government during natural calamities. The money for such organisations may come from philanthrophists and industrialists in a big way. Although more and more industrial complexes, dams, bridges, railways, etc. are taking earthquake safety factors into consideration in their design, reconstruction of big cities as a whole will require crores and crores of money which may be a difficult task. Also the poor quality of dwelling units in villages with the limited resources of people does not leave much scope on long term basis except training them to face the disaster on emergency basis.

APPENDIX 1

Modified Mercalli Intensity Scale of 1931

Scale	*Specifications*
I	Not felt except by very few under especially favourable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognise it as an earthquake. Standing motor-cars may rock slightly. Vibrations like passing of lorry. Duration estimated.
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy lorry striking building. Standing motor cars rocked noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows, etc. broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderately well built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbs persons driving motorcars.

Scale	*Specifications*
IX	Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.
X	Some well-built wooden structures destroyed; masonry and frame structures and their foundations destroyed: ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed over banks of rivers, etc.
XI	Few, if any, masonry structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and landslips in soft ground. Rails bent greatly.
XII	Damage total. Wave seen on ground surface. Lines of sight and level distorted. Objects thrown upward in the air.

APPENDIX 2

The geological time scale

Geological Period	*Holmes* (1965) *in millions of years*
Cenozoic (mammals)	
Quaternary	
Recent	
Pleistocene	2 to 3
Tertiary	
Pliocene	12±1
Miocene	25±2
Oligocene	40±2
Eocene	60±2
Paleocene	70±2
Mesozoic (reptiles)	
Cretaceous	135±5
Jurassic	180±5
Triassic	225±5
Paleozoic (invertebrates)	
Permian	270±5
Carboniferous	350±10
Devonian	400±10
Silurian	440±10
Ordovician	500±15
Cambrian	600±20
Pre-Cambrian (no developed fossils)	

APPENDIX 3

(a) Standard velocity models inside earth

Depth (km)	*Gutenberg Model Velocity (km/sec)*		*Jeffreys Bullen Model Velocity (km/sec)*		*Herrin Model Velocity (km/sec)*
	P-wave (*1959*)	*S-wave*	*P-wave* (*1948*)	*S-wave*	*P-wave* (*1968*)
0	5·55	3·36	5·55	3·36	6·00
15	6·30	3·55	6·30	3·55	6·75
33	8·16	4·65	7·75	4·35	—
40	—	—	—	—	8·05
100	8·00	4·40	7·95	4·45	8·12
150	7·85	4·35	—	—	8·20
200	8·05	4·40	8·26	4·60	8·32
300	8·50	4·60	8·58	4·76	8·68
413	9·06	5·00	8·97	4·96	9·19
413	9·06	5·00	—	—	—
500	9·60	5·30	9·66	5·32	9·68
1000	11·40	6·35	11·43	6·36	11·44
2000	12·80	6·95	12·70	6·90	12·78
2900	8·08	0	8·10	0	(2894)
4370	9·70	0	9·87	0	—
5120	10·48	0	9·40	0	—
5120	—	—	11·16	0	—
5370	11·13	0	11·21	0	—
6370	11·15	0	11·31	0	—

(b) Models for monitoring microearthquakes in India

Region	*Depth (km)*	*P-wave velocity (km/sec)*	*S-wave velocity (km/sec)*	*Remarks*
1. North-east India	0·00	3·95	—	Based on past earthquakes A.N. Tandon (1955).
	2·00	5·58	—	
	24·80	6·55	—	
	46·30	7·91	4·46	
2. Central Himalayan foot hills	0·00	3·40	—	Based on past earthquakes.
	4·00	5·72	—	
	6·61	29·00	—	
	8·22	49·00	4·61	
3. Himachal Pradesh (Kinnaur)	0·00	5·60	3·30	H.M. Chaudhury and H.N. Srivastava (1977).
	33·00	6·67	3·65	
	49·00	8·20	4·40	
4. Himachal Pradesh (Kangra)	0·00	5·72	3·29	Based on past earthquakes. After V.P. Kamble, R.K. Verma and H.M. Chaudhury (1974).
	24·00	6·61	3·72	
	45·00	8·22	4·73	
5. Madhya Pradesh (Indore Khandwa section, Narbada)	0·00	6·01	3·63	Deep Seismic Sounding Explosions. After H.N. Srivastava, R.K. Verma and G.S. Verma (1983)
	18·00	6·69	—	
	38·00	8·03	—	
6. Koyna region	0·00	4·80	—	Deep Seismic Sounding Explosions. After H.N. Srivastava, R.K. Verma, G.S. Verma and H.M. Chaudhury (1982); unpublished.
	1·5	5·82	3·41	
	17·0	6·61	4·09	
	36·0	8·23	4·60	
7. Bay of Bengal	0·00	6·28	—	G.S. Verma (1974).
	25·4	8·00	—	

APPENDIX 4

Earthquake Safety Rules

Before an earthquake

1. Keep stock of drinking water, some foodstuffs, first-aid equipment, a crow bar, shovel, pick and rope, electric torch and some candles and a helmet for every member of the family.

2. Ensure that water heaters and other gas appliances are firmly fixed and shut off when not in use, as broken gas pipes or appliances are likely to cause fire hazards.

3. Securely fasten fixtures, refrigerators and shelves to the wall and place large and heavy objects on the lower shelf. Top heavy objects should be braced or anchored.

4. Find out the location of the nearest first-aid post, Warden Post and Fire Station and approach for help if required.

5. Join the Civil Defence Organisation and train yourself and the members of your family in first-aid, rescue fire fighting, etc. which will help you, your family and your neighbours.

6. Conduct occasional home earthquake drills so that your family has the knowledge to avoid unnecessary injuries and panic in the event of an earthquake.

7. The more responsible members of the family may be taught how to turn off electricity, gas and water at the main switches or valves.

8. Be aware of what to do in various situations so that you are prepared in the event of an earthquake, e.g. at home, whilst driving a car, at work in a shop, a public theatre, cinema hall, etc.

   Certain other precautions, which are necessary in case of fire, should also be taken as far as possible:

1. Keep adequate water/dry sand stocked in accessible places.

2. All lofts and attics should be kept free from inflammable material.

3. Keep all inflammable stores, which are required, as much dispersed as possible.

During an earthquake

1. Do not panic. The motion is frightening, but unless it shakes something down on top of you it is harmless. The earth does not yawn open, gulp down a neighbourhood, and close up. So keep calm.
2. In the event, the safest place is an open space away from building. However, when this is not suitable do not try to run from a building during an earthquake.
3. If it catches you indoors, stay indoors. Take cover under a desk, table bench or in doorways, halls, and against inside walls or staircase. Stay away from glass.
4. Do not use candles, matches, or other open flames, either during or after the earthquake. Put out all fires.
5. If the earthquake catches you outside, move away from buildings and utility wires. Once in the open stay there until the tremor stops.
6. Do not run through or near buildings. The greatest danger from falling debris is just outside doorways and close to outer walls.
7. If you are in a moving car, stop as quickly as safety permits, but stay in the vehicle. A car is an excellent seismometer, and will jiggle on its springs during the earthquake, but it is a good place to stay until the earthquake stops.

After an earthquake

1. Check your utilities, but do not turn them on. Earth movement may have cracked water, gas and electrical conduits.
2. If you smell gas, open windows and shut off the main valve. Then leave the building and report gas leakage to authorities. Do not re-enter the house until a Civil Defence official says it is safe.
3. If water mains are damaged, shut off the supply at the main valves.
4. If electrical wiring is shorting, close the switch at the main meter box.
5. Turn on your transistor, radio or television to get the latest information/bulletins and aftershock warnings.
6. Stay off the telephone except to report an emergency.
7. Stay out of severely damaged buildings; after shocks can crash them down.

(Mainly after *U.S. Geological Survey*)

APPENDIX 5

Damaging earthquakes in India

Date		*Location*	*Magnitude on Richter Scale*	*Remarks*
1720	Jul 15	Near Delhi	6½	Many houses destroyed.
1803	Sept 1	Mathura	6½	Intensive fissures in fields through which water rose with considerable violence.
1803		Kumaon region	6½	300 persons were killed at Barabal.
1819	Jun 16	Kutch (Gujarat)	8·5	Bhooj—the chief town was reduced to ruins. About 1540 persons killed.
1828	Jun 6	Near Srinagar (J and K)	6	Number of persons killed 100, 1200 houses destroyed.
1869	Jan 10	Near Cachar (Assam)	7½	Earth fissures and sand craters very abundant.
1885	May 30	A few miles West of Srinagar	7	35000 lives were lost including 3500 human beings.
1897	Jun 12	Shillong plateau	8·7	Destruction of stone buildings almost universal in Shillong Gaolpara, Gauhati, Nowgong and Sylhet. 1542 persons killed.
1905	Apr 4	32·5°N, 76·5°E Kangra (HP)	8·5	Kangra, Dharamsala and neighbouring places completely ruined. About 20,000 persons killed.

1	2	3	4
1918 Jul 8	26·5°N, 97·5°E Srimangal (Assam)	7·6	Area of 4,500 sq km suffered heavy damage.
1930 Jul 2	25·8°N, 90·2°E Dhubri (Assam)	7·1	Large number of railway culverts and bridges cracked.
1934 Jan 15	26·6°N, 86·8°E Bihar-Nepal border	8·3	About 10,000 lives lost.
1938 Mar 14	21·5°N, 75·8°E (Madhya Pradesh)	6·0	Slight damage at Bhushawal, Khandwa, Godhra, Baroda and Nasik.
1941 Jun 26	12·4°N, 92·5°E (Bay of Bengal, near Andaman Islands)	6·0	Masonary work in Andaman Island damaged. Earth opened to few metres and closed.
1943 Oct 23	26·8°N, 94·0°E	7·2	Destruction over northeast Assam.
1947 Jul 10	32·6°N, 75·9°E (NE of Jammu)	6	Serious material damage at Bhadarwah.
1947 Jul 29	28·8°N, 93·7°E	7¾	Damage caused at Dibrugarh, Jorhat and Tezpur.
1950 Aug 15	28·46°N, 96·66°E	8·5	One of the disastrous earthquakes in history. 156 casualties due to earthquakes and landslides, 532 casualties due to consequent floods
1956 Jul 21	23·3°N, 70·0°E Anjar (Gujarat)	7·0	115 persons died and 414 persons injured.
1958 Dec 28	30·01°N, 79·94°E	6·3	Rupture of ground and a few landslides in an area of 150 sq km around Kapkote and cracking of buildings.

1	2	3	4
1963 Sept 2	33·9°N, 74·7°E Badgaum	5·3	79 people killed, 400 injured.
1966 Jun 27	29·7°N, 80·9°E Nepal-India Border	6·1	80 killed, many injured.
1967 Dec 10	17·37°N, 73·74°E Koyna	6·5	177 people killed and 2272 injured.
1969 Apr 13	17·9°N, 80·6°E Bhadrachalam (AP)	5·7	Kottagudam Thermal Power Station out of commission.
1970 Mar 23	21·7°N, 73·0°E Broach (Gujarat)	6·0	About 26 persons killed in the town of Broach and another 200 suffered injuries due to collapse of buildings.
1975 Jan 19	32·4°N, 78·4°E Kinnaur (HP)	6·8	44 people killed and several injured.
1980 Jul 29	29·56°N, 81·07°E India-Nepal border	6·1	150 to 200 people killed in Nepal and India; damage to buildings at Dharachulla, Pithoragarh.
1980 Aug 23	32·9°N, 75·6°E (Jammu)	5·2	15 people died; damage to houses at Kathua.
1982 Jan 20	6·93°N, 94·03°E Nicobar Islands	6·3	Damage at Campbell Jetty

APPENDIX 6

Some useful formulae

1. (*a*) Surface wave magnitude (M_s)

$$M_S=1\cdot66\ \log\triangle+\log_{10}\frac{A}{T}+3\cdot3$$

where $\triangle$ is epicentral distance,

A is Peak to Peak amplitude (microns),

T—Period in seconds, 18 to 22 (seconds) period computed from

Long period seismograms and response curve (Fig. 12)

(*b*) Body wave magnitude (M_b)

$$M_b=\log_{10}\frac{A}{KT}+Q+S$$

where Q is the depth distance factor (given in a Tabular form)

S is the station factor which is generally taken as zero.

K is the magnification at period T and response curve (Fig. 12)

A—Amplitude as measured from short period vertical seismograph in micron; peak to trough.

(*c*) Richter magnitude (M_L) is computed by largest trace amplitude in millimeters (peak to peak) from the Wood-Anderson seismogram and using a ready made graph connecting $\triangle$ (epicentral distance), trace amplitude and magnitude (M_L). Scale is valid upto$\triangle=600$ km.

(*d*) Conversion formulae between M_b, M_S and M_L

(*i*) $M_L=(1\cdot00\pm0\cdot57)+(0\cdot80\pm0\cdot01)\ M_D$
(for$\triangle=2^\circ$ to 10°)

(*ii*) $M_D=0\cdot56M_S+2\cdot9$

(*e*) Magnitude M and Energy E

(*i*) $\log E=11\cdot8+1\cdot5\ M$

(*ii*) $\log E=2\cdot88+1\cdot92\ M_L-1\cdot02\ M_L^2$

Strain Energy= $\sqrt{E}$

2. *Seismic Intensity*

(*i*) $I\,(R)=Io+3\cdot 7-0\cdot 0011\ R-2\cdot 7\log R$

for $R \geqslant 20$ km.

(Gupta, I.N. and Nuttli, O. W., 1976)

where Io is the maximum seismic intensity, and R is the epicentral distance (km)

(The relation needs to be modified for Indian region)

(*ii*) Acceleration, a.

$$\log a = \frac{I}{3} - 0\cdot 5$$

(This relation needs to be modified for Indian region but data for acceleration from past earthquakes are not available. These relations vary widely over different tectonic regions and depend upon the focal depth of earthquakes as well.)

3. *Maximum Magnitude using Gumbel's Distribution*

The cumulative probability that an extreme value (in our case "earthquake magnitude") will be less than the given quantity X, approaches the double exponential expression given by

$$(X)=\exp\left(-e^{-L\,(X-U)}\right)$$

where L and U are the parameters to be determined by any one of the available methods say using graphs (probability paper) or electronic computer.

4. *Fault dimensions*

(*a*) $\log A=0\cdot 89\ M_L-2\cdot 67$

(Tandon, A.N. and Srivastava, H.N., 1974).

where A is the aftershock area (km^2) for $5 \geqslant M \geqslant 7$

(*b*) (*i*) $\log L=0\cdot 62\ M_b+2\cdot 19$

(Press, F., 1967)

where L is the fault length (cm)

(*ii*) $\log L=0\cdot 3M+4\cdot 84$

(Srivastava, H.N., 1981)

(*iii*) $\log \dfrac{L}{V_F} = 0\cdot 5-1\cdot 9\,M$ for $2\cdot 5 \leqslant M \leqslant 8\cdot 5$

where V_F is the rupture velocity in km/sec (Bath, M., 1974).

(*c*) Seismic moment $(Mo)=\mu\ \bar{u}\ S$

where μ is the rigidity of rocks, S is the fault area and u is the average dislocation over the fault area.

(*d*) Apparent stress $(\eta\ \sigma) = \mu E/M_O$

where η is the efficiency of seismic radiation, σ is the average of the initial and final stress along the fault plane.

(*e*) Stress drop $(\triangle\sigma) = C\ \dfrac{M_O}{S^{\frac{3}{2}}}$

where C is a constant which depends upon fault shape and slip direction. For a circular crack $C{=}2{\cdot}4$.

5. *P and S wave velocities*

$$V_P = \left(\frac{\lambda+2\mu}{\rho}\right)^{\frac{1}{2}}$$

and $$V_S = \left(\frac{\mu}{\rho}\right)^{\frac{1}{2}}$$

where V_p is velocity for *P*-wave,

V_S is velocity for S-waves,

ρ is the density and

λ and μ are called Lame's constants.

6. *Crustal thickness*

Assuming horizontally stratified two layered model and the focus of the earthquake or explosion in the upper layer

$$t = 2\,H_1\ \frac{\sqrt{V_b{}^2 - V_g{}^2}}{V_g\,V_b}$$

$$t_n = 2\,H_2\ \frac{\sqrt{V_m{}^2 - V_b{}^2}}{V_m\,V_b} + 2\,H_1\ \frac{\sqrt{V_m{}^2 - V_g{}^2}}{V_m\,V_g}$$

where t and t_n are the intercept times of S^* (or P^*) and S_n (or P_n) respectively and H_1 and H_2 are the granitic and basaltic layers. The velocities and the intercepts are determined from travel time curves.

The total crustal thickness$=H_1+H_2$

7. *Distance and azimuth*

If θ and ϕ are the coordinates of an epicentre and θ' and ϕ' the corresponding coordinates of an observing station,

(*i*) Epicentral distance $(\triangle)$ is given by

$$\cos\triangle = AA^1 + BB^1 + CC^1$$

(*ii*) Azimuth, Z is given by

$$2+2\sin\Delta\sin Z = (A^1 - D)^2 + (B^1 - E)^2 + C^1$$

$$A = \sin\phi\cos\phi;\ B = \sin\theta\sin\phi$$

$$C = \cos\theta;\ D = \sin\phi,\ E = -\cos\phi$$

where A^1, B^1, C^1, etc. correspond to the station.

8. *Epicentral determination of near earthquakes*

$$(X_i - X)^2 + (Y_i - Y)^2 + (Z_i - Z)^2 = V^2 (t_i - t)^2$$

where t_i is the arrival time at a station "i"

X_i, Y_i, Z_i being the coordinates of the station.

t is the origin time and

X, Y, Z are the coordinates of the focus of the earthquake

V is the velocity of the concerned phase P_g or S_g or other phases as the case may be.

The above equation can be solved by least squares method after slight simplification using P and S times recorded at a number of stations. Hypo 71 computer program of U.S. Geological Survey is widely used for epicentral determination of near earthquakes. For this purpose, the velocity models (Appendix 3) may be employed in Indian region.

9. *Decay of aftershocks*

$$n(t) = A\,t^{-h}$$

where A and h are the constants and $n(t)$ is the number of aftershocks in time t

10. *Changes in velocity ratio V_p/V_s*

If t_p and t_s are arrival times of P and S-waves and V_P and V_S corresponding seismic wave velocities

$$V_P t_p = V_S t_s$$

Expressing

$$\frac{V_P}{V_S} = \frac{t_s - t_p}{t_p} + 1$$

$$= K + 1$$

the value of K can be found from the slope of the graph (straight line) between (S-P) time versus t_p and thus V_P/V_S can be readily calculated.

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Glossary

Accelerograph : A seismograph whose natural period of free vibration is very much shorter than that of the waves to be recorded.

Angle of declination : The deflection from true north of a magnetic needle in horizontal plane.

Alluvium : Sediments deposited by a river or stream.

Bending moment : The accumulative effect of all the flexure stresses on a particular cross-section is called the bending moment at that location and the total effect of the shear stresses is called the "Shear".

Buckling : The reaction of structural member to a compressive loading under which the member suddenly becomes unstable, with resulting excessive deflections and structural failure.

Compression and dilatation (or rarefaction) : Refer to the nature of the motion of P-waves at the recording station. When the ray emerges to the surface, displacement upward and away from the epicentre corresponds to compression, the opposite to dilatation. Physically, the volume is reduced in compression while it is increased in rarefaction.

Convection : Transfer of heat from one part of a fluid to another by flow of the fluid from the hotter parts to the colder.

Curie Temperature : The temperature marking the transition between ferromagnetism and paramagnetism, or between the ferroelectric phase and the paraelectric phase.

Cyclone : The closed system of air rotating counter-clockwise (in northern hemisphere) or clockwise (in southern hemisphere) around a centre of relatively low pressure.

Decibels : It is a logarithmic unit which means that amplification increases the power output by the number of decibels attributed to the amplification. In terms of voltage ratio, the gain is 1000 for 60 db and 1,000,000 for 120 db. In terms of power ratio, the corresponding gain is 10^6 and 10^{12} respectively.

Demultiplexing : A process which is used to separate two or more signals that were previously combined by a compatible multiplexer and transmitted over a single channel.

Dip : The inclination of a rock bedding plane from the horizontal.

Dipole : A pair of equal and opposite electric or magnetic charges whose centres are separated.

Discriminator : A circuit in which magnitude and polarity of the output voltage depends on how an input signal differs from a standard or from another signal.

Dispersion : The increase in velocity of observed surface waves with wavelength constitutes dispersion.

Earthquake focus : The region from where the earthquake originates inside the earth.

Earthquake : Vibrations or shakings caused in the earth's crust by sudden tectonic movements or volcanic eruptions.

Elastic rebound : The spring back action of an elastic body when a deforming force is suddenly removed.

Elastic limit : Maximum strain to which an elastic body may be subjected without permanent deformation.

Epicentre : The point on the surface of the earth lying immediately above the focus of an earthquake.

Fault : A break or shear on which there has been observable displacement of the two parts parallel to the plane of the break.

Fault scarp : Cliff along a fault produced by relative vertical displacement.

Filter : An arrangement for allowing certain frequencies to pass and suppressing the others.

Flora and Fauna : The animal population (fauna), plant population (flora) of a particular region, geologic period or environment.

Frequency : Vibrations per second. The reciprocal of period.

Frequency modulation : The alternation or regulation of the frequency of an electromagnetic wave.

Geomorphological : The study of the surface features of earth, primarily their origin and development. Physiography covers much the same subject matter, but according to some authors also includes oceanography and climatology.

Gouge : Rock that has been comminuted by fault movement.

Gravity anomaly : The difference between the observed value of the earth's gravity at a point and the expected value at that point, based on a given earth model.

Ground water : The water held in the pores and crevices of soil and in its underlying bed rock.

Hydrophone : Device for detecting sound in water.

Igneous rock : A rock formed by the solidification of either magma or lava. Granite and basalt are examples.

Ionosphere : The region in the atmosphere, between about 80 and 400 km where the sun's radiation ionizes most of the molecules of gas present.

Isoseismal line : A closed curve passing through points of equal earthquake intensity.

Landslide : Slipping of a mass of land from a higher to a lower level.

Laser : A device which is used for light amplification by stimulated emission of radiation.

or

An active electron device that converts input power into a very narrow, intense beam of coherent visible or infrared light.

Lava : A rock formed out of magma when it reaches the earth's surface through a volcano and/or a fissure and allows its dissolved gases to escape into the atmosphere.

Low velocity layer : A layer in the solid earth in which seismic wave velocity is lower than the layers immediately below or above.

Magnification : Ratio of the recorded response of a seismograph to the corresponding quantity in the actual motion of the ground.

Magnetosphere : A belt in which accumulation of electrically charged atomic particles takes place in the vicinity of earth by its magnetic field.

Meizoseismal area : The area within the isoseismals of highest intensity.

Microfracture : The numerous tiny breaks produced in a rock or mineral by application of force.

Multiplexing : A process in which a number of modulating waves or sets of information, may be sent simultaneously.

Normal fault : A fault with down throw on the upper or hanging wall side.

Palaeomagnetism : Study of natural remanent magnetization of rocks of different geological ages.

Phase : Onset of waves in a seismogram.

Polarisation angle : The ratio of $\tan^{-1} \frac{SH}{SV}$; SH and SV being the horizontal and vertical components respectively of the S-waves.

Quasars : Quasi-stellar astronomical object often a radio source; all quasars have large red shifts, they have small optical diameter, but may have large radio diameter.

Refraction : The change of direction of propagation of any wave, when it passes from one medium to another in which the wave velocity is different.

Resistivity : Resistance of a block of material having unit length and unit cross sectional area.

Resonance : Equality between the frequency of the driving motion of the force and the natural frequency of the body acted upon.

Rift : A narrow opening in a rock caused by cracking or splitting.

Rift valley : A deep, central cleft with a mountainous floor in the crest of a mid-oceanic ridge.

Rigidity : The ratio of the shear stress across the section to the shear strain, i.e. to the angle of distortion in radians. A measure of its resistance to change in shape.

Sand dune : A mound, a hill or a ridge of sand with a crest.

Scarp : A cliff formed by fault movements.

Sedimentary rock : Rock formed by consolidation or cementation of sediments derived from other rocks.

Seismology : Science of earthquakes from Greek word; seismos—an earthquake; deals with nature, cause, effect and recording of earthquakes; the earth's structure and in prospecting, engineering problems—man made or nature, detection of nuclear explosions, geothermal energy, rock burst.

Shear displacement : Two points, moved at right angles to the line joining them, are displaced in shear.

Shear stress : The stress associated with change in volume.

Simple harmonic motion : It is a kind of periodic motion, i.e. it repeats itself at constant intervals of time.

Slump : Slipping of soil down at slight incline.

Spalling : The clipping or fracturing caused by a compressional wave at a free surface.

Static electricity : State of accumulation of electrons (negative charges) and the state of deficiency of electrons (positive charges).

Strain : Deformation of an elastic body within the elastic limit of the material.

Stress : The internal restoring forces in an elastic body that oppose the action of a deforming force and tend to restore the body to its original size and shape when that force is removed. Also defined as force per unit area.

Strike : The direction of the trace of a bedding plane in the horizontal plane.

Subsidence : Downward vertical motion or sinking of land.

Susceptibility : A number that characterizes the magnetization of a substance when subject to a magnetic field.

Tectonic : Of earth deforming forces or structural processes; volcanic and other minor shocks due to less important causes are excluded from its definition.

Tectonic movements : Earth movements originating within the earth as a result of the movement of actual structures of the earth's crust.

Thunder cloud : A cloud in which sound is emitted by rapidly expanding gases along the channel of a lightning discharge.

Thrust fault : A fault with down-throw and the lower or foot wall side.

Transducer : Any device which converts the mechanical energy of the seismometer into electrical energy.

Triangulation : Method of precise surveying which starts with the exact measurement of a base line and then builds a system of triangles upon it, indicating changes in elevation of the ground surface.

Tsunamis : Oceanic water waves (popularly called tidal wave which is a misnomer) usually originating at or near the epicentre of an earthquake, located beneath or at the margins of an ocean.

Ultrasonic : Sounds that have frequencies too high for the human ear to hear, i.e. above 15,000 or 20,000 Hz.

Upwelling current : A current in which water rises from a deeper to a shallower depth, usually as a result of divergence of off-shore currents.

V.H.F. : Very high frequency waves (frequency 30-300 Hz); substantially straight line propagation analogous to that of light waves; unaffected by ionosphere.

Volcano : A vent or opening in the earth's crust through which rock fragments, lava, ash, steam and other gases rise to the surface in the course of an eruption.

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