Special Issue

Seismology in India—An Overview

Dr A. N. Tandon played a pivotal role in promoting seismology in India when he joined India Meteorological Department in 1942. It is commonly held that seismology in India practically grew with Dr Tandon. Born on April 10, 1912, Dr Tandon has carried out pioneering research work on varied topics of seismology.

Prof. Jai Krishna has played a pioneering role in the field of earthquake engineering and is an international authority in his field. Born on February 14, 1912, his vision and commitment has created a strong base for engineering seismology and related indigenous instrument development in India.

SEISMOLOGY IN INDIA – AN OVERVIEW UPTO 1970

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ABSTRACT – *The paper describes in brief the earlier history of the development of the science of seismology in the country, particularly instrumental seismology and its application to national development plans up to the end of the year 1970. After the second world war there was very rapid advancement in all branches of seismology and earthquake engineering throughout the world. Many new research organisations such as the National Geophysical Research Institute, Hyderabad and the School of Research and Training in Earthquake Engineering, University of Roorkee were established in India. The progress made at these institutions along with the older ones like the India Meteorological Department, the Geological Survey of India and other institutions, in different branches of seismology, upto the end of the year 1970, has been briefly discussed.*

EARLY HISTORY

The northern boundary of the Indian sub-continent extending from the Hindukush mountains in the West to the hills of Assam and Burma constitutes a region where the Indian plate collides against the Asian Plate and has thus been the scene of a large number of major earthquakes in the past. It is a part of the well known Alpide belt extending from Indonesia to Spain.

Prior to the development of Instrumental Seismology in India in the beginning of the present century, the scientific study of earthquakes was being undertaken by the Geological Survey of India which used to send field parties after the occurrence of every major earthquake and then publish their observations and conclusions in the form of memoirs and records of the Geological Survey of India. These publications contained all the important information concerning the earthquake, such as the damage caused to man made and natural structures in meizoseismal area, the observed intensity at various places (in R.F. or M.M. Scale), an isoseismal map of the affected region and their conclusions regarding the epicentre, time of occurrence, depth of focus and the possible cause of the earthquake. The first scientific study of an Indian earthquake was initiated by Dr. T. Oldham, the first Director General of the Geological Survey of India of the Great Cachar earthquake of 1869. He also compiled a catalogue of Indian earthquakes from the earliest times upto A.D. 1869. His illustrious son Dr. R. D. Oldham made a very thorough study of the Great Assam earthquake of June 12, 1897 and published his observations and results in the form of a memoir which even today is a classical work responsible for future progress in seismology not only in India but the whole world. It was in the study of this earthquake that Oldham, for the first time, recognised the existence of the longitudinal (P), Transverse (S) and Surface (L) waves on the records of seismographs and thus laid the foundation of modern seismology. His field observations of this great earthquake included such spectacular effects as-

- Changes in ground level and dislocation of the crust
- Large vertical movement of rocks along the Chidrang fault
- Visible waves along the surface of the ground
- Seismic seiches
- Rotation of pillars and monuments
- Overthrow of small stones embedded in the hill sides into the air showing acceleration exceeding that of gravity.

Oldham also published another memoir on the Rann of Kutch earthquake of 1819, nearly a century after its occurrence. This earthquake was also significant in many ways. It was felt over an area of nearly one million square miles and large scale changes in ground level and dislocation of the earth's crust took place. At a distance of nearly 5 miles to the north of Sindri it was observed that a mound of earth or sand was created at a place where prior to the earthquake the ground was low in level. The local inhabitants called it "The Allah Bund". Oldhams analysis of the survey report showed that it ran in a NW–SE direction for nearly 80 miles. There was general elevation of the tract to the north and depression to the south. An interesting feature of this dislocation was that the displacements to the north and south were in opposite directions, greatest in amount close to the boundary and decreasing as the distance increased.

A list of publications, on earthquakes of the G.S.I. from the year 1869 to 1969 was compiled by M. S. Balasundaram an ex-Director General of G.S.I. and is available on pages 11–13 of the publication entitled "Seismology in India" published by the Indian Geophysical Union in 1970.

Beginning of instrumental seismology

After the occurrence of the Great Assam earthquake of 12th June 1897, the necessity of installing some seismographs in the country was keenly felt and the Seismological Committee of the British Association recommended the installation of a few seismographs in India to assist in the study of seismic wave propagation and determination of seismic focii. The Govt. of India agreed at that time to establish seismological observatories at Alipore (Calcutta), Colaba (Bombay) and Madras. The instrument at Alipore was installed on 1st December 1898 and at Colaba and Madras (later shifted to Kodaikanal) in 1898–99. The instruments, installed at these places were Milne's self registering seismographs. The records obtained from these were regularly sent to the Seismological Committee of the British Association.

On the 5th of April 1905, a great earthquake occurred with its epicentre near Dharamshala (Punjab) and the necessity of installing some less sensitive instruments was felt. One such instrument designed by Prof. Omori of Japan was loaned to the Meteorological Department and installed at Simla. Similar instruments were later installed at Bombay, Agra and Dehradun.

After the first World War in 1922–23 Milne-Shaw seismographs were installed at the Colaba Observatory Bombay and subsequently at Agra, Calcutta, Hyderabad and Kodaikanal. The installation of these instruments considerably improved the recording capability of these stations and important earthquakes occurring anywhere in the world could be recorded. These instruments used continuous photographic recording with time marks impunged automatically on them every minute and hour. The absolute time of occurrence of phases could be read easily with an accuracy of ± 5 secs.

After the occurrence of the disastrous earthquake of Jan. 15, 1934 the Government of India appointed a Committee to review the state of the existing seismological organisations in the country. This Committee submitted its report in 1936 as a result of which a special officer was appointed under the Director General of Observatories to look after exclusively the seismological work in the India Meteorological Department. Prior to this, all seismological works were being looked after by Meteorological Officers of the Department in addition to their own work. During this period, however, some pioneering work in the seismological field was done. Special mention may be made of the work of Dr. S. K. Bannerji on the depth of earthquake focus and on microseisms associated with disturbed weather over Indian seas.

In the year 1939, the second World War broke out and seismological observatories in many parts of the world had to be closed down. In India too, no further expansion of the seismological organisation took place. After the war the Govt. of India, in 1945, appointed a Planning Committee for Geophysics to prepare plans for all geophysical work in the country. This Committee submitted its report in 1948 as a result of which the present seismological organisation was born with the main objective of expanding the network of seismological observatories and carrying on research work in all aspects of seismology including development of seismographs, study of the distribution and frequency of earthquakes, foreshocks and aftershocks, their depth, mechanism, seismic waves and travel times, microseisms, etc.

During the post war period very rapid progress was made in the field of seismology throughout the world, partly due to the general development in Science & Technology but mainly due to the efforts of developed countries to find out methods of detecting underground nuclear explosions. The total number of seismological stations in the world which was around 500 before the war increased several fold with improved equipment, thus increasing the sensitivity and reliability. The United States Coast and Geodetic Survey (USCGS) opened a world wide network of seismological stations equipped with three components of short and long period electromagnetic seismographs and arrangements for automatic impinging of time marks on seismograms and also absolute time directly from radio stations broadcasting time signals. These steps increased the accuracy of time measurements on seismograms to a fraction of a second as against a few seconds in the prewar period. In addition to these, several array stations were also established in many parts of the world which made it possible to detect earthquakes of magnitude 4 and above, occurring in any part of the world.

In view of the many multipurpose development projects proposed for implementation in the seismic regions of the country during the various five year plans, the study of seismicity drew a lot of attention from planners and there was, therefore, a general awakening in the country with regard to seismological studies and design of earthquake resistant structures. Many institutions other than the India Meteorological Department and the Geological Survey of India began taking interest in seismological and related problems. Some of these institutions are listed below.

- The National Geophysical Research Institute, Hyderabad.
- School of Research and Training in Earthquake Engineering, University of Roorkee.
- The Central Water and Power Research Station, Poona.
- Bhabha Atomic Research Centre, Bombay.
- Oil and Natural Gas Commission, Dehra Dun.
- The Survey of India, Dehra Dun.
- Regional Research Laboratory, Jorhat, Assam.
- Banaras Hindu University, Varanasi.
- Department of Mathematics, Bengal Engineering College, Calcutta.
- Department of Mathematics, University of Kurukshetra.
- Department of Geophysics, I.I.T. Kharagpur.
- The Geophysics Department of Andhra University Waltair.

The progress achieved in Seismological studies upto 1970 will now be reviewed in the following pages.

SEISMOLOGICAL OBSERVATIONS

Before independence the India Meteorological Department maintained seismological observatories at Bombay, Calcutta, Delhi and Kodaikanal and the Nizamiah Observatory at Hyderabad. By the year 1970, this network had increased to 18 permanent national observatories, 4 mobile observatories and 7 observatories located in the Beas and Sutlej catchment area for special studies. The observatories at Delhi, Poona, Shillong and Kodaikanal were equipped with standardised long and short period electromagnetic seismographs supplied by the US Coast and Geodetic Survey.

In the year 1967 a strong earthquake occurred near the Koyna Dam in Maharashtra and caused some damage to the dam in addition to considerable damage and loss of life in the nearby residential colony. To study the large number of aftershocks taking place in the region, the Met. Deptt. opened an observatory at Karad and the Central Water and Power Commission at Koyna, Satara, Govalkot, Pophli, Mahabaleshwar and Alore. Strong motion accelerographs were also installed in and near the main dam by CWPRS.

The India Meteorological Department also opened a temporary observatory at Kantharia near Broach (Gujarat) to study the tremors occurring in the region after the Broach earthquake of 23rd March, 1970. In connection with the Ramaganga–Yamuna projects, the Govt. of Uttarpradesh established seismological observatories at Kalagarh, Narendranagar, Tehri and Rudraprayag.

The National Geophysical Research Institute at Hyderabad also operated a seismological observatory equipped with both long and short period electromagnetic seismographs similar to those of standardised USCGS stations.

A most significant addition to the national network of seismological stations was the establishment of a seismological array station at Gauribidanur near Bangalore by the Bhabha Atomic Research Centre, Bombay. This station was capable of recording many more events than conventional seismographs due to its high sensitivity and low noise at Gauribidanur. The main purpose of this station was however, to discover ways of distinguishing between the records of underground nuclear explosions and natural earthquakes.

FIELD STUDY OF EARTHQUAKES

Field study of earthquakes has always been the responsibility of the Geological Survey of India. After the Koyna earthquake, the Centre Water and Power Research Station at Poona and the School of Research and Training, Roorkee associated themselves with field surveys of earthquake specially the engineering aspects. During the period under review a number of strong earthquakes occurred and the GSI conducted field surveys as usual. Special mention may be made of the Great Assam earthquake of 15th August 1950 (Mag. 8.5) and Koyna earthquake of 1967 (Mag. 6.5), the latter being of special significance as it occurred in a region which was hitherto regarded as relatively stable. At the invitation of the Govt. of India, a special team of geologists, seismologists and engineers was deputed by UNESCO to investigate into the causes of the earthquake, particularly the effect on the seismicity of the region as a result of filling up of the Koyna reservoir.

SEISMICITY STUDIES

Seismicity studies or the proneness of a place to earthquake hazards is of great economic significance specially for the development projects to be undertaken in seismically active regions. To get an idea of the seismic status of a place, or region a variety of geological and seismological information is required such as:

- Detailed information on past earthquakes, including isoseismal maps of important events.
- Catalogue of earthquakes giving details of epicentres, origin time, depth of focus and magnitude.
- Tectonic maps delineating the various fault systems along which earthquakes had occurred as well as those which are currently active.
- History of formation of geological structures in regions of earthquake activity.
- Detailed knowledge of the geological foundations on which the structures are to be built.

Based on the instrumental data on earthquake parameters collected by the IMD, the isoseismals of various earthquakes drawn by GSI, the Tectonic Map of India compiled by GSI, and other geological considerations, the Indian Standards Institution published a code for earthquake resistant design of structures (IS 1893–1966) in 1966 which also included a map of seismic zoning dividing the country in zones liable to different degrees of shaking during earthquakes. As a result of the Koyna earthquake of 1967 and the findings of the expert Committee on the Koyna earthquake, this map has now been revised by the Committee of ISI. It is expected that the revised code will be published soon.

It has been found that for any seismic region the number of earthquakes of different magnitudes in a given time interval do not take place at random but follow the law.

$\operatorname{Log} N = a + bM$,

where N is the number of earthquakes of Magnitude M, and a and b are constants. Some seismologists feel that this law could be made use of in seismicity studies for determining the recurrence of earthquakes of different magnitudes in a given region. Several institutions in the country namely (1) The India Meteorological Department (2) Banaras Hindu University (3) Central Water & Power Research Station Poona and (4) National Geophysical Research Institute have made attempts to utilise the above law for regional seismicity studies. Mention may be made of the papers published by Tandon and Chatterjee (1968) for the Himalayan region and areas around Delhi and Sonepat. Chauhan determined the value of the constant a and b for the Himalayan region and concluded that b/a represents the seismicity of an area rather than a or b. Many authors however believe that the constant b is a regional characteristic and a is a measure of seismicity.

In order, however, to assess the degree of damage to any structure, due to an earthquake some more information is necessary such as the geological foundation upon which the structure is to be based and its proximity to any known fault. This requires detailed geological mapping and parameters of even small earthquakes occurring in the region which can be obtained by establishing a close network of seismological stations in the region. Such networks have been established for the Beas and Sutlej catchments, the Koyna region, Ramaganga & Yamuna Projects and the region around Delhi and Sonepat.

ENGINEERING SEISMOLOGY

Engineering Seismology deals mainly with the behaviour of structures during earthquakes. To study this aspect a school of Research & Training was established at Roorkee, U.P. in 1960. Besides training engineers in the design of aseismic structures, the school has been carrying on fundamental and applied research on all problems connected with earthquake engineering. The main achievements of the school upto 1970 have been the following:

- Extensive studies of earthquake resistant small housing which has found application in defence projects, industrial establishments, etc.
- Design and construction of structural response recorders and establishment of 53 stations;
- Design and construction of strong motion accelerographs
- Construction of various types of shaking tables for model studies.
- Development of tiltmeters and extensometers.
- Investigation of foundations specially the liquefaction of soils during earthquakes,
- Rendering advice in the design of structures under various projects.

During the last ten years the school has published over 125 papers.

Engineering seismological studies are also carried on at the CWPRS Poona. Usually their studies are confined to the problems of earthquake engineering associated with various engineering projects undertaken by the CWPC. Their main investigation during the last few years have been related to the earth tremors taking place around the Koyna Dam. For this purpose they have been maintaining a close network of 6 sensitive seismological stations in the area. Sets of Strong Motion accelerographs have also been installed inside and outside the Koyna Dam. The foreshock of Sept 13, 1966, the main shock of Dec. 11, 1967 and a large number of strong aftershocks were recorded by these instruments. The accelerograms of the December shock are unique records, and will be of great use to designing engineers throughout the world. All the accelerograms obtained at Koyna and their analysis have been published by CWPRS, Poona.

SEISMIC WAVES VELOCITIES, AND THE STRUCTURE OF THE EARTH'S CRUST AND UPPER MANTLE

The study of seismic waves (P,S) as they travel through the earth's interior provides a very convenient method of investigating the earth's interior. These investigations have revealed that in general the earth's continental crust consists of two layers in addition to a thin layer of sediments. The upper layer consists of granitic rocks and is called the granitic layer and the lower one, the Basaltic layer. The discontinuity separating the crust from the Mantle is known as the "Mohorovicic Discontinuity" or simply the "Moho". Its depth varies from region to region, the deepest being about 60 kms under high mountains and about 5 to 10 kms under the oceans.

Investigation of P & S wave velocities in India with the help of seismograms of earthquakes obtained at short distances have been undertaken by many workers in different regions. The results obtained by them are summarised in Table 1.

Due to uncertainty in the determination of epicentral parameters, some errors are introduced in the determination of travel times of P & S waves at short distances and hence in the determination of crustal structure. The errors can be minimised considerably by creating large artificial explosions and recording them at near distances. The Geological Survey of India and the Oil and Natural Gas Commission have conducted a few such experiments but with smaller explosives. The N.G.R.I. in collaboration with Russian scientists have carried out Deep Seismic Sounding Experiments along a few profiles in the country.

After the Koyna earthquake of 1967, the GSI carried a seismic survey of the areas around Koyna. The results indicated that the trap rock velocity varies from 4.7 to 5 kms/sec. The travel time curves indicated a high velocity discontinuity underlying the trap rock below the ground surface at a depth of 200 meters at Pophli, 500 meters near Karad and 670 meters at Rampur. It could not be said with certainty that the above depths represented the base of the traps.

In another seismic investigation in the Trap rock areas of Maharashtra, Mysore and Andhra Pradesh, to find out the thickness of the basaltic lavas and crustal depths, the following results were obtained

Trap rock velocity– 4.8–5.2 kms/sec.

P wave velocity below discontinuity 5.7–6.5 kms/sec.

These velocities were found to be of the same order as in the Cambay area.

During February and March 1965 the Indian Naval Physical Laboratory, in collaboration with German Scientists participating in the Indian Ocean Expedition Programme, carried on refraction experiments to study the structure of the crust in the Ocean bottom near Laccadive Islands, the Gulf of Cambay, and the Rann of Kutch. For the Gulf of Cambay area their results indicated that volcanic ash and pumice existed at a depth of 3000 m from the sea level. Eruptive basalt underlying the upper Deccan trap appears to have been uplifted at a distance of 80 kms from the coast. The thickness of the Pleistocene sediments over the continental shelf is nearly 2500 m and it gradually decreases over the continental slope. The depth of the Mohorovicic discontinuity under the continental slopes appears to be of the order of 13 km.

In the Gulf of Kutch, the results indicated the depth of the upper Deccan Traps over the continental shelf, between 1 and 1.3 km. They are not observed over the continental slope. The thickness of the Miocene sandstones and Pleistocene sediments overlying the upper Deccan traps is about 600 m and 300 m

TABLE I

Region	Gangetic Valley		Northeast India		Indian Region		Deccan Shield			Himalayan foothills		Near Gauribidanur Array		
	Vp	Vs	Vp	Vs	Vp	Vs	Vp	Vs	T	Vp	T	Vp	Vs	T
1. Sedimentary	—	—	—		—		—			2.7	6	—	—	—
2. Granite	5.26	3.29	5.58	3.43	—	—	5.67	—	22.5	6.2	8	5.67	3.46	15.8
3. Basaltic	6.21	3.71	6.55	3.85	—	—	6.44	—	18.5	6.9	14	6.51	3.96	18.9
4. Base of Moho	7.80	4.38	7.91	4.46	8.0	4.54	8.25	4.75	—	8.2	—	7.98	4.61	—
5. Author	Roy (1939)		Tandon (1954)		Nag (1967)		Tandon & Chaudhury (1968)			Kaila, Reddy and Narain (1968)		Arora (1969)		

N.B. Vp = P wave velocity (km/sec), Vs = S wave velocity (km/sec), T = thickness (km).

respectively. The thickness of the same layers over the continental slopes is 2800 m and 2000 m respectively. Other crustal layers observed in this area are the lower Deccan traps and the eruptive basalts. These have been found at depths of 3 and 5 kms respectively from sea level.

R. K. Dube of the India Meteorological Department, using the method of Dowling and Nuttli has analysed the Travel Times of P & S waves, and computed the Upper Mantle Structure over the Indian subcontinent. He observed an increase in the velocity of P waves from below the Moho to the top of the Low velocity channel which is clearly indicated. The top of the channel occurs at a depth of 140 kms and the thickness is about 50 kms. The velocity rises steeply below the low velocity layer.

Another method due to Gutenberg uses the P & S wave data of deep earthquakes for determining the velocity–depth relations. The method consists in observing Travel Times of deep shocks at small epicentral distances. The travel time curve has a point of inflexion at which the apparent velocity V observed at the surface will be minimum.

Using this method, the author found that in the Hindukush region, a low velocity layer exists at a depth of 160 km so far as S waves are concerned. No clear cut minima is obtained for P waves in which the velocity appears to remain constant from the Moho down to a depth of 140 kms and then increases rapidly.

USE OF SURFACE WAVES

Surface waves appear on records of long period seismographs as the most prominent group. They travel along the Earth's surface and are much slower in speed than the body waves. They are of two types viz. the Love waves and the Rayleigh waves. The particle motion in Love waves is horizontal and perpendicular to the ray path and hence they are not recorded on the vertical component. While in Rayleigh waves it is along a retrograde ellipse. Both types are dispersive, that is, their velocities are dependent on the period. This effect is due to greater penetration of the longer period waves. The longer period waves therefore travel faster and appear earlier in seismograms. Dispersion studies of these waves provide a very important method for investigating the elastic properties of the wave guide. Experimentally obtained dispersion curves are compared with theoretical dispersion curves based on assumed earth models to give the elastic parameters of the layers and the structure of the wave guide.

A very large amount of work has been done on this subject throughout the world. Seismologists of the India Meteorological Department and the National Geophysical Research Institute, Hyderabad have been engaged in this type of work for a number of years. In the majority of cases the work has been confined to wave periods upto 70 seconds limiting the studies to the investigation of the crust only. Waves having periods larger than 70 sec., penetrate the earth's upper mantle and are called Mantle Rayleigh or Love Waves. The author in collaboration with H. M. Chaudhury made a detailed study of long period records of the Alaska Earthquake of 1964 at Delhi in which the vibrations continued for over 48 hours and periods as high as 10 minutes were recorded. Some of these waves made more than 20 rounds of the earth. The mantle Rayleigh waves have a group velocity minimum of 3.6 kms/sec, at a period of 240 sec. The dispersion curves fitted with the theoretical curves assuming the existence of a low velocity layer in the upper mantle, and thus lent support to the Gutenberg Model.

A number of authors in IMD and NGRI have applied surface wave dispersion data to study the crust along various sections of the country. The author and H. M. Chaudhury analysed the records of Long Period Seismograms of Delhi and Shillong pertaining to a shock in the Atlantic Ocean whose epicentres lay on the great circle path through these stations. The results indicated an average crustal thickness of 40–45 km between Delhi and Shillong.

In another study Tandon and Chaudhury studied the records of Long Period Seismograms obtained at Delhi of the High Yield Russian Nuclear explosions carried out in 1962 over their testing ground at Novaya Zemlya. They found that Rayleigh waves as well as the M.2 waves were very well recorded. The experimental dispersion curves obtained showed that the average crustal structure between Novaya Zemlya and Delhi is 45 km thick whereas under the mountain range across the path, it is 55 km thick. In addition to the surface waves, the pressure wave travelling with the speed of sound was also recorded both by seismographs and barographs on a number of days.

Chaudhury studied in detail the records of the Delhi observatory of a number of earthquakes occurring near the Manipur–Burma border. Dispersion curves of Rayleigh, M-2, Love and higher model Love waves were drawn for group as well as phase velocities and obtained the following results for the Indogangetic plains.

	Sediments	Granitic	Basaltic
ρ	3.88	6.15	6.58
β	2.30	3.55	3.88
σ	2.340	2.817	2.922
H	3	17	20

Long period Press-Ewing seismographs were installed at Bhakra, Dehra Dun and Delhi to determine the phase velocities of Rayleigh waves over the Punjab region. The results obtained from an analysis of two years records gave a crustal thickness of 40 km over the Punjab plains.

Gupta and Hari Narain of NGRI, Hyderabad have studied the dispersion of surface waves along paths across the Himalayas and the Tibetan Plateau. They obtained an average crustal thickness of 65–70 kms under the Himalayas. H. K. Gupta has also studied the surface wave velocities between period range 20–40 seconds, and used crossing path technique of Santo to divide the Asian continent into regions of same Rayleigh or Love wave group velocity dispersion characteristics.

THEORETICAL SEISMOLOGY

In the India Meteorological Department S. N. Bhattacharya and S. N. Chatterjee have been working on the propagation of Love and Rayleigh waves in vertically inhomogeneous media. Bhattacharya gave a systematic method to obtain inhomogeneity for which the SH wave equation or Love wave equation can be solved in terms of transcendental functions. He also took up the case of Love wave dispersion in a laterally inhomogeneous layer lying over a homogeneous half space. Chatterjee obtained the frequency equation of Love waves in a medium consisting of two finite layers over an infinite half space, the inhomogeneous layer being sandwiched between the homogeneous layer and a homogeneous half space. In another paper Chatterjee has derived the frequency equation for Rayleigh waves in a heterogeneous layer lying over a homogeneous half space.

At the University of Kurukshetra theoretical work is conducted under the leadership of Prof. S. D. Chopra. The main problem undertaken by his group concerns the propagation of elastic waves in layered media, inhomogeneous media and in anisotropic media. A number of papers have also been published on Finite Source problems and the application of statistical methods to seismology.

A group of theoretical workers at the NGRI, Hyderabad has been investigating problems connected with the propagation of Love Waves under conditions of anisotropy and inhomogeneity represented by

- Power law distribution
- Exponential variations
- Hyperbolic variations of rigidities, velocity and density.

Studies have also been made of the deformation of pulse shapes by media or by moderate or rapid velocity variations.

At the Centre of Advanced Study in Applied Mathematics of the University of Calcutta studies have been made on Source Mechanisms of Earthquakes. Theoretical expressions for surface displacement associated with point sources as well as with some sources of finite dimensions in infinite half space, have been obtained. The results could be used in the investigations of earthquake mechanism at the hypocentre by comparing the theoretical results with the traces recorded in seismograms. Dr. I. N. Gupta of the Panjab University, Chandigarh has made theoretical studies on body wave radiation patterns from different sources by the use of reciprocity theorem. He has also published papers on standing waves in a layered half space.

The theoretical investigations carried on at the BHU concerned the dispersion characteristics and radiation patterns of surface waves and the deformation of pulse shapes in different types of anisotropic, homogeneous or inhomogeneous layered media. Analysis of the possible curves, related to the production of anisotropic elastic conditions in the upper mantle region due to non-uniform stress field.

MODEL SEISMOLOGY

Investigations of seismological problems in the laboratory by using two or three dimensional models are being carried on in the laboratories of the Geological Survey of India, Calcutta and the Indian School of Mines, Dhanbad. Dr. D. K. Chaudhury at Dhanbad made an experimental determination of body wave velocities along an internal layer of a two dimensional model. The model consisted of a single low velocity layer (plexiglued) between large sheets of higher velocity medium parelytes. The results indicated that the observed phase velocity is a function of layer thickness and wave length. A velocity minimum is observed when the wavelength is twice the layer thickness and a velocity maximum when the wave length is three times the layer thickness.

Studies are also being made on a two dimensional model of the wave amplitudes from a directed source. In this model the radiation pattern due to a directed source, (as happens in natural earthquakes) could be studied.

A pulsed ultrasonic equipment for model seismology studies was designed and constructed in the Geophysical Lab. of the Geological Survey of India in 1964. The equipment has been used to carry out the following type of investigations.

- Measurement of compressional (P) wave velocities in specimens of rock formations, ore bodies, and water saturated porous rocks. For the various types of Deccan traps the velocity was found to vary from 5.5. to 6.5 kms/sec.

- Measurement of the elastic moduli of different rock types.
- *Absorption of compressional waves in different* types of rock samples. The absorption coefficient showed a definite trend to increase with decrease in wave velocity.
- Study of head waves in a large number of two dimensional horizontal and inclined layer models.
- Model studies of diffraction pattern of converted waves formed by rock blocks of different dimensions in a tank.

MICROSEISMS

The background noise in siesmograms due to various natural and man made causes is known as "microseisms". The period of microseisms ranges from fraction of a second to nearly 30 seconds or more. Microseisms of the period range 2–10 seconds have a special significance as their origin has been traced to weather disturbances in the sea. Dr. S. K. Banerjee, a former Director General of India Meteorological Department had shown as early as 1930 that the monsoon winds and cyclonic storms over the Indian seas generated microseisms which were recorded by Milne-shaw type seismographs of the observatories at Bombay, Calcutta and Agra. He also developed a theory for the origin of the microseisms on the assumption that the pressure due to the height of the sea waves was communicated to the sea bottom due to the slight compressibility of water. Since Dr. Banerjee's time the scientists of IMD have been continuing their researches on this phenomenon and a number of papers have been published on the subject.

The author observed that microseisms generated by cyclonic storms of sufficient intensity in the Bay of Bengal and also in the Arabian Sea were recorded at all inland stations of India if the storm centre was within 200 m depth contour. It has been observed that the amplitude of microseisms was maximum at the time of crossing the coast. The mean amplitude and period for different months at Madras recorded by Sprengnether Microseismograph during 1955 to 1959 was studied by Anjaneyulu. The amplitude is maximum in July and minimum in February; a second maximum occurs in November. Saha noticed that microseisms consisted of 70% Rayleigh waves and 30% Love waves. Nag used the amplitude method of Jensen to find the direction of the source of microseisms. Krishna and Sankaran of the seismology group of BARC, Bombay studied the seismic noise using the Array data of Gauribidanur. They also observed that oceanic disturbances associated with cyclonic activity from the Bay of Bengal results in enhancement of microseism energy in the spectral band 3.5 to 4.5 seconds. In two cases when cyclonic disturbances existed in Bay of Bengal they found *the direction of approach of microseisms, calculated* from the data obtained by the array agreed with the actual bearing of the cyclonic disturbances.

INSTRUMENTS

For the last two decades the India Meteorological Department has been designing and constructing seismological equipment for installation at observatories operated by them.

The following types have been constructed and brought into use.

- Wood Anderson seismographs.
- Short Period Vertical and Horizontal electromagnetic seismographs.
- Sprengnether type EM seismographs of period in the range of 7 seconds.
- Photographic recorders.
- Electronic amplifiers for use with seismographs.
- Visible pen writing recorders.
- Time marking clocks of pendulum type.
- Other accessories required at seismological observatories.

The Earthquake Engineering School of the University of Roorkee has successfully developed and constructed the following type of instruments.

- Strong Motion accelerograph.
- Structural Response recorders.
- Roorkee seismoscope.
- Water tube tiltmeter.

While working at Cal Tech USA in 1948 Dr. S. K. Chakravarti, had given the theory of Benioff type Electromagnetic Seismographs. After return to India he continued his work on the theory of electromagnetic seismographs and methods of calibration, and has since published a number of papers in collaboration with his colleagues at the Centre of Advanced Study in Applied Mathematics, University of Calcutta. In one of the papers, a set of standard curves has been constructed from which the magnification curve for any combination of free periods of seismometer and galvanometer and various values of damping could be drawn.

In the IMD *response characteristics of electro*magnetic seismographs have been studied by Chaudhury. The use of the T type attenuator in seismograph circuits and the limits of the attenuating factor have been discussed by him in one of the papers. In another paper he has discussed the conditions under which the magnification of the system can be changed without disturbing the response characteristics. It was observed that this was possible only when the seismometer and the galvanometer had the same period and the damping of the two are suitably altered.