EVALUATION OF EARTHQUAKE PARAMETERS IN KOYNA AND DAKPATHER REGIONS

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ABSTRACT

Investigations of earthquake hazards to important engineering projects in seismically active regions of India have been gaining increased importance. The Koyna Hydroelectric Project in the Peninsular Shield, in the Maharashtra State and the Yamuna River Valley Project in the Himalayas, in the Western Uttar Pradesh are two such projects and therefore investigations were planned in these two regions with a view to studying the following:-

(1) The response of existing engineering structures during various earthquakes and the average response spectra for the Koyna region on the basis of three available accelerograms.

(ii) Possible source mechanism and the cause of the recent seismic activity in the Koyna region.

(iii) Order of the tectonic stress field, if any, operative in the Dakpather region.

(iv) The rate and nature of creep displacements along the known planes of recent movements in the Dakpather region.

As, geophysical instruments needed for such studies were not readily available, it was first necessary to design and develop some of these, which constitute the major part of the work. The instruments designed and developed for the purpose were as follows:-

(i) Multiple Structural Response Recorder and Roorkee Seismoscope: These devices produce records to give the maximum relative displacement response of idealised engineering structures which are dynamically equivalent to their pendulums.

(ii) Portable Water Tube Tiltmeter: This system is capable of measuring small scale secular ground tilt associated with elastic strain energy accumulation and release as well as with rock creep or movements across known faults or thrusts.

For the studies in the Koyna region, all these instrument were used whereas in the Dakpather region only the Portable Water Tube Tiltmeter and Multiple Structural Response Recorders were employed for measurements. The data thus obtained though useful for the evaluation of earthquake hazards, was not in itself sufficient to permit a complete analysis and therefore, all other relevent data available for the two regions were also studied. During the period of investigation, the Koyna region has exhibited greater seismic activity as compared with the Dakpather region. It was, therefore, possible to make a more complete study for the former. However, for the Dakpather region a qualitative analysis was possible leading to some broad conclusions.

In the Koyna region, one event was simultaneously recorded by the Multiple Structural Response Recorder, the Roorkee Seismoscope and a United Electrodynamics AR-240 Accelerograph. The two dimensional plots of the computed relative displacement response in the horizontal plane were prepared and compared to the records of the seismoscopes. The comparison brings out the potential of these simplified devices for collection of Structural response data.

Strong motion records were available for three of the Koyna earthquakes, on the basis of which average velocity response spectra for the Koyna region have been computed. Further more, analyses of these records have been carried out to permit comparison of important characteristics. A model has been proposed for the source region which is in conformity with the above common features as well as with other observations made during the earthquakes. The seismic activity has been explained as arising from the tectonic reorientation of dykes due to shear.

In the Dakpather region, the Portable Water Tube Tilt-Meter was employed for the Measurement of small displacements due to tectonic stress field, if any, across a plane of sub-recent movement and the Nahan thrust. Other indirect evidence of recent movements and these observations have been discussed. The temporary seismological observatory in the area recorded some events with epicentres in the region. But the tilt measurements do not give any conclusive evidence of tectonic movements. Some estimates of creep and seismic displacement were made on the basis of recorded data. It is felt that continued measurements over a number of years may provide a better understanding of the tectonic activity.

CERTIFICATE

Certified that the thesis entitled "EVALUATION OF EARTHQUAKE PARAMETERS IN THE KOYNA AND DAKPATHER REGIONS", which is being submitted by Shri P.N.Agrawal in fulfilment of the requirement for the award of the Degree of Doctor of Philosophy in Geophysics of the University of Roorkee is a record of his own work carried out by him under our supervision and guidance. The matter embodied in this thesis has not been submitted for the award of any other degree.

Furthermore he has worked part-time from October 1966 to August 1970 on this problem.

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(ii) Yamuna Valley Development Scheme, Irrigation Department, Government of Uttar Pradesh, Lucknow.

(iii) Engineering Geology Division, Geological Survey of India, Lucknow.

(iv) India Meteorological Department, Government of India, New Delhi.

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CHAPTER 1

INTRODUCTION

1.0. GENERAL

On an average, the earth is rocked by some thousands of earthquakes everyday of which 3 may be disastrous and about 250 large enough to be felt by human beings, whilst the majority of them go unnoticed as they occur in remote areas and are only registered by the most sensitive seismographs. However, all parts of the globe do not share their effects equally as earthquakes are mainly confined to two narrow elongated belts each covering about two third of a great circle and intersecting the other almost orthogonally. Besides these, ofcourse there are other regions also of minor seismic activity particularly the mid-oceanic ridges and the continental margins. With the growth in population and progress in industry, earthquakes have increasingly attracted the attention of man as potential sources of havoc and misery.

India is bordered by three broad, almost circular convex mountain arcs of the Alpine Himalayan System. These are respectively the Burmese arc on the east, the Himalayan arc on the north and the Baluchistan arc on the north east. Together they account for almost all the intermediate and most of the shallow focus earthquakes of India. Southwards the subcontinent forms a triangular peninsula, whose western side is a deep fault scarp which, like continental margins elsewhere on the globe, is still live.

Adjoining these active boundaries lie regions some of which have great power and industrial potential. In the northeast, Assam which witnessed one of the greatest earthquakes in recorded history is also one of the major oil producing areas with a growing industrial complex whilst along the Himalayan arc where nearly 40 major earthquakes have occurred during the past 100 years and where most of the rivers of North India rise, a number of irrigation and power projects have been established.

In the south only about 25 earthquakes of moderate intensity are recorded to have occurred during the past 370 years, mostly on the western coast, but this long held invincibility of the peninsula was rudely shaken by the Koyna earthquake of 1967 which aroused so much public interest that geologists have dubbed the original supposed stability of the peninsula as a myth and it is now felt that perhaps there is hardly any region in the country where earthquake hazards could be entirely discounted.

In these seismic areas, a number of engineering projects are existing and many more are being planned in the proximity of major active thrusts or faults. The occurrence of earthquakes and also the creep movements along some of the known faults thus present a potential hazard to these projects and necessitate [illegible] investigations of the earthquake parameters so that adequate safety provisions in the design of structures could be adopted in the respective regions. The Koyna and Dakpather regions are two such sites where important engineering structures are located and it is in this context that the evaluation of the earthquake parameters in these two regions was undertaken.

1.1. NATURE OF PROBLEMS INVOLVED

Some of the more important questions whose answers form a prepequisite to the design of earthquake resistant structures may be enumerated as follows:-

(i) Evaluation of general seismicity parameters.

(ii) Earthquake source parameters particularly in relation to the ground motion characteristics.

(iii) Preparation of the average response spectra for a region on the basis of ground motion characteristics of past earthquakes as well as recording of the response of idealised engineering structures during various earthquakes.

(iv) Estimates of the tectonic stress field and the associated aseismic creep across known faults or thrusts.

(v) Estimates of maximum likely seismic displacements in a region.

The above list is by no means exhaustive and is only intended to indicate the general nature of these problems. The solutions of most of these problems are generally obtained through a statistical approach and it is therefore necessary that sufficient data covering a number of years be available for making these studies.

1.2. PREVIOUS INVESTIGATIONS

The problems mentioned above have already been investigated for some or the other regions of the country. One of the earliest parameters used for the evaluation of seismicity was the maximum earthquake intensity experienced during past earthquakes. Recent investigations, however, have utilized the frequency-magnitude relationships and the strain release or tectonic flux density characteristics. The utility of such approach is already well appreciated and, depending upon the data available, a number of such investigation reports for various regions are now available. For the Koyna region, in particular, a number of such studies have already been carried out by various investigators (Tandon and Choudhury, Guha et. al., Chouhan, Gupta et al) but for the Dakpather region no specific study has been possible due to paucity of data although a general seismicity evaluation has earlier been done (Chouhan 1966).

One of the next important aspects which has been investigated in detail earlier is the behaviour of man made structures to random and complex ground vibrations produced by earthquakes. Since such computation would in general be very tedious, the Response Spectrum Technique (Hudson 1956) has been introduced to simplify this problem. This technique makes use of a single degree of freedom viscous damped linear mechanical oscillator whose equation is as follows:

$$\ddot{X} + \frac{c}{m}\dot{X}_r + \frac{k}{m}X_r = \ddot{y}(t)$$

where X_r is the relative displacement between the rigid support and the mass m, c a constant proportional to the damping force and k the spring constant. This can be considered to represent a dynamically equivalent man made structure. The relative displacement response spectra (S_d) is defined as the maximum value of the relative displacement X_t when the oscillator support is subjected to an earthquake motion, and is given by:

$$S_d = \left[\frac{2\pi}{T\sqrt{1-n^2}}\int_0^{t_0}\ddot{y}(\tau)\,e^{-\frac{2\pi n}{T}(t-\tau)}\,\mathrm{Sin}\,\frac{2\pi}{T}\sqrt{1-n^2}(t-\tau)\,d\tau\right]_{max}$$

where T is the undamped period, n the fraction of critical damping and t_0 the duration of the earthquake.

For, small damping, say less than 20% of critical, as is generally involved in man made structures, this equation can be simplified as:

$$S_d = \left[\frac{2\pi}{T}\int_0^{t_0}\ddot{y}(\tau)\,e^{-\frac{2\pi n}{T}(t-\tau)}\,\mathrm{Sin}\,\frac{2\pi}{T}(t-\tau)\,d\tau\right]_{max}$$

The expression for relative velocity (S_v) and acceleration (S_a) response spectra can also be obtained by suitably differentiating the expression for S_d. We can thus prepare a family of curves for each S_d, S_v, S_a against the natural period for varying values of damping. These curves serve a useful purpose in revealing the behaviour of an equivalent man made structure for design purposes.

Such techniques have been widely in use particularly on the basis of the ground motion data collected in the California region. Housner (1959) has prepared average velocity response spectra for the California region, and, in the absence of an alternative, these have been used in other seismic regions also. Since the ground motion at any location associated with the passage of elastic waves constituting an earthquake would be related to the local geological conditions, the depth of focus, the epicentral distance, the energy release or source mechanism, etc., such application of the results from another region may not at all be representative of the actual conditions. Thus for the evaluation of response of an idealised structure in a region, records of the local ground acceleration versus time should form the basic data needed. However, the requisite instruments, namely the strong motion accelerographs, being rather expensive, can normally be installed at a few locations only, low cost simplified pendulum devices, namely seismoscopes, have been therefore finding increased applications in obtaining greater instrumental coverage. These directly yield a point on the relative displacement response spectrum curve corresponding to the period and damping of the device. This background was utilised in planning the investigation in the regions under study.

In order to evaluate the parameters of the energy release mechanism which in turn influence the ground motion and the structural response, a theoretical source field is often postulated and results predicted by it checked with actual observations. Fault plane solutions are one of the more commonly utilised outcome of such investigations and are available for a number of earthquakes in different regions. Also laboratory experiments designed to shed light on the inter-relationship of various source parameters namely, total energy release, magnitude, stress level, stress drop, confining pressures, rate of loading, velocity of fracture propagation, etc. have been conducted by a number of investigators (Scholz , Byerlee and Brace, Chi-Yu King and Leon Knopoff, etc.) some of these results have been used to work out a model for the source mechanism of seismic activity in the Koyna region.

The observations of deformations and rupture in major fault zones are often important in the evaluation of seismic risk. For example, data from the Imperial Valley, California during 1941-1954 show that the two sides of the Imperial fault have moved relative to one another at a rate of 8.5 cm/year and that the fault was 25 to 40 kms deep there. Strain is concentrated in a band of 150 kms width centred on the fault and the highest rate of strain accumulation near the fault was 1.0x10^{-6}/year. Aseismic strain release termed creep was first reported at Hollister on the San-Andreas fault about ten years ago and has been producing displacements on the fault by about 1 cm/year. These examples would demonstrate the utility of the measurements of ground deformation or related displacements in the proximity of major faults. Towards this goal, tilt measurements were planned in the two regions under investigation.

1.3. REGIONS AND THEIR PROBLEMS UNDER INVESTIGATION

1.3.1. The Koyna Region

In the Koyna region on the west coast of south India is located the Koyna Hydroelectric Project, an important power project for the Maharashtra State. The pre-construction investigations of the Koyna Dam and its reservoir region could have hardly taken cognisance of the seismic activity of the area since no important earthquake reports pertaining to the area were available except for some rare minor events in the neighbourhood. Further, as the area under reference was located in a shield region, seismic considerations could not find their way in the investigations. However, during the late fifties, a number of project officials located in the area reported earth tremors. Thereafter the seismic activity increased substantially so much so that a network of four seismological observatories was commissioned in the region. Until September 1967 the maximum magnitude of any event did not exceed 3.8. Subsequently, several larger events occurred in the region, some of the more important ones during September and December 1967 and October 1968. The largest of these was the December event which caused considerable structural damage. The increased seismic activity naturally triggered considerable interest amongst project officials in particular and the seismologists in general. The following studies have been made in this regard.

(a) The response of existing engineering structures during various earthquakes and the average response spectra for the region on the basis of recorded accelerograms.

(b) Possible source mechanism and the cause of the recent seismic activity.

1.3.2. The Dakpather Region

The Yamuna River Valley Scheme is a major irrigation-cum-power project undertaken by the Irrigation Department, Government of Uttar Pradesh. The Stage II, Part II of this scheme envisages construction (now under way) of a 5.6 km long and 7.5 meter finished diameter water pressure tunnel traversing two major thrusts namely the Krol and Nahan thrusts. Apart from these, there are a number of other important man made structures being located in the region. The Dakpather region is in the vicinity of Kalsi in the Lower Himalayas. The preconstruction stage investigations point out to the possibility of the existence of a tectonic stress field in the region which has to be estimated to provide necessary design factors for the engineering structures being constructed there. Therefore, investigations were conducted in order to evaluate the following aspects:

(a) The response of existing engineering structures during earthquakes. However, no data could be obtained for the purpose since no earthquake large enough to cause appreciable structural response occurred in the region during the investigations.

(b) Order of the tectonic stress field, if any, operative in the region.

(c) The rate and nature of creep displacements along the known planes of movements.

1.4. METHODOLOGY ADOPTED

Various alternative methods were explored which could yield a reasonably short term evaluation of the seismic parameters under investigation. In the Koyna region, already a suitable net of seismological observatories was in operation and sufficient data was available for a planned investigation. In addition to this, tilt measurements were conducted in order to ascertain whether any permanent tilting accompanied the earth tremors occurring there or not. Since shocks large enough to cause low structural response were occurring, the instruments to record the maximum relative displacement response were also installed.

In the Dakpather region considerable data was available on the rock properties both on the basis of the laboratory and field tests. There was no seismological observatory in the area and hence one temporary observatory was operated through the assistance of India Meteorological Department in the region.

Tilt measurements were conducted across a sub-recent plane of movement and the Nahan thrust. However, the installation of instruments for recording structural response did not yield any data since no event large enough to cause appreciable response occurred during the period.

1.5. PLAN OF THIS THESIS

The investigations planned in the Koyna and Dakpather regions with a view to evaluating some of the earthquake parameters and analysing the data thus collected, alongwith other available relevent data for this purpose are reported in the following chapters.

The geophysical instruments employed for the investigations were not readily available and therefore their design and development had to precede the actual investigations. This part of the work which claimed the maximum effort is given in the next Chapter and naturally forms a major aspect of the total contribution.

The data for the Koyna region apart from that actually recorded during the investigations was mainly obtained from the Central Water and Power Station, Poona (Guha, 1968) and from the records of the India Meteorological Department (Tandon and Choudhury, 1968). These are given in Chapter 3. The data for the Dakpather region was mainly taken from the various available reports of the Yamuna River Valley Project of the Irrigation Department Government of Uttar Pradesh, and those of the Geological Survey of India (Krishnaswamy and Jalote) and is given alongwith the tilt and seismic data recorded during the investigation in the Chapter 4.

The analyses and the discussions of the results, which also forms an important part of this study, are given under two seperate sections for the two regions in Chapter 5. This Chapter also includes conclusions that could be drawn from the studies made for those two regions.

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CHAPTER 2

DESIGN, DEVELOPMENT AND DESCRIPTION OF INSTRUMENTS USED

2.0. GENERAL

As mentioned earlier the instruments needed for the proposed studies were not readily available and it was therefore considered desirable to develop some of them, which in particular, could yield the following information:

(i) Records of maximum relative displacement response spectral values for dynamically idealised structures and

(ii) Records of small scale ground tilt associated with elastic strain energy accumulation and release or with rock creep or movements across known faults and thrusts.

The instruments designed and developed for the above purpose were the Multiple Structural Response Recorder, the Roorkee Seismoscope and a Portable Water Tube Tiltmeter. These alongwith their full details have been described in this Chapter.

2.1. MULTIPLE STRUCTURAL RESPONSE RECORDER AND ROORKEE SEISMOSCOPE

2.1.0. Background for the Development

Perhaps the earliest effort to record the effect of earthquake ground motions was made in 1911 (Galitzin, 1913). Galitzin thought of employing a set of rectangular blocks of different sizes freely resting on the ground for estimating the violence of the ground motion by observing which one of these blocks would be overturned during a particular earthquake. Following these lines Suyehiro (1926) developed a vibration analyser which consists of a series of cantilevers with different natural periods but equal damping. This device directly gave the response values of typical dynamically equivalent structures. The Medvedev's (1962) "CBM Seismometer" consisting of a conical pendulum of 0.25 second and 0.8 percent of critical damping was also based on the same principle and the level of its records was related to the various grades of intensity.

Subsequent to the development of response spectrum technique (Hudson, 1956), the utility of such simplified devices was better understood as their results represented some particular points on the response spectrum curves. After examining a number of computed response spectrum curves for earthquakes in the Pacific coast, Hudson concluded that the particular point on the curves corresponding to 0.75 second period and 10% of critical damping was the best representative of the curve and gave maximum information about it. Following this the United States Coast and Geodetic Survey and the California Institute of Technology (Cloud and Hudson, 1961) jointly produced a device with these specifications, called a seismoscope. Seismoscopes have since been widely in use. Another such device used in Japan has been described by Takahasi and Hatori (1963) as the 'ERI-II type Seismoscope'. The recording element of this instrument had a 0.75 second period and an adjustable damping within the range of 10 to 47% of critical.

The next step in this development naturally led to the use of a suitable combination of recorders with a view to provide greater number of points on the response spectrum curves. For example, Nazarov's (1959) instrument consisted of 12 recording elements, nine measuring the horizontal motions and three the vertical. The periods of these elements covered a range of 0.08 to 1.2 seconds but were about equally damped. Krishna and Chandrasekaran (1965) used a combination of six seismoscopes of periods 0.40, 0.75 and 1.25 seconds and 5% and 10% of critical damping which were so chosen as to cover the range of dynamic properties of more common structures likely to be constructed in the seismic regions of India. This combination of six Structural Response recorders has been in use and was found to be satisfactory for the earthquake engineering requirements of strong motion recording. These Structural Response Recorders were further modified into a compact instrument (Agrawal and Chandra, 1969) and named as Multiple Structural Response Recorder.

However, the Multiple Structural Response Recorders which, with pendulums of 1.25 seconds and 0.4 seconds period, can record upto 1g and 2g responses respectively, the truly strong motion recording devices. In general, events of moderate sizes are likely to result in lower response values, particularly at distances from the epicentre and may not be adequately recorded on the Multiple Structural Recorder. Another device was therefore designed and developed (Agrawal, 1969a) which was capable of recording response in the range of 10% to 30%g. These were made to possess four different combinations of dynamic specifications namely 0.40 and 0.75 second periods and 5% and 10% of critical damping.

2.1.1. Description of Multiple Structural Response Recorder

The instrument weighs 25 kg and its dimension, with the cover on, is 50x45x30 cm (vide Figure 2-1). It consists of six pendulums in two parallel rows of three each. Each pendulum consists of three circular weights joined together with three symmetrically fixed narrow strips. The lowest weight in the form of a curved disc is capable of moving in the magnetic field of a pair of permanent magnets fixed for each pendulum to provide damping. The middle pendulum weight has a built-in lower suspension vice. The upper suspension vice is held by the pendulum support which is attached to the main recorder support. In order to obtain the desired period of the pendulum a suitable spring steel wire is chosen and its length adjusted whilst the desired damping is obtained by adjusting the gap between the magnets. However, the damping varied with amplitude of recording. A typical graph showing variation of damping with the amplitude is given in Figure 2-4. The specifications chosen are given in Table 2-1. The upper pendulum weight, which is variable for the three different periods, carried a

FIG. 2-1. PHOTOGRAPH OF THE MULTIPLE STRUCTURAL RESPONSE RECORDER (WITHOUT COVER)

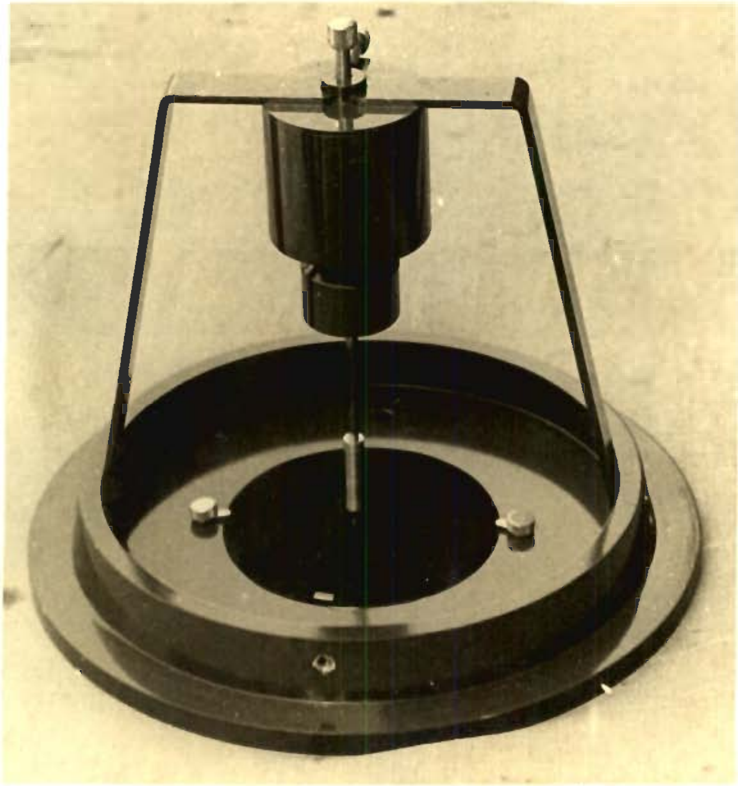


FIG. 2-2. PHOTOGRAPH OF THE ROORKEE SEISMOSCOPE (WITHOUT COVER)

TABLE 2-1

Specification of the Pendulums in the Multiple Structural Response Recorder

Pendulum No.	Period	Tilt Sensitivity	Damping
1	1.25 sec	6.00 cm/radian	5% of Critical
2	0.75 sec	4.00 cm/radian	
3	0.40 sec	1.25 cm/radian	
4	0.40 sec	1.25 cm/radian	10% of Critical
5	0.75 sec	4.00 cm/radian	
6	1.25 sec	6.00 cm/radian	

smoked watch glass whereon rests a stylus. The pivot mounted stylus is fixed to the pendulum support and is free to move around a horizontal axis only in a fixed position. When the pendulum vibrates, the stylus marks a trace on the smoked glass. A heavy rectangular base is used to provide adequate fixity with the ground, and a sturdy cover to protect the instrument from damage. A pair of opposite faces of the cover have louvers for permitting ventilation of the instrument to avoid condensation of moisture during large diurnal temperature changes. Other minor modifications and improvements in the design of each pendulum are as follows:

(i) The stylus is supported on pivots instead of knife edges to eliminate the possibility of shifting of the initial position of the stylus during recording.

(ii) The design of pendulum suspension was changed in order to achieve proper fixity of suspension at its desired length. Earlier the effective length of the suspension varied at different amplitudes of recording due to its inadequate fixity.

(iii) The stylus pressure is provided by the weight of the stylus arm and not by the spring steel wires. In earlier instruments the stylus pressure was liable to change from the initially adjusted value.

(iv) New clamps were provided to hold the watch glass in position and prevent it from jumping.

(v) A stylus clamp was provided to avoid scratching of the record while removing the smoked plate.

Additionally, the design was also improved with a view to simplifying the calibration procedures. Detailed design drawings for each component were prepared. Thus the instrument has a standardised form permitting more efficient field installation, calibration and maintenance. The calibration procedure and the design details for various components are given in Appendix-I.

2.1.2. Description of Roorkee Seismoscope

The 'Roorkee Seismoscope' is a new instrument (Agrawal, 1969a). It has a circular base of 26.5 cm diameter, weighs about 3.5 kg and is 27 cm high (vide Figure 2-2). A section side view of the recorder and a plan of the gimbal suspension are given in Figure 2-3. The pendulum consists of a rod having a heavy mass capable of sliding along it and usually fixed near its upper hinged end and a stylus of self adjusting length at its lower free end. The pendulum is suspended on a gimbal which is held by a two legged support fixed to the recorder base. Its movement can be made to be identical in all azimuths by equally tightening the four allen-key screws in the gimbal. This can easily be achieved by using a torque spanner. Check nuts for the allen-key screws were also provided to retain the adjustment. If jewel points are used in the gimbal suspension and the pendulum is given a circular oscillation, the successive circles of the spiral scratched by the stylus on the smoked recording plate are so close that the smoke is fully removed in that portion of the plate, showing that the stylus friction is very small. The stylus pressure required for suitable recording is only 0.25 gm and has a negligible variation in the recording range. Even such a small stylus pressure retains the stylus in contact with the recording plate during the range of recording since it can attain only a small momentum due to acceleration. The use of suitable size of electroplated steel balls between cups on the ends of the allen-key screws in the gimbal, as shown in Figure 2-3 introduces

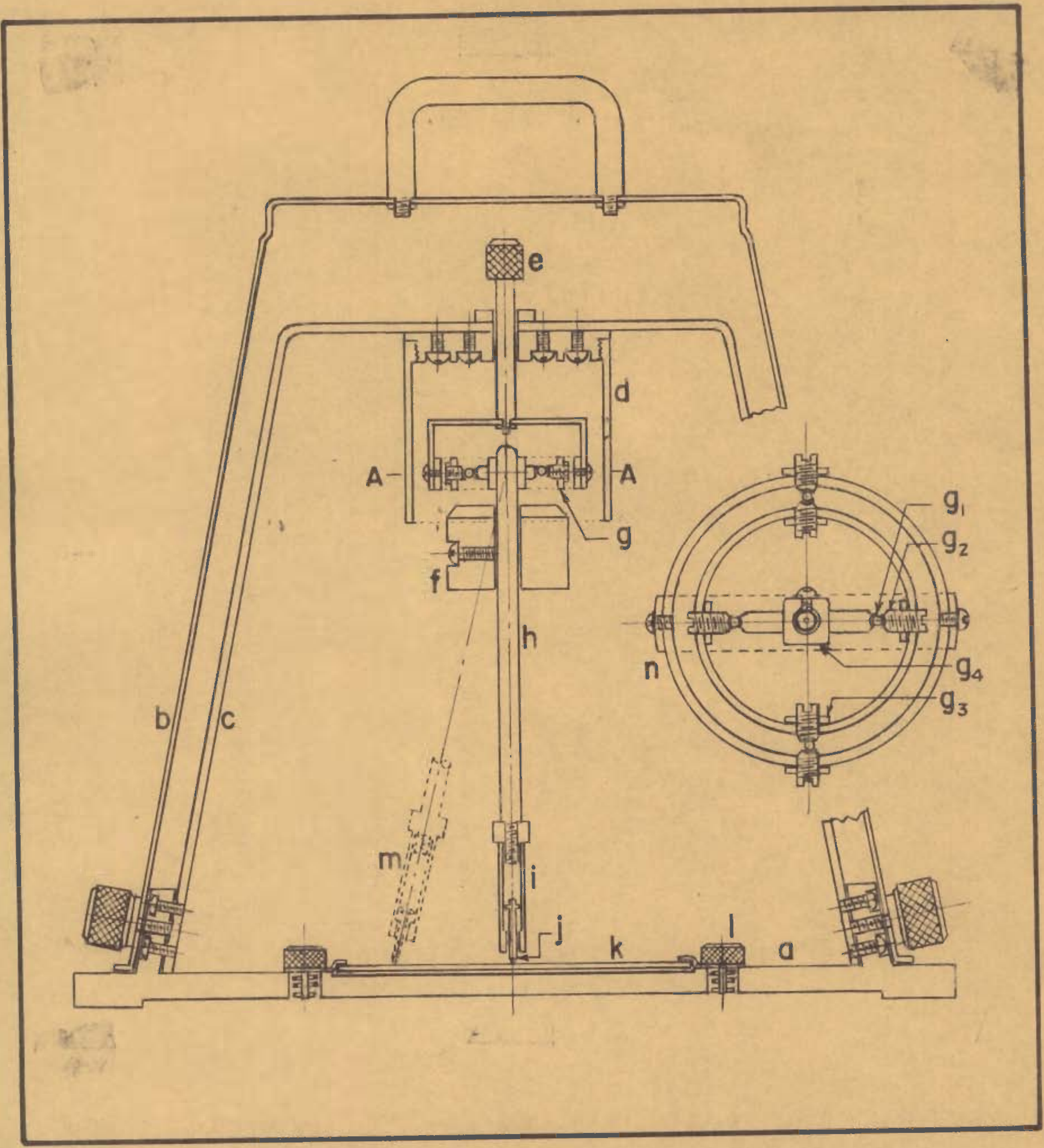


FIG. 2-3. SECTION SIDE VIEW OF ROORKEE SEISMOSCOPE

a_BASE, b_COVER, c_PENDULUM SUPPORT, d_PENDULUM COVER, e_PENDULUM RAISING NOB, f_PENDULUM MASS, g_GIMBAL SUSPENSION, h_PENDULUM ROD i_STYLUS NOZZLE, j_STYLUS, k_RECORDING PLATE, l_RECORDING PLATE CLAMP, m_DISPLACEED POSITION OF THE STYLUS END OF THE PENDULUM DURING STRONG BASE MOTION, n_ SECTION AT A A SHOWING PLAN OF THE GIMBAL SUSPENSION, g_1 _ELECTROPLATED STEEL BALL, g_2 _ALLEN-KEY SCREW WITH CUPPED ENDS, g_3 _ALLEN-KEY SCREW CHECK NUT, g_4 _PENDULUM GIMBAL LINK WITH CUPPED ENDS friction and damps the pendulum movement. The larger the ball or the cup size the greater is the damping due to increased friction. Since the amount of the desired damping is low, the equivalent damping can be determined at approximately the same amplitude as that in field recording. The variation of damping versus amplitude is shown in Figure 2-4. At an amplitude of 10 mm which roughly corresponds to an acceleration response of 10% g, the damping can be determined with reasonable accuracy. The ordinarily available electroplated steel balls showed a remarkable damping stability in field use during a pilot trial of over eight months before the design was finalised. This was further confirmed during subsequent longer use. A protective cover is provided for the gimbal suspension to ensure its better maintenance. The position of the pendulum mass can be raised or lowered for period adjustment from 0.40 second to 0.75 second while the pendulum length under equilibrium position remains unaltered. The entire pendulum assembly can be raised by about 2 cm, bringing the stylus away from the recording plate of 11 cm diameter clamped to the base. This is to avoid scratching of the recording plate while placing it for recording as well as at the time of removing the record.

The Roorkee Seismoscope and the Structural Response Recorders with identical period and damping specifications were fixed on a shake table and a random motion of suitable intensity was given by a hammer impact. The maximum trace amplitudes obtained simultaneously for both were interpreted in terms of acceleration response values. It was observed

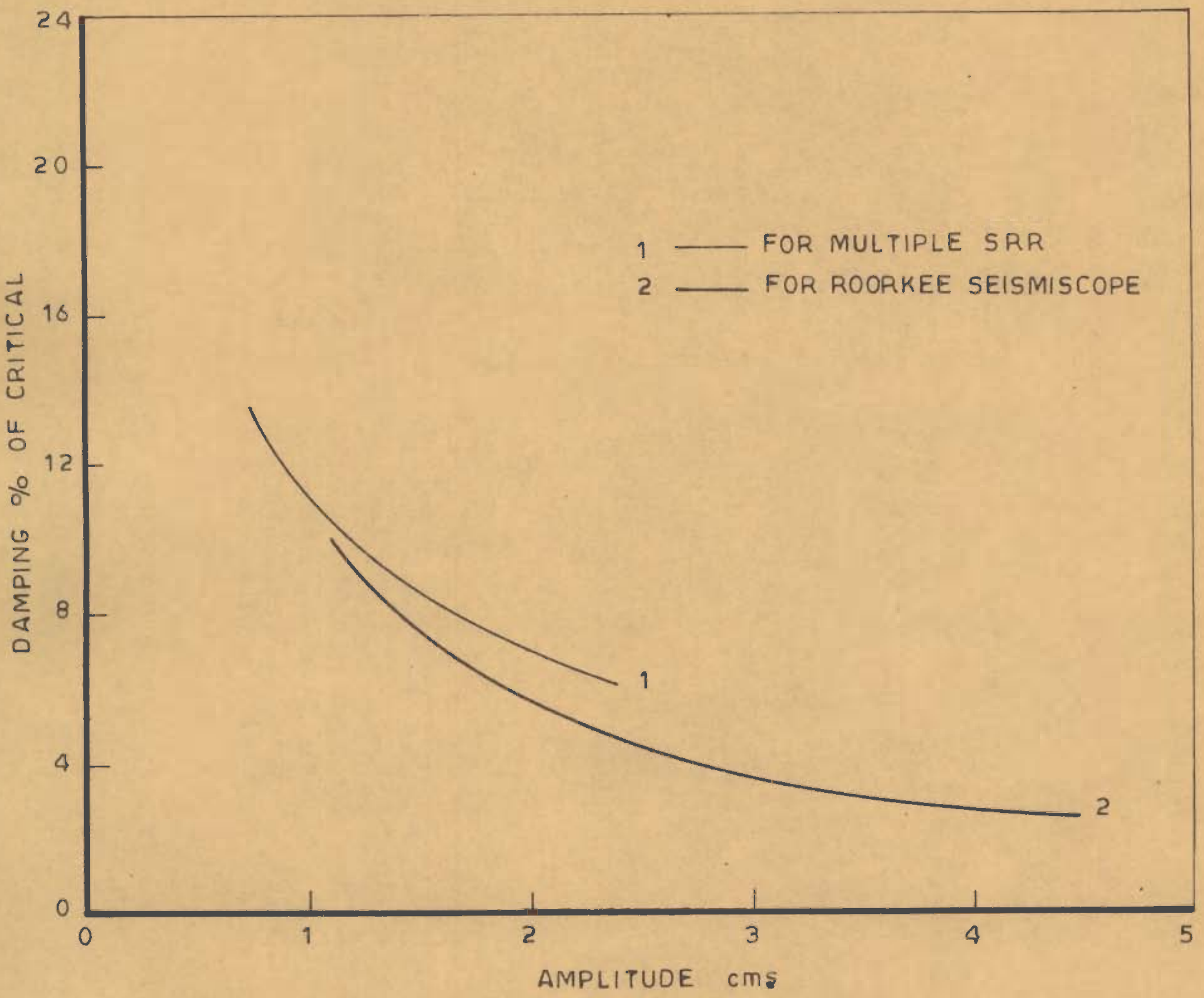


FIG. 2-4.TYPICAL GRAPHS SHOWING VARIATION OF DAMPING VERSUS AMPLITUDE OF RECORDING IN MULTIPLE SRR AND ROORKEE SEISMOSCOPE

that the results from these devices as given in Table 2-2 agreed well.

TABLE 2-2

Comparison of Seismoscope Results from Shake Table Test

	ROORKEE SEISMOSCOPE			SRR (SINGLE UNIT)		
A.	Period 0.40 sec Damping 5% of critical L+ = 15 cm			Period 0.40 sec Damping 5% of critical, Tilt sensitivity 1.733 cm/radian		
Sl. No.	Double Amplitude(max) mm	ϕ degrees	Acceleration % of g	Double Amplitude(max) mm	ϕ degrees	Acceleration % of g
1	93.5	17.28	30.15	10.8	17.88	31.2
2	33.0	6.28	10.95	4.0	6.61	11.5
B.	Period 0.75 sec Damping 5% of critical L = 15 cm			Period 0.75 sec Damping 5% of critical, Tilt sensitivity 3.623 cm/radian		
Sl. No.	Double Amplitude(max) mm	ϕ degrees	Acceleration % of g	Double Amplitude(max) mm	ϕ degrees	Acceleration % of g
1.	57.5	10.85	18.9	14.2	11.22	19.5
2.	88	16.35	28.5	21.8	17.24	20.0

+ The length of the pendulum under equilibrium condition.

The maximum deflection (ϕ_{max}) of the recorder pendulum during an earthquake can easily be determined from the record and the pendulum dimensions, provided a suitable solution is available for its equation of motion.

The equation of motion for a single degree freedom linear viscous damped pendulum (Krishna and Chandrasekaran, 1962) is:

$$\ddot{\Phi} + \frac{c\,b^2}{I_o}\dot{\Phi} + \frac{m\,g\,a}{I_o}\Phi = -\frac{m\,a}{I_o}\ddot{y}\,(\tau)$$

where

Φ is the angle of deflection,

m mass of the pendulum,

I_o the moment of inertia about any axis through the centre of rotation,

c viscous damping coefficient,

a distance from centre of rotation to the centre of mass,

b distance from centre of rotation to the line of action of damping force,

g acceleration due to gravity and

$\ddot{y}(\tau)$ horizontal ground acceleration due to earthquake.

The solution to this equation is:

$$\phi = \frac{2\pi}{gT\sqrt{1-n^2}}\int_0^t \ddot{Y}(\tau)\,e^{-\frac{2\pi n}{T}(t-\tau)}\sin\frac{2\pi}{T}\sqrt{1-n^2}(t-\tau)\,d\tau$$

where $T = 2\pi\sqrt{\dfrac{I_o}{mga}}$ and $n = \dfrac{C}{C_c} = \dfrac{cb^2}{2\sqrt{mgaI_o}}$

On the other hand the equation of motion for a single degree of freedom coulomb damped pendulum can be written as:

$$\ddot{\Phi} + \frac{m\,g\,a}{I_o}\Phi + \frac{F}{m}\,\mathrm{sgn}\,(\dot{\Phi}) = -\frac{m\,a}{I_o}\,\ddot{y}\,(\zeta)$$

where all the notations have above meaning and F is the constant friction term. The term $\frac{F}{m}$ is equivalent to $4\pi^2\Delta/T^2$, where Δ is 1/4th of the reduction in the displacement per cycle during free vibration of the pendulum. The above equation with constant friction can be solved for Φ by numerical techniques.

In the Multiple Structural Response Recorder provision for viscous damping by a permanent magnetic field was made, whilst in the Roorkee Seismoscope no auxiliary arrangement for viscous damping was provided with a view to further simplifying its design. However, the absence of an auxiliary damping did not appreciably change the behaviour of the system would be clear from the following discussion.

In any real system, viscous and non-viscous friction would in general occur and only their relative magnitudes may be made to vary by the choice of proper design. Usually there will be a lower limit beyond which it may not be feasible in such simple devices to reduce the inherent damping of the system. This lower limiting value of inherent damping of the system would be of greater significance particularly in situations where the total damping requirement is low. In the Multiple Structural Response Recorder the inherent damping of the system constitute upto about 50% and 90% of the total damping requirement for 0.40 and 1.25 second pendulums respectively. For the 0.75 second period pendulum this was about 60%. The relative magnitude of the inherent damping and the specially provided viscous damping would also depend on the amplitude of recording apart from the design features of the system and this variation again would have greater importance for systems with low damping. With this background it was felt that perhaps for damping upto 10% of critical the introduction of small external viscous damping may not appreciably change the behaviour even if the system's inherent damping itself was suitably increased to the desired level. In order to examine this view point and to permit appropriate choice of the solutions to represent the behaviour of the two devices, the deviations of their amplitude decrement curves from the ideal amplitude decrement curves assuming both constant and viscous friction were studied (vide Figures 2-5 and 6). In both these cases the actual behaviour was more or less identical but closer to the viscous damping curve.

Hudson (1960) using the solution for the viscous friction obtained results for the type of pendulum used in the Multiple Structural Response Recorder. This compared very well with the computed values within the workable accuracy as would be expected on the basis of the comparison given in Figures 2-5 and 6. As the actual damping behaviour of the Roorkee Seismoscope was barely distinguishable from that of the Multiple Structural Response Recorder, it was considered justifiable for all practical purposes to use Hudson's solution for this instrument. Another

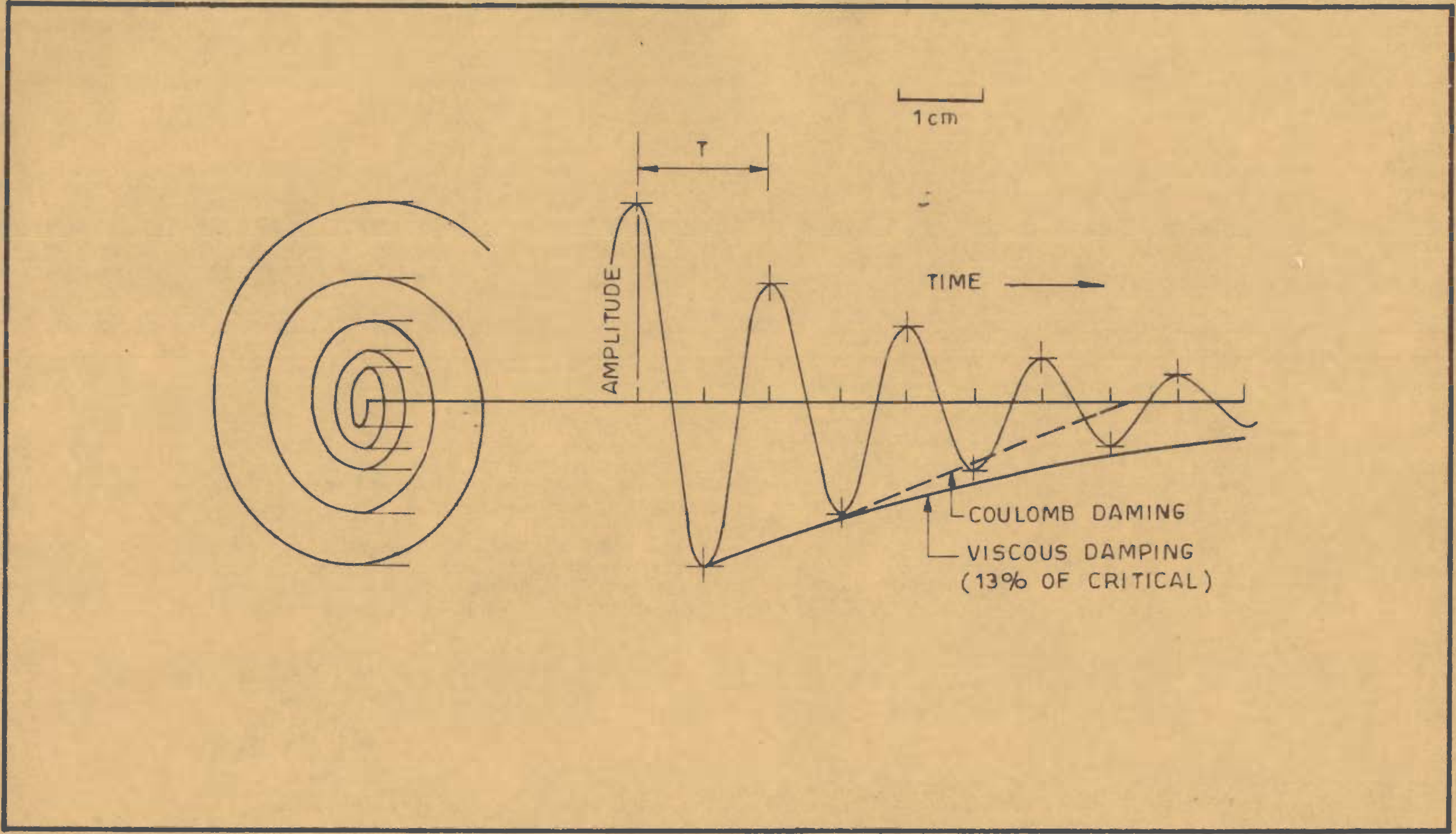


FIG. 2-5. GRAPH SHOWING AMPLITUDE DECREMENT BEHAVIOUR OF THE MULTIPLE SRR

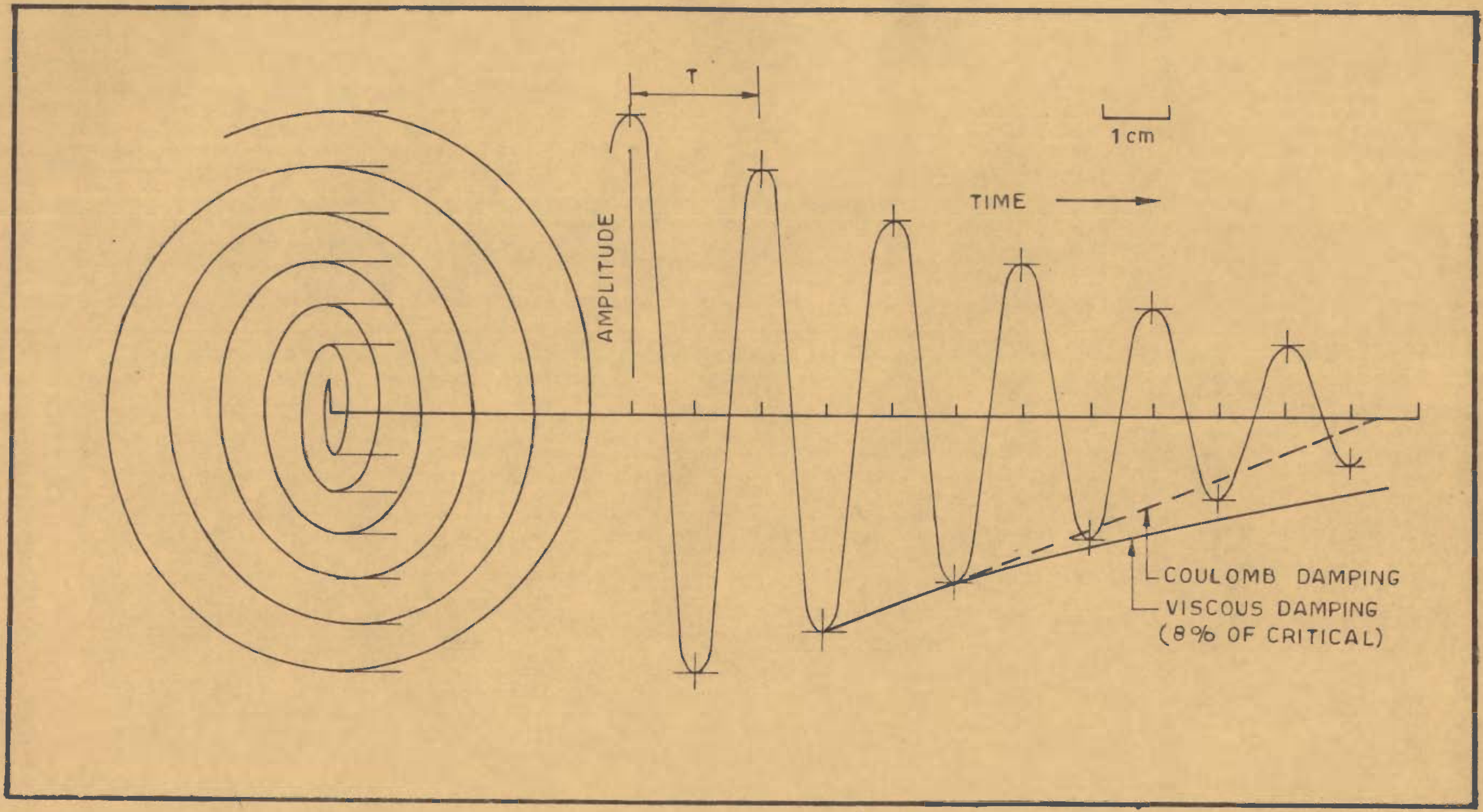


FIG. 2-6. GRAPH SHOWING AMPLITUDE DECREMENT BEHAVIOUR OF THE ROORKEE SEISMOSCOPE

important reason for adopting this solution lies in the fact that the techniques developed and generally made use of for structural analysis are based on viscous damped oscillators and the results from these devices would be directly utilised in such analysis.

The equation of the recorder pendulum motion thus selected can be compared with the equation of motion of a single degree freedom viscous damped linear oscillator and the following relation (Hudson and Cloud, 1967) obtained between Φ_{max} and maximum relative displacement response value (S_d).

$$S_d = \frac{g\,T^2}{4\,\pi^2}\;\Phi_{max}$$

The usual approximate relation between S_d and the relative velocity response (S_v) value is given below:

$$S_v = \frac{2\,\pi}{T}\;S_d$$

or $$S_v = \frac{g\,T}{2\,\pi}\,\Phi_{max}$$

Similarly, the acceleration response, which is the absolute acceleration of the system mass (not the ground acceleration) is:

$$S_a = \frac{2\,\pi}{T}\;S_v = \frac{4\,\pi^2}{T^2}\;S_d$$

Thus from the records obtained during an earthquake S_d, S_v or S_a for the dynamically equivalent idealised structure can easily be obtained.

2.1.3. Limitations of these Devices

Devices similar to the Multiple Structural Response Recorders and Roorkee Seismoscopes have been in use elsewhere. Damping in these devices which varies with the amplitude of recording, is an important parameter influencing the structural response. In general, different pendulums will give records of different amplitudes and at those amplitudes the damping in the devices would generally be different. Thus the objective of plotting response curves could never be achieved by employing a combination of these devices, although a number of points on different response curves would be obtained. But whereas damping can be estimated with reasonable accuracy at larger amplitudes, its determination involves large uncertainties at lower amplitudes of recording. Hudson and Cloud (1967) have discussed in detail the uncertainties of damping at the low levels of recording for their seismoscope with 0.75 second period. The limitations discussed by them are all valid for the 0.40 and 0.75 seconds pendulums of the Multiple Structural Response Recorder. However, for the 1.25 second pendulum the stylus friction alone results in 5% of critical damping at 5 mm double amplitudes producing additional inaccuracy in damping estimates. In any mechanical device using stylus for recording, the above mentioned uncertainity shall always exist at low amplitudes. As a solution to this it was considered desirable that these devices could be made to write large records even for small response values so that uncertainties in the determination of damping could be reduced. This idea was incorporated in the 'Roorkee Seismoscope' which employs no auxiliary damping arrangement and is mainly damped by non-viscous friction. The influence of friction increased very sharply at amplitudes lower than 5 mm. The increased nonlinearity of variation of damping with amplitude at this low level of recording in the Roorkee Seismoscope still retained the same limitations.

2.2. DEVELOPMENT OF PORTABLE WATER TUBE TILTMETER

2.2.a. Background of the Development

The earliest reference known to the author regarding the use of water surface as a reference in the observations of the tilting of the earth's crust was reported by Takahasi (1930) employing a pair of water pipes. Subsequently, during the 1940's a number of reports of observations employing water tube tiltmeter, were published. Description of one such system employed for the observations of determination of the earth's crust at Aburasubo Miura Peninsula was given by Hagiwara et al (1949). Perhaps the earliest reference of a Portable Water Tube Tiltmeter giving details of the design of the instrument used was made by Eaton (1959) who employed it for measurement of ground deformation associated with volcanic activity in Hawaii. Another detailed report on the design of a Recording Water Tube Tiltmeter was published by Eto (1966). Such systems have high inherent accuracy on account of the time independent common reference surface. Therefore, it was considered desirable to develop a portable system for measuring small scale movements asso-

2.2.1. Description of Portable Water Tube Tiltmeter

The system developed (Agrawal and Gaur, 1968) is somewhat similar to the one described by Eaton (1959). Figures 2-7 and 8 show this instrument in the initial and final stages of development. The system consists of two cylindrical vessels (inner diameter 105 mm, outer diameter 120 mm and height 215 mm) each provided with a microscope and a dry battery, contained in separate boxes, and an alkathine tubing of 55 meter length. The vessels have a built-in partition at their mid-heights and the two halves are screwed together just below the partition. On the lower side at the centre of the partition, a 0.5 mm pitch micrometer spindle is provided whose free pointed end intrudes in the upper half of the vessel through a leak proof cell. A micrometer disc with 100 divisions alongwith a micrometer spindle guide at its centre is capable of rotation at a fixed position and the rotation of the disc moves the spindle up and down. A pointer fixed at right angles to the micrometer spindle at its lower end slides against the main scale. A suitable gear arrangement is provided to permit the slow movements of the micrometer spindle. A vernier attached to the micrometer disc provides a least count of .0005 mm (0.5 micron). The upper pointed end can be illuminated by a bulb whose position is adjustable and is attached to the top lid of the vessel. The base plate of the vessel forms a seat which enables it to be replaced on the base-hub in exactly the same position during successive measurements. The vessels are made heavy, their weight distributed uniformly throughout, so as to avoid overturning

FIG. 2-7. PHOTOGRAPH OF THE PORTABLE WATER TUBE TILTMETER SYSTEM IN ITS INITIAL STAGE OF DEVELOPMENT

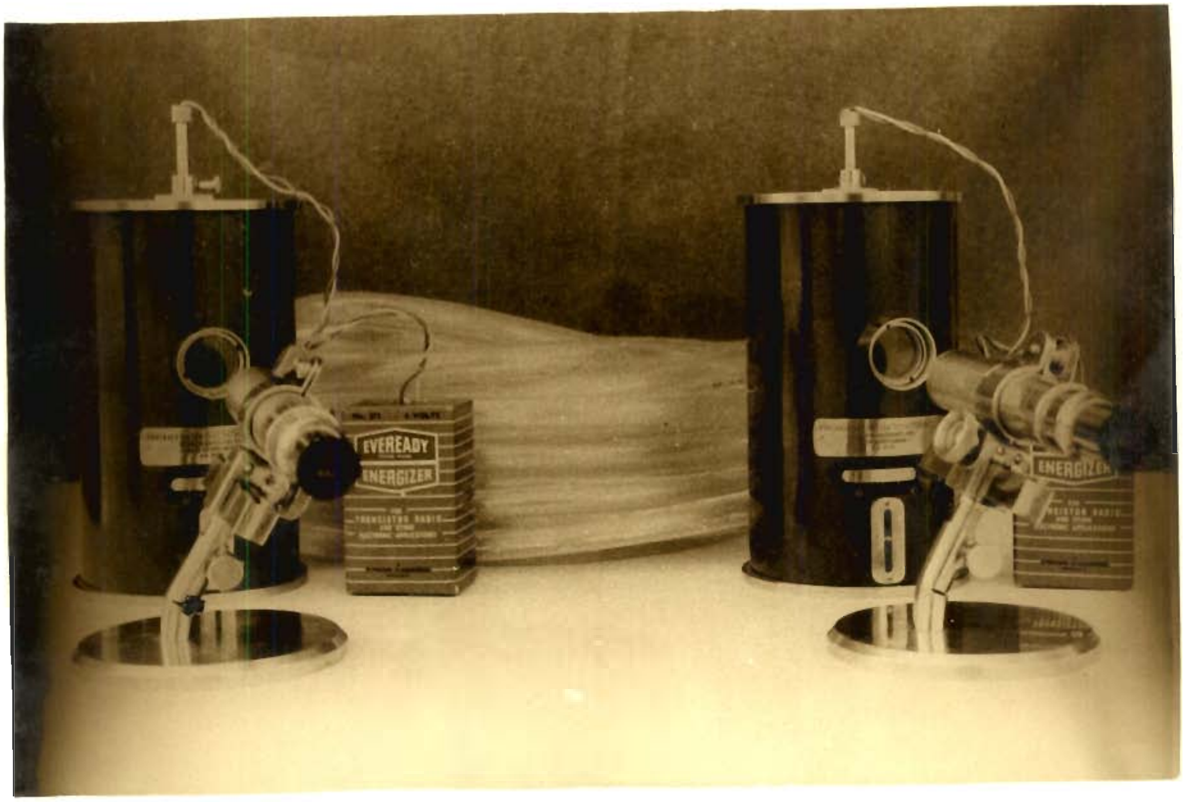


FIG. 2-8. PHOTOGRAPH OF THE PORTABLE WATER TUBE TILTMETER SYSTEM IN ITS FINAL STAGE OF DEVELOPMENT

and to ensure identical fixity to the base-hub during successive measurements without the need of an auxiliary screwing arrangement. A viewing window is provided just above the main scale. The water tube is connected opposite to the viewing window at the lowest level in the upper half of the vessel. The microscope on a separate stand is used for viewing the pointer of the micrometer spindle while making a setting. The line of sight can be made inclined to the water surface aiding more accurate setting of the pointer.

2.2.2. Equation of Motion of the Water Level in the System

For the purpose of the above analysis, water can be considered to be an ideal homogeneous, frictionless, continuous and incompressible fluid. Let us consider the equation of the water surface in the tiltmeter system for which a schematic diagram is given in Figure 2-9 where:

A_1, A_2	are the cross-sectional areas of Pot 1 and 2,
a	the cross-sectional areas of the water tube, the length of water tube,
L	the height of water surfaces in the two pots above the centre of the water tube, after equilibrium has been established,
Z_1, Z_2	the heights above datum of the water surfaces in Pot 1and 2 and
h_1, h_2	the heights of water surfaces in Pot 1 and 2 above its equilirbium position.

From the Euler's equation we can write the equation of motion of the water surface in the system as follows:

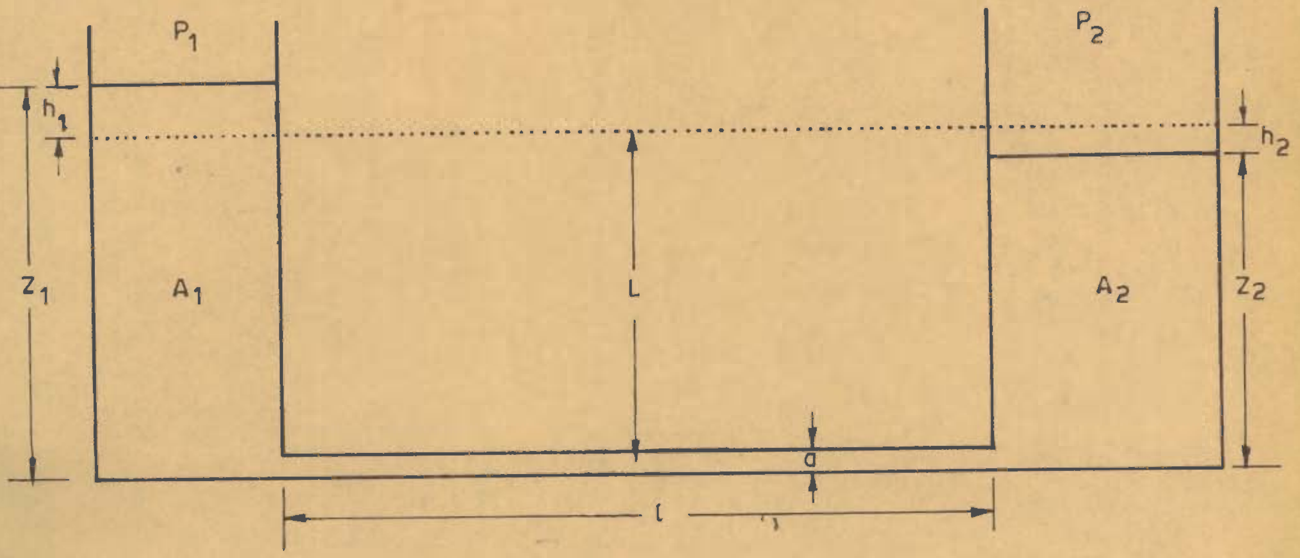


FIG. 2-9. SCHEMATIC DIAGRAM SHOWING MOVEMENT OF WATER IN THE PORTABLE WATER TUBE TILTMETER

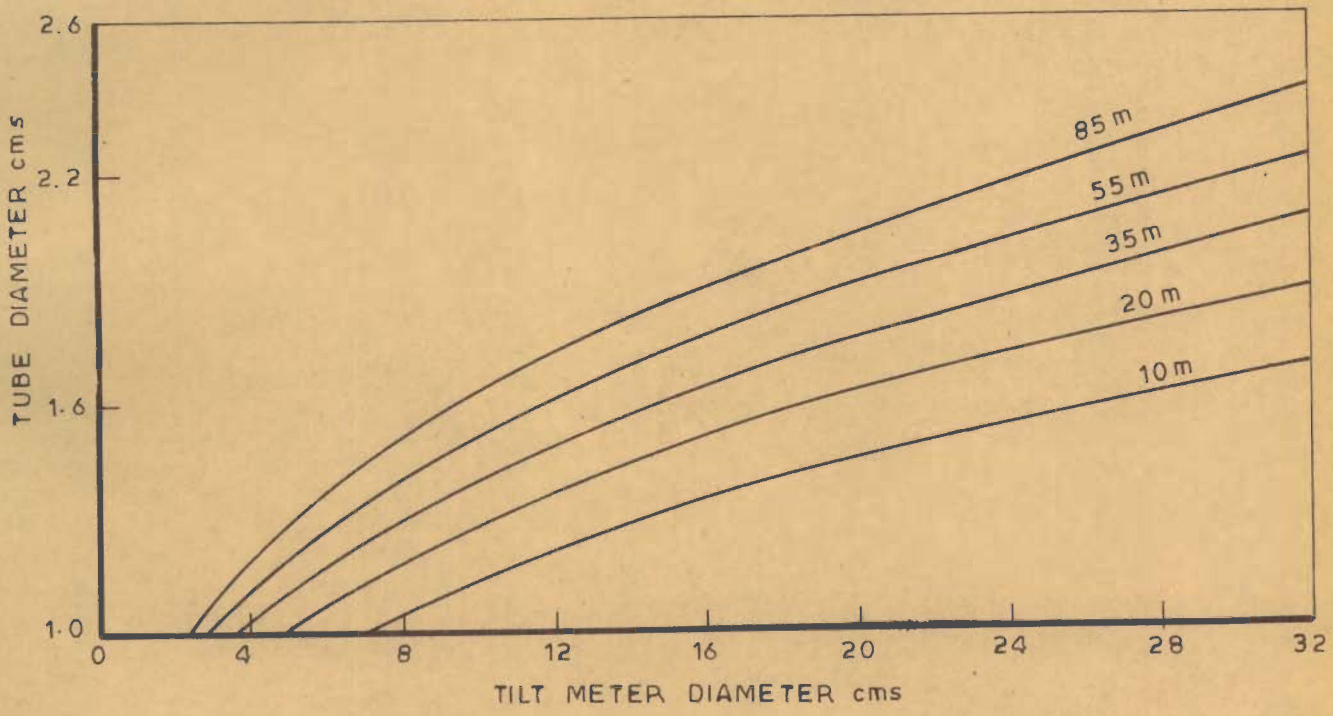


FIG. 2-10. GRAPHS SHOWING TUBE VERSUS TILTMETER DIAMETERS COMPUTED FOR CRITICALLY DAMPED MOVEMENT OF WATER SURFACE WITH DIFFERENT TUBE LENGTHS

$$\frac{\partial}{\partial s}\left(\frac{1}{2}v^2\right) + \frac{1}{\rho}\frac{\partial p}{\partial s} + g\frac{\partial z}{\partial s} + \frac{\partial v}{\partial t} = 0$$

where the body force is conservative and other symbols have the following meaning.

v is the velocity of the water,

ds element of the stream line,

p external pressure,

z height above an arbitrary

ρ density of the water.

The line integral of Euler's equation along a stream line from Pot 1 and 2 through the water tube can be expressed as:

$$\frac{1}{2}(v_2^2 - v_1^2) + \frac{1}{\rho}(p_2 - p_1) + g(Z_2 - Z_1) + \frac{dv_1}{dt}\int_1^2 \frac{A_1}{A(s)}\,ds = 0$$

where subscripts 1 and 2 indicate the values of variables in Pot 1 and 2 and $A(s)$ is the cross-sectional area of the water tube.

This equation can be rewritten in the following form:

$$\rho\left(L + \frac{A_1}{a}\ell + \frac{A_1}{A_2}L\right)\frac{d^2h}{dt^2} + \frac{\rho}{2}\left(1 - \frac{A_1^2}{A_2^2}\right)\left(\frac{dh}{dt}\right)^2 + \rho g\left(1 + \frac{A_1}{A_2}\right)h = 0$$

or $\left(2L + \frac{A}{a}\ell\right)\frac{d^2h}{dt^2} + 2\rho gh = 0,$ as $A_1 = A_2$

The first term represents the inertia pressure which tends to resist any change in the motion of water whilst the second term is the pressure tending to bring the system to equilibrium. Another term need be included in the equation to account for the pressure required to overcome the internal friction in the water flowing through the tube which is long and narrow. By Hagen Poiseuille's law this term can be calculated and included in the equation as follows:

$$\frac{d^2h}{dt^2} + \frac{8\pi\eta\ell A}{\rho a^2(2L+\frac{A}{a})}\frac{dh}{dt} + \frac{2\,gh}{(2L+\frac{A}{a}\ell)} = 0$$

where η is the viscosity of water. For the system under discussion $2L \ll A\,\ell/2$ which simplifies the equation to:

$$\frac{d^2h}{dt^2} + \frac{\pi\eta}{\rho a}\frac{dh}{dt} + \frac{2\,gha}{\ell A} = 0$$

This equation can be solved for h and the values of A and a, computed for critically damping the movement of the water surface when connected by a tube of suitable length. Critical damping is necessary in order that the water surface comes to rest in the shortest time after water has been filled in the system. The various possible tube and pot diameters for the critically damped condition were computed for different tube lengths and are plotted in Figure 2-10. The system described here was designed for use with a 55 meter long tube.

2.2.3. Performance of the System

An unaided human eye can normally resolve a separation of upto 0.10 mm. A microscope of 30 times magnification improved the resolution to 0.1/30 x 2 mm i.e. 2 microns. The factor of 2 in the demominator is introduced on account of the gap between water surface and pointer being effectively doubled as the setting is made by viewing the gap between the pointer and its image. The least count of the instrument micrometer being 0.50 micron, it can conveniently permit measurements of this magnitude. In order to test the accuracy of setting and also to study the influence of personal error, the following tests were carried out.

(a) Reproducibility Test: The system was placed on two fixed bases and observations taken both with and without changing the common water level during a test. Each reading was found to deviate by not more than ± 3 microns giving a standard deviation of within about 4 microns. However, this error could be further reduced by suitably training the eye, since the contribution of the personal error was found to be substantial. Typical graphs for these results are given in Figure 2-11.

(b) Laboratory Test: A 15 x 20 cm, U-shaped, section steel channel was supported on two knife edges 5 meters apart. The channel was loaded at its centre by weights in steps of 1 kg. One tilt base-hub was fixed a little distance away from the beam and the other was built-in the steel channel itself at the point where provision for loading was made. Thus the flexure of the beam for different loads could be measured by the system. The results thus obtained show a close agreement with those obtained theoretically.

(c) Field Test: Three series of measurement were made at Dakpather over a period of several hours. The

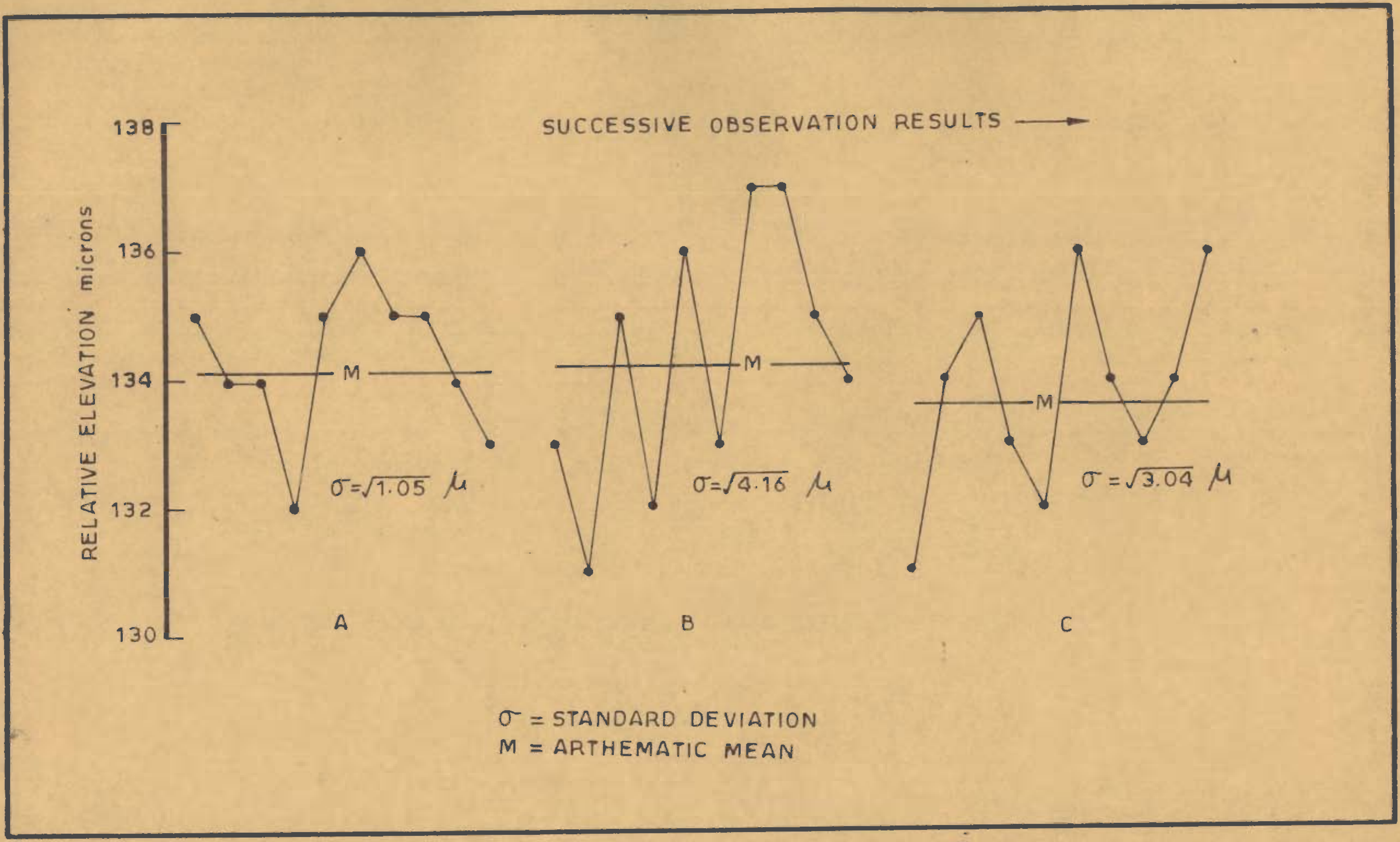


FIG. 2-11. TYPICAL GRAPHS SHOWING THE SCATTER OF TILTMETER RESULTS DURING THE REPRODUCIBILITY LABORATORY TEST A, B AND C – THREE SEIRES OF MEASUREMENTS WITH AND WITHOUT CHANGING WATER LEVEL

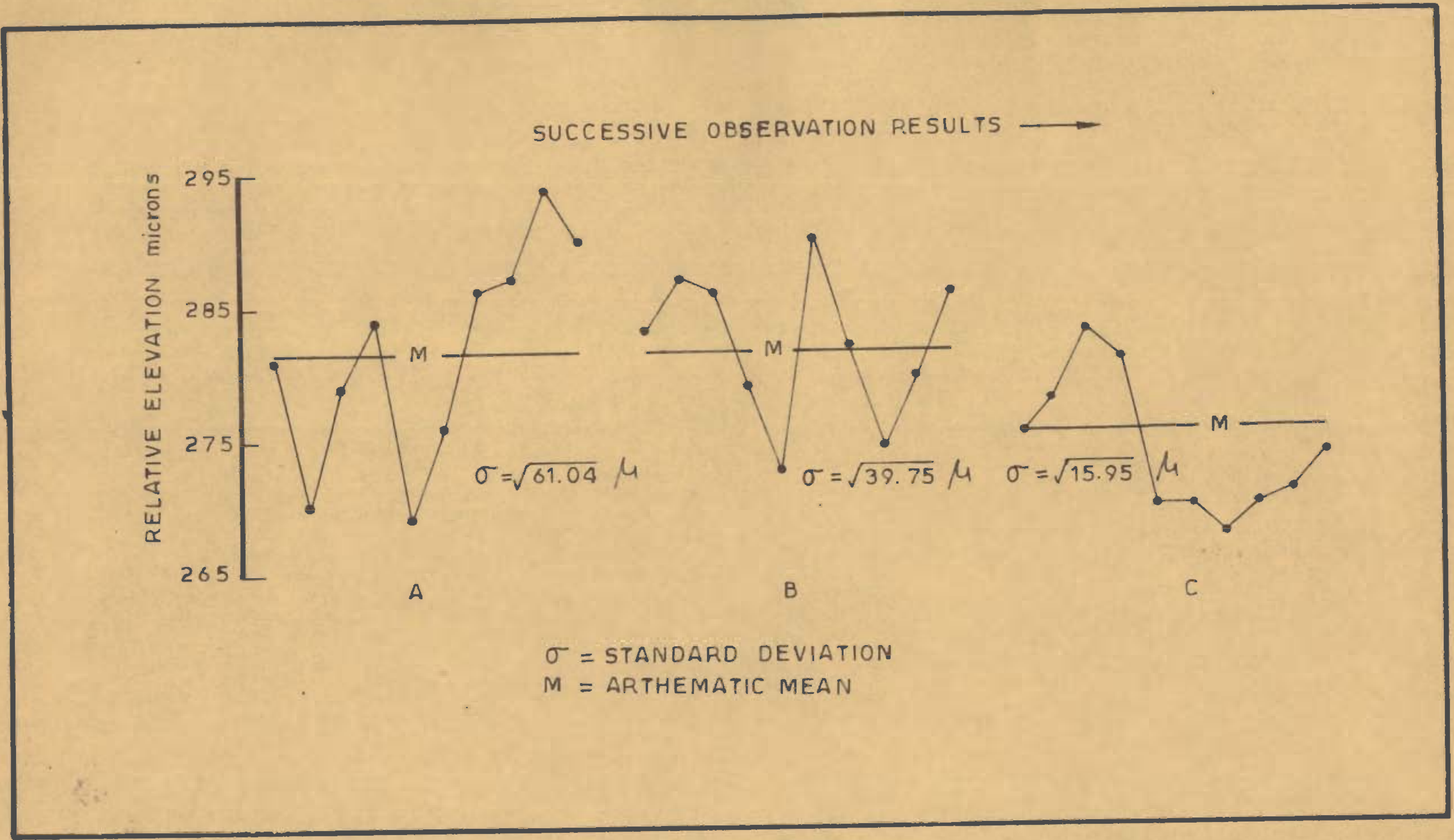


FIG. 2-12. TYPICAL GRAPHS SHOWING THE SCATTER OF TILTMETER RESULTS IN THE FIELD APPLICATION DURING THREE SERIES OF MEASUREMENTS A_INTIAL SERIES, B_AFTER REST FOR 2 HOURS AND C_AFTER CHANGING THE WATER LEVEL

representative set of observations have been plotted in Figure 2-12. Which gives a standard deviation within 8 microns. In the beginning a lowering of the reading at both the tiltmeters was observed which was found to be due to the entry of water in the minute voids along the micrometer spindle by capillary action.But this did not influence the relative elevation figures perhaps because it happened identically to both the micrometers.

From these tests an accuracy of ± 10 microns of the performance of the system could be established.

2.2.4. Factors Influencing Field Measurements

The ground deformations in any region may be considered to consist of two components (i) local and (ii) regional deformations. Local deformations may vary widely both in space and time and may arise from various causes notably, differential heating, differential loading, underground mining, action of ocean tides on the coast, earth tides, and variation in the underground water table. All these local deformations are caused by non-tectonic processes and are usually larger compared with regional deformations. The latter, on the other hand, could arise both from tectonic as well as non-tectonic processes. For example, continuous pumping of ground water could result in ground deformations of a regional character. Influence of such factors had therefore to be eliminated from the figures. This could be achieved by a suitable planning of the measurements and by accounting for any possible sources of deformations. Detailed field procedures used to achieve this are given in Appendix - II. The working conditions in the field also influence the measurement accuracy which in general increase the personal error.

CHAPTER 3

DATA FOR THE KOYNA REGION

3.0. GENERAL

Koyna is located at 17° 23' N 73° 45' E on the West coast of India. It lies to the SSE of Bombay at a distance of 190 km and to the east of the continental divide about 80 kms inside the coast line. The Koyna river, a tributory of the river Krishna, flows roughly parallel to the coast line right from its source near Mahabaleshwar for a distance of 60 kms upto Koyna. At Koyna the river takes an abrupt easterly turn and meets the river Krishna near Karad which flows across the Peninsula into the Bay of Bengal. The Koyna dam, 103 meter high rubble concrete gravity dam, lies at an altitude of 580 meters above sea level. The underground power house is located at Pophali about 1 km away to the NNW of Koyna. The relevent data utilised for the evaluation of earthquake parameters in this region have been discussed in the following pages.

3.1. GEOLOGY

The Koyna region is located in the western Ghats of the triangular Peninsular Shield of the Indian subcontinent generally considered a stable block consisting of older metamorphosed basement rocks which have been subjected to tectonic activity during the various geological times, resulting in the formation of rifts and down faulted depressions in its interior and on the coastal margins. In these troughs were deposited the Cuddapahs, Vindhyans, Gondwanas and other younger formations. The Gondwana rocks were laid down as a thick series of fluviatile or lacustrine deposits in shallow and slowly sinking basins following the Hercynian orogeny. The shield was also affected by the great diastrophic movements in the western parts which resulted in the outpouring of Deccan traps (the basaltic flows) over the existing Precambrian and younger formations, at a time which marked the beginning of the Himalayan orogeny (Cretaceous to Eocene-Oligocene times). The Gondwana rift system exhibits a radial pattern converging towards the northern shield and their trend gradually changes from E-W in Bihar-Bengal and NW-SE along the Mahanadi to NWN-SES along the Godawari suggesting a N-S rift filled with Gondwana sediments lying below the Traps. The thickness of the Traps vary greatly from place to place, average estimates being 2 to 3 kms. Detailed structural mapping has not been done for the entire region but investigations have revealed the existence of several faults and shear zones. The Western ghats escarpment extending N-S for 450 km appears to be associated with a major fault. Another major fault is the E-W rift, 70 km in width, extending along the Namada Tapti river system. A NW-SE fault system close to the shelf towards the sea and parallel to the present coast line with downthrow towards SW has been traced recently. Fractures having N-S and WNW-ESE trends are met within the Traps at several locations.

The western slopes of the scarp of the Western Ghats in Koyna region usually referred to as the Sahyadri ranges are sudden, abrupt and rugged whereas the eastern slopes are gradual and comparatively less rugged. The eastern slopes are marked with large flat hill-tops and ridges forming the water-shed between its long V-shaped valleys, though the main water-shed in the area is due to the continental divide itself. The hill-tops have laterite cappings of variable thicknesses and slopes are also covered with lateritic soil. Hot springs with temperature ranging from 49°c to 69°c also occur from Cambay in the north to Ratnagiri in the south a few kilometers inside the western coast.

In the Koyna region itself the basaltic lava flows show more or less uniform lithological character .They however, do not show any surface evidence of intrusions nor of dislocations in the Koyna valley. Only a set of predominantly vertical joints roughly in N-S directions is present. However, the lava flows show some zones of shearing and shattering.

3.2. GRAVITY ANOMALIES

The Koyna region of low Bouguer Anomaly (-100 milli-gals) flanked by high positive anomaly zones represents an area of high gravity gradients which in turn reflect uneven distribution of subsurface matter producing conditions of instability. Glennie (1932) has worked out a gravity gradient of about 2.5 milligals-per km between Colaba (+ 63 milligals) and Panvel (-18 milligal). However, no such variations have been reported in the Deccan traps perhaps because their sources probably lie in the basement. Glennie therefore, attributed the large gravity gradients to the presence of a large dyke parallel to the coast which might have acted as a feeder to the lava flows.

3.3. SEISMIC HISTORY

Peninsular India has been largely regarded as one of the aseismic Precambrian blocks. Such a belief was probably founded on the basis of minor earthquake activity in living memory and absence of the historical data regarding past earthquakes. The earthquakes reported for the Peninsula have been listed by Guha et al (1968) and broadly show that the shield suffered only minor activity along the coastal margins. The Koyna region itself was not visited by any important earthquake since the shock of 1764. The seismological observatory at poona which was first equipped with a sensitive Benioff seismograph in the 1950's recorded only minor activity in this area. But at the beginning of the last decade the officers of the Koyna Hydroelectric Project, who were posted in the region reported a number of earth tremors. Soon a network of four Seismological Observatories was commissioned for the region. The number of earthquakes felt between January 1963 and September 13,1967 showed a gradual increase. An earthquake of magnitude 5.7 (estimates ranging upto 6) with its epicentre at 17^{o} 24.0' N, 73^{o} 44.8' E occurred on September 13,1967 and caused some minor structural damage. Subsequently on December 11,1967, occurred the largest event of magnitude 6.5 (estimates ranging upto 7.5) wracking havoc in the Koyna area and even affecting the dam. Eversince then, a large number of shocks have continued to occur in this region.

3.4. SEPTEMBER 13,1967 KOYNA EARTHQUAKE

The September 13,1967 earthquake had a magnitude of 5.7 (Guha et al, 1968) Epicentre: 17° 24.0'N 73° 44.8' E; Origin time 06 48 24 hours GMT and Focal depth. 4 kms (as determined by the India Meteorological Department from data obtained by the Indian Stations (Tandon and Choudhury, 1968). It was felt throughout an area of 120 kms radius and caused great panic amongst the people at Koyna. Minor cracks in the plaster appeared in a number of buildings at Koyna and a few poorly constructed houses in rubble masonry were damaged by the partial failure of their walls. The estimated maximum intensity was VII. The frequency distribution of foreshocks and after-shocks is given in Figure 3-1 and would show that the activity attained its normal trend within about two to three weeks. The record obtained from a strong motion accelerograph (United electrodynamics AR-240) located in the dam at foundation level was reproduced in a report by Guha et al (1963). An enlarged version of this record was prepared for the purpose of digitization and is shown in Figure 3-2. The digitized data is given in Table 3-1.

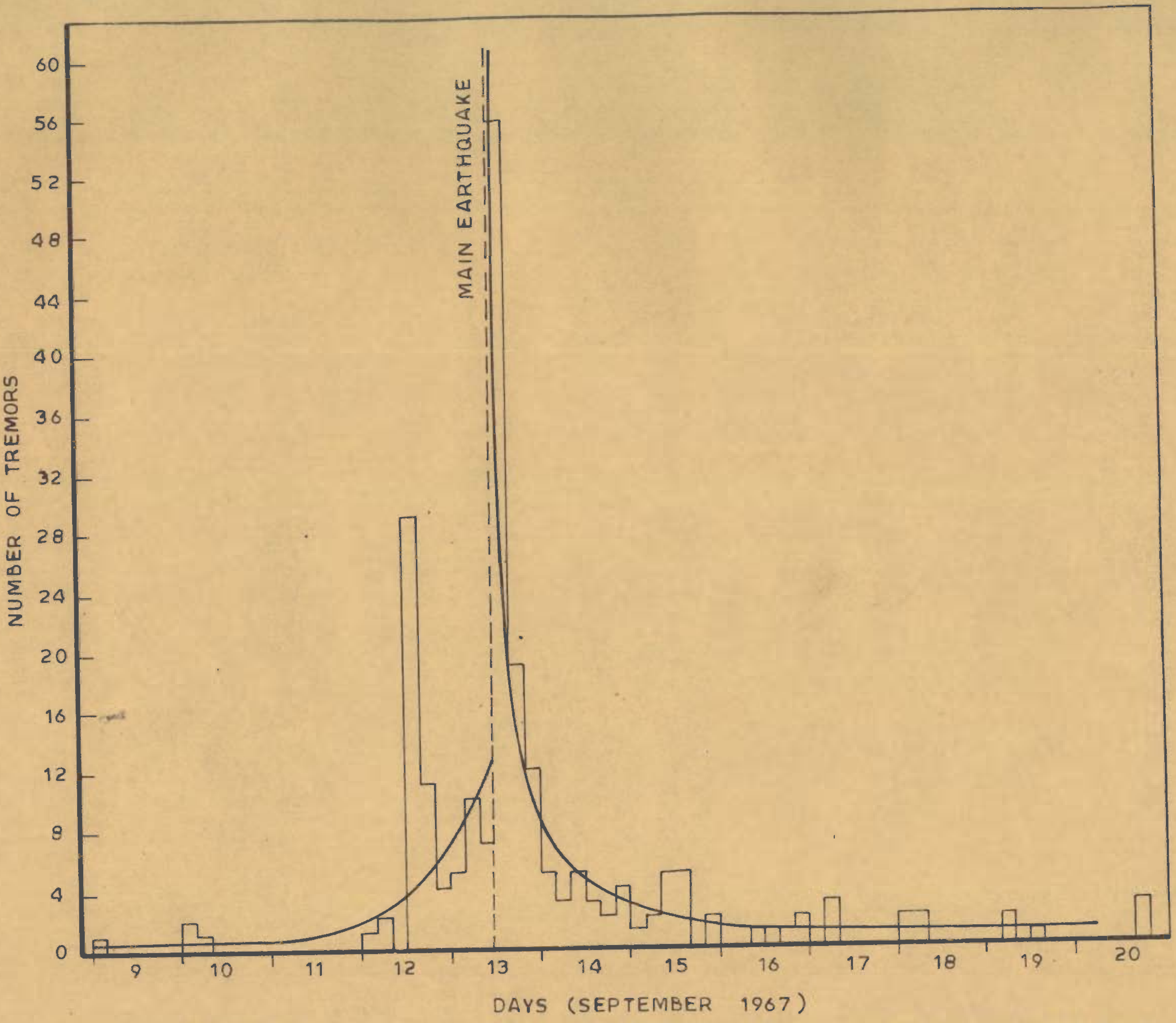


FIG. 3-1. FREQUENCY DISTRIBUTION OF FORESHOCKS AND AFTERSHOCKS FOR SEPTEMBER 13, 1967 KOYNA EARTHQUAKE GUHA ET AL

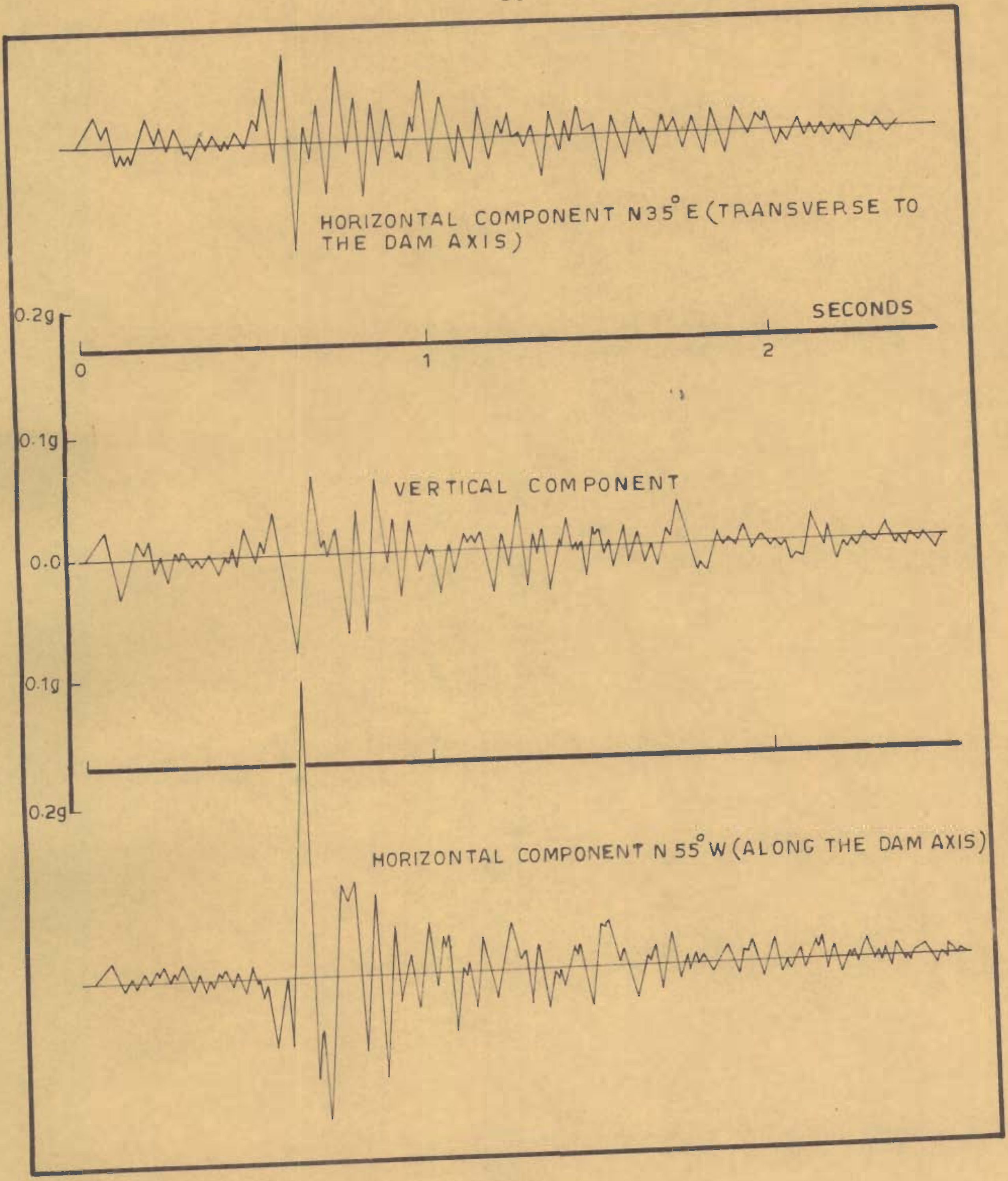


FIG. 3-2. ACCELEROGRAM OF THE SEPTEMBER 13, 1967 EARTHQUAKE AT KOYNA

TABLE 3-1

Digitized Data of September 13,1967 Koyna Earthquake

Transverse Component

NO.	TIME	ACCLN.	TIME	ACCLN.	TIME	ACCLN.	TIME	ACCLN.
1	0.0000	-.006137	.0547	.022261	.0771	.000140	.0925	.015025
2	.1212	-.022031	.1335	-.011458	.1494	-.021017	.1590	-.012826
3	.1702	-.018703	.2117	.019996	.2345	-.005386	.2500	.011272
4	.2707	-.012194	.2941	.010127	.3234	-.012119	.3361	-.009103
5	.3409	-.017972	.3680	.002732	.3877	-.009778	.4079	.004526
6	.4308	-.009751	.4436	-.001255	.4510	-.008484	.4760	.006281
7	.5031	-.009462	.5287	.016859	.5425	.004469	.5611	.044986
8	.5882	-.022909	.6143	.064597	.6478	-.096016	.6744	.010304
9	.6920	-.018371	.7159	.028087	.7441	-.038477	.7744	.064891
10	.8031	-.015006	.8292	.034418	.8510	-.053060	.8776	.028216
11	.8994	-.026375	.9244	.024227	.9500	-.018649	.9617	-.013425
12	.9686	-.021550	.9909	.013337	1.0026	.001228	1.0212	.046770
13	1.0478	-.025736	1.0819	.034668	1.1239	-.024311	1.1382	.011584
14	1.1696	-.030393	1.1962	.025094	1.2228	-.021492	1.2500	.013402
15	1.2648	-.000035	1.2781	.020151	1.2898	-.003518	1.3074	.003939
16	1.3297	-.012145	1.3558	.009112	1.3781	-.038084	1.4079	.023626
17	1.4329	-.014379	1.4515	.012484	1.4680	-.009693	1.4893	.024436
18	1.5042	.000326	1.5154	.011170	1.5239	.001562	1.5329	.010178
19	1.5632	-.040559	1.5925	.017142	1.6324	-.023944	1.6585	.021895
20	1.6760	-.004137	1.6882	.004187	1.7117	-.019313	1.7382	.018969
21	1.7558	-.004397	1.7797	.013285	1.8026	-.016294	1.8308	.013248
22	1.8627	-.020906	1.8936	.020787	1.9255	-.020480	1.9622	.020333
23	1.9946	-.007010	2.0212	.013928	2.0414	.006707	2.0478	.016052
24	2.0803	-.015739	2.1005	.000592	2.1159	-.009898	2.1446	.011040
25	2.1659	-.006700	2.1845	.007997	2.2021	-.006344	2.2202	.005240
26	2.2404	-.005097	2.2553	.005296	2.2670	-.003721	2.2845	.002082
27	2.3037	-.010776	2.3244	.008217	2.3590	-.000473	2.3824	.009930

Longitudinal Component

NO.	TIME	ACCLN.	TIME	ACCLN.	TIME	ACCLN.	TIME	ACCLN.
1	0.0000	-.003638	.0500	.013252	.0845	-.012769	.1063	.001246
2	.1218	-.010645	.1436	.003372	.1595	-.008074	.1792	.006544
3	.1861	.004750	.1984	.009462	.2186	-.005546	.2287	.003320
4	.2372	-.002476	.2547	.010522	.2819	-.013681	.3021	.003018
5	.3191	-.014495	.3329	-.005188	.3414	-.011129	.3585	.004247
6	.3696	-.002735	.3776	.004510	.4021	-.010197	.4154	.004152
7	.4372	-.016473	.4590	.008827	.4664	-.009108	.4755	-.004676
8	.4893	-.019509	.5053	-.009308	.5265	-.062519	.5590	-.004778
9	.5702	-.061086	.6228	.233827	.6436	-.087819	.6595	-.046053
10	.6750	-.119101	.7234	.070944	.7393	.055973	.7601	.072112
11	.7872	-.066118	.8196	.064689	.8457	-.086425	.8734	.038018
12	.8893	-.027166	.9186	.014022	.9420	-.032935	.9734	.039518
13	.9946	-.014251	1.0111	.025015	1-0239	.015837	1.0292	.026358
14	1.0478	-.050815	1.0707	.001051	1.0808	-.005163	1.0898	.005065
15	1.1069	-.034180	1.1271	.023614	1.1648	-.026127	1.2117	.035257

Table Continued

NO.	TIME	ACCLN.	TIME	ACCLN.	TIME	ACCLN.	TIME	ACCLN.
16	1.2351	.004174	1.2494	.012637	1.2648	-.030452	1.2872	.017578
17	1.3138	-.034085	1.3329	-.003388	1.3446	-.011665	1.3510	-.003210
18	1.3611	-.020527	1.3925	.014935	1.3989	.006205	1.4085	.016001
19	1.4404	-.034011	1.4723	.032571	1.4840	.028448	1.4936	.034394
20	1.5196	.000377	1.5351	.010487	1.5707	-.028243	1.6047	.005766
21	1.6117	-.000734	1.6271	.013676	1.6452	-.024498	1.6755	.021362
22	1.7010	-.017083	1.7191	.003413	1.7297	-.007814	1.7452	.005268
23	1.7563	-.004771	1.7707	.003420	1.7978	-.008493	1.8356	.010445
24	1.8702	-.012252	1.8840	.007351	1.8989	.004292	1.9095	.014404
25	1.9446	-.016281	1.9771	.017914	1.9994	-.012813	2.0117	-.002987
26	2.0255	-.009896	2.0489	.007827	2.0686	-.009424	2.0952	.016612
27	2.1010	.008341	2.1122	.015796	2.1335	-.010629	2.1531	.009752
28	2.1765	-.013697	2.1957	.004018	2.2063	-.000376	2.2127	.005282
29	2.2234	-.006519	2.2510	.016573	2.2702	.000073	2.2819	.002944
30	2.2925	-.006039	2.3031	.007345	2.3223	-.010188	2.3372	.012109
31	2.3643	-.004196	2.3734	.000442	2.3787	-.005603	2=3962	+= 35 5
32	2.4095	-.002033	2.4196	.009575	2.4521	-.007285	2.4696	.002440

Vertical Component

NO.	TIME	ACCLN.	TIME	ACCLN.	TIME	ACCLN.	TIME	ACCLN.
1	0.0000	.000675	.0595	.024328	.1021	-.031901	.1531	.017211
2	.1723	.002720	.1888	.016520	.2047	-.012049	.2228	.003085
3	.2420	-.020296	.2643	.006843	.2771	-.001733	.2877	.007168
4	.3148	-.005835	.3292	-.001522	.3382	-.006993	.3585	.003696
5	.3898	-.013010	.4090	.001232	.4218	-.003940	.4297	.009401
6	.4446	-.009102	.4675	.026326	.4984	-.005052	.5111	.013181
7	.5234	.003117	.5468	.037359	.6148	-.080218	.6638	.068111
8	.6898	.007445	.7000	.013658	.7106	-.001787	.7313	.023557
9	.7648	-.063537	.7936	.040031	.8180	-.063958	.8489	.063459
10	.8792	-.008827	.9000	.026289	.9196	-.035631	.9457	.025558
11	.9755	-.015769	.9941	.007195	1.0069	-.001396	1.0127	.003493
12	1.0361	-.033690	1.0585	.006754	1.0739	-.018875	1.1063	.015641
13	1.1164	.006455	1.1303	.012528	1.1393	.005267	1.1521	.017117
14	1.1893	-.034888	1.2117	.015180	1.2335	-.014010	1.2648	.039757
15	1.2872	-.030323	1.3031	.014262	1.3175	-.004557	1.3313	.017954
16	1.3526	-.034795	1.3819	.008153	1.3888	.001779	1.4063	.027251
17	1.4212	-.001349	1.4319	.005607	1.4372	-.002988	1.4468	.005894
18	1.4622	-.024633	1.4803	.017280	1.4872	.009275	1.4984	.014749
19	1.5117	-.006148	1.5271	.006432	1.5675	-.017895	1.5696	.019288
20	1.5851	-.012872	1.6117	.014215	1.6361	-.013806	1.6478	.004404
21	1.6686	-.015911	1.6957	.015469	1.7069	.006124	1.7281	.037065
22	1.7808	-.021511	1.7936	-.012340	1.8122	-.019770	1.8420	.010563
23	1.8632	-.003537	1.8781	.005184	1.9031	-.002256	1.9218	.016236
24	1.9452	-.004832	1.9744	.007718	1.9989	-.002984	2.0175	.003801
25	2.0308	-.003329	2.0468	.002275	2.0585	-.016113	2.0739	-.009175
26	2.0962	-.013211	2.1276	.024513	2.1553	-.003682	2.1707	.012142
27	2.1936	-.018268	2.2143	-.001269	2.2255	-.007068	2.2446	-.000881
28	2.2622	-.006989	2.2898	.005253	2.3117	-.005011	2.3452	.015216
29	2.3686	-.007053	2.3824	-.000415	2.4005	-.007861	2.4180	.003359
30	2.4329	-.003042	2.4510	.003287	2.4829	-.011598	2.5260	.004746
31	2.5585	-.006292	2.5829	.002240	2.6095	-.002564	2.6271	.004354

TABLE 3-2

Magnitude of December 11,1967 Koyna Earthquake

Name of Station or number of Stations	Magnitude (M_S or M_B)	Source of the determination	Type of instrument	Type of the foundation
Delhi	7.5 (M_S)	I.M.D.	Standard W.A.	Rock
Delhi	6.5 (M_B)	I.M.D.	Benioff, Vertical	Rock
Vizagapatanum	7.4 (M_S)	I.M.D.	Standard W.A.	Rock
Pong	7.5 (M_S)	I.M.D.	Standard W.A.	Rodk
Bokaro	7.5 (M_S)	I.M.D.	Standard W.A.	Rock
Port Blair	6.5 (M_S)	I.M.D.	Standard W.A.	Rock
Dehradun	8.2 (M_S)	I.M.D.	Standard W.A.	Alluviam
Athens	5.9	-	-	-
Pasadena	6.5	-	-	-
Uppsala	6.25	Uppsala Observatory Sweden	-	-
Four very near Stations	7.0	CWPRS	Standard W.A.	Rock
Eighteen Stations	6.0 (M_S)	USCGS	-	-
Few European Stations	6.3 (M_B)	BCIS	-	-
Nine Stations in USSR	6.5-6.75	USSR	-	-

3.5. DECEMBER 11,1967,KOYNA EARTHQUAKE

Almost three months later on December 11, 1967, Koyna was again rocked by a shock of magnitude 6.5 (M_B, Delhi) which was the largest event in the recorded seismic history of Peninsular India. It caused some minor damage to the dam and extensive damage to other structures in the Koyna area. Typical damage photographs are given in Figure 3-3. It resulted in 180 deaths, injuries to 3,000 persons, damage to 10,000 houses, dislodging of 0.2 million persons, power shut down amounting to a loss of rupees twenty million interms of industrial production, etc. The isoseismal map prepared by the School of Research and Training in Earthquake Engineering(Arya et al, 1968)is given in Figure 3-4.

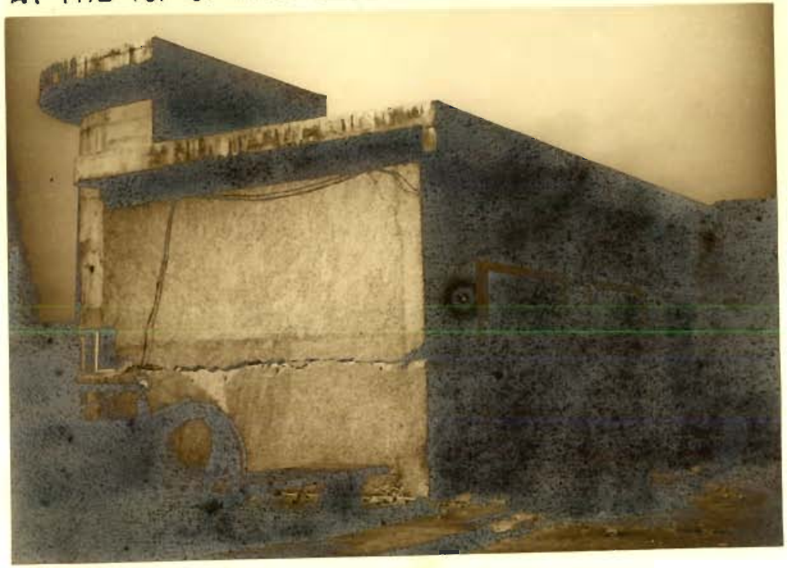
3.5.1. Magnitude Discrepancies

Table 3-2 gives the different reported magnitudes for this event and show a large variation in the values. Tandon and Choudhury(1968) have attempted to explain this by considering the existence of channel waves propagated in a low velocity (granitic) layer, sandwitched between Basaltic layers of higher velocities

3.5.2. Source Parameters

Determinations of epicentre, origin time and depth of focus by different organisations also varied considerably and are given in Table 3-3.

DAMAGED CONTROL ROOM CONSTRUCTED IN RCC AT THE TOP OF THE KOYNA DAM



DAMAGED PARAPET WALL AND THE TILES OF THE SIDE WALL AT THE TOP OF THE KOYNA DAM

DAMAGED BUILDING OF A PUBLIC SCHOOL AT KOYNA

DAMAGED TO ONE OF THE PORTALS OF THE SPILWAY BRIDGE HAVING ROCKER BEARING

FIG. 3-3. PHOTOGRAPHS SHOWING TYPICAL DAMAGE AT KOYNA DECEMBER 11, 1967 EARTHQUAKE

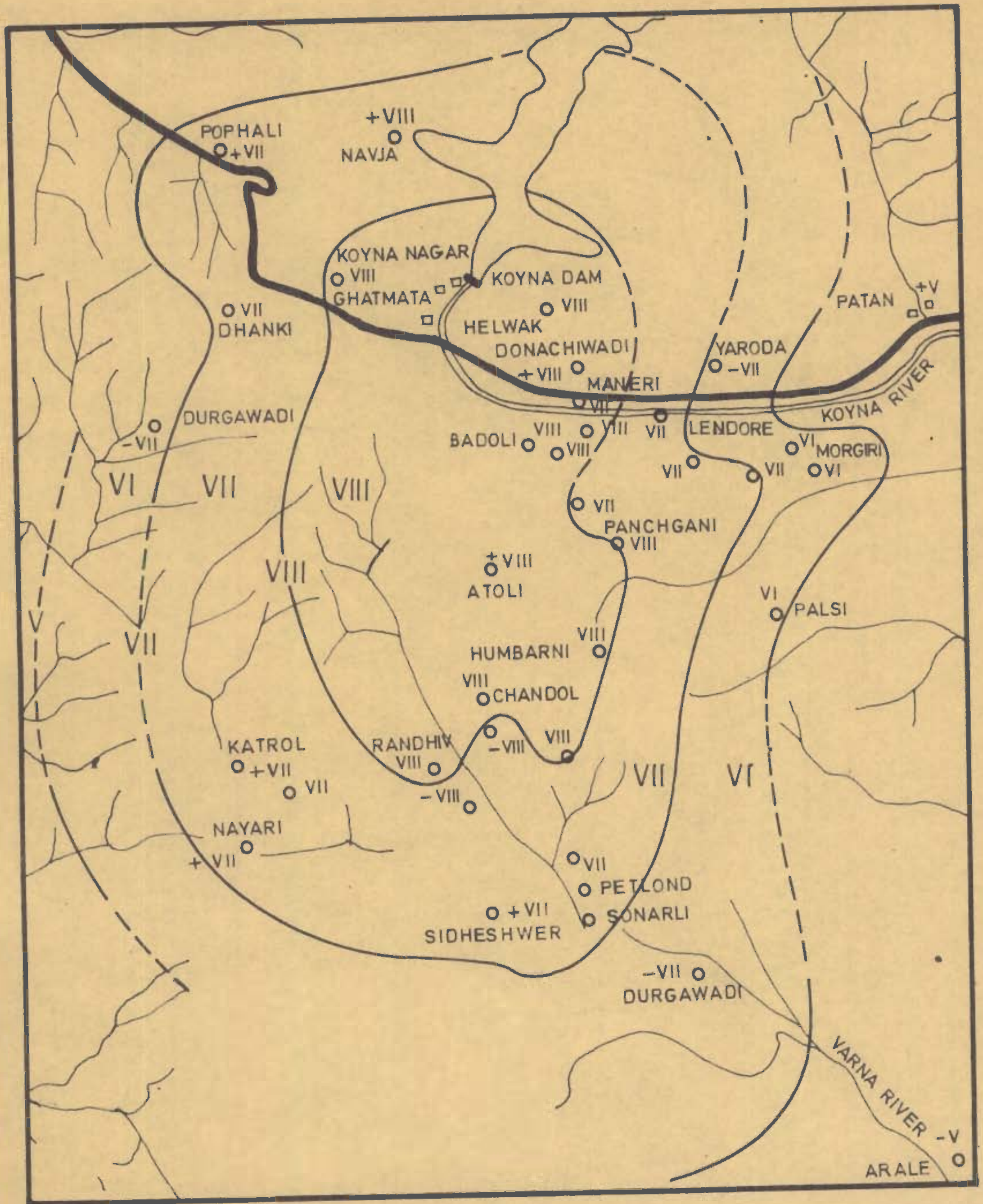


FIG. 3-4. ISOSEISMAL MAP OF DECEMBER 11, 1967 EARTHQUAKE AT KOYNA ARYA ET AL

TABLE 3-3

Epicentre, Origin Time and Depth of Focus of
December 11,1967 Koyna Earthquake

Epicentre		Origin Time GMT	Depth of Focus km	No. of Sta-tion	Source	Remarks
°N Φ	°E					
17.45	75.76	22 51 24.3	35	94	USCGS	P data for Δ >20°
17.50	73.78	22 51 23.7	29	127	USCGS	P and PKP data for Δ > 20°
17.56	73.92	22 51 23.8	33	109	USCGS	P data for all distances.
17.58	73.93	22 51 24.0	33	139	USCGS	P and PKP data for all distances.
17.37	73.75	22 41 19.0	8	169	IMD	P and PKP data for all Δ. Δ<16° travel time $t = (\Delta/8.24)+6.3$. For rest as in J.B.Tables.
17.50	73.73	22 51 17.0	12.1	4	CWPRS	P_g travel time at 4 near stations

3.5.3. Fault Plan Solution

Fault plane solution for December 11,1967 event utilising the directions of initial motions has been obtained by Tandon and Choudhury(1968) by plotting the data on Byerly's extended distance projection. The data of initial movement from 89 observatories have been plotted and two orthogonal circles have been drawn separating the compressions and dilatations. Of the total data used, 11 sets of observations were not consistent with this fit as shown in Figure 3-5. Theoretically, either of these circle could represent

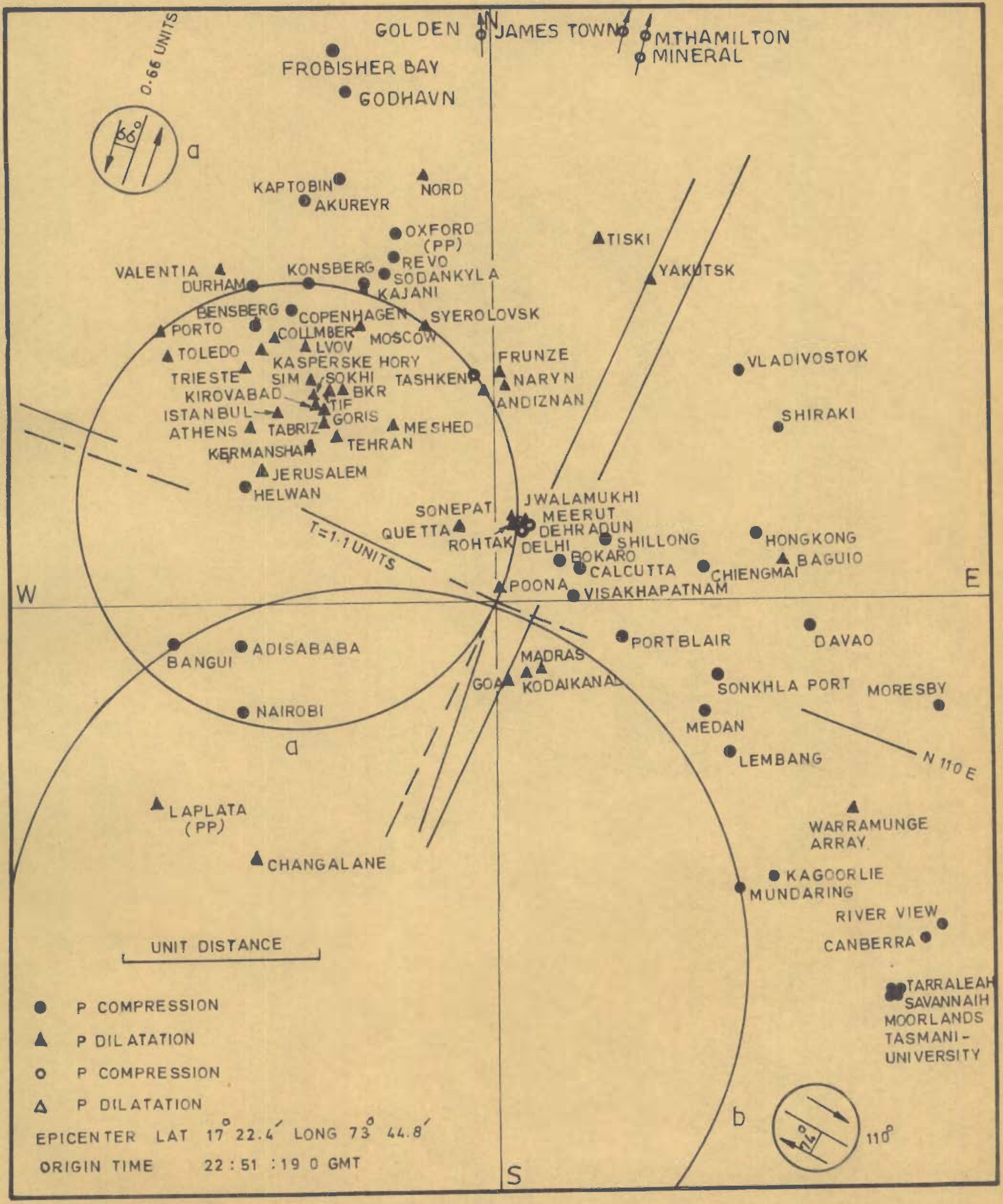


FIG.3-5 FAULT PLANE SOLUTION FOR DECEMBER 11,1967 KOYNA EARTHQUAKE TANDON AND CHAUDHURY, 1968

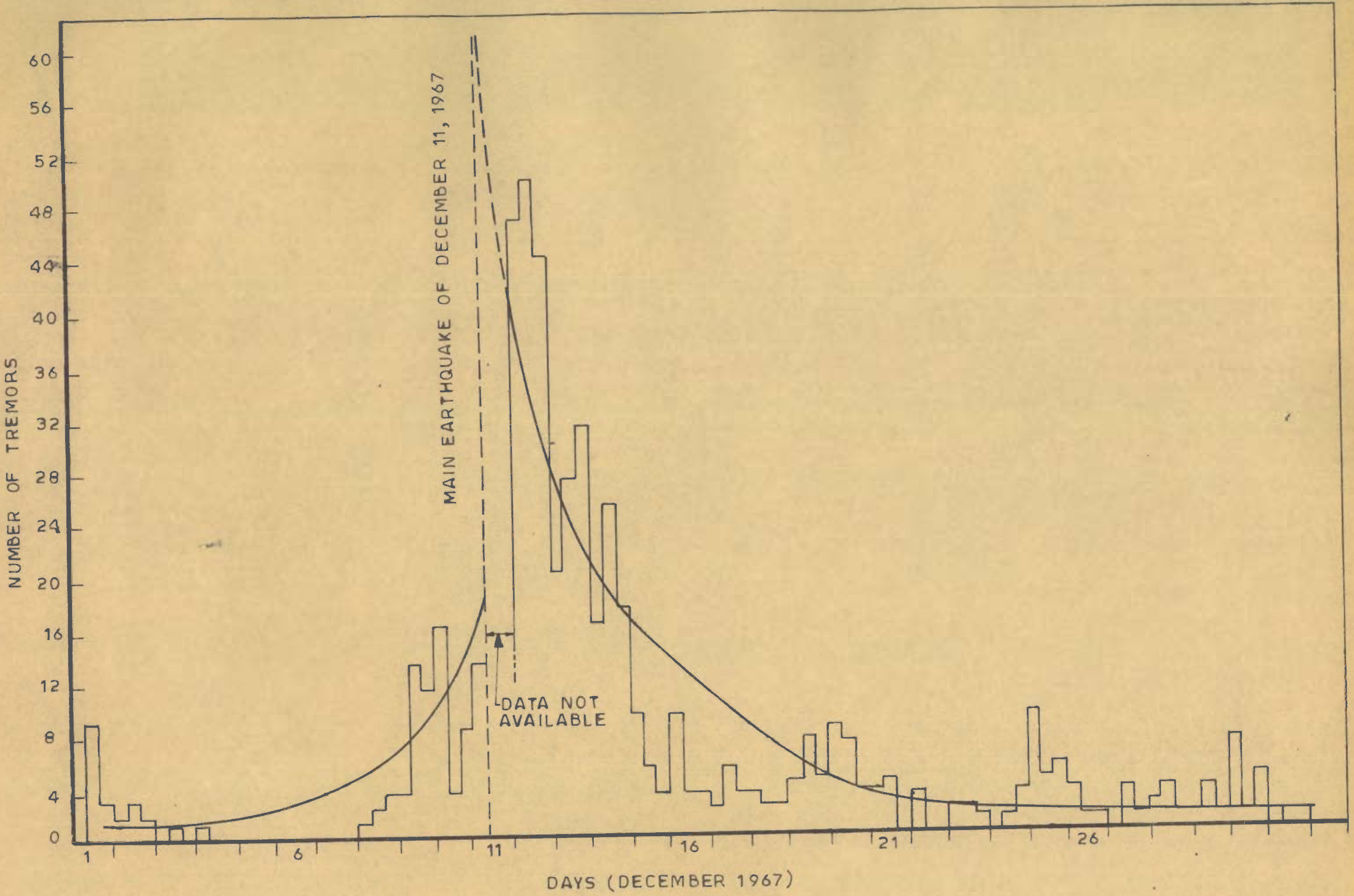


FIG. 3-6. FREQUENCY DISTRIBUTION OF FORESHOCKS AND AFTERSHOCKS FOR DEC. 11, 1967 KOYNA EARTHQUAKE GUHA ET AL

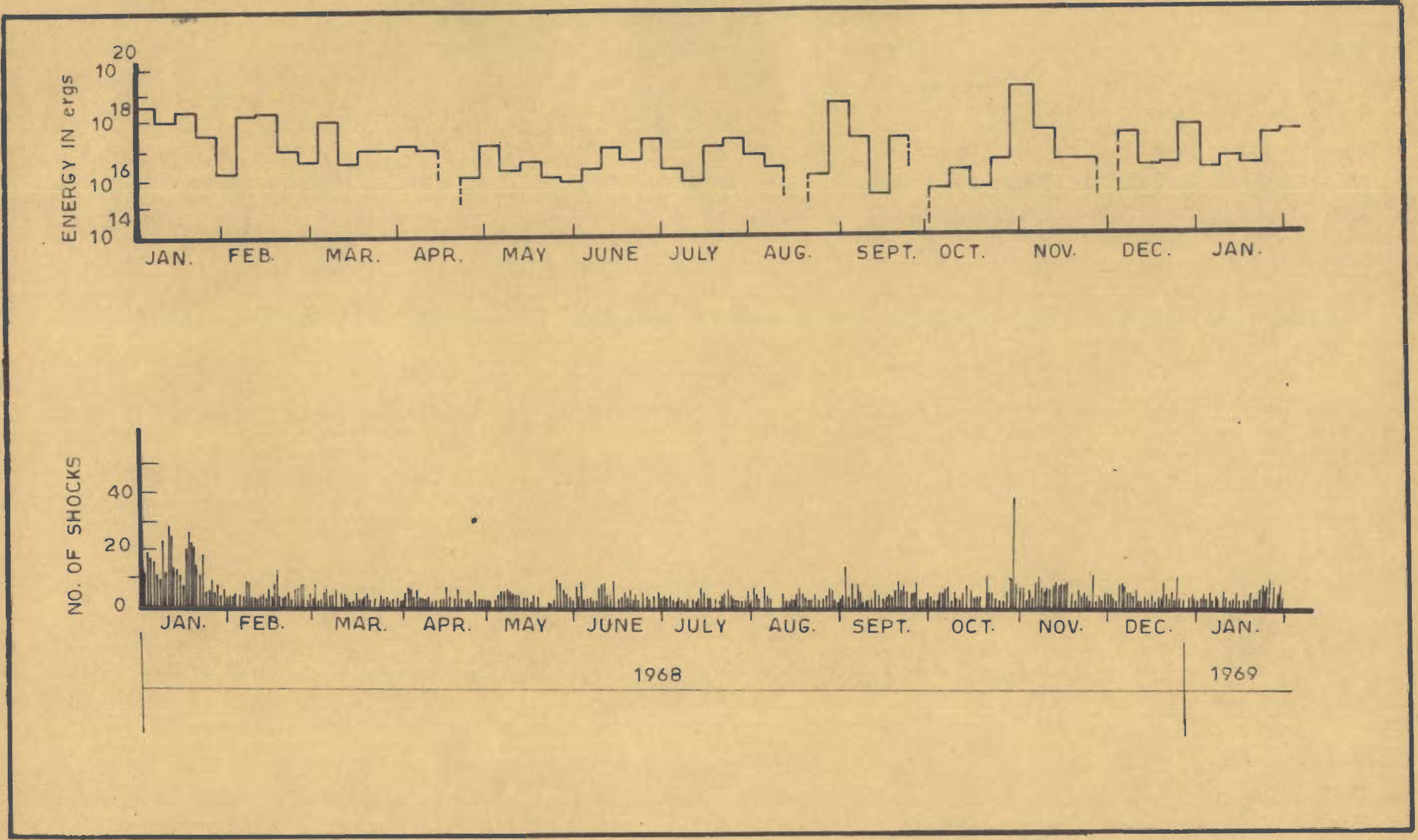


FIG. 3-7. WEEKLY EARTHQUAKE ENERGY RELEASE AND EARTHQUAKE FREQUVENCY DURING 1968 FOR KOYNA REGION GUHA ET AL

a fault. According to Tandon and Chaudhury the solution gives a sinistral strike slip fault striking N 26° E and dipping at an angle of 66° in a N 296 E direction. Gupta et al (1969) in their fault plane solution find a N 33° W striking fault.

3.5.4. Foreshocks and Aftershocks Sequence

The distribution of foreshocks and aftershocks of the December 11,1967 earthquake was similar to those of the September 13,1967 earthquake and is given in Figure 3-6 (Guha et al,1968). Within twenty four hours of the main event, instruments at Poona recorded about 200 aftershocks. Parameters for some important aftershocks are given in Table 3-4. The plot of weekly energy release in shocks in the Koyna region during 1968 is given in Figure 3-7.

TABLE 3-4

Important Aftershocks of December 11,1967 Earthquake

Date	Epicentre °N	°E	Origin Time GMT	Magnitude
11.12.67	17°16.4'	73°40.6'	20 49 47.5	5.8
12.12.67	17°17.1'	73°38.9'	06 18 33.5	6.2
12.12.67	17°17.1'	73°37.9'	15 48 51.7	5.9
13.12.67	17°30.0'	73°37.3'	19 19 45.5	5.6
24.12.67	17°19.5'	73°42.9'	23 49 51.0	5.8

3.5.5. Accelerogram of December 11,1967 Earthquake

This earthquake was recorded by a United Electrodynamics AR-240 Accelerograph and a traced copy of the record has been given in Figure 3-8. The analysis of this accelerogram has been carried out by Jai Krishna et al (1969) and was readily available for this study.

3.5.6. Frequency - Magnitude Relationship

Guha obtained the following relationship between the logarithm of the frequency N of earthquakes of magnitude equal to or larger than M and the Magnitude (M) (vide Figure 3-9).

$$\text{Log } N = 4.257 - 0.8\, M$$

Gupta et al (1969) also prepared a similar plot with somewhat lesser data available to them and they also found the value of the constant equal to 0.8

3.5.7. Wave Velocities and Crustal Structure

Tandon and Choudhury utilised the data of the December 11,1967 earthquake recorded at Indian Observatories within 1500 kms, for determination of wave velocities and crustal structure. The number of observations for the P_n phase was 8 and smaller for others. $\bar{P}$ and S_n were feeble while P^* and S^* were comparatively stronger. The travel time curves for $\bar{P}$, P^*, P_n and S_n are given in Figure 3-10. Due to lack of data, analysis of S^* and S_g was not possible. However, the strongest phase in the S group corresponded

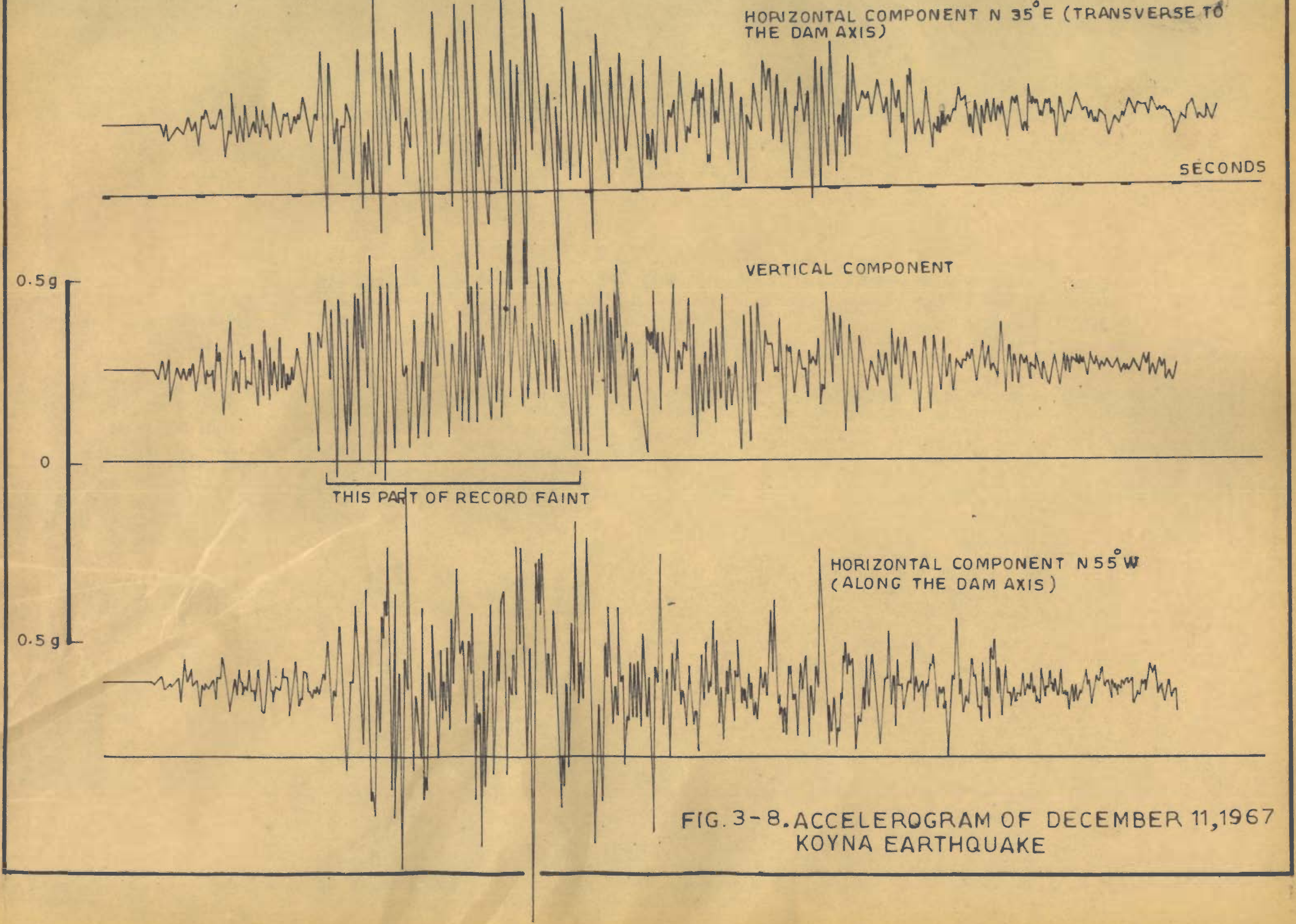


FIG. 3-8. ACCELEROGRAM OF DECEMBER 11, 1967 KOYNA EARTHQUAKE

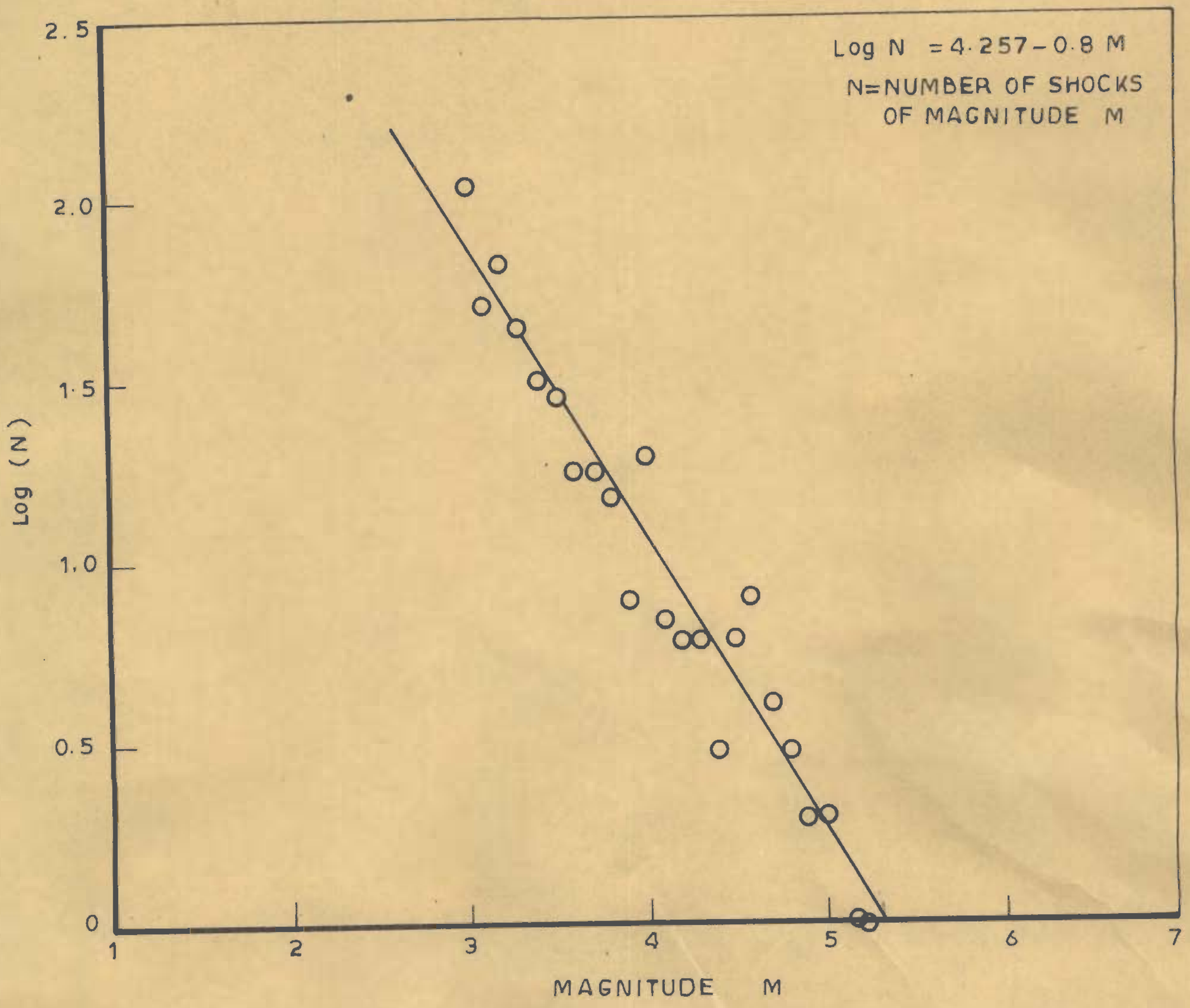


FIG. 3-9. GRAPH SHOWING FREQUENCY–MAGNITUDE RELATIONSHIP FOR EARTHQUAKES IN THE KOYNA REGION GUHA ET AL

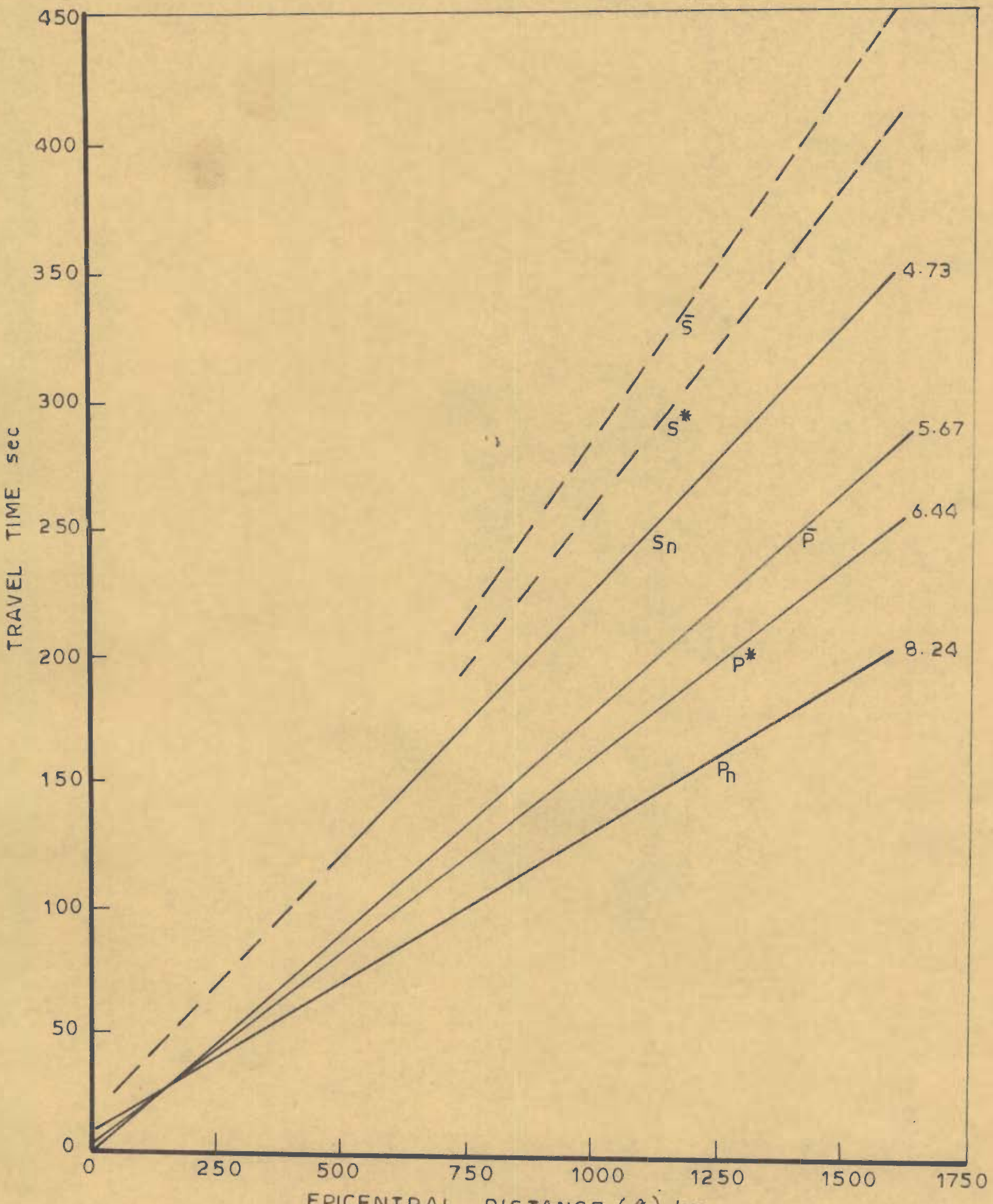


FIG. 3-10. TRAVEL TIME CURVES DRAWN ON THE BASES OF DATA FOR DECEMBER 11, 1967 KOYNA EARTHQUAKE

TANDON AND CHOUDHURY, 1968

to a velocity of about 3.5 km/sec. The average crustal structure for the Deccan shield derived on the basis of P- data by Tandon and Choudhry is as follows:

Thickness of the granitic layer	22.5 kms
Thickness of the Basaltic layer	18.5 kms
Depth of Mohorovicic Discontinuity	41.0 kms

3.6. EARTHQUAKE FREQUENCY AND THE WATER LOADS IN THE RESERVOIR

In the earthquake frequency plots no definite and systematic trend of variations of frequency could be identified. However, correlation between the inflow hydrograph or reservoir water levels and distribution of earthquake frequency or the elastic energy released in the area have been claimed to exist by Guha et al and Gupta et al. Figure 3-11 gives all these parameters and the weekly energy release side by side. A number of opinions have been expressed to relate the Koyna earthquake with the possible effects of the Koyna reservoir e.g., (a) The Koyna earthquake was caused by the water loads or water in the reservoir (b) the earthquake was only triggered by the water loads and (c) the observed correlation may be a mere coincidence. Gupta et al conclude that whenever water level has crossed the 642 meter mark and has been retained for a long time the seismic activity has increased considerably with a certain time lag. During the 1969 monson, Koyna received a heavy rainfall and the water level remained above the 642 meter mark for about two weeks - the longest duration

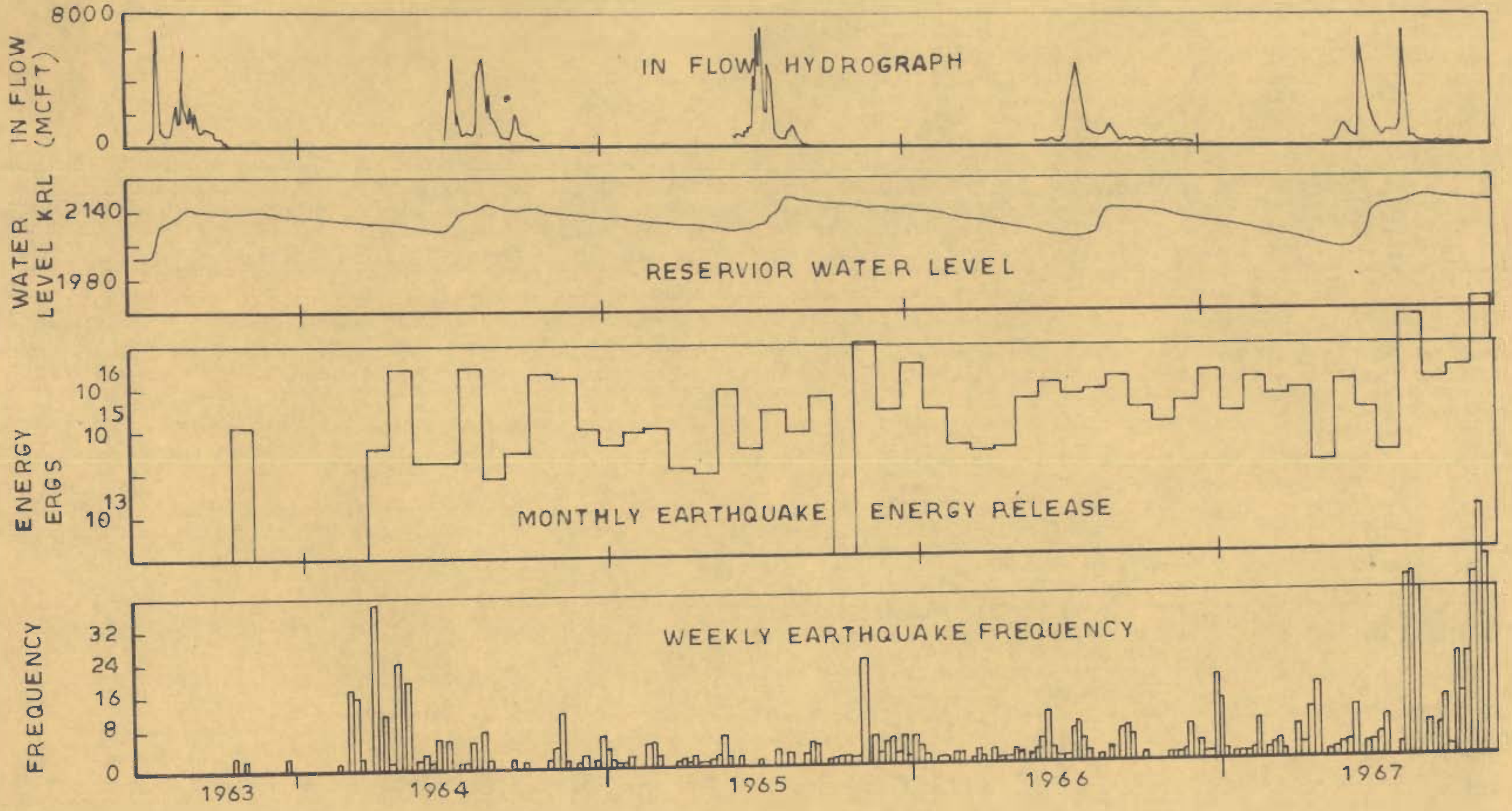


FIG. 3-11. INFLOW HYDROGRAPH RESERVIOR WATER LEVEL, MONTHLY EARTHQUAKE ENERGY RELEASE AND WEEKLY EARTHQUAKE FREQUENCY FOR KOYNA REGION (JAN. 1963 TO DECEMBER 1967) GUHA ET AL

in the history of the dam, although fearing increase of seismic activity, an abortive attempt was made to lower the level by opening the flood gates, the latter resisting efforts to operate them on account of the increased friction caused by lateral water loads. However, there was no increase of earthquake activity during this period.

3.7. TILT MEASUREMENTS IN THE REGION

The Portable Water Tube Tiltmeter was employed for the measurement of earthquake surface tilting in the region subsequent to December 11,1967 event.

3.7.1. Tilt Base-hub Installations

In order to avoid uncertainties in the tilt measurement due to differential surface heating it was considered necessary to make the measurements at an underground location. Since it was not possible to construct suitable tunnels exclusively for this purpose for want of time and resources, the existing underground Pophali Power House cavity and its adjoining structures were selected for the purpose. The tilt base-hubs were fixed in suitable cavities drilled in the rock wall behind the lining of the tunnel as shown in Figure 3-12. It was considered desirable to fix bases at larger distances but the base spacings in each pair was limited to about 30 or 40 mts. In order to provide even this spacing at some of the locations where the tunnel was sloping, one of the bases had to be installed at the floor level of the tunnel and the other near its roof. If the usual kind

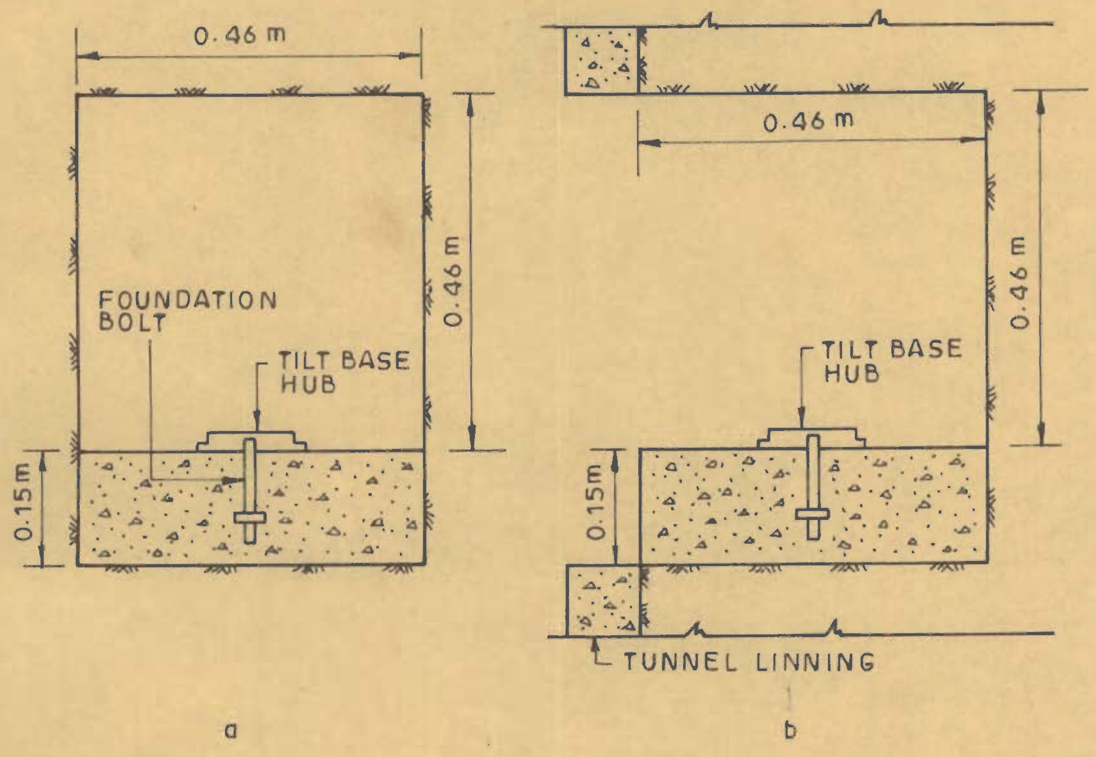


FIG. 3-12. SECTION OF THE TILT BASE-HUB INSTALLATION ALONG A VERTICAL PLANE PASSING FROM ITS CENTRE a-PARALLEL AND b- PERPENDICULAR TO THE ROCK FACE

of pillars were constructed for installation of the base-hubs at the locations where the tunnel was sloping, these would have had to be of different heights and might have resulted in some errors due to differential expansion and settlement, which was avoided by adopting the above procedure. The locations of these bases have been marked on the layout plan of the underground structures in the Pophali area given in Figure 3-13. These installations permitted measurements of tilt along two perpendicular lines.

3.7.2. Tilt Data

The measurements were commenced in September 1968 and have since been repeated three times. The observations did not reveal any permanent tilt in the area associated with the shocks occurring there.

3.8. MULTIPLE SRR AND ROORKEE SEISMOSCOPE INSTALLATIONS AND THEIR RECORDS

During the December 11,1967 earthquake, the Monolith 17 (M17) of the Koyna Dam, the highest monolith of the non-over-flow section located adjacent to the over-flow section was strongly shaken. The period of this monolith has been computed by Chandrasekaran et al (1968) and the damping was estimated. Guided by these computations and estimates as well as convenience of instrument design, the 0.40 sec and 5 percent of critical damping instrument was selected to simulate the Monolith 17 for obtaining its response during future shocks. Roorkee Seismoscopes were installed in pairs with 0.40 and 0.75 second periods, the latter one to provide an intermediate point on the response spectrum. Also, the

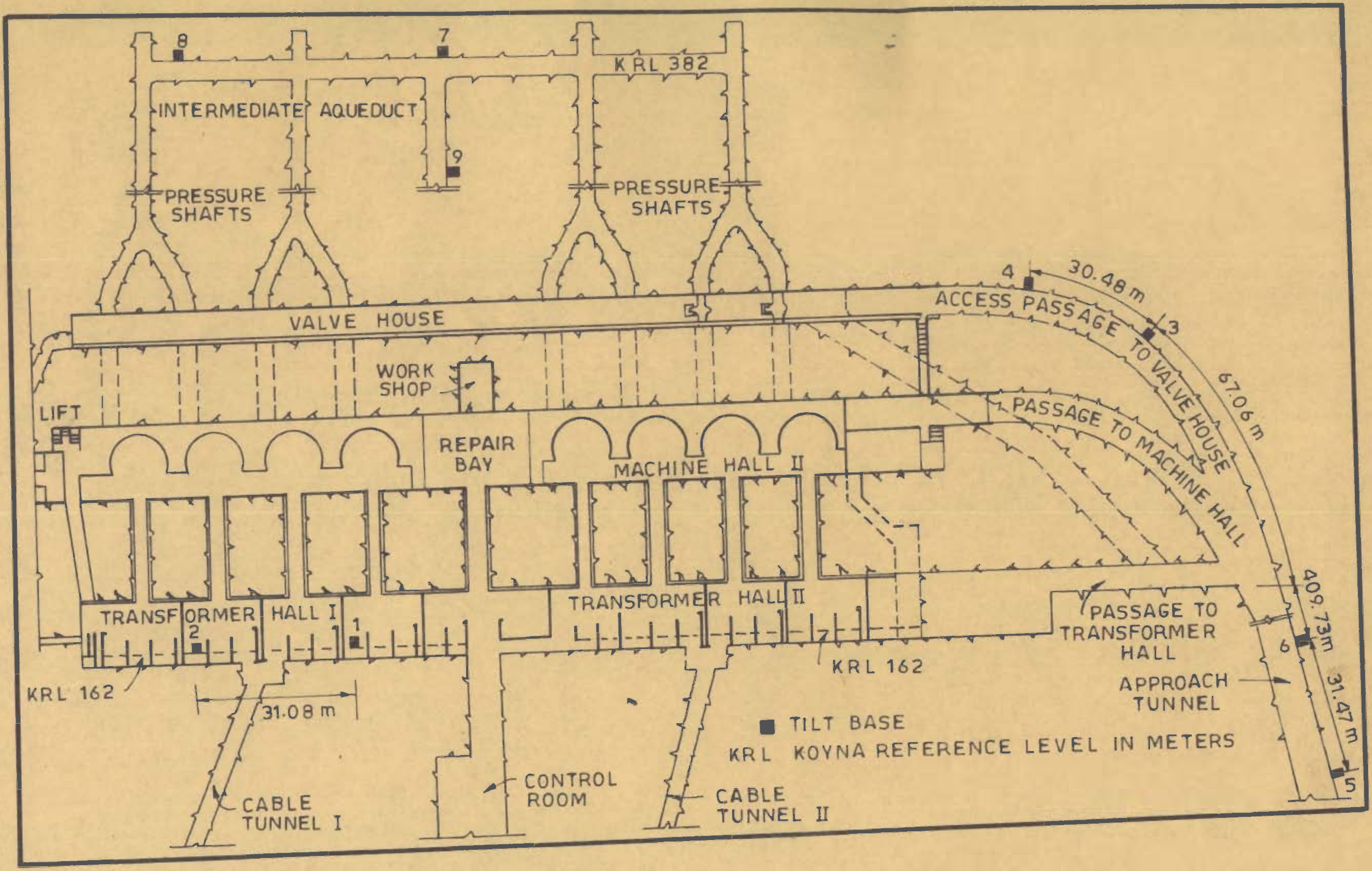


FIG. 3-13. LAYOUT PLAN OF THE UNDERGROUND POPHALI POWER HOUSE SHOWING LOCATIONS OF THE TILT BASE-HUB INSTALLATIONS

Multiple Structural Response Recorders selected for installation in conformity with the general strong motion observation programme contained pendulums with these specifications. The locations of these instruments are marked on the map in Figure 3-14.

On October 29,1968 an earthquake of magnitude 5.2 occurred in the region and was recorded by the Roorkee Seismoscope the Multiple Structural Response Recorder and also the United Electrodynamic AR-240 accelerograph. Records from these three instruments are reproduced in Figure 3-15, 16 and 17. The digitized data for this earthquake is given in the Table 3-5. The Roorkee Seismoscope installations also recorded another event on June 27,1969 and the records are given in Figure 3-18.

3.9. CAUSE OF KOYNA EARTHQUAKES

The epicentre of foreshocks and aftershocks of Koyna earthquake when plotted on the map (Gubin,1969) form a strip 25 km long and about 10 kms wide striking approximately N-S. The depth of the focus of these shocks varied from 3 to 8 kms with the exception of one shock at 27 km. The area of maximum intensity of Koyna earthquakes was also elongated approximately N-S, the source had a vertical extension of the order of 25-30 kms in the crust. It follows from this that below the Trap lies a zone of near vertical active faults of N-S strike as represented in Figure 3-16. Earthquakes in Koyna region according to Gubin (1969) are due to unequal uplift of the western margins of the basement rocks of the Deccan Traps along the fault zones described earlier.

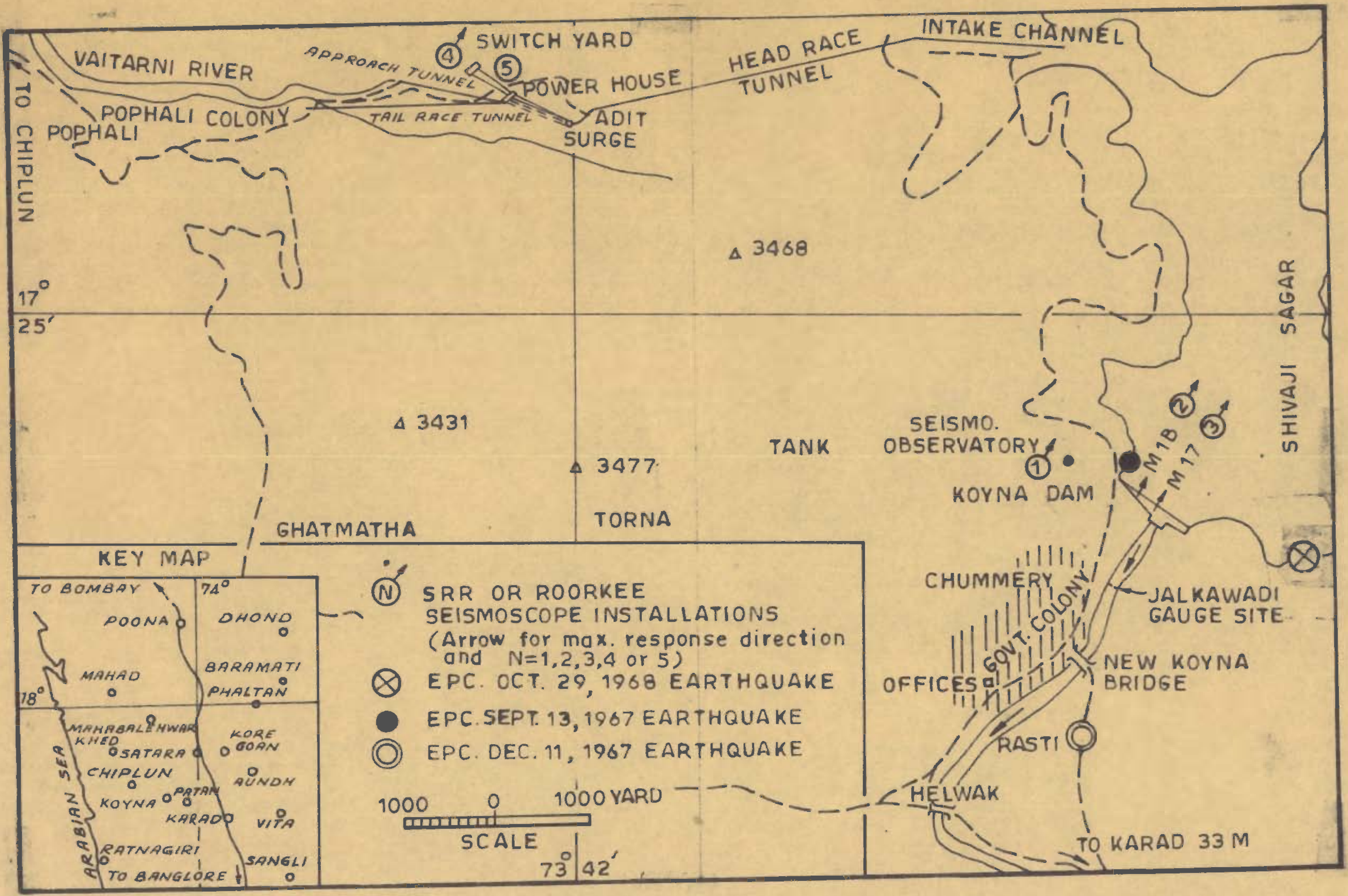


FIG. 3-14. MAP OF THE KOYNA HYDROELECTRIC PROJECT LAYOUT SHOWING INSTRUMENT INSTALLATIONS

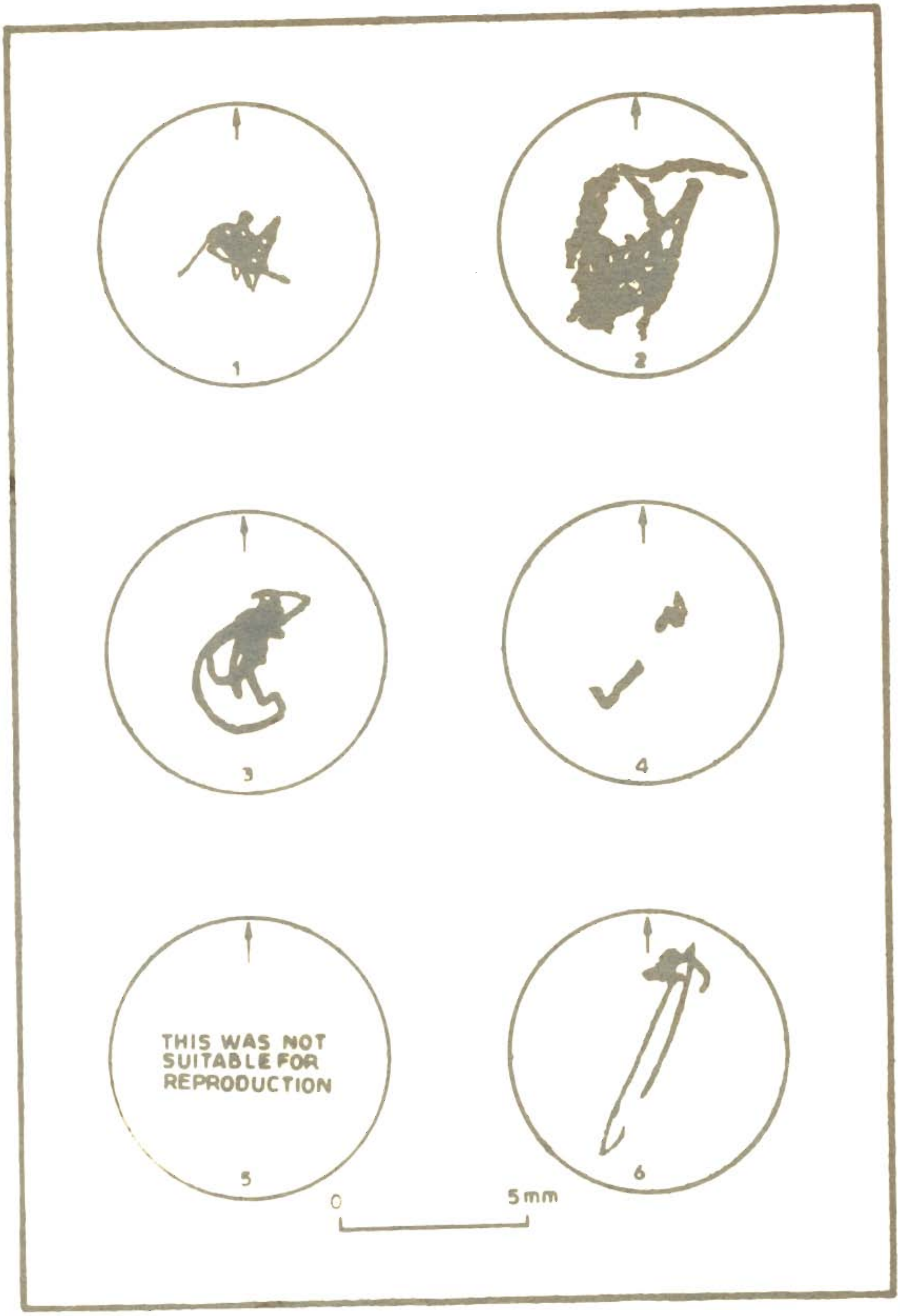


FIG 3-15 PHOTOGRAPHICALLY ENLARGED RECORDS OF THE ROORKEE SEISMOSCOPES OBTAINED DURING OCTOBER 29, 1967 EARTHQUAKE AT KOYNA

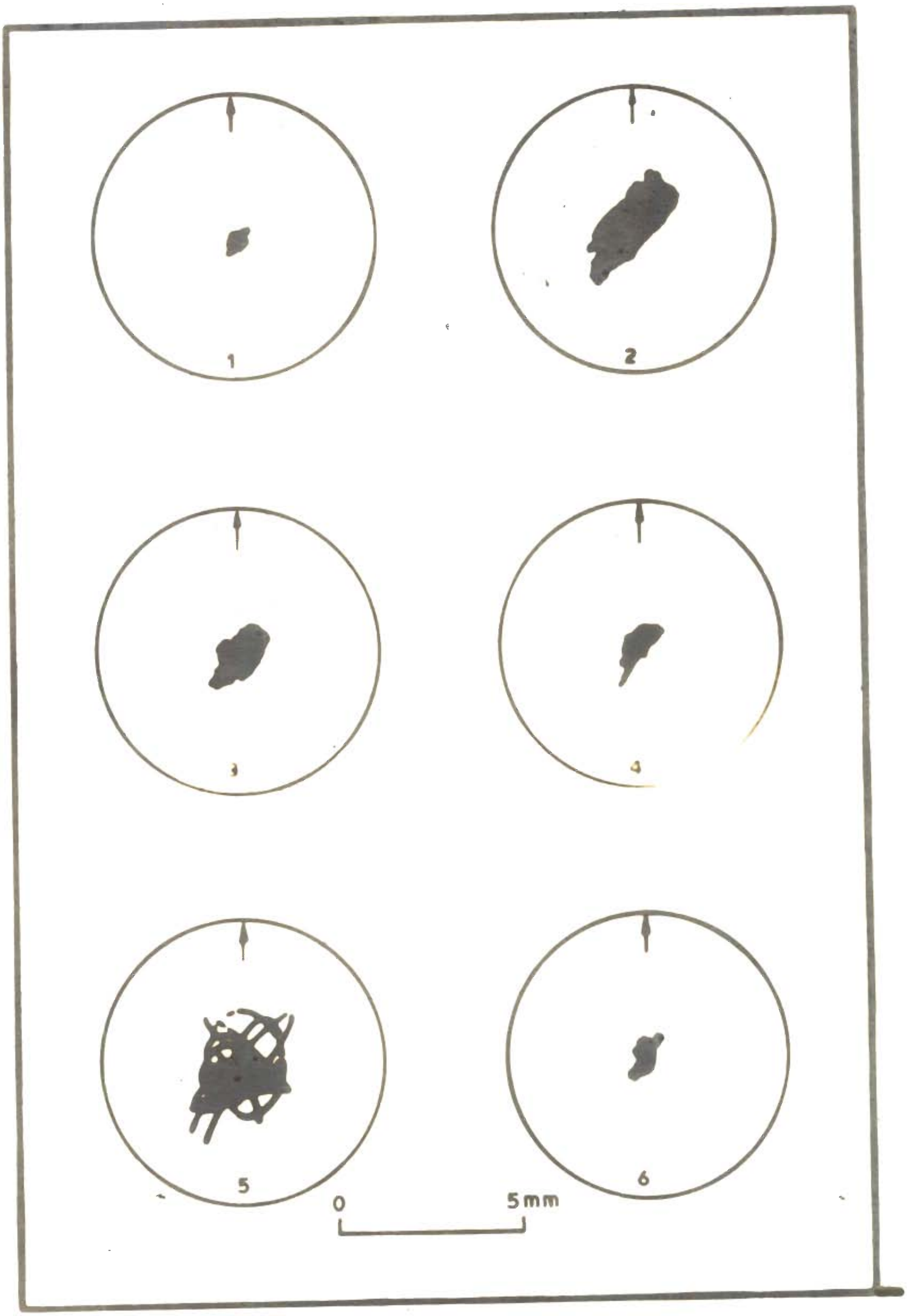


FIG 3-16 PHOTOGRAPHICALLY ENLARGED RECORDS OF THE MULTIPLE SRR OBTAINED DURING OCT. 29, 1967 EARTHQUAKE AT KOYNA

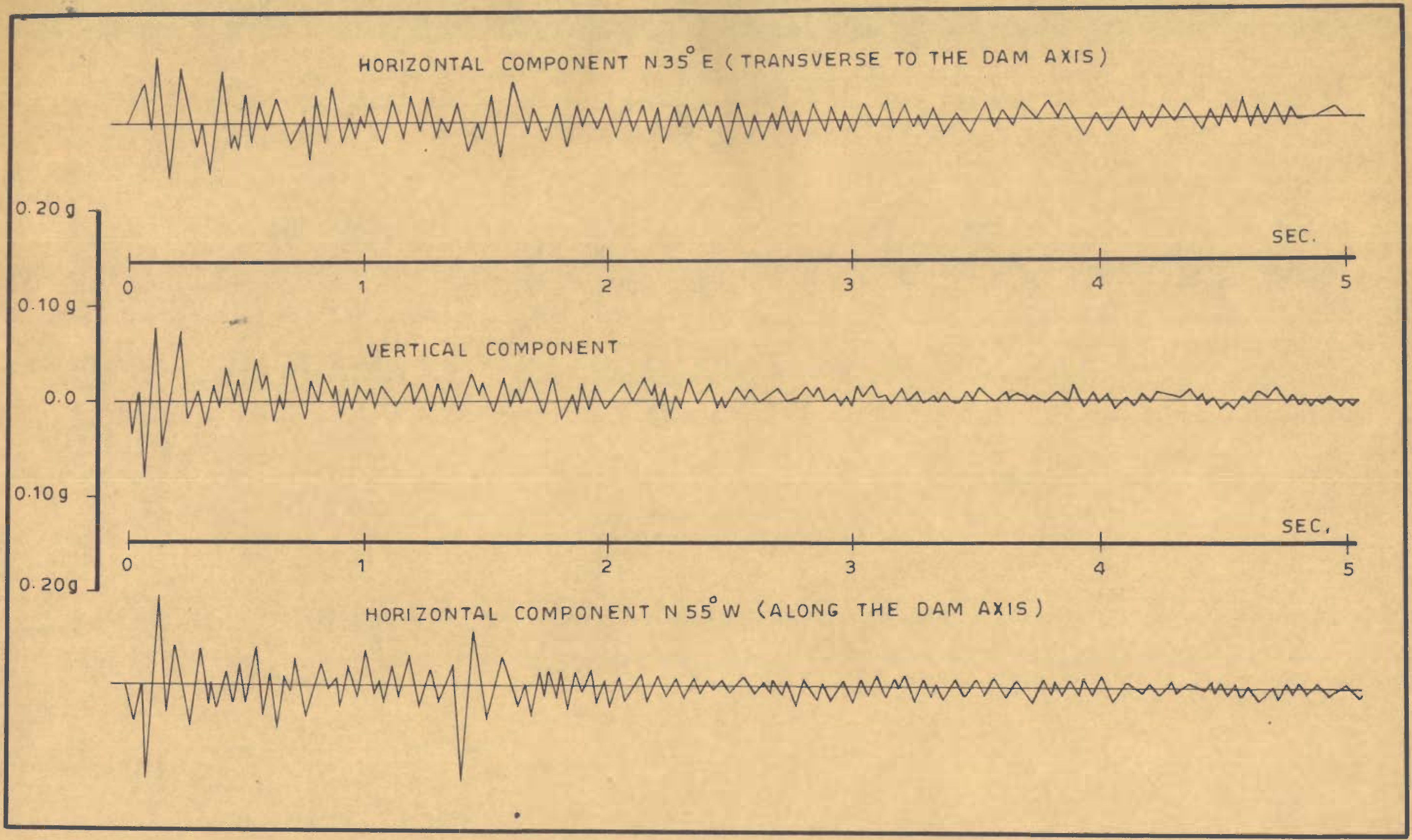


FIG. 3-17. ACCELEROGRAM OF THE OCTOBER 29, 1968 EARTHQUAKE AT KOYNA

TABLE 3-5

Digitized Data for October 29,1968 Earthquake at Koyna

Transverse Component

NO.	TIME	ACCLN.	TIME	ACCLN.	TIME	ACCLN.	TIME	ACCLN.
1	0.0000	-.006532	.0681	.037879	.0984	-.013684	.1212	.067524
2	.1787	-.065746	.2242	.055736	.2878	-.030797	.3106	-.004810
3	.3424	-.058700	.3939	.053529	.4363	-.033518	.4469	-.015705
4	.4666	-.031026	.4924	.026984	.5227	-.026925	.5484	.021458
5	.5833	-.009268	.6181	.023707	.6848	-.024645	.7393	.007248
6	.7666	-.044374	.7954	.027945	.8257	-.025599	.8606	.036316
7	.9060	-.025282	.9318	.005704	.9590	-.021219	.9772	.005874
8	.9924	-.008741	1.0151	.017595	1.0681	-.024686	1.1136	.021801
9	1.1560	-.022072	1.1893	.028229	1.2272	-.012576	1.2606	.026136
10	1.2954	-.020090	1.3181	.003914	1.3454	-.015311	1.3833	.020316
11	1.4272	-.035161	1.4696	-.000300	1.4893	-.019555	1.5303	.028809
12	1.5636	-.040994	1.6151	.044453	1.6742	-.015262	1.7045	.012214
13	1.7469	-.020519	1.7954	.019727	1.8333	-.030396	1.8787	.019102
14	1.9030	-.004023	1.9242	.014156	1.9560	-.008960	2.0000	.020060
15	2.0348	-.018502	2.0757	.020159	2.1060	-.012623	2.1439	.016376
16	2.1742	-.015252	2.2121	.016444	2.2348	-.026006	2.2727	.012634
17	2.2954	-.006653	2.3257	.018464	2.3560	-.006612	2.3939	.018504
18	2.4242	-.009666	2.4484	.019687	2.4939	-.025857	2.5333	.020483
19	2.5757	-.018119	2.6030	.006978	2.6363	-.018890	2.6696	.008906
20	2.6909	-.010401	2.7242	.016619	2.7500	-.014275	2.7727	.011971
21	2.8060	-.017394	2.8484	.018503	2.8939	-.014340	2.9166	.012671
22	2.9515	-.012835	2.9712	.012245	3.0075	-.014425	3.0530	.017192
23	3.0954	-.008719	3.1378	.020190	3.1712	-.011123	3.2196	.015840
24	3.2575	-.008922	3.2757	.004564	3.2954	-.012839	3.3333	.011426
25	3.3787	-.016634	3.4272	.006246	3.4818	-.017022	3.5454	.017598
26	3.5681	-.009862	3.6136	.007799	3.6515	-.008117	3.6924	.015338
27	3.7515	-.001410	3.7954	.017008	3.8333	-.000468	3.8636	.014892
28	3.9500	-.022037	3.9939	.002925	4.0439	-.017303	4.0924	.006471
29	4.1515	-.020755	4.1787	.004632	4.2196	-.015203	4.2590	.009749
30	4.3030	-.008561	4.3484	.013271	4.4166	-.015956	4.4484	.005149

Longitudinal Component

NO.	TIME	ACCLN.	TIME	ACCLN.	TIME	ACCLN.	TIME	ACCLN.
1	0.0000	.003884	.0424	-.037967	.0727	.007484	.1060	-.093018
2	.1363	.096065	.1651	-.027971	.2090	.045624	.2878	-.040350
3	.3181	.042563	.3590	-.018571	.3712	.009139	.3939	-.020611
4	.4318	.016336	.4575	-.016946	.4878	.025818	.5151	-.019436
5	.5530	.040683	.5909	-.032785	.6136	.015798	.6515	-.043767
6	.6787	.013299	.6969	-.004125	.7181	.028635	.7727	-.032900
7	.8257	.024490	.8606	-.002625	.8863	.010437	.9121	-.021286
8	.9393	.024206	.9787	-.011023	1.0030	.039498	1.0454	-.010020
9	1.0681	.008460	1.0909	-.016687	1.1181	.023406	1.1515	-.011028
10	1.1818	.035238	1.2303	-.022777	1.2742	.019604	1.3181	-.015231

Table Continued

NO.	TIME	ACCLN.	TIME	ACCLN.	TIME	ACCLN.	TIME	ACCLN.
11	1.3636	.027152	1.4090	-.096483	1.4484	.058271	1.5121	-.033730
12	1.5681	.033743	1.6424	-.019655	1.6696	.003469	1.6984	-.029777
13	1.7272	.018057	1.7500	-.010159	1.7651	.018390	1.7954	-.012152
14	1.8181	.014844	1.8500	-.023806	1.8787	.017856	1.9090	-.006890
15	1.9363	.018560	1.9651	-.016221	1.9924	.008459	2.0181	-.022070
16	2.0545	.010710	2.0833	-.014800	2.1378	.014492	2.1696	-.016423
17	2.2090	.013659	2.2500	-.009151	2.2878	.011669	2.3212	-.011905
18	2.3636	.011234	2.3818	-.006537	2.4090	.008504	2.4393	-.001163
19	2.4696	.008473	2.5045	-.005441	2.5530	.010369	2.6060	-.005864
20	2.6363	.008412	2.6742	-.005109	2.6848	.008401	2.7121	-.005116
21	2.7348	.008779	2.7727	-.020568	2.8030	.010317	2.8606	-.012848
22	2.8863	.007229	2.9106	-.012073	2.9575	.006464	3.0030	-.014762
23	3.0378	.008411	3.0636	-.008570	3.1030	.013835	3.1363	-.008159
24	3.1666	.012701	3.1878	-.001188	3.2121	.013494	3.2575	-.016598
25	3.2878	.010444	3.3166	-.008070	3.3333	.003136	3.3651	-.012287
26	3.4151	.010141	3.4545	-.008747	3.5000	.010594	3.5318	-.007524
27	3.5696	.010656	3.6227	-.008597	3.6621	.006887	3.7272	-.012732
28	3.7727	.010872	3.8000	-.008013	3.8181	.010155	3.8439	-.007572
29	3.8742	.010999	3.9166	-.007475	3.9378	.012244	3.9651	-.008179
30	4.0030	.015041	4.0454	-.013079	4.1030	.005929	4.1666	-.003617
31	4.1969	.003770	4.2287	-.004668	4.2757	.008930	4.3060	-.002982
32	4.3606	.006001	4.4060	-.000858	4.4393	.008475	4.4545	-.003462

Vertical Component

NO.	TIME	ACCLN.	TIME	ACCLN.	TIME	ACCLN.	TIME	ACCLN=
1	0.0000	-.005864	.0166	-.041051	.0363	.005220	.0590	-.084037
2	.1060	.071424	.1393	-.055695	.2151	.066884	.2454	-.025854
3	.2893	.008017	.3196	-.031819	.3575	.012886	.3818	-.012260
4	.4121	.031308	.4393	-.006967	.4545	.020803	.4878	-.020182
5	.5318	.039202	.5606	.004408	.5787	.023686	.6090	-.030410
6	.6303	.002378	.6515	-.015023	.6803	.035134	.7439	-.026710
7	.7727	015732	.8030	-.007459	.8227	.022254	.8636	-.005573
8	.8742	.011408	.8939	-.025669	.9242	.007905	.9424	-.015268
9	.9696	.009817	.9984	-.006021	1.0121	.007875	1.0303	-.013750
10	1.0606	.009412	1.1181	-.011823	1.1803	.015600	1.1969	-.010649
11	1.2287	.012528	1.2651	-.018729	1.2954	.013333	1.3212	-.013290
12	1.3469	.012209	1.3787	-.015564	1.4333	.022709	1.4681	-.000033
13	1.4833	.012338	1.5196	-.018892	1.5636	.019775	1.5909	-.013004
14	1.6166	.007496	1.6378	-.010230	1.6742	.019558	1.7287	-.020499
15	1.7636	.018949	1.8015	-.026148	1.8484	.000978	1.8666	-.017900
16	1.8924	.012660	1.9212	-.018159	1.9454	.008926	1.9818	-.015305
17	2.0530	.012298	2.0924	-.006122	2.1424	.017578	2.1742	-.001242
18	2.1848	.010374	2.2090	-.013872	2.2287	.008971	2.2545	-.024919
19	2.2742	.001402	2.2939	-.012815	2.3257	.016254	2.3636	-.008704
20	2.4106	.013865	2.4409	-.011113	2.4621	-.001377	2.4787	-.012508
21	2.5257	.009305	2.5515	-.004486	2.5787	.007213	2.6106	-.006161
22	2.6909	.006169	2.7424	-.003626	2.8030	.008251	2.8333	.000294
23	2.8500	.008873	2.8818	-.004863	2.9181	.004593	2.9469	-.010310
24	2.9666	.002150	2.9848	-.009333	3.0075	.013185	3.0318	-.002122
25	3.0621	.012720	3.0909	-.001785	3.1181	.002620	3.1515	-.005290
26	3.1848	.009581	3.2090	-.004170	3.2409	.006064	3.2757	-.002211

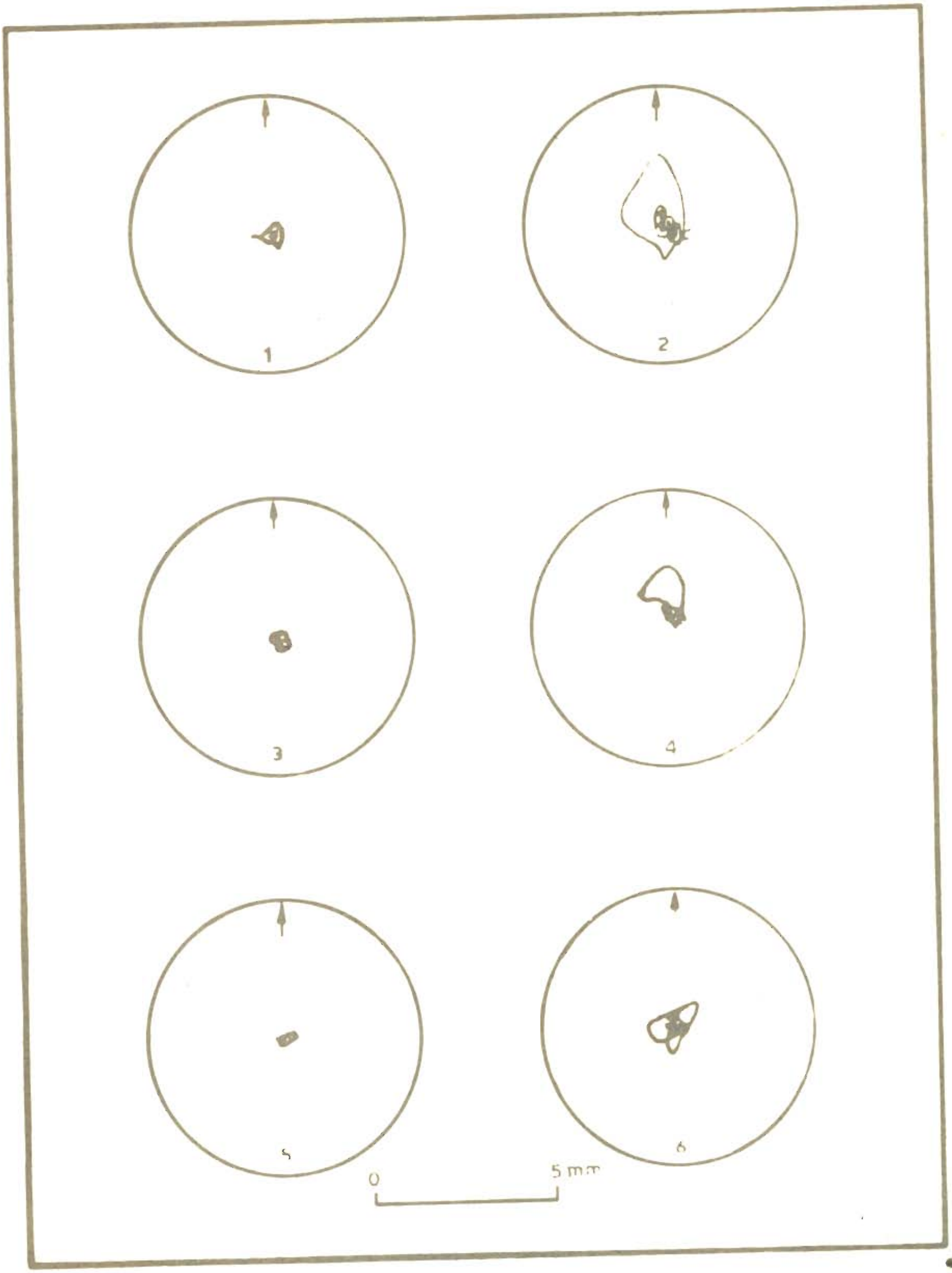


FIG. 3-18 PHOTOGRAPHICALLY ENLARGED RECORDS OF THE ROORKEE SESMOSCOPES OBTAINED DURING JUNE 27, 1969 EARTHQUAKE AT KOYNA

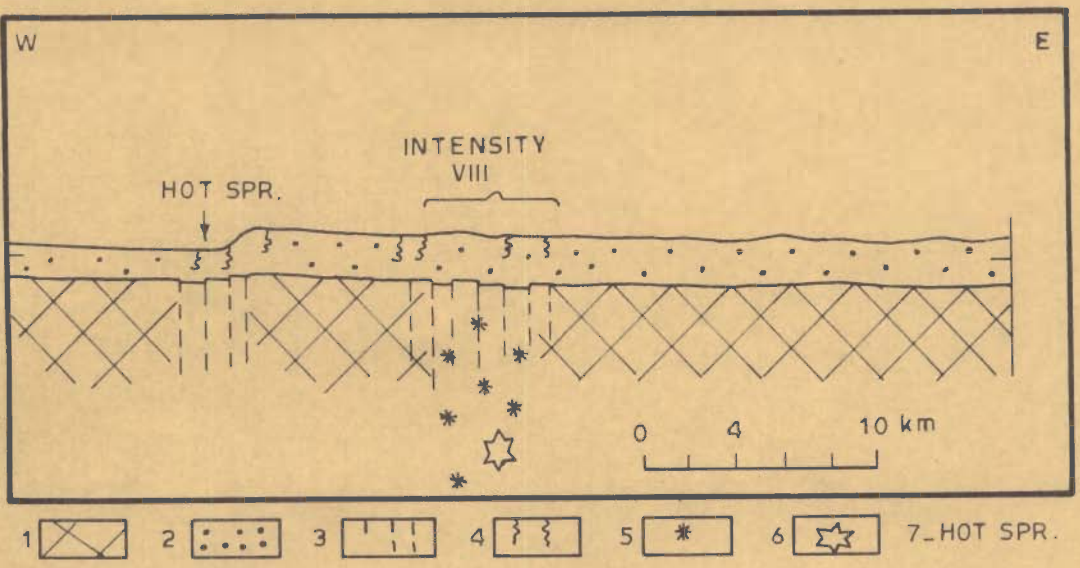


FIG. 3_19. SCHEMATIC GEOLOGICAL PROFILE ACROSS WESTERN GHATS GUBIN 1968

1_BASEMENT ROCKS, 2_DECCAN TRAPS, 3_SUPPOSED FAULTS, 4_FISSURES IN TRAPS, 5_SOURCES OF EARTHQUAKES, 6_FOCUS OF DECEMBER 11,1967 EARTHQUAKE AND 7_HOT SPRINGS

CHAPTER 4

DATA FOR THE DAKPATHER REGION

4.0. GENERAL

Dakpather is located at 30° 30' N and 77° 50' E, and lies at a distance of 48 kms by road from Dehradun, slightly to the west of the line joining Dehradun and Chakrata (see map in Figure 4-1). The river Tons flowing roughly West to East Swerves down South at Chibbro and meets the river Yamuna flowing roughly East to West at Dakpather. A water pressure tunnel, 5.6 kms long and 7.5 meters finished diameter, from Chibbro to Khodri (the river bank opposite Dakpather) is being constructed which would be traversing a highly crushed intra-thrust zone between the Krol and the Nahan thrust planes. The relevent data utilised for the evaluation of earthquake parameters in the region traversed by the tunnel have been given here.

4.1. GEOLOGY

The region under reference falls under the Kumaon Lower Himalayas, adjacent to the main boundary fault. The Lower Himalayas are thrusted over the foot hill belt consisting to a narrow spread of Siwalik sediments. The Kumaon Lower Himalayas are marked by a strong tectonic activity and are traversed by a number of secondary faults and thrusts. The secondary fault zones diverge in a westward direction and at places roughly merge with the main boundary fault towards the east. For over 400 kms, towards the east to Krol thrust runs parallel and almost coincides with the

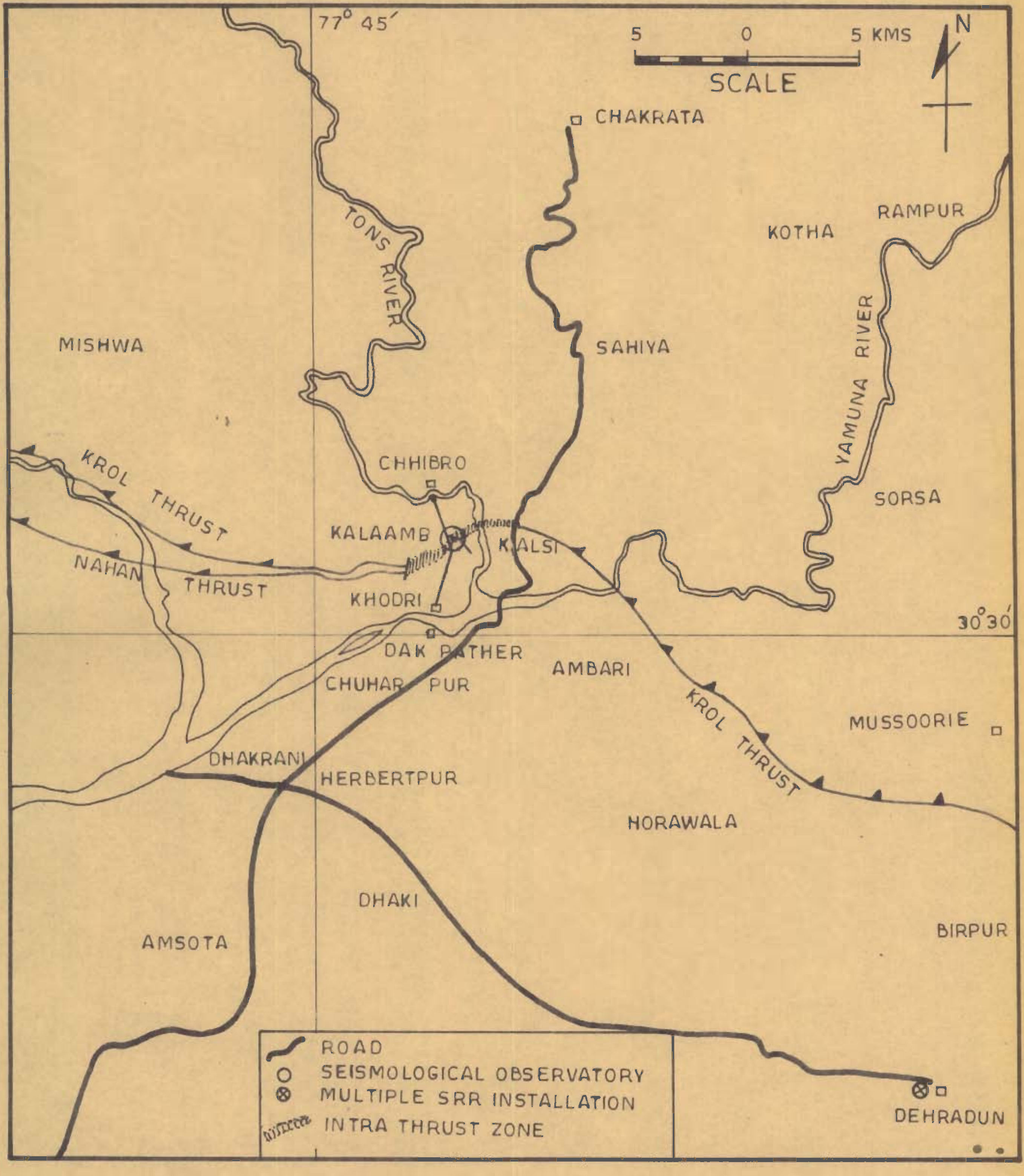


FIG. 4-1. MAP SHOWING THE DAKPATHER REGION ALONGWITH SOME IMPORTANT TOWNS

main boundary fault. The area under investigation lies in this zone.

The regional geology of the area has been mapped by Auden (1942) and more recently by others (Krishnaswamy and Jalote, 1968; Mehta, 1962 etc.) The tectonic sequence thus worked out for this region is given in Table 4-1.

TABLE 4-1

Tectonic Sequence for Yamuna Valley Scheme Region

		Nagthat series	Mainly Quartzites with slares	Exposed in the Tons loop tunnel area and at the Ichari diversion site
	Devonian	----------Thrust----------		
Palccozoic		Chandpur series	Mainly slates with minor quartzites	
		----------Thrust----------		
	Silurian	Mandhali series	Boulder beds states quartzites and limestones	Exposed at the underground power house site near Chibbro.
----------	----------	----------Krol thrust----------	----------	----------
	Eocene and Lower Miocene	Subathu Dagshai series	Crumpled red shales and siltstones; black plastic clays with gypsum; sheared limestone.	Exposed in region traversed by tunnel joining Chibbrq and Khodri.
Tertiary				
----------	----------	----------Thrust----------	----------	----------
	Middle Miocene	Nahan series	Sandstones, claystones and siltstones.	Exposed at Khodri, at outlet portal of the tunnel.

The most important structural features of the area are the Krol and Nahan thrusts although a number of other planes of movements also exist. A map of the area showing the location of Krol and Nahan thrusts is given in Figure 4-2. The Krol thrust has brought the Mandhalis over the younger Subathu-Dagshai shales. The thrust plane shows heavy crushing and copious water seepage. The Nahan thrust has brought the Subathu-Dagshais in juxtaposition with the Nahan Sandstones. The thrust plane does not show any marked crushin the sandstones, possibly due to the weak character of Subathus which have borne the brunt of crushing,nor any water seepage. Thus the characteristics feature of the Nahan thrust is only the stratigraphic position of the formations involved,and the drainage of the area appears to be controlled by structural features. Several streams flow along these thrust planes. In some places in this area, with narrow outcrops of the intra thrust zone material, these streams have removed the Subathus, bringing the Mandhalis directly over the Nahans, producing an impression of the two thrust planes having merged. Thus misleading outcrops have been produced by the differential erosion in the region. Other planes of movements are in the form of tear faults or of the recent scree material being over ridden by the Subathus.

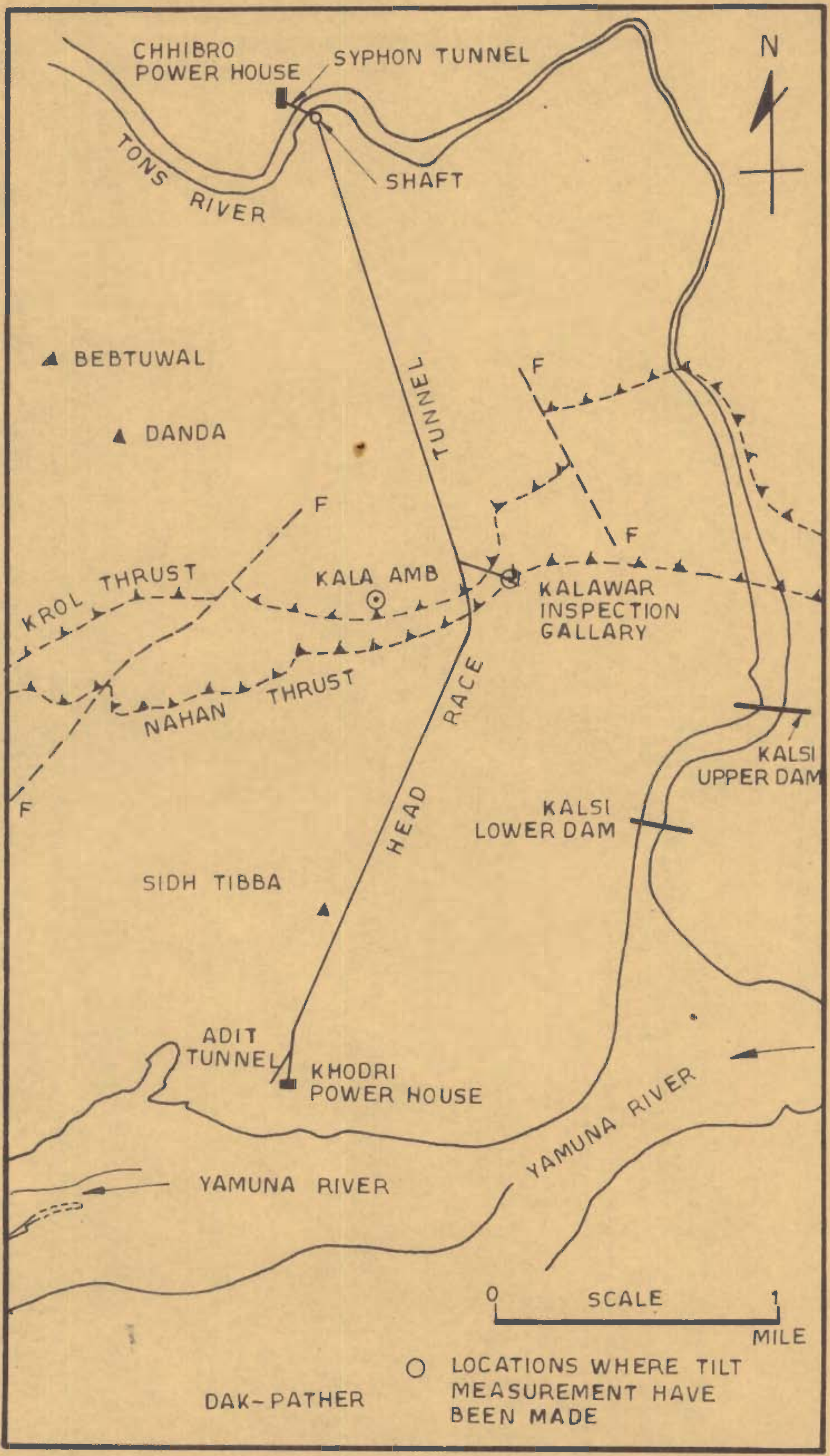


FIG. 4-2. MAP OF THE DAKPATHER REGION SHOWING THE KROL AND THE NAHAN THRUSTS

4.2. GRAVITY ANOMALIES

All along the main boundary fault the Bouguergravity anomalies are negative with sharp gradients on either side of the fault, attaining high positive values below the northern peaks and low negative values in the Indo-gangetic planes. The Bouguer anomaly at Dakpather is of the order of -130 milligals (Gulatee, 1956).

4.3. SEISMIC HISTORY

From the existence of major thrusts and a great number of secondary planes of movements it is evident that the region has been subjected to seismic activity in geologically recent times. The age of these movements is not known with any certainty but Auden (1933) considers that the Krol thrust might have resulted from the seismic activity spread over a long period. The available estimates range from Pre-Pliocene to Post-Pliocene. In historic times the only major earthquake reported anywhere near the area was the 1905 Kangra earthquake, a secondary epicentre being near the region under reference. There has been a controversy about the association of the secondary focal plane with the Krol or the Nahan thrusts but even recent investigations have been unable to establish either of these possibilities with any certainity. The nearest Seismological Observatory at Dehradun did not record any significant activity either. During 1969, through the assistance of the India Meteorological Department and the Yamuna Valley Scheme a temporary observatory was operated at Kalawar and the near earthquake data obtained is given in Table 4-2. The earthquake activity

TABLE 4-2

Near Earthquakes Recorded at Temporary Seismological Observatory at Kalawar

Date	Time in GMT	S_g-P_g sec	Epic. Dist(Δ) kms
May 1969			
7	07 52 14.4	0.7	6
20	20 59 50.9	1.5	13
21	07 50 04.6	0.8	7
28	17 04 13.0	1.4	12
29	20 01 14.2	1.2	11
30	13 33 10.5	1.1	10
June 1969			
4	08 15 25.5	1.1	10
5	07 48 39.2	1.1	10
7	03 02 06.9	2.2	19
14	07 45 53.4	0.9	8
25	07 49 58.0	1.2	11
30	07 41 01.5	1.0	9
July 1969			
1	04 10 43.9	1.5	13
2	04 41 24.8	5.5	48
4	07 49 34.1	0.9	8
6	02 03 45.5	1.0	9
7	09 11 22.3	1.3	11
8	13 17 20.0	0.6	5
12	20 52 11.3	0.7	6
August 1969			
24	17 30*	1.1	10
25	20 28*	0.5	4
29	17 47*	2.9	25
30	10 18 03.2	3.4	29
September 1969			
3	07 38 56.6	0.7	6
3	17 24 04.8	0.7	6
13	09 50 58.0	0.6	5
16	20 33 22.4	5.5	48
17	20 32 08.9	1.5	13
17	22 32 06.7	3.8	36
18	00 16 10.6	2.7	24
20	15 43 16.9	1.0	9
22	08 28 43.5	2.6	23
October 1969			
14	13 01 17.9	1.6	14
15	12 36 55.5	1.1	10
17	13 03 18.3	0.9	8
17	13 19 20.1	1.0	9
19	09 05 20.0	0.8	7
28	12 52 32.3	0.9	8

* Approximate time due to the absence of time marks on the record.

recorded here between May to October 1969 was rather low but the sources being indicative of weak zones. The

Multiple Structural Response Recorder installations in the region at Dehradun, Narendra Nagar and Tehri did not yield any data since no earthquake big enough to cause appreciable structural response occurred during the period of investigations.

4.4. LEVELLING DATA FROM SURVEY OF INDIA

Repeat observations of levelling between Dehradun and Mussoorie before and after the 1905 Kangra earthquake showed a level change of the order of 10 to 12.5 cms whereas it remained unchanged over the Mussoorie-Saharanpur line. This would suggest that Dehradun moved up, with respect to Mussoorie by the observed order of level change.

During 1908, levelling was carried out along the Dehradun Kalsi route and repeated during 1927-28. The three bench marks at river Tons (near Dehradun), Saharanpur and Ambari (near Yamuna Bridge) all three to the south of the Nahan thrust showed a rise of 0.13, 1.38 and 2.5 cms respectively.

4.5. OBSERVATIONS IN THE KALA AMB DRIFT

An exploratory drift of 2.5 x 2 mts section and 190 mts length has been excavated at Kala Amb. The section along the drift is given in Figure 4-3. A sub-recent thrust plane dipping at 30° in a northerly direction is present at 102 meters along which the scree has been over ridden by the Subathu clays. Highly crushed quartzites,

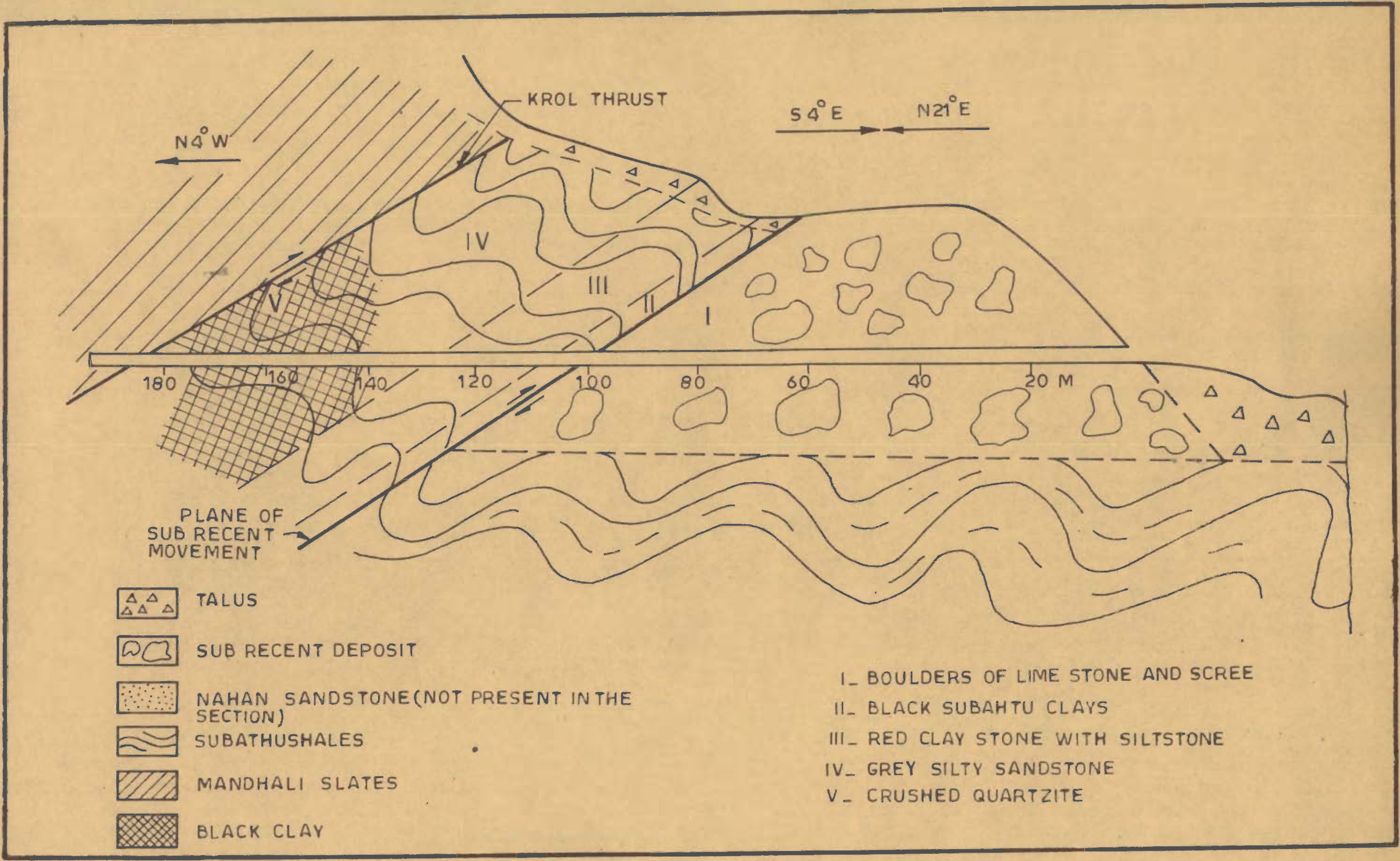


FIG. 4-3. GEOLOGICAL SECTION ALONG THE KALA-AMB DRIFT

grey sandstone and siltstone, saturated with water, are met at 139- 149 meters and are almost in flowing conditions. Probably it is in this zone that the tear fault, as revealed by surface observations has been encountered. The Krol contact has been met at 190 meters. An attempt to take a drill hole at 140 meters resulted in jumping of the entire drilling rig due to upthrust.

4.6. FLAT JACK TEST DATA

Flat jack test consists of cutting a slot in the rock face, which results in the expansion of the rock into the slot. A flat jack is grouted into the slot and pressure applied by means of a hydraulic-jack until the rock is restored to its original position. The pressure required to restore the strains is called the cancellation pressure and is a measure of the stress in the rock. A number of flat jack tests have been conducted in different rock formations of the area and at each location tests were carried out by orienting the flat jack in three orthogonal directions to give the stresses in two horizontal (N-S and E-W) and a vertical direction. The results bring out the existence of a large stress field in the N-S direction at each of these locations compared to the other two components.

4.7. TIWAG'S RADIAL PRESS TEST DATA

Tiwag's Radial Press test has been conducted in the red shales in the head race tunnel at a short distance from the Khodri end. The test was carried out in three stages to obtain pressures of 3,5 and 7 kg/cm² in the increasing order, the pressure of 5 kg/cm^2 corresponding to the internal pressures in the tunnel. The deformation showed an erratic trend. The value of modulus of deformation thus obtained was of the order of 10^6 kg/cm^2. After the test for determination of modulus of deformation, the radial press equipment was left in its position with no pressure applied. But the out flow of the liquid from the flat jack was stopped. A pressure of 1 kg/cm^2 developed due to rock deformations in the first 30 hours and remained constant, thereafter. However, the associated rock deformations continued for a longer time.

4.8. TILT MEASUREMENTS

4.8.1. Tilt Base-hub Installations in Kala Amb

Since indirect evidences of recent movements were available in the region, it was considered desirable to make direct measurements of tilt employing a Portable Water Tube Tiltmeter. To avoid the influence of local factors, it was necessary to plan these measurements in an underground tunnel. An exploratory drift at Kala Amb was under excavation during 1968 and, to start with, this drift was used for this purpose particularly with a view to extending the measurements across the Krol thrust which the tunnel was planned to reach. Three tilt bases were installed, one on the subrecent deposits and two on the Subathu shales at distances of 15-20 meters. As the floor of the drift was sloping, a limit was imposed on the maximum possible spacing between the bases. The first two bases were intended to give the order of displacement across the plane of subrecent movement. It was intended to tie these bases to that across the Krol thrust and therefore a third base was installed in the already excavated portion of the drift towards the Krol thrust. Due to bad seepage condition, additional bases could not be installed in the drift and the movement across the Krol thrust could not be monitored.

4.8.2. Tilt Base-hub Installations at Kalawar

An inspection gallery starting at Kalawar and reaching the head race tunnel alignment was under construction during 1969. The section along the gallery is given in Figure 4-4. The Nahan thrust has been traversed by the gallery, between 164 meters (at the over break portion of the crown) to 240 meters (on the floor). But the measurements of movement along the thrust employing the Portable Water Tube Tiltmeter could not be conducted since the gallery had a large slope and was in continuous use for construction purposes. Therefore, a horizontal cross-cut on the left wall of the gallery at 282 mts which also traversed the Nahan thrust was selected for the purpose of tilt measurements. The plan of the cross-cut and the positions of all the tilt bases in this cross-cut are indicated in Figure 4-5. The distance of the excavated face from tilt bases 1 and 2 was kept equal so that the influence on them of the sequeezing of the tunnel cavity be indentical as far as possible. However, to permit a study of the influence of squeezing of the cavity on the observations,

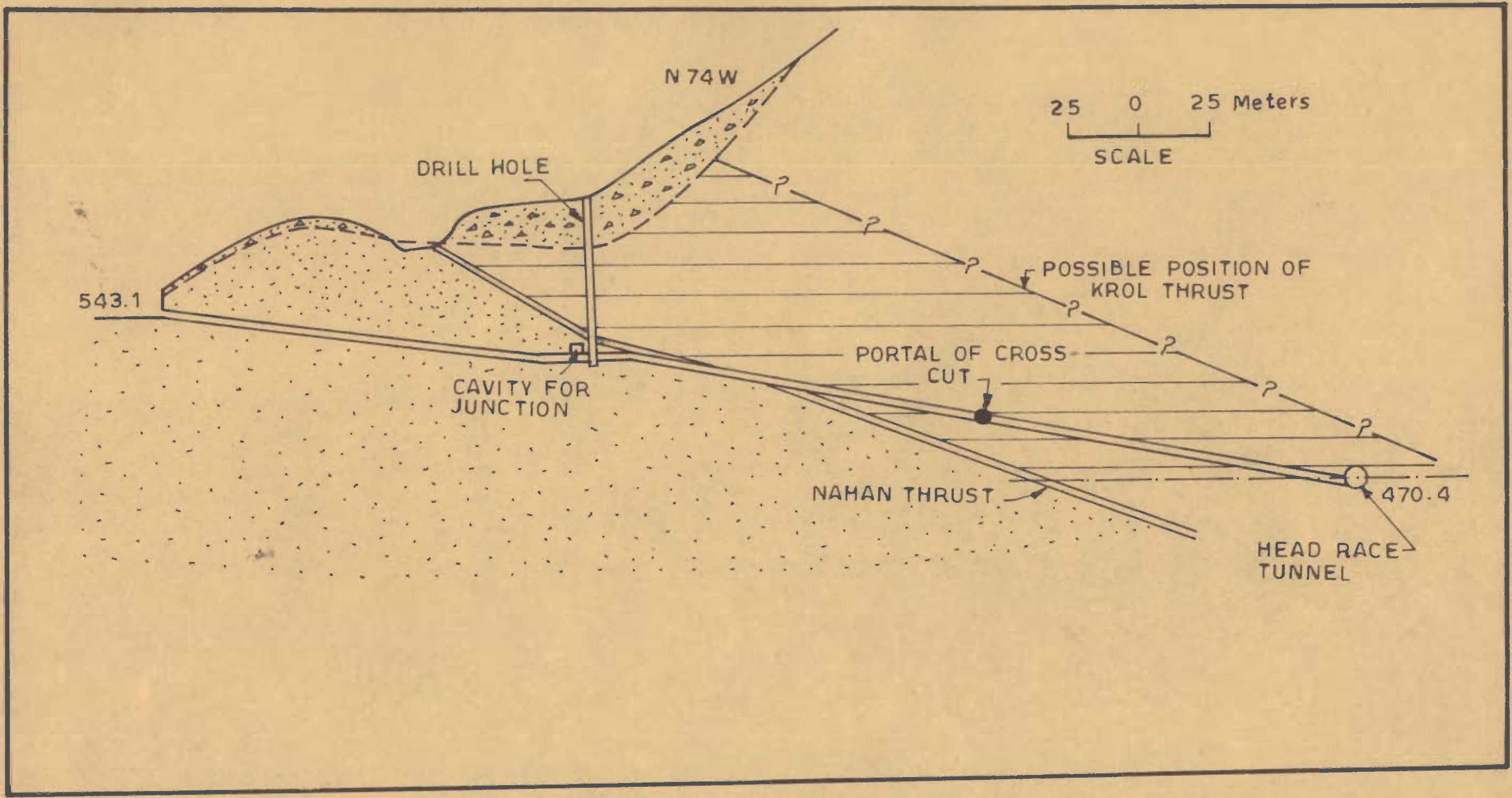


FIG. 4-4. GEOLOGICAL SECTION ALONG THE KALAWAR INSPECTION GALLERY

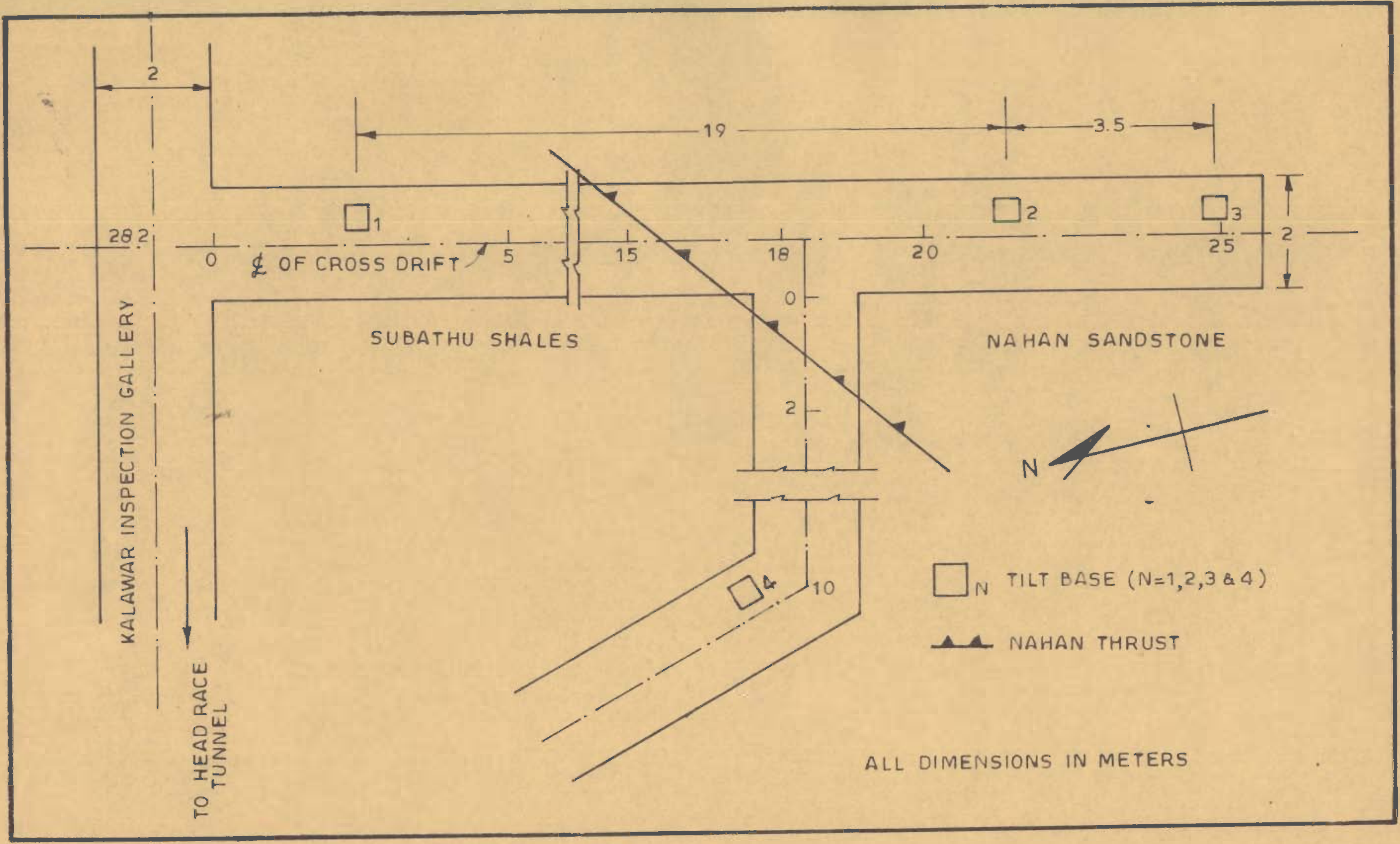


FIG. 4-5. PLAN OF THE CROSS-CUT OF THE KALAWAR INSPECTION GALLERY AT 282 METERS, ALONG WITH THE POSITIONS OF TILT BASE-HUB INSTALLATIONS

if any, a third base close to the unexcavated face was installed and measurements were commenced in September 1969. During early 1970, a secondary cross-cut, as shown in the Figure 4-5, was excavated and a fourth base fixed. The lines joining bases 1,2 and 2,4 are about equally oblique to the strike of the Nahan thrust. Thus the measurements between the bases 2 and 4 offered a check on those between the bases 1 and 2.

4.8.3. Tilt data

Tilt measurements across the plane of subrecent movements were commenced from June 1968 and recorded a large floor swelling in the Subathu clays. The data have been given in Table 4-3(a). Unfortunately however, measurements had to be discontinued as poor rock conditions,

TABLE 4-3(a)

Tilt Observations in Dakpather Region

LOCATION: Kala Amb Drift

Sl. No.	Date	Reading in mm		Relative Height mm	Height change mm	Days since last obs.	Movement Rate mm/month
		Base No.1	Base No.2				
1.	13.6.68	11.400	7.249	4.151			
					20.315	290	2.10
2.	30.3.69[1]	34.0	9.544	24.466			
					9.965	95	3.15
3.	3.7.69	32.332 + (3+2)[2]	13.091	34.431			
		Base No.1	Base No.2				
1.	13.6.68[3]	9.692	16.892	7.00			

---

[1] Approx. reading since the different was beyond the range of instrument.

[2] Packing plates (3+2) = 18.199 mm

[3] Reading could not be continued afterwards due to poor rock

resulted into the breaking of timber supports rendering the gallery unsafe. Tilt measurements across the Nahan thrust plane in the cross-cut were commenced in September 1969 and repeated every 4 to 6 weeks. The data have been given in Table 4-3(b) alongwith the calculated rate of creep movements. The measurements in the secondary cross-cut were commenced in April 1970 and repeated only once in August 1970. This data is also included in Table 4-3(b).

TABLE 4-3(b)

Tilt Observations in Dakpather Region*

LOCATION: Kalwar Inspection Gallery Cross-cut at 282 Meters

Sl. No.	Date	Reading in mm Base No.1	Reading in mm Base No.2	Relative Height mm	Height change mm	Days since last Obs.	Movement Rate mm/month (a)	Movement Rate mm/month (b)
1.	17.9.69	20.746	26.135	5.389				
2.	5.11.69	12.474	19.623	7.149	1.760	49	1.09	
3.	31.1.70	14.783	24.744	9.961	2.812	87	0.97	1.00
4.	24.4.70$^+$	14.331	25.555	11.224	1.263	83	0.45	0.80
5.	21.8.70	10.127	23.098	12.971	1.747	119	0.44	0.67
		Base No.1	Base No.2					
1.	17.9.69	24.821	20.798	2.798				
2.	5.11.69	23.234	20.777	2.457	.341	49	0.21	
3.	24.4.70	20.509	19.280	1.229	1.228	170	0.21	
4.	21.8.70	15.238	17.705	-1.467	2.696	119	0.68	
		Base No.2	Base No.4					
1.	24.4.70	24.314	17.612	7.702				
2.	21.8.70	18.070	13.246	4.824	2.878	119	.72	

a. Since the last reading.
b. Since the beginning of the measurement.
* Tunnel was lined after third reading.

CHAPTER 5

ANALYSIS AND INTERPRETATION OF DATA AND CONCLUSIONS

5.0. GENERAL

The data for the two regions have been separately analysed to answer some of the problems of these regions. The availability of greater quantitative data for the Koyna region enabled a more systematic analysis for this region as compared with that for the Dakpather region. Possible interpretations of the results obtained have been discussed separately in the following sections:

5.1. THE KOYNA REGION

5.1.1. ANALYSIS OF SEPTEMBER 13,1967 KOYNA ACCELEROGRAM

The tracing prepared from the enlargement of a printed copy of September 13,1967 Koyna accelerogram given in Figure 3-2 was used for digitization at each peak and trough of the three traces, i.e. at unequal intervals of time, upto about 2.5 seconds. The digitized data is given in Table 3-1. The number of points digitized varied between 42-50 per second for the three traces with the vertical component having the least number. These details of digitization have been included here to indicate the possible sources of additional inaccuracies compared to a normal case where the original accelerogram is available for use. The base line has been located to give a minimum mean square computed ground velocity at the end of each trace. The integrated ground displacements and velocities for the three orthogonal components, namely two horizontal and one vertical component, have been obtained. Integration has been carried out using Simpson's rule (Brady, 1966). The plots of the ground displacements and velocities for the respective components are given in Figures 5-1,2 and 3. The relative displacement, velocity and acceleration response of viscous damped oscillators with 5% of critical damping and 0.40 second period for the three components were computed. This was done to permit comparison of normalised response for the three Koyna earthquakes.

5.1.2. ANALYSIS OF OCTOBER 29,1968 KOYNA ACCELEROGRAM

The tracing prepared from the enlargement of a photo copy of the October 29,1968 Koyna accelerogram (Figure 3-17) was used for digitization at each peak and trough of all the three traces, upto about 4 seconds.The number of points digitized varied between 24-32 per second for the three traces, with vertical component having the highest number(see digitized data in Table 3-5).The integrated ground displacements and velocities for the three components are given in Figure 5-4,5 and 6. The relative displacement velocity and acceleration response of viscous damped oscillators with 0.40 second period for the three components were computed. This was done to permit comparison of normalised response for the three Koyna earthquakes for which data was available. The relative displacement response for oscillators having 0.40 and 0.75 second periods and with 10%, 20% and 40% of critical damping

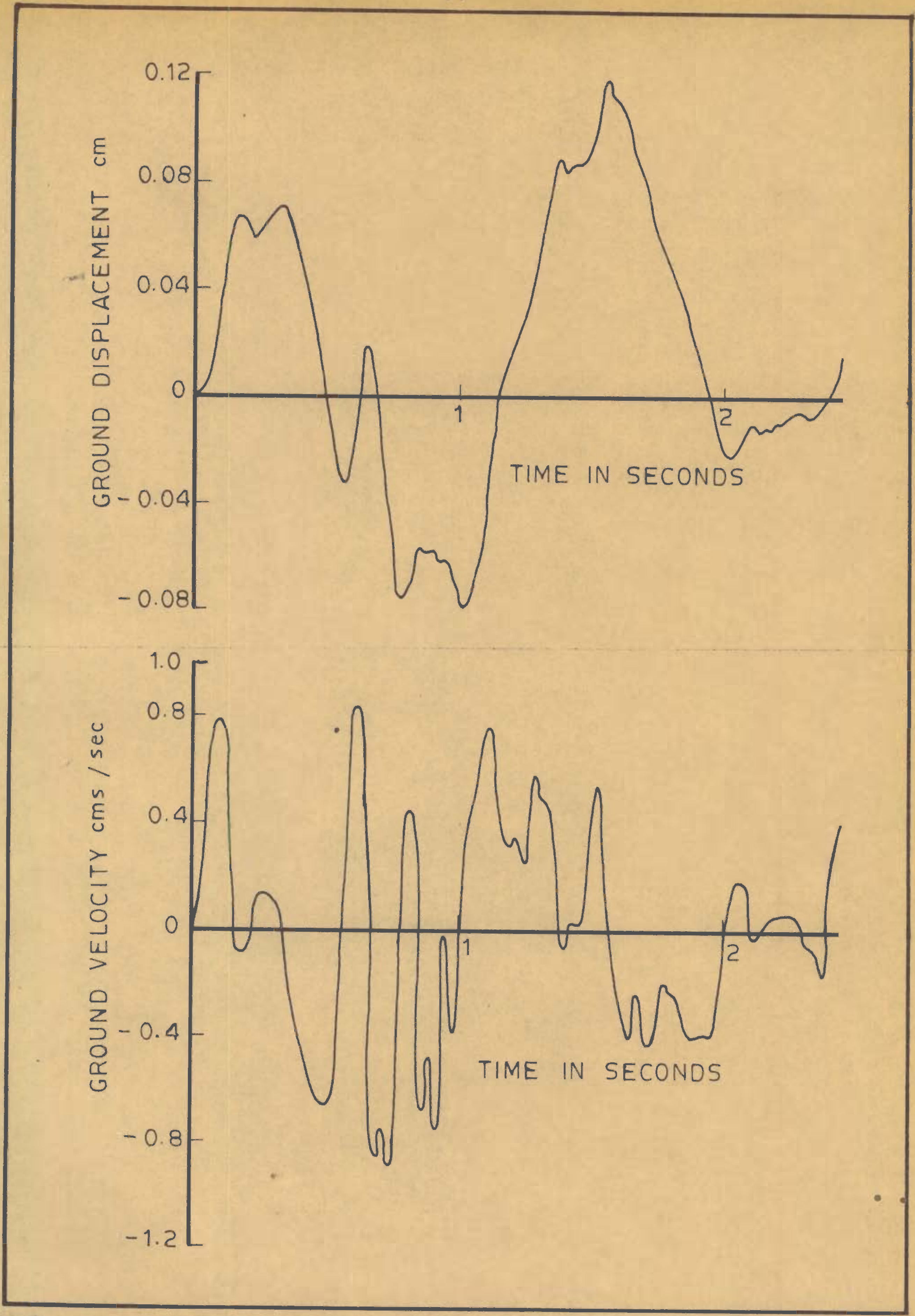


FIG. 5-1. COMPUTED GROUND DISPLACEMENT AND VELOCITY FOR HORIZONTAL COMPONENT IN THE DIRECTION N 35° E (TRANSVERSE) OF THE SEPTEMBER 13, 1967 EARTHQUAKE AT KOYNA

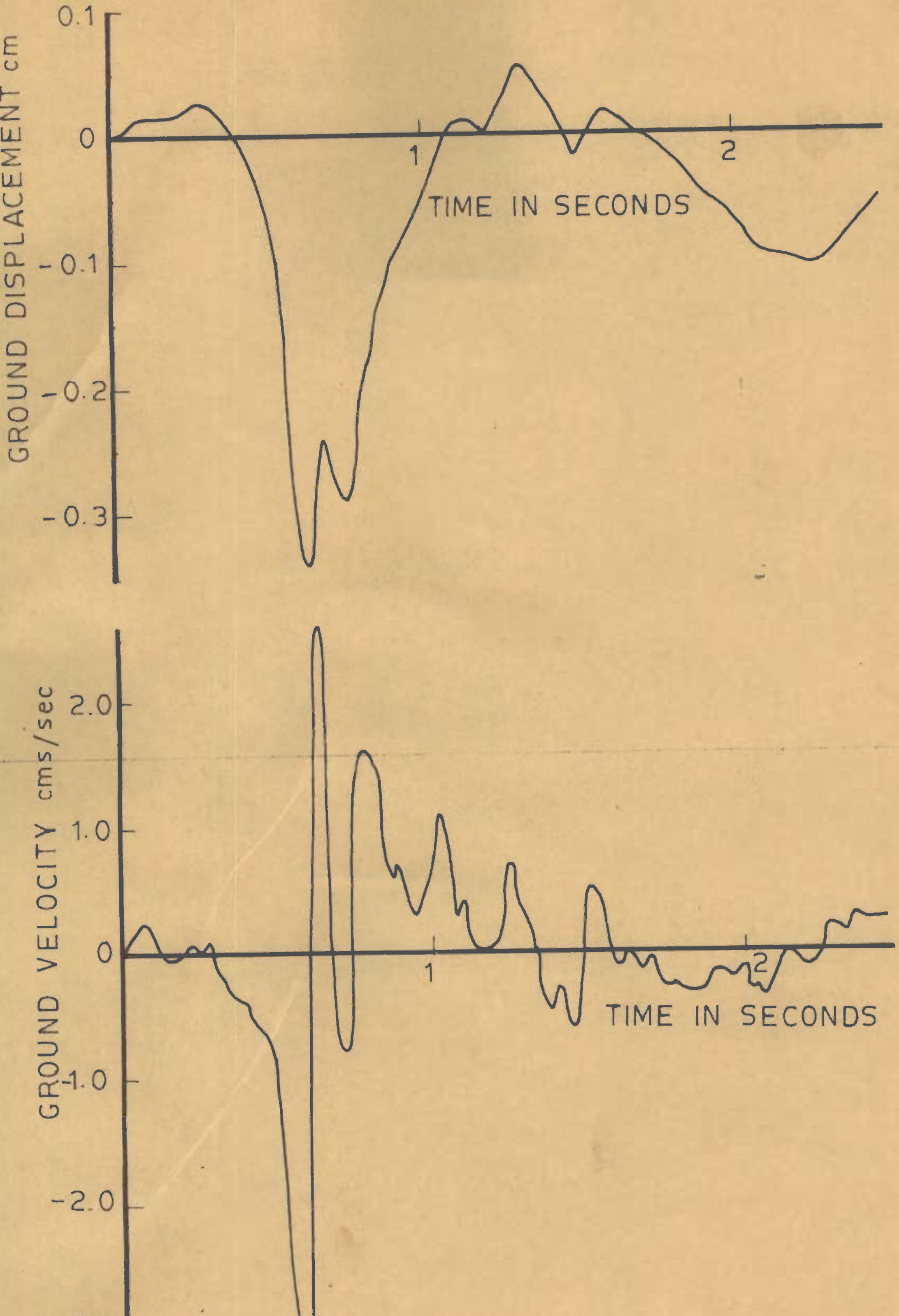


FIG. 5-2. COMPUTED GROUND DISPLACEMENT AND VELOCITY FOR HORIZONTAL COMPONENT IN THE DIRECTION N 55° W (LONGITUDINAL) OF THE SEPTEMBER 13, 1967 EARTHQUAKE AT KOYNA

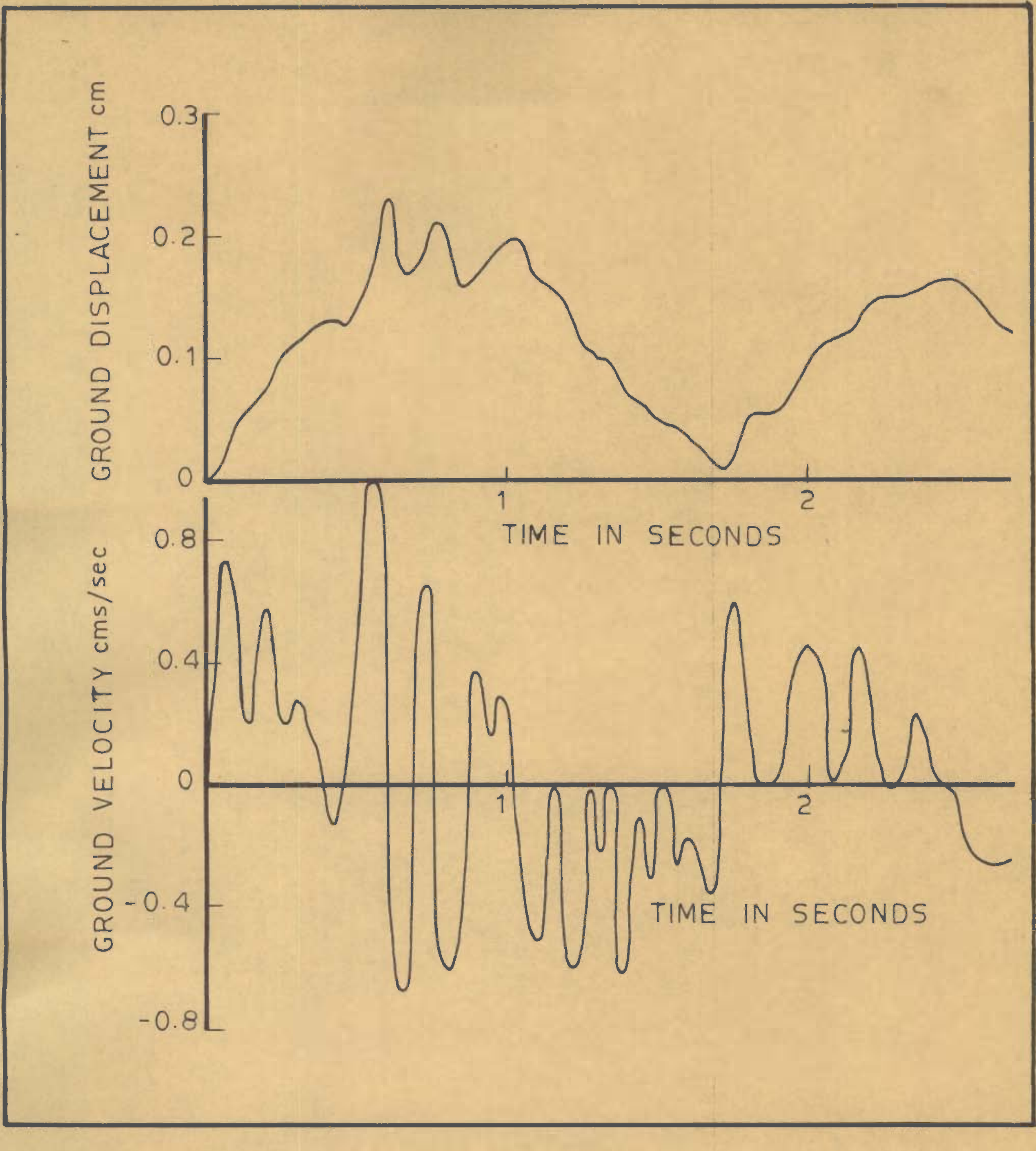


FIG. 5-3. COMPUTED GROUND DISPLACEMENT AND VELOCITY FOR VERTICAL COMPONENT OF THE SEPTEMBER 13, 1967 EARTHQUAKE AT KOYNA

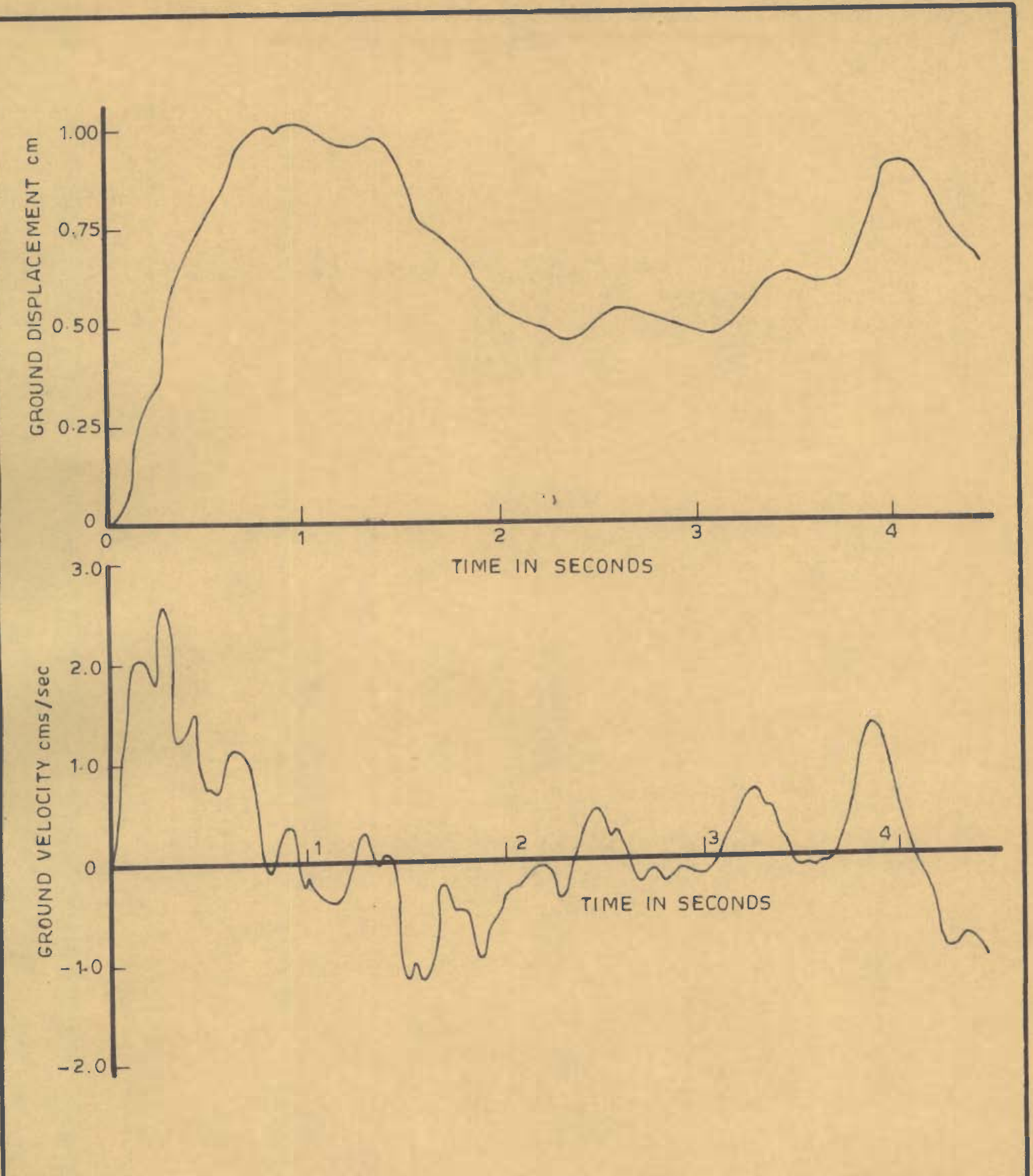


FIG. 5-4. COMPUTED GROUND DISPLACEMENT AND VELOCITY FOR HORIZONTAL COMPONENT IN THE DIRECTION N35°E (TRANSVERSE) OF THE OCTOBER 29, 1968 EARTHQUAKE AT KOYNA

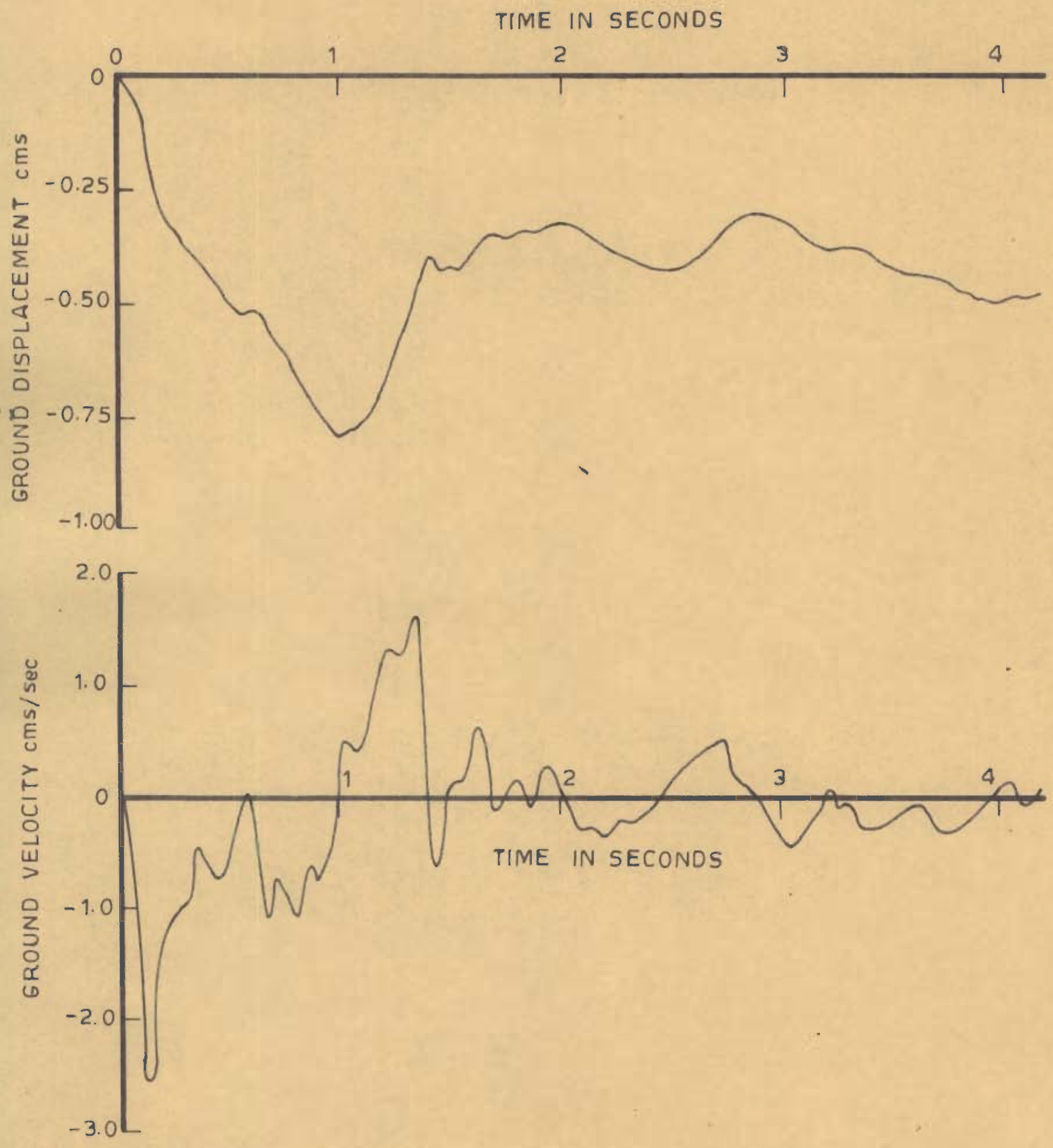


FIG. 5-5. COMPUTED GROUND DISPLACEMENT AND VELOCITY FOR HORIZONTAL COMPONENT IN THE DIRECTION N 55°W (LONGITUDINAL) OF THE OCTOBER 29, 1968 EARTHQUAKE AT KOYNA

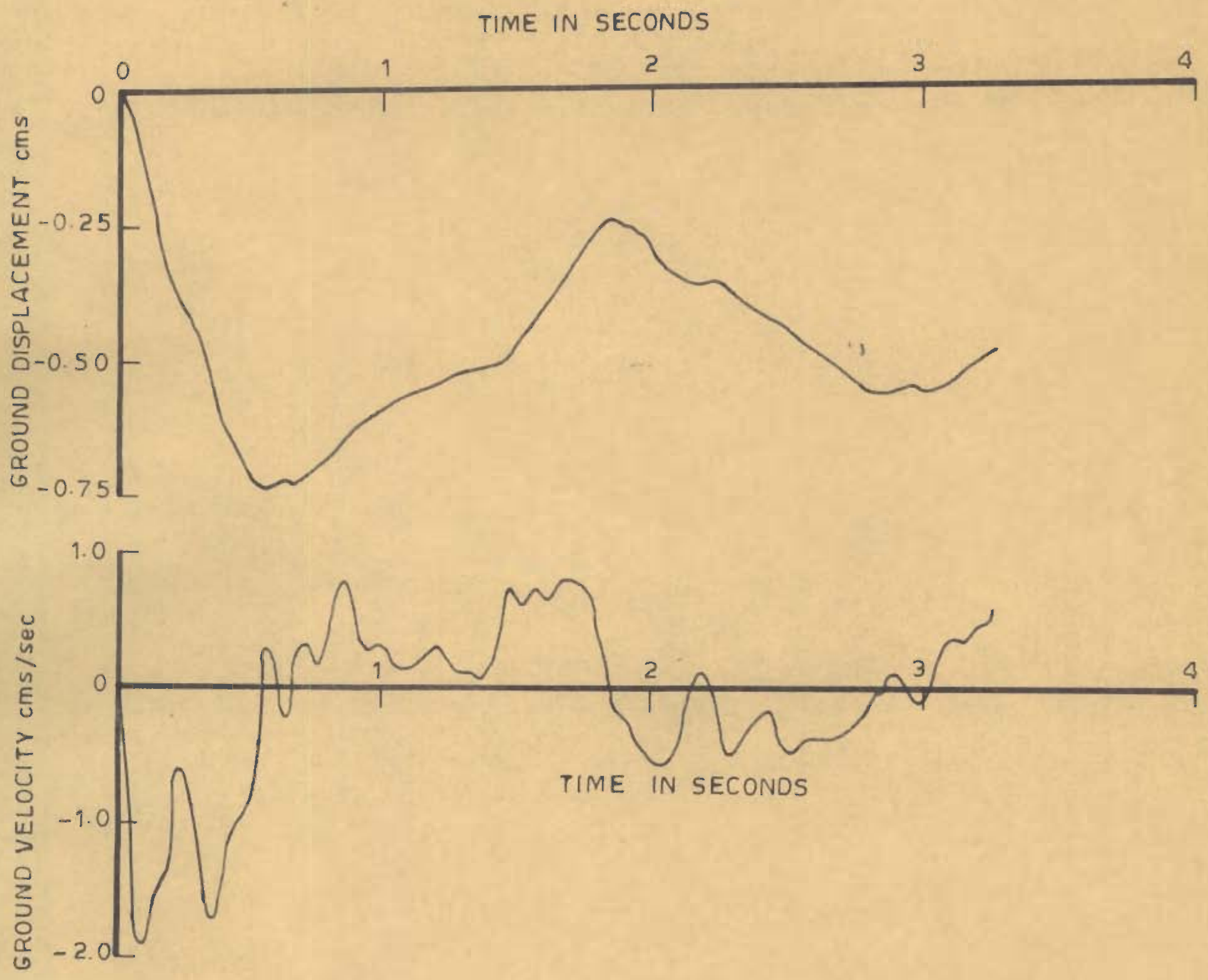


FIG. 5-6. COMPUTED GROUND DISPLACEMENT AND VELOCITY FOR VERTICAL COMPONENT OF THE OCT. 29, 1968 EARTHQUAKE AT KOYNA

were computed only for the horizontal components and two dimensional plots of response in a horizontal plane were prepared. This was done with a view to evaluating the potential of the seismoscopes.

5.1.3. ANALYSIS OF SEISMOSCOPE DATA

The Multiple Structural Response Recorder installed in the seismological observatory located on the down stream side of the Koyna dam had recorded the October 29,1968 earthquake (vide Figure 3-16). These were analysed and the relative maximum displacement, velocity and acceleration response values were calculated (Agrawal, 1970,a). The results are given in Table 5-1. During this event the Roorkee Seismoscope installed in pairs at all the three locations yielded records (vide Figure 3-15). The maximum relative displacement, velocity and acceleration response values were calculated and the results are given in Table 5-2. The records from the Roorkee Seismoscopes during the June 27,1969 earthquake (Agrawal, 1969,c) were also analysed and the results are given in Table 5-3.

The damping estimates were obtained by extrapolation. The level of recording was so small that two successive amplitudes could not be measured at that level. Therefore, from the plots of damping versus amplitude, prepared for each instrument, extrapolation of damping at the level of recording was done. At such low amplitudes, the variation in damping is not identical in all cases and the ..

TABLE 5.1

Multiple Structural Response Recorder Results

Record No. in figure 3-16	Location and its No. in figure 3-14	Period sec	Damping % of critical (nominal)	Recorded Amp. (12 times) mm	Tilt Sensitivity mm/rad	Φ_{max} rad	S_d mm	S_v mm/sec	S_a % of g
1.	Seismological Observatory downstream side near Koyna Dam; No. 1.	1.25	20	5.2	58.63	0.007	2.7	13.5	0.7
2.		0.75	15	11.1	41.47	0.022	3.1	25.9	2.2
3.		0.40	5	24.0	17.18	0.116	4.6	72.2	11.6
4.		0.40	12	7.8	12.87	0.050	2.0	31.4	5.0
5.		0.75	8	10.9	34.89	0.026	3.7	31.0	2.6
6.		1.25	6	18.5	57.20	0.027	10.5	52.5	2.7

The direction of maximum response was approximately N 30° E for all the records.

TABLE 5-2

Roorkee Seismoscope Results

Record No. in figure 3-15	Location and its No. as marked in figure 3-14	Period sec	Damping % of critical nominal	Recorded Amp. (12 times) mm	Φ_{max} rad	S_d mm	S_v mm/sec	S_a % of g
1.	Instrument room Koyna Dam: M,1 B; No. 2	0.75	15	24	0.013	1.80	15.1	1.3
2.	Instrument room Koyna Dam: M,1 B; No. 2	0.40	20	24	0.013	0.51	8.0	1.3
3.	Foundation Gallery Koyna Dam: M,17; No. 3	0.75	20	26	0.014	2.00	16.7	1.4
4.	Foundation Gallery Koyna Dam: M,17; No. 3	0.40	20	36	0.020	0.79	12.4	2.0
5.	Control room, switch yard, Porhali Power House; No. 4	0.75	20	54	0.030	4.20	35.2	3.0
6.	Control room, switch yard, Pophali Power House; No. 4	0.40	20	64	0.035	1.40	22.0	3.5

The direction of maximum response was approximately N 30° E for all the recorders.

TABLE 5-3

Structural Response Results Obtained from Roorkee Seismoscope During June 27,1969 Earthquake in Koyna Pophali Region

Record No. in figure 3-18	Location and its No. as marked in figure 3-14	Period sec	Damping % of critical nominal	Recorded Amp. (6 times) mm	Dir. of MAX. Amps.	Φ_{max} rad	S_d mm	S_v mm/sec	S_a % of g
1.	Instrument room Koyna Dam: M,1 B; No.2	0.75	20	3.5	N 10° E	.004	0.56	4.69	0.4
2.	Instrument room Koyna Dam: M,1 B; No.2.	0.40	20	11.0	N	.012	0.46	6.98	1.2
3.	Foundation Gallery Koyna Dam: M,17; No.3.	0.75	20	3.0	N	.003	0.42	3.51	0.3
4.	Foundation Gallery Koyna Dam: M,17; No.3.	0.40	20	9.0	N	.010	0.38	5.77	1.0
5.	Control room, switch yard, Pophali Power House; No. 4	0.75	20	2.0	N 40° E	.002	0.26	2.34	0.2
6.	Control room, switch yeard, Pophali Power House; No. 4	0.40	20	7.0	N 40° E	.008	0.30	4.56	0.8

extent of influence of friction is uncertain. Thus the estimates of damping are only nominal and can not be used with reliability.

5.1.4. ELASTIC STRAIN REBOUND INCREMENTS

Elastic strain rebound increments for the two periods, one starting from the very beginning of the available data in January 1967 and the other after the December 11,1967 event were plotted on the basis of weekly strain energy release values given by Guha. The two plots thus prepared are given in Figure 5-7 and 8 and were utilised for examining whether there was a change in the phase of the fault movement.

5.1.5. COMPARISON OF THE DECEMBER 11,1967; SEPTEMBER 13, 1967 AND OCTOBER 29,1968 STRONG MOTION DATA

To permit comparison of the strong motion data obtained during December 11,1967, September 13,1967 and October 29,1968 Koyna earthquakes, some of the characteristic features of the data for these three events have been given in Table 5-4. It may be worthwhile mentioning here that original accelerograms were not available for this analysis. Additional inaccuracies might have crept in the results on account of this. Perhaps the comparison would be still valid since the additional inaccuracies are common to all the three earthquakes compared. The locations of epicentre in relation to the location of the instruments were given in Figure 3-14 and the latitude and longitude

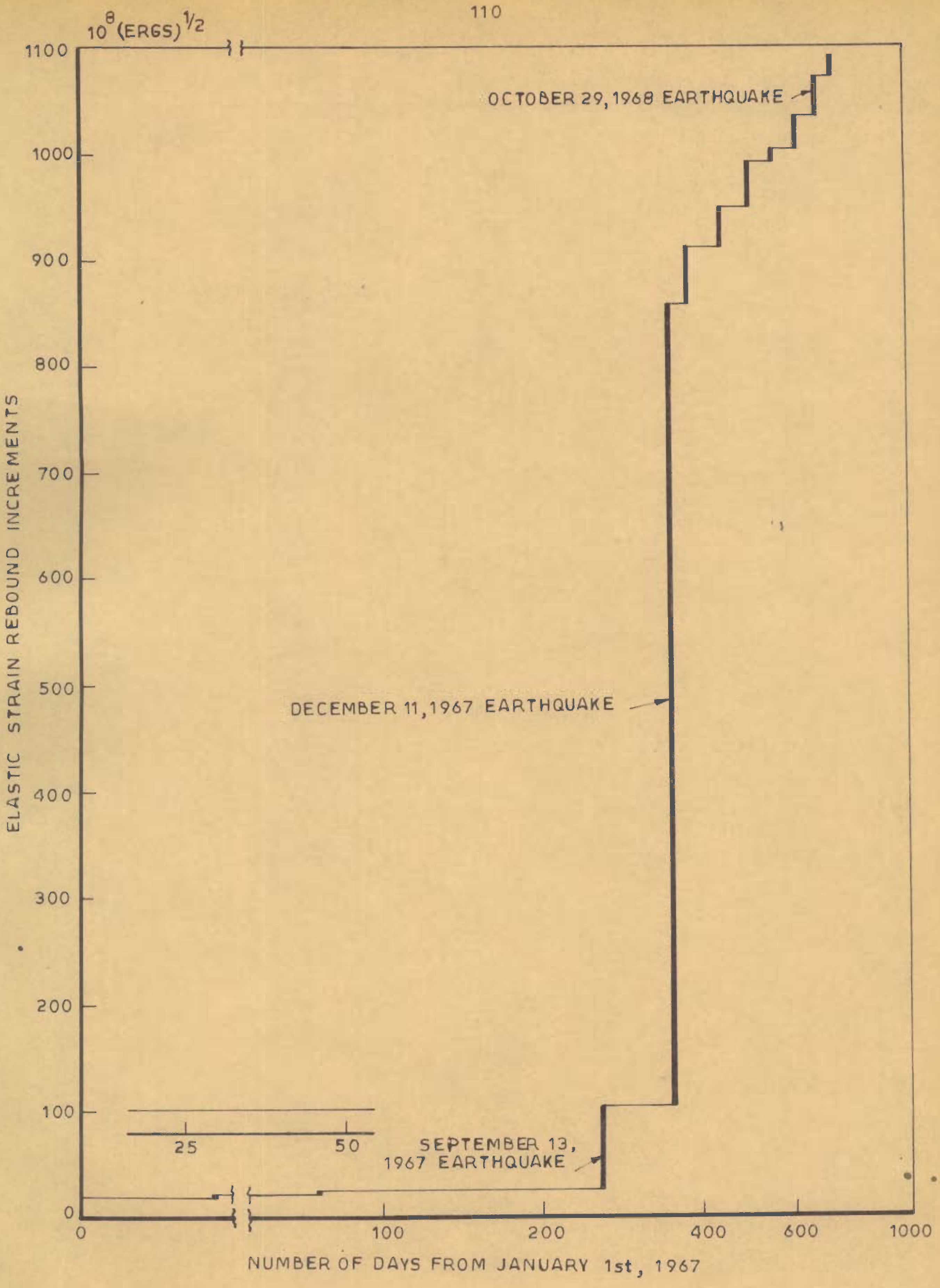


FIG. 5-7. ELASTIC STRAIN REBOUND INCREMENTS OF THE KOYNA REGION STARTING FROM 1st JANUARY 1967

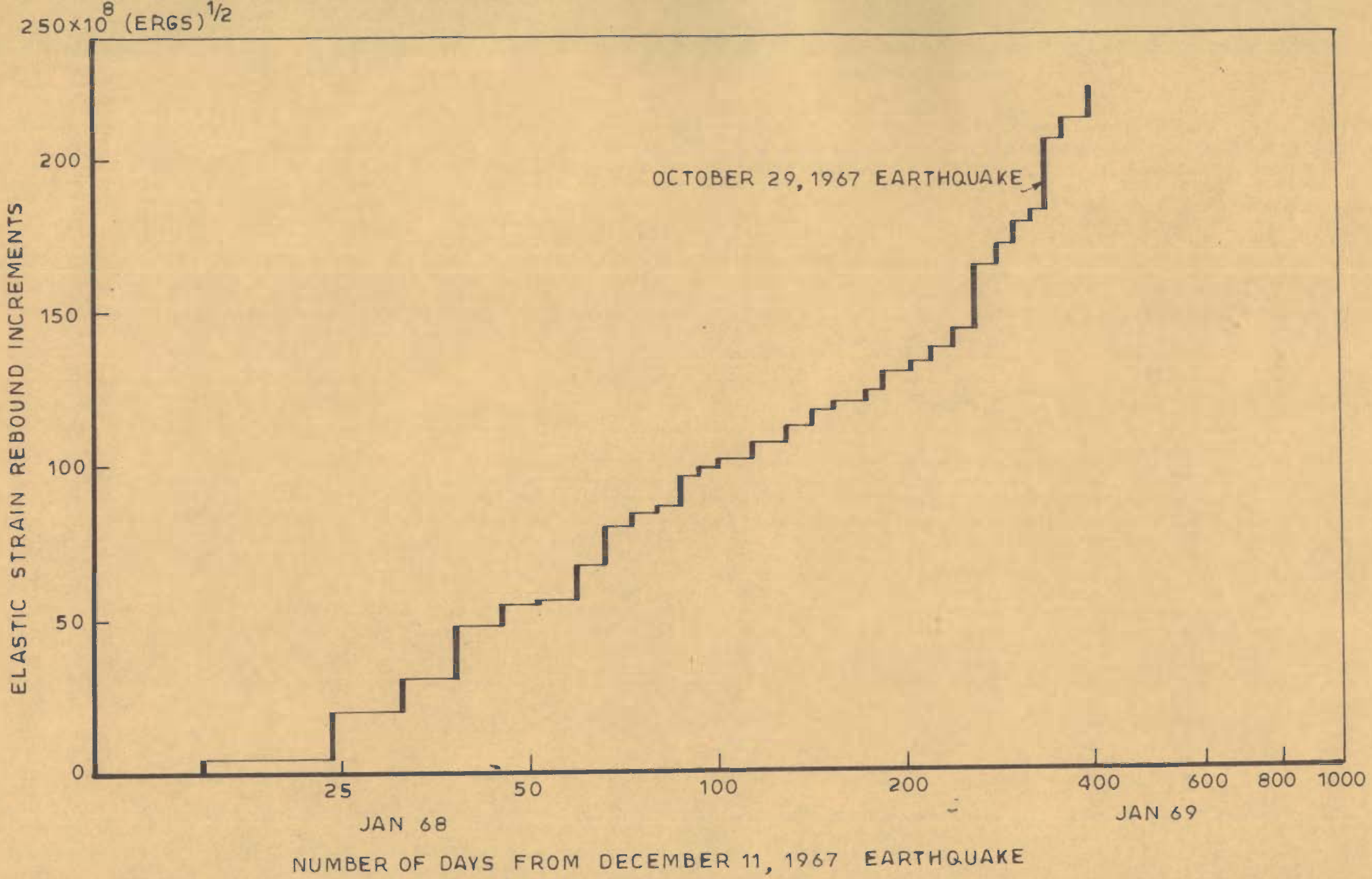


FIG. 5-8. ELASTIC STRAIN REBOUND INCREMENTS OF THE KOYNA REGION STARTING FROM DECEMBER 11, 1967 EARTHQUAKE

TABLE 5-4

Characteristic Features of the Three Koyna Earthquakes

Event	Component	Maximum Ground			Time to Max. Accln. sec	Zero-Axis Width of Accln.Max. sec	Cycles per sec	Zero Crossings per sec		Maxima per sec Average* N_m	$\frac{No}{2\ N_m}$
		Disp. cm	Vel. cm/sec	Accln. % of g			Range	Range	Average* No.		
Sept 1967	T	0.119	0.888	0.096	0.648	0.040	21-23	30-36	31	19	.81
	V	0.238	1.030	0.080	0.615	0.070	20-22	31-40	31	19	.81
	L	0.340	3.296	0.234	0.623	0.060	25-29	32-33	27	19	.71
Dec. 1967	T	21.640	20.080	0.490	3.131	0.050	12-15	18-26	21	13	.82
	V	28.840	25.580	0.340	3.797	0.050	13-15	24-26	24	14	.86
	L	13.300	24.190	0.630	3.852	0.050	15-20	20-22	21	16	.65
Oct. 1968	T	1.020	2.614	0.068	0.121	0.050	12-14	24-31	24	13	.92
	V	0.734	1.897	0.084	0.059	0.050	14-16	30-31	25	14	.90
	L	0.790	2.559	0.096	1.136	0.050	14-15	25-28	26	14	.93

T component in the direction N 35° E, i.e. transverse to the axis of the dam.
V component in the vertical direction.
L component in the direction N 55° W, i.e. along the axis of the dam.

* Average has been taken for 2 seconds trace containing maximum acceleration.

TABLE 5-5

Location of Epicentres of the Three Earthquakes Under Study
in Relation to the Location of the Instruments

Event	Latitude	Longitude	Estimated Epicentral Distance
Epicentre of the September 13,1967 Earthquake	17° 24.0' N	73° 44.8' E	1 km
Epicentre of the December 11,1967 Earthquake	17° 22.4' N	73° 44.8' E	4 kms
Epicentre of the October 29,1967 Earthquake	17° 23.5' N	73° 46.0' E	3.5 kms
Location of the Koyna Dam:	17° 23.95' N	73° 45.0' E	

Distance between	M 18 - M 13	About 200 Meters
Distance between	M 13 - M 17	About 50 Meters
Elevation Difference between	M 17 and M 1B	About 50 Meters

Distance of Seismological Observatory on the downstream side of the Koyna Dam from M1B about 300 Meters.

and estimated epicentral distances are given in Table 5.5. The results of Table 5-4 bring out the following features of these three events.

(i) The zero axis widths, for the acceleration peaks of the three components for the December 11,1967 and October 29,1968 events are found to be identical inspite of the difference in their magnitude. In fact even for the September 13,1967 event the zero axis width is comparable.

(ii) The peak ground acceleration recorded were associated with the component in the N 55°W in all the three events.

(iii) During both the December and October events the large horizontal ground displacement was in the component perpendicular to the one containing the acceleration. peak. However, during the September event the same component contained both the peaks of acceleration as well as of displacement.

(iv) The frequencies associated with the December 1967 and October 1968 accelerograms are of comparable order. The September 1967 accelerogram had higher frequencies associated with it.

(v) In general, the time of occurrence of a peak as measured from the starting point of the record increased with increasing peak acceleration value for the three events. However, amongst the three components of the events themselves such a systematic variation did not exist.

The epicentre of the September shock was closest to the accelerograph as compared to that for the other two events. Thus the higher frequency content ~~y~~ of the September accelerogram was as expected.

5.1.6. COMPARISON OF RESULTS FROM SEISMOSCOPE AND ACCELEROGRAM DATA ANALYSIS

The Multiple Structural Response Recorder was installed in the seismological observatory on the down stream side of the Koyna dam on the same rock on which the dam foundation rests and about 300 meters away from the location where accelerograph was installed in the dam. The Roorkee Seismoscopes were installed in pairs about 200 meters apart at two positions in the body of the dam and at foundation levels. The accelerograph was also installed in the body of the dam at foundation level at an intermediate location 50 meters from the Roorkee Seismoscope in M 17. However, all these locations are closely spaced on the same rock formation i.e. the same Basaltic lava flow, except that the level was different by about 50 meters.

The difection of the maximum relative displacement response (S_d) on Multiple Structural Response Recorder and Roorkee Seismoscopes was almost transverse to the dam axis and therefore only the analysis of one of the two horizontal components (N 35° E) recorded by the accelerograph was used for comparison of results. The plot of S_d versus period obtained through the relevent accelerograph trace is given in Figure 5-9. The results from Multiple Structural

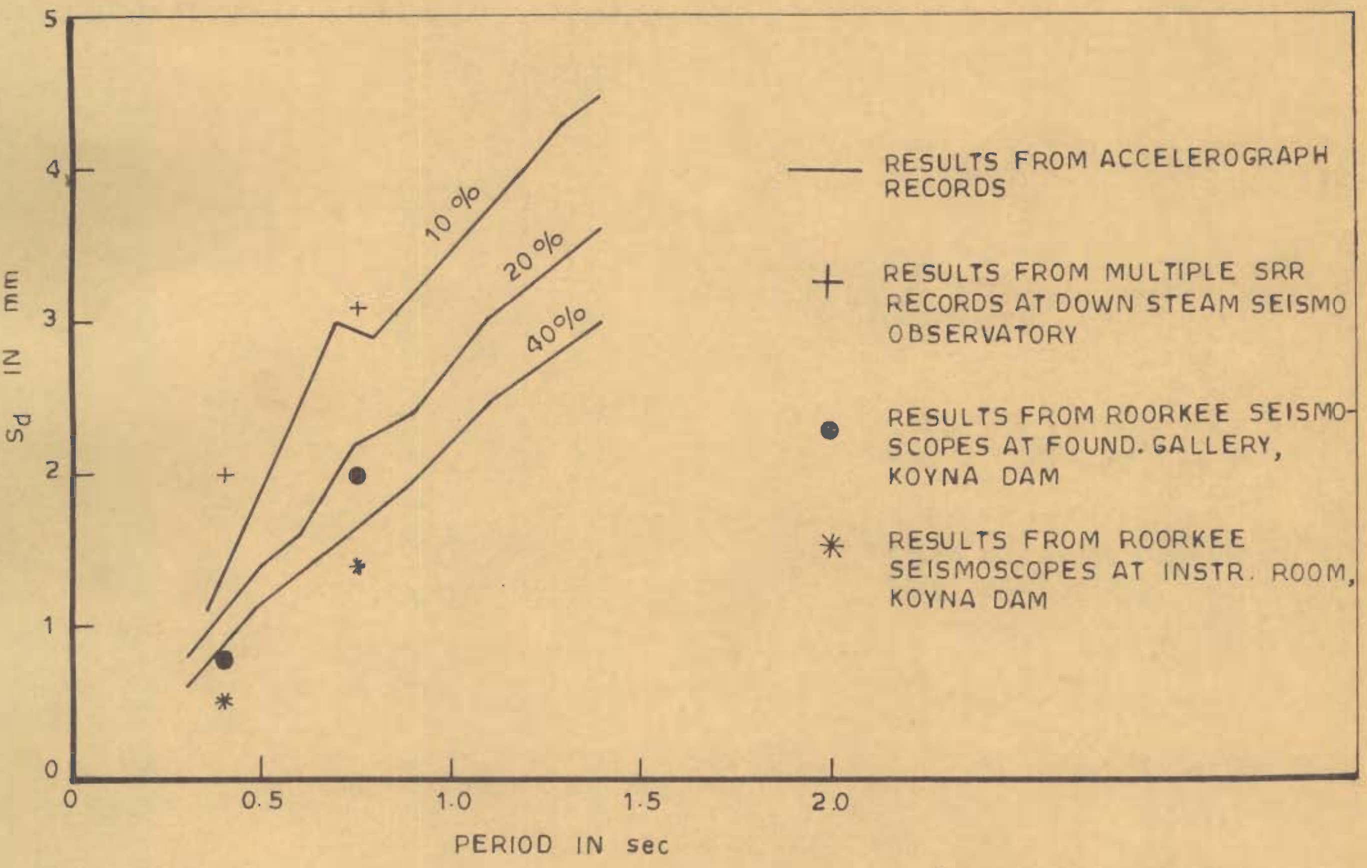


FIG. 5-9. COMPARISON OF COMPUTED RELATIVE DISPLACEMENT RESPONSE AND SEISMOSCOPE RESULTS DURING OCT. 29, 1968 KOYNA EARTHQUAKE

Response Recorder and Roorkee Seismoscopes are also plotted. The spectrum values as interpreted from the records are in general agreement with those computed from the accelerogram if it is kept in mind that the damping in the seismoscopes is nonlinear with amplitudes and has large uncertainties at the lower level of recording due to friction. The results from 0.75 second period pendulum of the Multiple Structural Response Recorder compares very favourably with the computed results. The results from 0.40 second pendulum indicate higher . response. The results from 1.25 second pendulum do not ofcourse show any comparison. The Roorkee Seismoscope apparently had much higher damping at the level of recording and did not permit relative evaluation of results.

5.1.7. COMPARISON OF PLOTS OF COMPUTED RESPONSE IN HORIZONTAL PLANE AND SEISMOSCOPE RECORDS

From the two horizontal components of the October accelerogram, the relative displacement response of a single degree of freedom oscillators having 0.40 and 0.75 second periods and each with 10, 20 and 40 percent of critical damping have been computed. Their two dimensional plots reduced to a size comparable to the seismoscope records are given in Figure 5-10. Reduction of all these plots to the same scale and equal to that of the seismoscope records was not felt necessary since the intention was only to compare the broad features and shape of the two.

The theoretical results correspond to linearly damped oscillators whereas the seismoscope records correspond to

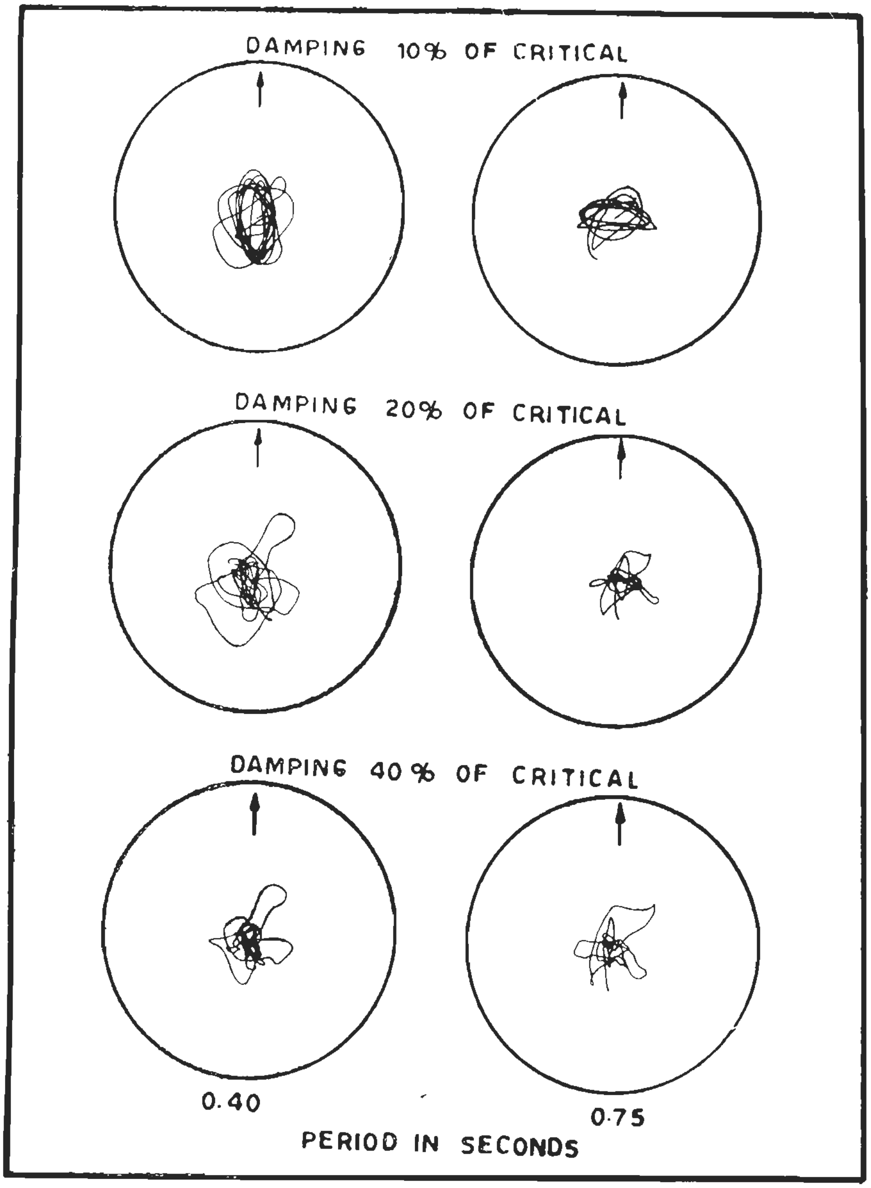


FIG. 5-10 TWO DIMENSIONAL PLOTS OF COMPUTED RESPONSE IN HORIZONTAL PLANE FOR DIFFERENT OSCILLATORS DUE TO OCT. 29, 1968 EARTHQUAKE AT KOYNA (ARROWS POINTING NORTH)

nonlinearly damped oscillators. Even then, the direction of maximum computed response was found to be the same as recorded by the Multiple Structural Response Recorder and the Roorkee Seismoscope. However, only three records from Multiple Structural Response Recorder showed broad similarlity of shape to the computed plots and these are given side by side in Figure 5-11. Here also the performance of 0.75 second pendulum is in greater conformity with the theoretical results.

5.1.8. COMPARISON OF NORMALISED COMPUTED RESPONSE DURING THREE KOYNA EARTHQUAKES

In order to compare the characteristic features of the acceleration response spectra for the September 13,1967, December 11,1967 and October 29,1968 Koyna earthquakes in relation to their different magnitudes, the plots for computed acceleration response spectra for each component of the three events have been prepared and are given in Figure 5-12. To obtain a clearer picture the nine components of acceleration spectra were normalised at their maximum response acceleration values. These are plotted and shown in Figure 5-13. The two figures do not reveal any special points except that for December event,the higher values of response were spread over a range of periods from 0.10 to 0.60 second whereas in other cases there was more or less regular decrease in the response from a peak value at 0.10 second. The decrease in response was more rapid in the case of September shock.

0.40 SECOND
SRR RECORD

COMPUTED Sd FOR
PERIOD 0.40 SECOND
DAMPING 10% OF CRITICAL

0.75 SECOND
SRR RECORD

COMPUTED Sd FOR
PERIOD 0.75 SECOND
DAMPING 10% OF CRITICAL

0.75 SECOND
SRR RECORD

COMPUTED Sd FOR
PERIOD 0.75 SECOND
DAMPING 20% OF CRITICAL

FIG. 5-11. COMPARISION OF TWO DIMENSIONAL COMPUTED RELATIVE DISPLACEMENT RESPONSE AND THE CORRESPONDING MULTIPLE SRR RECORDS OBTAINED DURING OCT. 29, 1968 EARTHQUAKE AT KOYNA

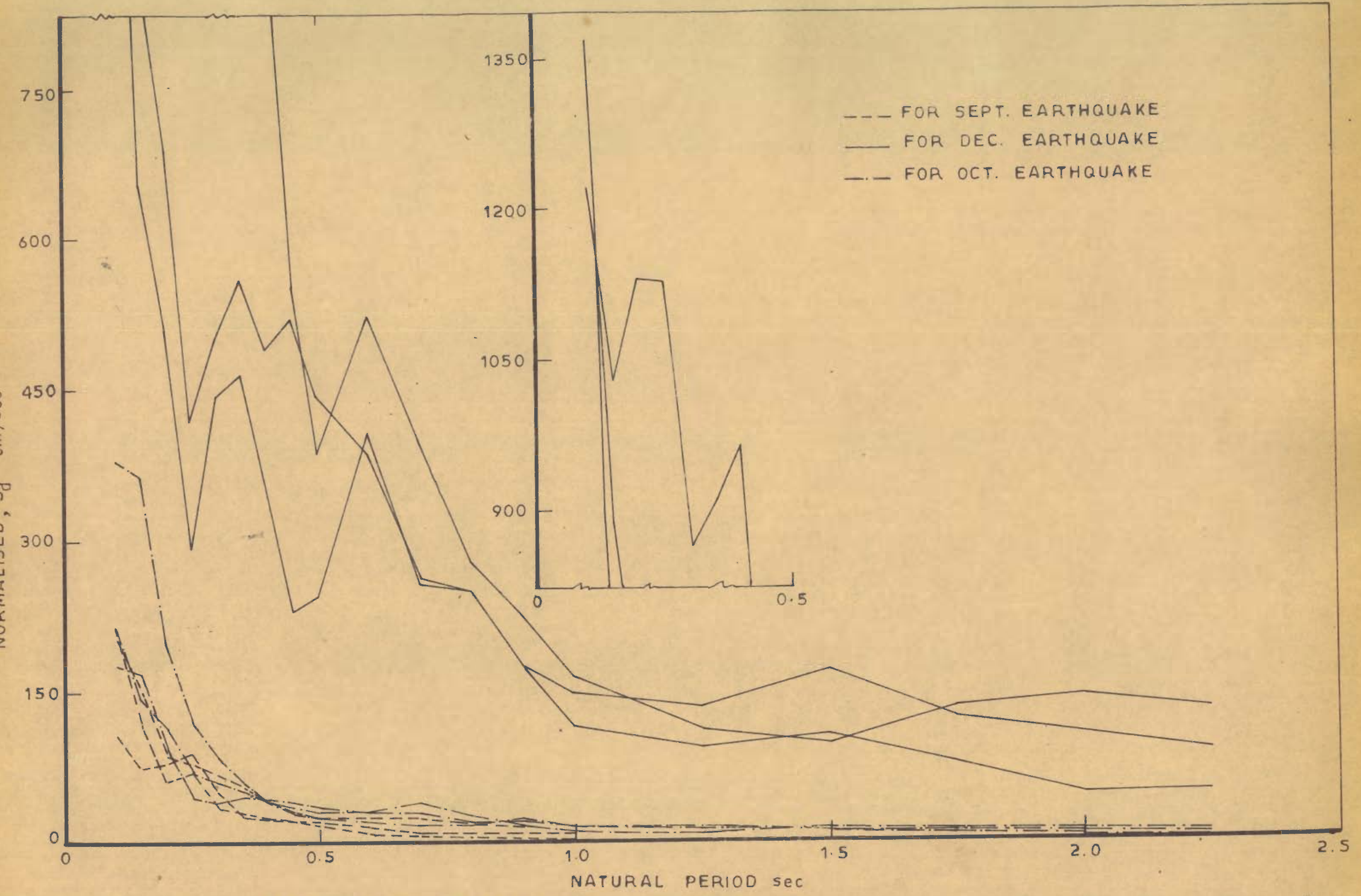


FIG. 5-12. GRAPH SHOWING COMPUTED ACCELERATION RESPONSE (5% OF CRITICAL DAMPING) FOR ALL THE NINE COMPONENTS OF RECORDED GROUND MOTION DURING THREE KOYNA EARTHQUAKE.

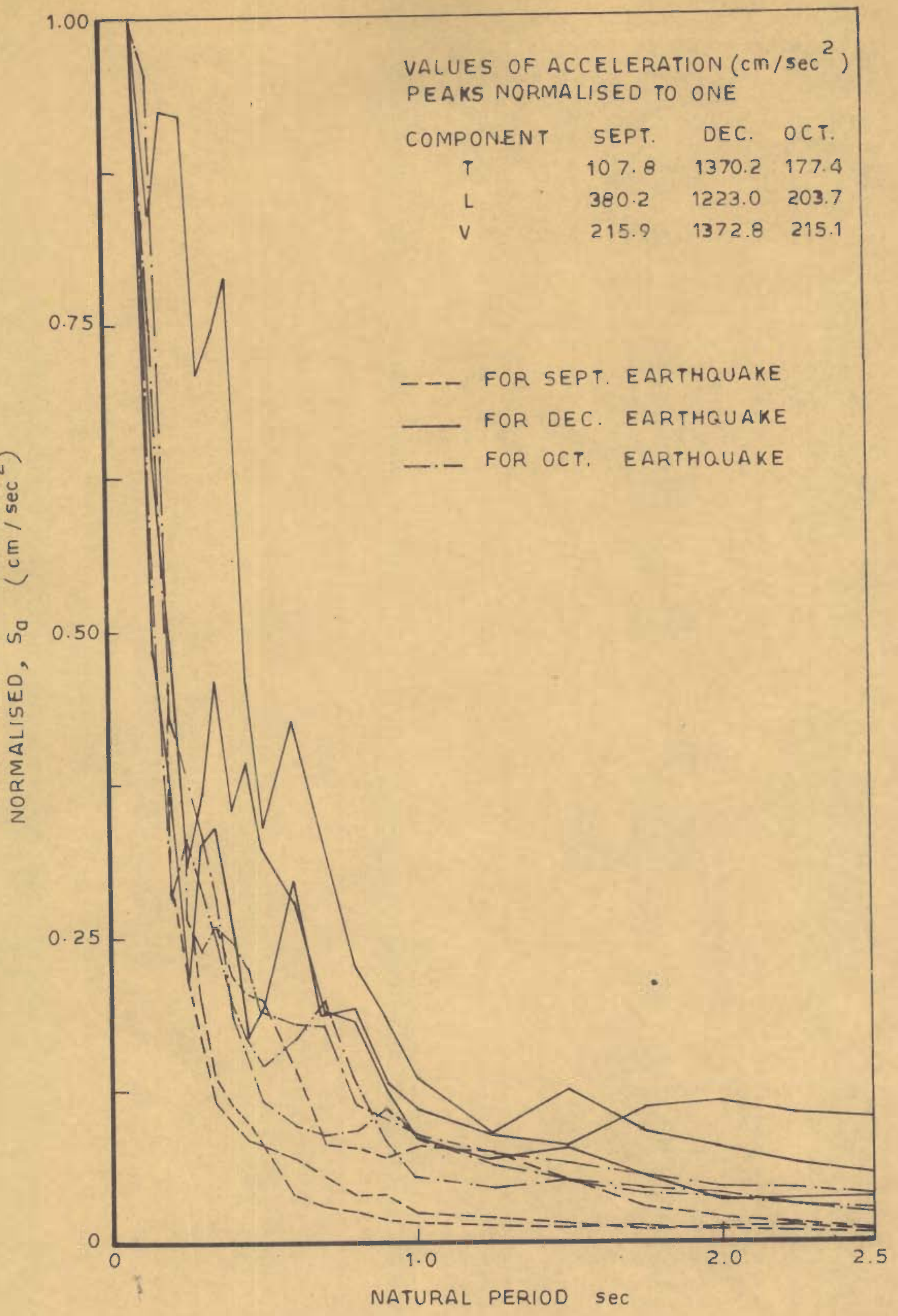


FIG. 5-13. NORMALISED (FOR PEAK VALUE) COMPUTED ACCELERATION RESPONSE (5% OF CRITICAL DAMPING) FOR ALL THE NINE COMPONENTS OF RECORDED GROUND MOTION DURING THREE KOYNA EARTHQUAKE

5.1.9. AVERAGE VELOCITY SPECTRA FOR KOYNA EARTHQUAKES

The maximum relative displacement response (S_d) for 20 different oscillators with periods in the range of 0.10 to 2.50 second and each with 5% of critical damping were computed for all the three components of the recorded ground motions during each of the three koyna earthquakes, namely the September 13,1967, December 11,1967 and October 29,1968 earthquakes. The pseudo velocity response spectra value were computed on the basis of these S_d values. The nine curves thus obtained were normalised such that the area below each of them became equal to the area below the Houner's standard curve for 5% of critical damping within the same period range. The normalising factors thus computed are given in Table 5-6. It may be worthwhile mentioning here that the computed response curves for the September 13,1967 earthquake exhibited an abrupt decrease of response to a low level, lower than even for the relatively smaller magnitude earthquake of October 29,1968. This point is clearly seen in the Table 5-6, the normalising factors being considerably higher for September shock.

TABLE 5-6

Normalising Factors for Various Components of Recorded Ground Motion

Component	September 13,1967 Earthquake	December 11,1967 Earthquake	October 29, Earthquake
Longitudinal (N 55° W)	7.060	0.409	5.967
Traverse (N 35° E)	12.398	0.660	5.567
Vertical	15.727	0.551	5.836

The normalised data thus obtained was used to compute average values of maximum relative displacement (S_d), pseudo maximum relative velocity response (S_v) and the maximum relative acceleration response (S_a). The averaging of these parameters was done for the three longitudinal (N 55° W), the three transverse (N 35° E), the three vertical and all the nine components and the results are given in Figures 5-14, 15 and 16. The results show some deviations from those which where obtained by Housner (1959). The concentration of higher velocity and acceleration response values towards the shortest period range was the main feature. The response peaks occurred arround 0.15 second period. As already pointed out by Housner (1959) this feature would be as expected in view of the average epicentral distances corresponding to the ground motion data in Koyna being within about 5 kms. However, apart from the effect of epicentral distances, possibility of a small part of these differences in response characteristics being on account of the differences in the source parameters can not be ruled out. The analysis clearly brings out the need for collection of more ground motion data and separate computations of the average response spectra for different seismic regions.The highest value of acceleration response out of the nine components of the recorded ground motion corresponds to the vertical component of the December 11,1967 earthquake. In the case of September 13,1967 shock the rapid decrease in response to a very low level with increasing period led to a high normalised response. Thus the normalised average response values became much higher compared to even those due

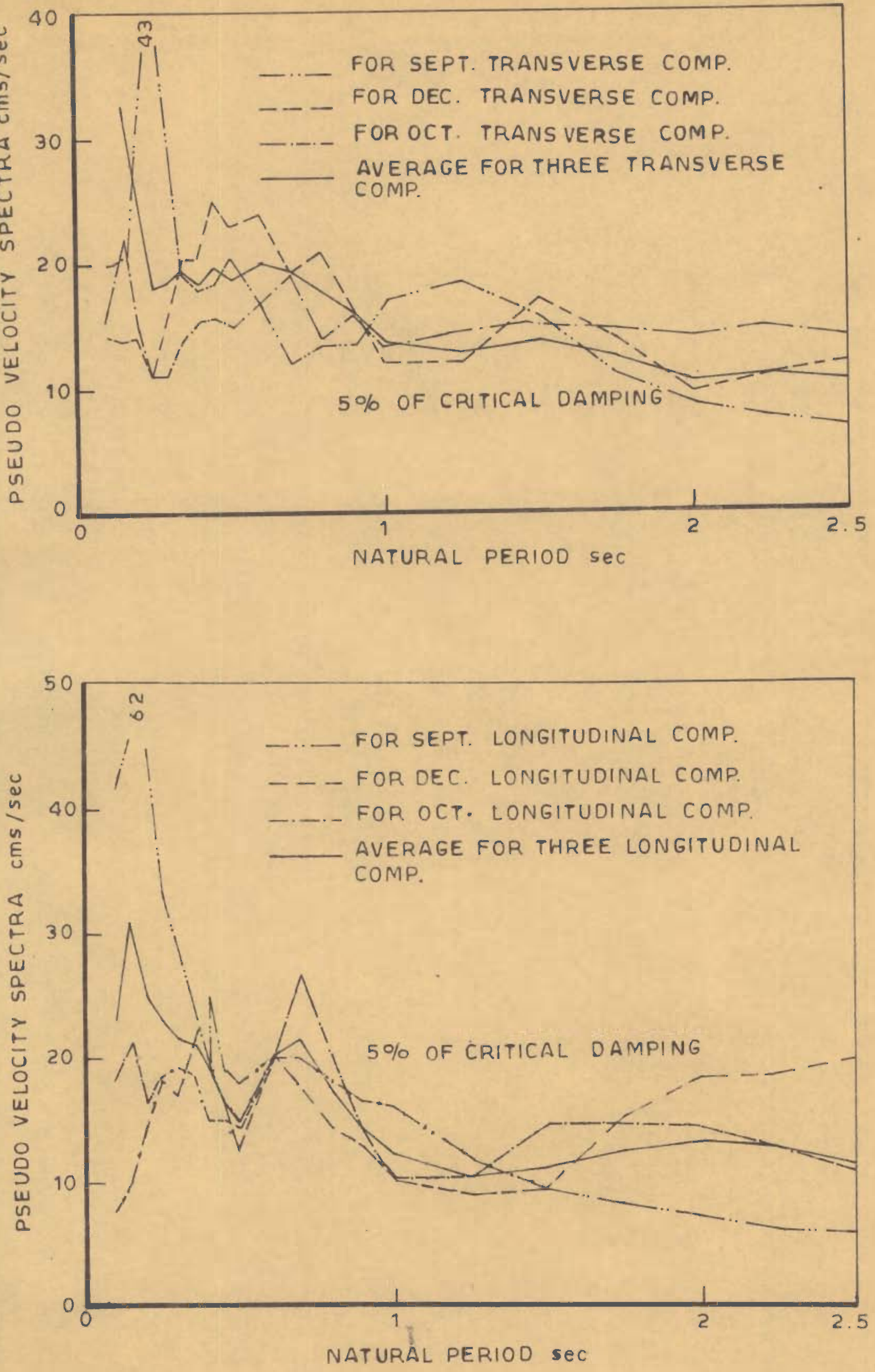


FIG. 5-14. NORMALISED AVERAGE PSEUDO VELOCITY SPECTRA CORRESPONDING TO TRANSVERSE AND LONGITUDINAL COMPONENTS OF THREE KOYNA EARTHQUAKES

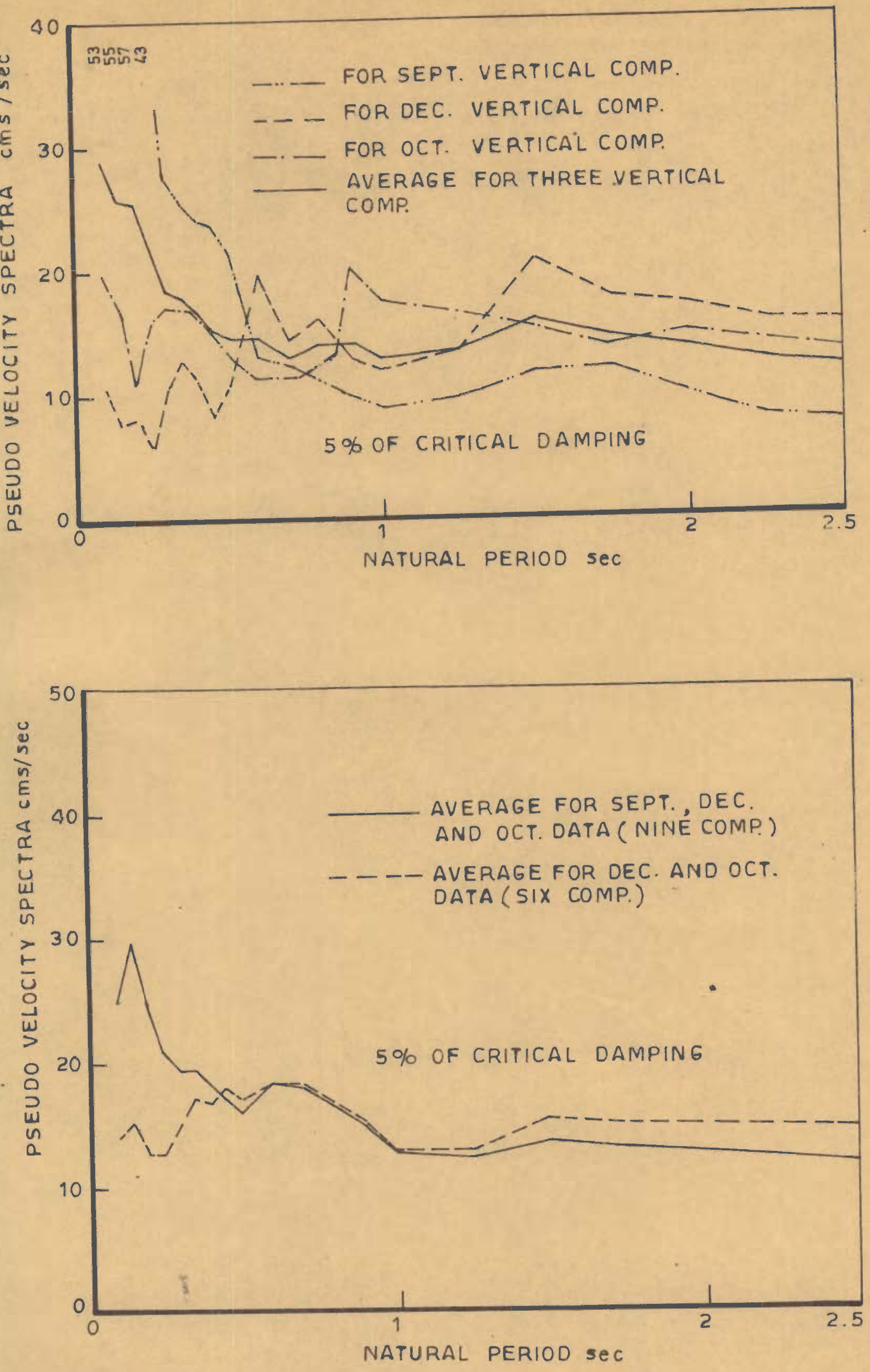


FIG. 5-15. NORMALISED AVERAGE PSEUDO VELOCITY SPECTRA CORRESPONDING TO VERTICAL COMPONENTS, ALL THE NINE COMPONENTS & FOR DEC. AND OCT. KOYNA EARTHQUAKE

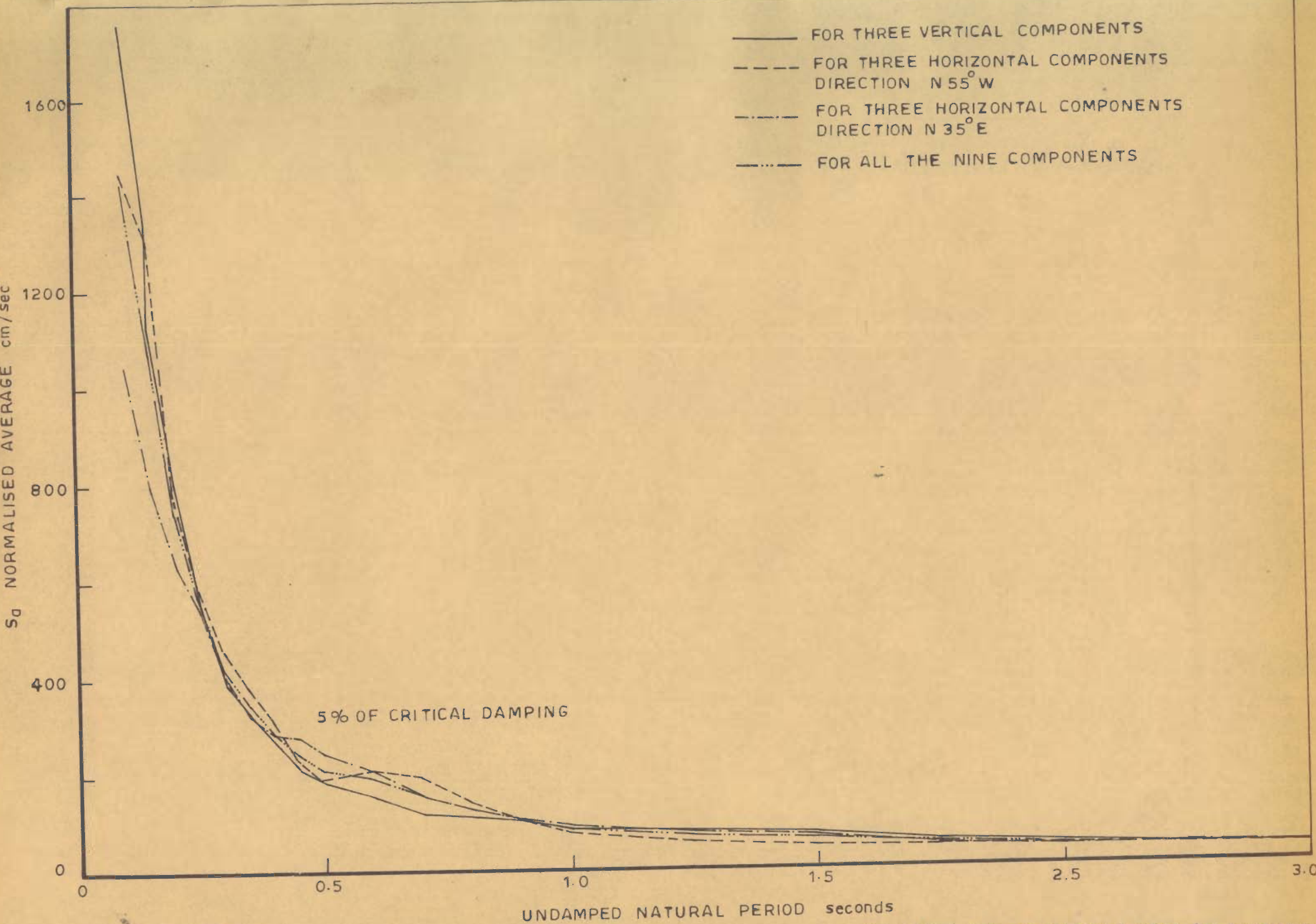


FIG. 5-16. NORMALISED AVERAGE ACCELERATION RESPONSE SPECTRA(5% OF CRITICAL) FOR TRANSVERSE LONGITUDINAL, VERTICAL AND ALL THE NINE COMPONENTS OF THREE KOYNA EARTHQUAKES

to December shock. The estimated epicentral distance corresponding to the September data is approximately within 1 km, whereas for the other twoevents it was estimated to be, roughly equal and about 4 km. The analysis therefore shows that the averaging of response at greater distances was not as much susceptible to the variation in the epicentral distances for various events used as for the near distance cases. Possibly the rate of shift of the response with changing distance from higher to lower period range is slower at distances more than 15 kms (corresponding to the shortest distance for which data was analysed by Housner, 1959) and much higher for shorter distances. Thus averaging for only six components of normalised S_v corresponding to December and October shock (see Figure 5-15) gave a picture more comparable to that drawn by Housner for 16 kms distance from small shock. Another point worth mentioning here is that the variation in the magnitude seems to have a reduced influence at shorter distance.

5.1.10 SIGNIFICANCE OF TILTMETER OBSERVATIONS

Observations of tilt of the earths surface on specially installed tilt bases employing Portable Water Tube Tiltmeters (Agrawal, 1970,b) were commenced in September 1968. Measurements were repeated after the October 29,1968 earthquake of 5.2 magnitude, one of the largest event after the December 11,1967 earthquake, these measurements do not reveal permanent tilt at any of these locations. Even the repetition of observations in July 1969, i.e. after the occurrence of a number of significant events, did not reveal any tilt. The system employed for the measurements on the base hubs at a distance of 30 meters or more was in a position to resolve tilts in excess of 0.04 arc seconds.

A report on tilt measurements (Marshall and Stephens 1968) in respect of Denver earthquakes, at Waterton, Colorado shows that permanent resultant tilting as high as 1.15 arc seconds occurred following a single earthquake of magnitude 5.0 . Even the events in the range of magnitudes 1 and 2 were found to be accompanied with tilts of the order of .15 arc seconds. These measurements were made at a station 50 kms away from the epicentre.

The site of observations in Pophali was within 10 kms from the epicentre and did not show any permanent tilting. Since, in general, several events followed the repeat tilt measurements, it might be argued that the cumulative tilt during the successive events was reduced to less than 0.04 arc seconds owing to some of these having opposite signs. However, on the basis of the above mentioned reports, tilts have been reported to occurrin the same direction in a majority of events. These negative results therefore lead to the conclusion that the earth's surface layer was not participating in the energy release.

5.1.11. SOURCE REGION FOR KOYNA EARTHQUAKES

5.1.11.0. General

Records of the December 11,1967 Earthquake at Koyna as well as of other smaller events in the region possess some very notable features, namely.

1. the preponderance of the higher frequencies in the accelerogram (around 12 - 15 cps.)
2. ground acceleration peak of 0.63 g which is high even after allowing for the proximity of the epicentre to the place of recording.
3. discrepancies in the magnitude and depth values determined from near and distant station data.

The above characteristic features of Koyna Earthquakes, particularly of the one which occurred on December 11,1967 can be related to its possible source parameters on the basis of present understanding of the physical processess responsible for earthquake phenomena.

5.1.11.1. Significance of Stress Level in Relation to Participating Fault Rock Volume

In an earthquake source region occupied by a competent fault rock material, higher stresses can develop before the initiation of a slip or fracture, compared to the case where the fault rock material is less competent (Benioff, 1951,a). Thus in the former case larger strain energy can accumulate before a slip or fracture takes place. In other words, a smaller volume in competent rocks can store and therefore release greater strain energy.

Investigations of the stress drop during frictional sliding at confining pressures upto 5 kb by Byerlee and Brace (1968) indicated that the stiffness of loading system and the rate of loading had no influence on the stress drop and the confining pressures and rock types were the controlling factors. In a source region at a higher stress level, larger stress drop would be expected after initiation of slip. Similar conclusions have been arrived at by Scholz (1968) on the basis of his laboratory experiments on microfracturing in rocks and have been stated in terms of variation in the constants a and b of the frequency-magnitude relation. Further, Chi-Yu King and Leon Knopoff (1968,b) on the basis of their investigations of relationship amongst earthquake magnitude and fault parameters have concluded that the stress drop increases with magnitude. These studies would suggest that for generation of an earthquake of a given magnitude in a competent fault rock under high stress condition, the dimensions of source regions participating in energy release could be smaller compared to a case where the stress level is low.

5.1.11.2. Frequency Character of the Disturbance at Source and the Stress Level

Measurements of the velocity of crack propagation in glass plates conducted by De Noyer and Pollack (1963) gave higher velocity values for regions under greater strain i.e., implictly under higher stress level. The duration of dislocation in a fault rock should therefore be shorter in a source region at a higher stress level owing to the higher velocity of propagation of fracture. This would also imply that the interval of the stress drop during dislocation at any point of the fault is shorter in such a case. The rate of stress drop or the velocity of dislocation propagation appear to be characteristic parameters of the earthquake mechanism which may determine the frequency character of the elastic disturbance at the source (Aki, 1968). A higher rate of stress drop characteristic of a fault rock under high stress condition and therefore of a higher velocity of propogation of fracture is likely to impart a high frequency character to the disturbance at source.

5.1.11.3. Frequency Character of the Disturbance at a Distance from the Source

Gutenberg (1958) gave the following expression relating the period T_0 at source and the period T at a distance D, of an elastic disturbance:

$$T^2 = T_0^2 + \frac{5\eta D}{V^3\rho}$$

where η is the coefficient of friction, ρ the density and V the wave velocity in the medium. Thus, if the period of disturbance at the source, is shorter all other factors remaining the same, the period at a distance will also be smaller. Let us now consider the second term on the right hand side in the above equation. Competent material in the source region would produce a large value of V and small values of η. At shorter distances where the quantity $5\eta D$ is much smaller than ρV^3 and the major wave path would lie in the high velocity medium, the influence of the second term on the wave period would be negligible permitting the disturbance to retain its original period. At large distances the disturbance would in general acquire an average character due to increased influence of the second term. Therefore, depending upon the source parameters and the nature of the media, the elastic disturbance, in some particular cases, may exhibit special frequency character at short distances.

5.1.11.4. Source Parameters for December 11,1967 Koyna Earthquake

On the basis of the preceeding discussions and the observed high frequency content of the accelerogram written at a distance of about 4 km from the epicentre, it is reasonable to visualise a competent source rock under high stress condition. The average velocity along the wave paths at a distance of 4 km is therefore likely to be high compared to that for a source region under a lower stress level. The wide range of values obtained for the depth of focus varying from 8 to 35 km would suggest a large vertical extension of the source, radiating energy predominantly in the vertical direction. Such conditions can be expected to exist if the dislocation took place along vertical fissures filled with igneous material. Geology of the area suggests that the dykes which might have provided passage to the lava flows during the Deccan Trap activity could be the possible venue.

Perhaps in the case when energy is radiated perferentially in the vertical direction and the short period content of the disturbance at source in high, the near distance observatories would receive greater energy and therefore, write large records. This would result in large ground acceleration peaks, smaller depth estimates and higher estimates of magnitude from near data. On the other hand at large distances the elastic disturbance would acquire an average character due to long wave paths and the magnitude determinations are likely to be smaller and depth estimates larger compared to those obtained from near station records. Also the latter will be more representative of the actual energy release.

5.1.11.5. Proposed Model for the Source Region for Koyna Earthquakes

The Koyna region which is located on the Deccan Traps has suffered intense volcanic activity over a long period in the geological past. An attempt to relate the present seismic activity of the region to the decay phase of volcanic activity has appeared earlier (Dutta, 1968) in which the strain energy release was considered to be derived from the transfer of thermal energy. The model for source region proposed here also envisages its association with the decay phase of the volcanic activity though the major fraction of the strain energy might be due to tectonic processes operative there. The model is schematically shown in Figure 5-17.

The successive extrusions of magma from the magmatic chamber in the form of dykes would cause a rise of the intruded formations. After the volcanic activity has subsided, there

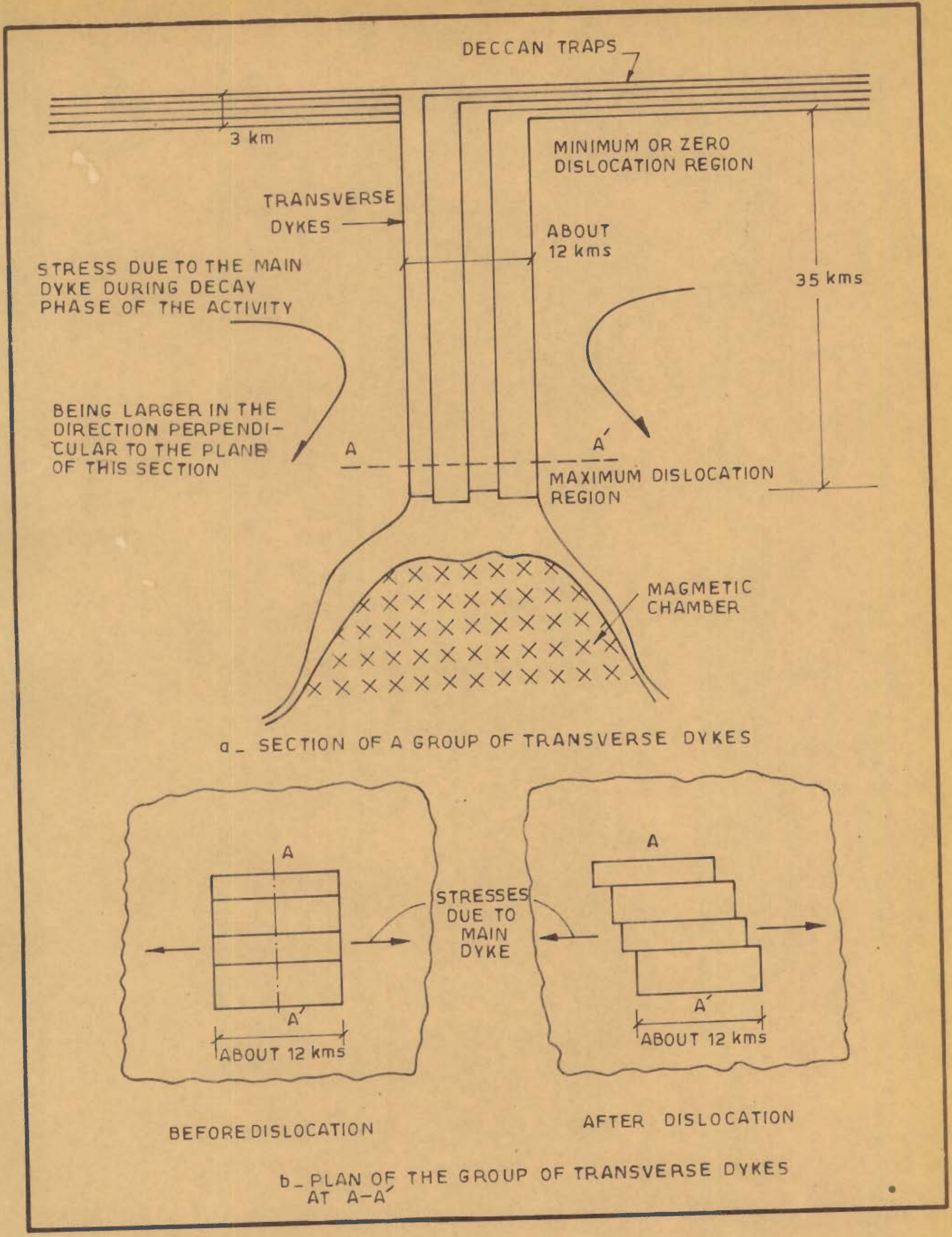


FIG. 5-17. SCHEMATIC DIAGRAM OF THE PROPOSED MODEL OF THE SOURCE REGION FOR KOYNA EARTHQUAKES

would be a tendency for the region to subside also, thereby creating a void around the dykes at depth. In a group of dykes having larger extension in one of the two horizontal directions parallel to the contact planes, the tensile field in a horizontal plane due to the void will largely be perpendicular to the contact planes and would thus have no influence on these dykes. But, perhaps this tensile field would tend to reorientate dykes in transverse fissures as are usually present in most of the dyke systems. Such a possibility envisaging tectonic reorientation of dykes by shear has been considered by Hopgood (1966) to explain the structure of the Lewisian Gneiss of the Isle of Barra in the outer Hebrides, Scotland. The dykes are likely to remain stationary at the top whilst suffering dislocations at depths. Such shear dislocation may occur simultaneously at one or more faces. The intention of showing a number of possible planes of shear in the proposed model is to cover the spacial distribution of various epicentres. However, during an individual event the movement may only be along single plane. The multiplicity of the December event discussed by Gupta et al (1969) suggest movements along two planes. The movements associated with a tectonic reorientation of dykes due to a tensile field in the horizontal plane would largely be strike slip which is borne out by fault plane solutions of the koyna earthquake (Tandon and Choudhury, 1968; Gupta et al 1969). The vertical extension of the source region right from 3 to 38 kms has been assumed to include the extreme values of the depth of focus obtained from various observatories. The lateral dimensions have been arrived at by considering the approximate order of the rock volume that could provide energy storage for a 6.5 magnitude earthquake as well as the scatter of epicentre locations for various events in the region.

5.1.12. CONCLUSIONS

The conclusions arrived at on the basis of the preceeding analysis are given below:

1. The frequencies appearing in the accelerogram of the September 13,1967 Koyna earthquake were found to be higher compared to those in the accelerogram of December 11,1967 and October 29,1968 earthquakes as would be expected because of the nearness of the epicentre in the former case.

2. The ground acceleration peak consistently occurred in the N 55° W component, which suggests that the stress conditions in the source region remained unchanged during the period. Even the graph of the elastic rebound increments broadly reveal this condition. However, this is understandable since the elastic strain build-up must have taken a long time to initiate the activity and may therefore take proportionately longer time to return to the minimum strain level of the region.

3. Comparison of the computed acceleration response curves normalised at their peak values for the three Koyna earthquakes studied, show that for increasing magnitude there higher response values exhibit a spread over a large period range.

4. The average velocity response spectrum computed after normalising the area under each curve for the three Koyna earthquakes have been compared to the average spectra (Housner, 1959) worked out for the earthquakes in the California region. A shift in higher response values towards the lower period as expected and discussed by Housner, is the special feature of these plots and is due to the high frequency content of ground motion records. The normalised average response results obtained for Koyna and those given earlier by Housner (1959) tend to suggest that the shift of high response values to shorter periods due to reduction in the epicentral distance may be more rapid near the epicentre. Thus the averaging of response results at shorter distances need be based on data corresponding to comparable epicentral distances.

5. On the basis of some of the common characteristics of the Koyna earthquakes it has been possible to suggest that the fault rock was perhaps under high stress condition and the energy release was predominently in the vertical direction.

6. The Koyna earthquakes could perhaps be considered due to the tectonic reorientation of dykes by shearing.

7. Negative results of the tilt measurements would tend to suggest that the earth's surface layers did not participate directly in the elastic strain energy release. Had any tilt been observed, it would have offered a significant evidence to support the association of seismic activity at Koyna with the water loads in the reservoir, as has been considered probable by some investigators.

8. The potentiality of the Multiple Structural Response Recorder and Roorkee Seismoscope has been demonstrated by the agreement obtained between the seismoscope results and the computed results even at the low level of recording when utilization of the records of the Multiple Structural Response Recorder and Roorkee Seismoscope for the quantitative analysis may not normally be considered desirable.

9. As damping in both the Multiple Structural Response Recorder and the Roorkee Seismoscope varies with the amplitude of recording, it would not be possible to draw response spectrum curves even by employing a number of such devices as these would yield only a number of points on different response curves. In order to obtain data which could be utilised in drawing response curves it would be necessary to employ devides which have linear damping characteristics.

10. It would be desirable to employ a pair of these simplified devices in their present form for each period and damping combination, one to cover the entire range of the likely response values and another complementary device to cover a small lower range only. The advantage of this would lie in the fact that the uncertainties involved in the determination of damping at low amplitudes of recording would influence very low response values only.

5.2. THE DAKPATHER REGION

5.2.1. DISCUSSION ON THE RECORDED SEISMIC ACTIVITY AT KALAWAR

Seismic recording for purposes of a short term evaluation of the seismic status of a region have normally to be made at magnifications of the order of a million but, as the second best arrangement possible, a set of three component electromagnetic seismographs with magnifications of 0.1 million was installed at the temporary seismological observatory at Kalawar in May 1969 by the India Meteorological Department. Shortly afterwards it became apparent that the noise recorded by the two horizontal seismographs was rather large. Their magnifications were therefore reduced to 25,000 but not until 4 weeks had already lapsed since their installation. This observatory was operated for a short period of six months, i.e. until October 1969 whereafter it was unfortunately removed. During this period as many as about 35 events were recorded as originating within a radius of 50 kms most of them lying within a radius of 6 to 14 kms. However, most of these events were feeble, approximately of magnitude 1, and were recorded by the vertical seismograph which had four times the magnification of the horizontal components. Thus it was not possible to determine the direction of these events with reference to the observatory directly from the records.

As most of the field test conducted in the area point out to the existance of a N-S compressional field, the seismic activity may be associated with the two major thrust planes in the region which have a number of secondary fault planes associated with them showing evidence of recent movements. Further, the observations that the feeble activity was recorded by the vertical component seismograph only could, apart from the higher magnifications of this instrument, be perhaps due to the fact that these events originated very close and possibly almost below the recording site resulting in large vertical movements. A majority of events at a distance of about 6-14 kms could therefore, be taken to represent the mean depth at which the higher stresses are operative. The depth of the level of activity was considered to be about 6 kms, by taking the mean distance as 10 kms and allowing for some deviations from the vertical of the line joining the focus to the place of recording. Some part of the variation of the calculated source distance i.e. 6-14 kms may be due to the variations in the depths and the other part due to the fault length. On the basis of these considerations it has been assumed that the length of the fault along which strain is being released is about 4 kms. In view of the frequent release of strain during a number of small events, we can presume that the rock conditions as exposed on the surface extend atleast to a depth of about 6 kms preventing larger accumulation of elastic strain. The minor activity at depth is in turn causing creep movements of the surface formations.

5.2.2. DISCUSSION ON THE FIELD TEST RESULTS

A number of field tests have been conducted in the area in order to evaluate the strength properties of the various rock types and also to investigate if there was any tectonic stress field operative in the area. The strength characteristics of the Nahan sandstones were found to be relatively better but those of the intra thrust zone material rather poor. This fact was very clearly borne out by the observations of the behaviour of steel ribs (tunnel supports) in the Nahan sandstones and the intra-thrust zone sections of the Kalawar inspection-gallery. It is, therefore, quite logical to expect creep movements along the plane of contact between materials of such diverse strength characteristics particularly if a stress field exist in the region.

Several field tests and observations tend to suggest the presence of a N-S stress field in the region. One of the early observations in this connection was the sudden jumping of the drilling rig in the Kala-Amb when the drilling tool reached the Krol thrust plane. This was related to (Krishnaswamy and Jalote, 1968) the development of additional squeezing pressures at the Krol contact on account of the stress field. A more quantitative information was derived from the flat jack tests conducted in three orthogonal directions at a few locations which tend to show the existence of a N-S stress field. The development of pressure in the flat jack of the Tiwag's Radial Press, after the total release of the pressure and stopping of the out flow of the fluid, could also be related to the possible existence of a stress field.

5.2.3. DISCUSSION ON TILTMETER DATA

The significance of tilt measurements taken across the plane of sub-recent movement and the Nahan thrust have been separately discussed in the following two paragraphs.

5.2.3.1. Significance of Tilt Data from Kala-Amb Drift

Tilt measurements were commenced across the plane of sub-recent movement in the Kala-Amb Drift in June 1968 and were twice repeated subsequently. The second set of observations was however only approximate since the difference of the elevations between the bases had become larger than the range of the Tiltmeter system. However, the next set of reading taken by interposing packing plates of standard thicknesses on the lower base could be relied upon. Over a period of about 1 year an average rate of 2.4 mm/month upward movement of the base in the Subathus was recorded. If the movement which resulted in the recent scree material being overlain by the older Subathu shales are considered to be still continuing, the direction of these movements will be the same as those recorded. But it was not possible to determine what part of the measured movement was related to the earlier movements. The squeezing of the drift in the Subathu Shales section was quite notable. The side timber supports had either penetrated into the floor or their lower parts covered by the swollen floor. The measurement of tilt had to be discontinued, apart from other reasons, due to the reduced clearance between the top of the tilt-base pillar and the ceiling of the drift, preventing replacement of the Tiltmeter on it. If the entire movement recorded is considered as arising from the squeezing effect, it is logical to expect some reduction in the movements even after allowing for the poor rock conditions and inadequate lining. On the contrary the intermediate reading, although only approximate, suggested an increase in the rate of movements. There may be possibility that some part of the movements recorded may be related to the existence of a natural N-S stress field.

5.2.3.2. Significance of Tilt Data from Kalawar Cross-cut

Tilt measurements were repeated four times inside the Kalawar cross-cut on two bases across the Nahan thrust with the respective excavated faces equidistant from both. These revealed an upward movement of Base 1 in the Subathus in relation to the Base 2 in the Nahan Sandstones. The rate of movement showed a large decrease during successive tests which may be attributed to a reduction in the initially large influence of the squeezing of the cavity on one of these bases possibly the one located on the shales. The three repeat-measurements on Base 1 in relation to Base 3 on the Nahan sandstones which was very close to the excavated face showed a more or less steady rate of creep which was also smaller in magnitude. These observations could be explained by assuming that Base 2 was subsiding due to the influence of the excavation of the cavity. In view of the relatively poor strength characteristics of shales such a large influence of cavity on Base 2 is anomalous. Ofcourse, this is too meagre a data to base any useful conclusions on but the anomalous tilts as recorded could be explained if we consider that the N-S stress field was causing a downward movement of the Nahan sandstones. The measurements on Base 2 and 4 show agreement with the direction of movement recorded on Base 1 and 2. The minimum rate of movement recorded so far was 0.44 mm/month.

5.2.5. CONCLUSIONS

On the basis of the preceeding discussions the following conclusions can be made:

1. The over-riding of the scree material by the Subathus as seen in the Kala-Amb Drift is a direct evidence of recent creep movements. On the basis of tilt measurements taken there it can be concluded that the secular creep rate is smaller than 2 mm/month at this location. The observed creep rate was 2.4 mm/month of which a major portion is likely to be due to the influence of the squeezing of the cavity.

2. Tilt measurements across the Nahan thrust in the Kalawar Cross-cut from September 1969 to August 1970 gave an average creep rate of .67 mm/month suggesting that either the base in the Nahans was moving down or that in the Subathus moving up or both were moving together. The average rate of secular creep may not be more than 0.40 mm/month since the minimum creep rate observed was 0.44 mm/month of which a substantial fraction is likely to be due to the influence of the sequeezing of the tunnel.

3. Most of the field observations and tests suggest the existence of a N-S compressional stress field.

4. The seismic activity recorded at the temporary seismological observatory indicate that the N-S stress field may be maximum at a depth of about 6 kms.

5. The frequency of strain release in the form of minor events would be suggestive of poor average strength characteristics of the rocks at about 6 kms depth.

6. An important observation was the positive tilt results in the Dakpather region and the negative results in the Koyna region. These results would clearly show the potentiality of the Portable Water Tube Tiltmeter in measuring infinitesimal tilts.

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APPENDIX - I

CALIBRATION PROCEDURE AND DESIGN DETAILS OF MULTIPLE STRUCTURAL RESPONSE RECORDER

DESCRIPTION OF THE CALIBRATION STAND

The calibration stand can hold any of the instrument pendulums. The detachable pendulum support can be fixed to the calibration stand in the same way as in the pendulum support in the instrument. The stand has a heavy rectangular base, and a support which can be rotated through 360° around a vertical axis. The support usually vertical can also be made inclined to the vertical by known angles (5°, 10° and 15°) and yet rotated through 360° while holding a pendulum. The upper end of the support has a platform with a provision for fixing the stylus in the same relative position with respect to pendulum as in the instrument. For the convenience of packing, the base of the stand and support are unscrewed and kept. They can easily be assembled for use.

INSTRUMENT CALIBRATION

(a) Period Adjustment

(i) The spring steel wires, of specified diameters, welded to the centre of the upper vice jaw are used to suspend the pendulums in such a manner that the lower pendulum weight has a free oscillation between the magnets.

(ii) A watch glass is placed in its position on the upper pendulum weight and the period of the pendulum determined by counting the time taken for a number of oscillations. The lower suspension vice permits adjustment of the suspension length to obtain the desired period.

(iii) The change in the suspension length for the period adjustment is made while retaining the lower pendulum weight in an intermediate position between the magnets. This is possible because the upper suspension vice jaw is long enough to permit the pendulum to be fixed in any position in a range of about 2 cm.

(iv) Thus the periods are adjusted in each of the pendulums to the desired value.

(b) Stylus Pressure Adjustment

(i) The stylus is removed and fixed to the calibration stand.

(ii) The stylus clamp is released and the stylus weighing nut screwed on to the rear of the screw carrying the stylus balancing counter weight and its check-nut.

(iii) The counter weight is suitably moved so as to balance the stylus arm in a horizontal position. As a check to the adjustment, a jerk is given to the stylus arm after which it again comes to rest in a horizontal position. The check-nut is then tightened.

(iv) The weighing nut is then removed thus leaving the stylus pressure adjusted.

(v) Two weighing nuts are provided, one light and another slightly heavier. They are used for the stylus pressure adjustment of pendulums with 5% and 10% of damping respectively. The pendulum with 5% of critical damping is provided with a slightly lower stylus pressure.

(c) Tilt Sensitivity Calibration

(i) The pendulum corresponding to the stylus fixed on the calibration stand is detached from the instrument at its detachable pendulum support and fixed to the stand.

(ii) The vertical support of the calibration stand is tilted through an angle of 5° and clamped.

(iii) A smoked glass plate is clamped in position and stylus lowered to rest on it.

(iv) The pendulum is gently rotated through 360° by holding it at the stylus clamp. Care is taken not to permit oscillations of the pendulum.

(v) The stylus is clamped and the tilt record removed. The instrument cum pendulum number is marked on it and thereafter it is lacquered.

(vi) Similar tilt calibration records are obtained by giving inclinations of 10° and 15° to the support of the pendulum.

(d) Damping Adjustment

(i) After the pendulum and the corresponding stylus have been calibrated for period, stylus pressure and tilt sensitivity, these are fixed to the instrument in their normal position without disturbing any of the above adjustments.

(ii) A smoked plate is placed in its position and the stylus lowered to rest on it.

(iii) The pendulum is gently pulled by holding it at the bottom weight to displace from the vertical by about 30° and a circular twist is given.

(iv) A nearly circular or elliptical spiral is scratched on the smoked plate.

(v) The damping is determined by calculating the ratio of two successive amplitudes at double amplitude levels of about 2 to 2.5 cm.

(vi) The gap between magnets is adjusted to give the ratio of successive amplitudes a value of 1.17 and 1.37 corresponding to 5% and 10% of critical damping respectively.

(vii) The final damping records are preserved for future reference for all the pendulums.

DESIGN DETAILS

The various components of the Multiple Structural Response Recorder have been alloted reference numbers. The reference numbers and the design drawing for all these components bearing the reference numbers are given in the paper entitled " Design Details of Multiple Structural Response Recorder" whose reprint is attached at the end.

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APPENDIX - II

DETAILED FIELD PROCEDURE OF TILTMETER OBSERVATIONS

TILT BASE-HUB INSTALLATIONS

At those locations whose relative elevations have to be determined using a Portable Water Tube Tiltmeter, specially made tilt base-hubs are permanently fixed at approximately the same horizontal level. The height of these installations has to take into account the fact that viewing for setting the pointer has to be done in a horizontal direction and therefore the instrument should preferably be placed at eye level. The maximum distance at which these bases could be constructed for measurement with the system developed and reported here is only 50 meters. If necessary, protective covers are provided to ensure proper maintenance of these base-hubs over long periods.

STEPWISE FIELD PROCEDURE

1. The Portable Water Tube Tiltmeter system consisting of two boxes holding the tiltmeters with their accessories and separately packed alkathine tubing are stored with care. However, before proceeding to the field all the items required as listed below are checked:

Tiltmeter (two), Microscope with stand (two), Dry battery 6.0 volts (two), Bulb for attaching to the top lid of the tiltmeter (two), Alkathine tubing with water (55 meters), Tube stoppers (two), Thermometer (one), Bottle full of water (3 litre), Methylated spirit (0.5 litre), Observation forms, Towel, Pencil.

2. If, at the site of observation, filtered water supply is not available, the tube is earlier filled with clean water and the stopper fitted to its ends. A bottle full of water is taken for additional requirements.

3. The tiltmeters and the base-hubs are numbered. During successive measurements, the same tiltmeter has to be placed on the base on which it was placed in the previous set of observations. Accordingly the appropriate boxes are placed near the two permanent base-hubs on which the measurements are to be made.

4. The base-hub cover, if any, is removed and the base-hub is lightly brushed with a soft brush or cloth and then cleaned with cotton soaked in methylated spirit.

5. The tiltmeter is taken out from the box and placed over the base carefully, the viewing window being on the front side. The base plate of the tiltmeter just fits into the permanent base-hub.

6. The microscope tube and its stand detached in two parts for convenience of packing are placed separately in the box. After assembling, it is placed in front of the tiltmeter.

7. The bulb attachment for illuminating the micrometer spindle's free end, which is kept detached for convenience, is screwed to the top lid of the tiltmeter and connected to the battery.

8. The alkathine tubing is suitably spread between the two bases to lie at a level lower than the level of base-hubs and it is ensured that no kinks are left. If the distance between the base-hubs is less than the tube length, an extra length of tubing is coiled up and kept at some intermediate point.

9. The two ends of the tube are raised simultaneously to the height of tiltmeters placed on the respective bases and the stoppers are opened.

10. It is ensured that no air bubble is trapped any where in the tube and then the two ends are fixed to the respective tiltmeters ensuring that the tube is loose enough so as not to pull the tiltmeter from its base-hubs.

11. The top lids of both the tiltmeters are unscrewed and kept by their sides. The water is then poured into one of the two tiltmeters from the water bottle. The top lids are opened to permit water to flow to the other tiltmeter.

12. The water is poured till it has approximately attained the mid-height of the viewing window in both the tiltmeters. If there is any air bubble trapped near the

tube connecting nozzle, it is removed by gently tilting the tiltmeter in the direction of the nozzle.

13. After the water surface has come to rest, the top lids are fixed to the tiltmeters and the illuminating bulbs switched on.

14. A check is made that no water leakage is taking place due to some damage to the system during transit.

15. The micrometer spindle is moved up and then downwards to remove air bubbles entrapped in the micrometer spindle threads. The free end of the spindle is brought to the water surface.

16. Using the microscope, the pointer is suitably focused.

17. The line of sight is made slightly inclined to the horizontal such that it is higher on the side away from the eye still retaining the pointer in the field of view. This would permit seeing the image of the pointer in the water surface.

18. The focusing is further improved by adjusting the position of the bulb which can be rotated, raised or lowered and clamped.

19. Now the system is ready for the measurements. The pointer and its image are brought together just to touch each other at both the tiltmeters.

20. The reading is taken. The main scale is read to half a millimetre. The reading of the micrometer disc and the vernier together give twice the value in millimetres of the three digits after decimal.

An example for reading the Tiltmeter: In a setting (say) when the main scale pointer is between 11th and 12th division of the scale and is more close to 12th division i.e. micrometer disc has taken a complete revolution and a part of the second revolution, the main scale reading is 11.5. The value of the micrometer disc marking increase in clockwise manner. The full division which has crossed to the left of the zero on the vernier is read, say it is 63. The vernier division coinciding with the micrometer disc scale division mark is read, say it is 6. The micrometer and vernier reading together is thus 0.636 divided by two. The total reading is obtained by adding the two i.e. $11.5 + \frac{0.636}{2} = 11.818$ mm.

Sometimes when the main scale pointer has just crossed half of the main scale division or is about to cross, doubt may arise regarding the main scale reading. This doubt is avoided by making the main scale pointer to coincidewith the lower nearest main scale division and watching carefully whether more or less than one revolution of the micrometer disc is required for the setting.

21. The reading as above is taken either when the pointer is moved upto come in contact (make) with its image, or else the pointer and its image are first

joined and spindle moved down till they just get detached (break).

22. A record is made whether the reading was taken at make or break. For one pair of reading the observations are taken at both the tiltmeters in the same manner.

23. A minimum of three pairs of reading are taken which do not differ by more than 3-5 microns. A change of water level would indicate some water leakage. It is ensured that there is no water leakage in order to get reliable readings.

24. The observations are repeated after interchanging the tiltmeters on the two bases. However, the first set of observation is always taken by placing the same tiltmeter on the same base in all successive measurements.

25. The observations are entered in a suitable tabular form.

26. The temperature reading is taken near both the base hubs and is noted down. Suitable hour of the day is chosen to permit taking observations under similar temperature conditions as far as possible.

27. All the desired entries in the observation blank are completed before the system is packed.

28. The relevant steps are traced back in order to pack the instrument.

29. The tiltmeter is placed in the box up-side down so that the small quantity of water which may have entered in the leak proof cell flows out and does not enter the micrometer spindle guide. Preferably a hot air blower is used for drying the micrometer.

30. Care is taken in coiling the tubing after each observation so that it does not get any twists or kinks to render it unserviceable for later use.

CLEANING OF MICROMETER SPINDLE

The micrometer spindle is made of hardened steel and developes a fine iron-oxide film which has to be removed after each field use to ensure smooth working of the system. The procedure for doing this is given below:-

1. The tiltmeter is placed upside down and the base plate unscrewed.

2. The main scale pointer is attached to the micrometer spindle through a L-shaped connector, and is detached by loosening the round knurled nut and then unscreweing it.

3. The micrometer spindle alongwith the L-shape connector is unscrewed from the micrometer guide.

4. The screw is suitably cleaned and replaced in its original position.

5. The main scale pointer and the instrument baseplate are refixed as before.

PERIODIC LUBRICATION OF LEAK PROOF CELL WASHER

After a suitable interval of time the leather washer in the leak proof cell has to be lubricated. For doing this first the micrometer spindle is removed as per previous operation and then the Tiltmeters are unscrewed at their middle. To the lower face of the upper portion is attached the leak proof cell which is opened by unscrewing three screws. The leather washer is then oiled and cell cover fixed back in its position. The pots can then be assembled.

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DESIGN OF MULTIPLE STRUCTURAL RESPONSE RECORDER SET

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Synopsis

A multiple structural response recorder set incorporating six recorders of period 0.40, 0.75 and 1.25 sec and 5% and 10% of critical damping in each, in a compact from has been designed. The recorder has been described and design details reported.

Introduction

The behaviour of structure when subjected to random and complex ground motions associated with the passage of earthquake waves is the basic data required for more effectively designing structures. This objective is achieved more conveniently by the introduction of response spectrum technique. Structural Response Recorder is a simplified instrument which can be made to possess the dynamic properties of range of typical structures enabling direct interpretation of its records in terms of maximum relative response spectral values.

Realising the need for obtaining quantitative information during actual earthquakes regarding the maximum relative responses spectral values of structures likely to be constructed in the seismic regions of the country for enabling their economical design, Structural response recorder installation programme was initiated by School of Earthquake Engineering, University of Roorkee in 1959. To start with, the required instruments were designed, developed and manufactured at the University. Instruments with period of 0.40, 0.75 and 1.25 sec and with 5% and 10% of critical damping in each i.e. total six instruments comprising a standard set were selected for installation, since these covered in general the range of structures likely to be constructed in those areas. It was towardsthe end of the year 1962 that first set of instruments were installed at Roorkee. There after, these are being installed at number of suitably seleced locations. Through the experience gained during the early installations, progressive improvements have been incorporated in the instrument design and efleciency of the programme increased. A compact disign having six recorders with the fore said specification on

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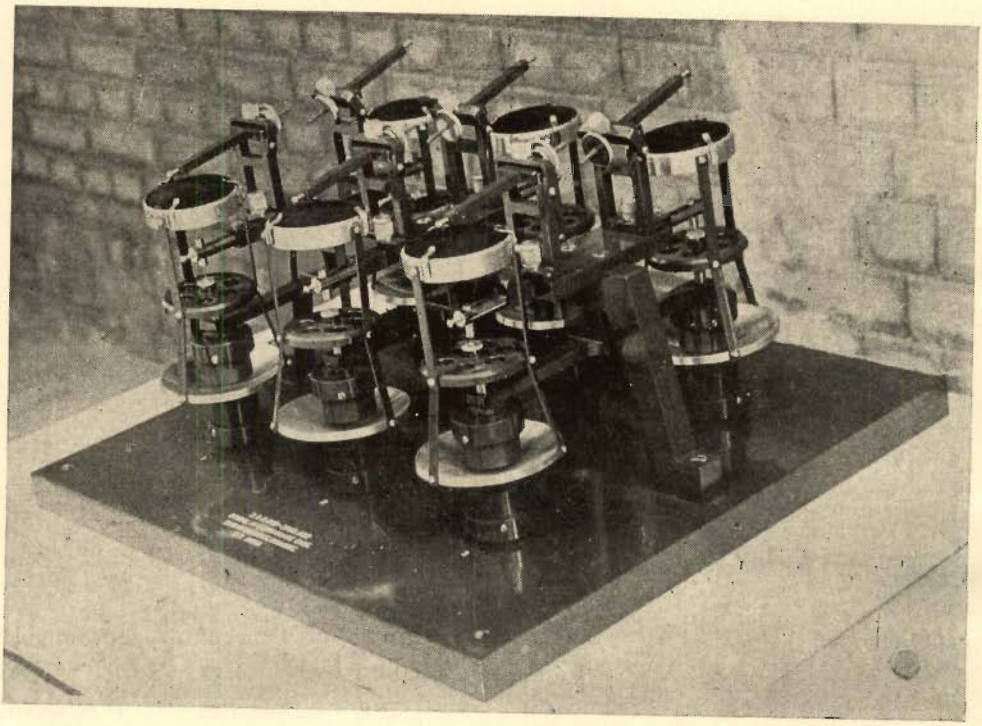

Fig. 1 Photograph of the multiple structural response recorder (cover removed).

a single base, named as multiple structural response recorder (SRR Model-2) has been adopted for installation since 1968. This instrument has been described and its complete design details as utilised in the component wise manufacture at the School workshop are given in this paper.

Description of the Multiple Structural Response Recorder Set :

The size of recorder with its cover fixed is $50 \times 45 \times 30$ cm and weight 25 kg. Figure 1 shows the instrument with cover removed. It consists of six pendulums fixed in two parallel rows of three each. Each pendulum has three circular weights. The lowest weight, in the form of a curved disc, is capable of moving in the magnetic field created by a pair of permanent magnets provided for each pendulum, thus damping the pendulum vibration. The pendulums are serially numbered at the base plate. Their period and damping are to be adjusted to valuse given in Table I. However, if so desired for specific application, the period and damping may be adjusted to other values in a limited range. The upper pendulum weight carries a smoked watch glass on which is resting a stylus. The stylus is fixed to pendulum support and has a freedom to move in a vertical plane only. Thus when the pendulum vibrates the stylus would mark a trace on the smoked glass. The middle pendulum weight has a built-in lower suspension vice. The suspension vice is held by the pendulum support which is attached to the main recorder support. A

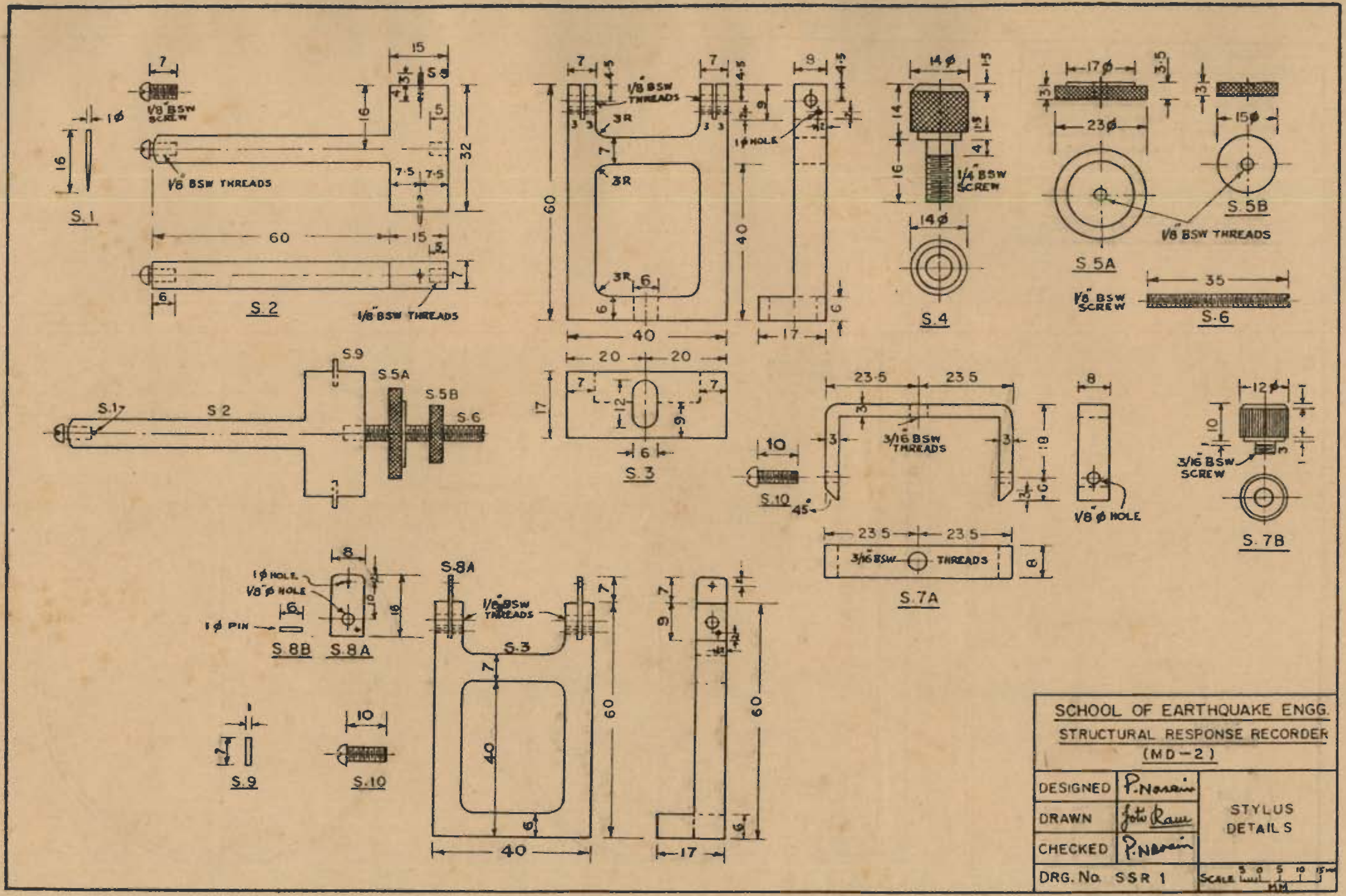

Fig. 2 Design drawings of components of pendulum assembly.

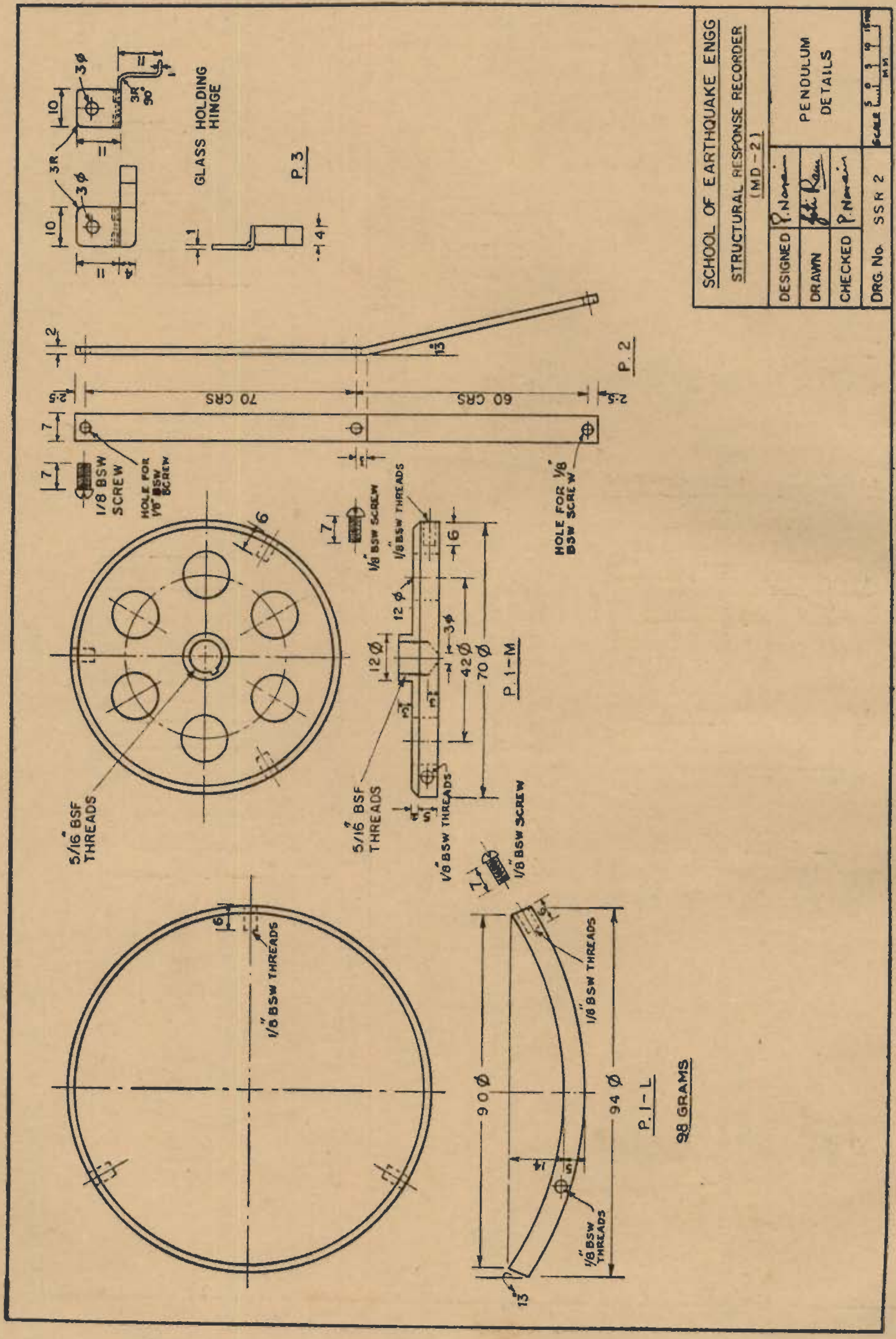

Fig. 3 Design drawings for some components of pendulum assembly.

TABLE No. 1

Pendulum No.	Period Sec	Tilt Sensitivity* cm/radian	Damping % of critical
1.	1.25	6.00	5
2.	0.75	4 00	5
3.	0.40	1.25	5
4.	0.40	1.25	10
5.	0.75	4.00	10
6.	1.25	6.00	10

*These are average values and need be determined in each case separately.

heavy rectangular base for rendering adequate fixity with the ground when installed and a sturdy rectangular cover to protect the instrument from damage are provided. The cover lid can be separated from the vertical sides of the cover box. Knurled head screws have been provided for fixing the cover.

Design Details:

Instead of installing six recorders each on separate base requiring more space, it was considered desirable to design a compact instrument having all the six recorders in one. Also since these recorders are to be installed at distant places and only inspected at a conside abl gap of time or just after recording during a strong motion earthquake, it was necessary that the instruments are of standard quality with uniform specification. In view of these requirement detail design was done. The drawing incorporating all the design details were prepared and are given in Figure 2 to 6. The drawing for base, cover and main support are not given here, since their dimensions do not control the instrument characteristics. The numbers appearing for each component in the drawings are described in the list of components given. On the basis of these drawings, component wise manufacture was planned for the recorder. After manufacture of all the components for several sets the assembling of the instrument was done Towards standardising the instrument quality, tolerances were fixed for manufacture of each component. This enabled easy recorder assembly, making any component replaceable by another piece and thus meeting the requirements of the structural response recorder installation programme.

Nomenclature for the various components:

Reference number on the design drawing	*Name of the component*
S—1	Stylus
S—2	Stylus arm
S -4	Stylus stand fixing screw
S—5A	Stylus arm balancing weight
S—5B	Stylus arm balancing weight check nut.
S—6	Screw carrying stylus arm balancing weight.
S—7A	Stylus clamping lever
S—7B	Stylus clamping lever knob.

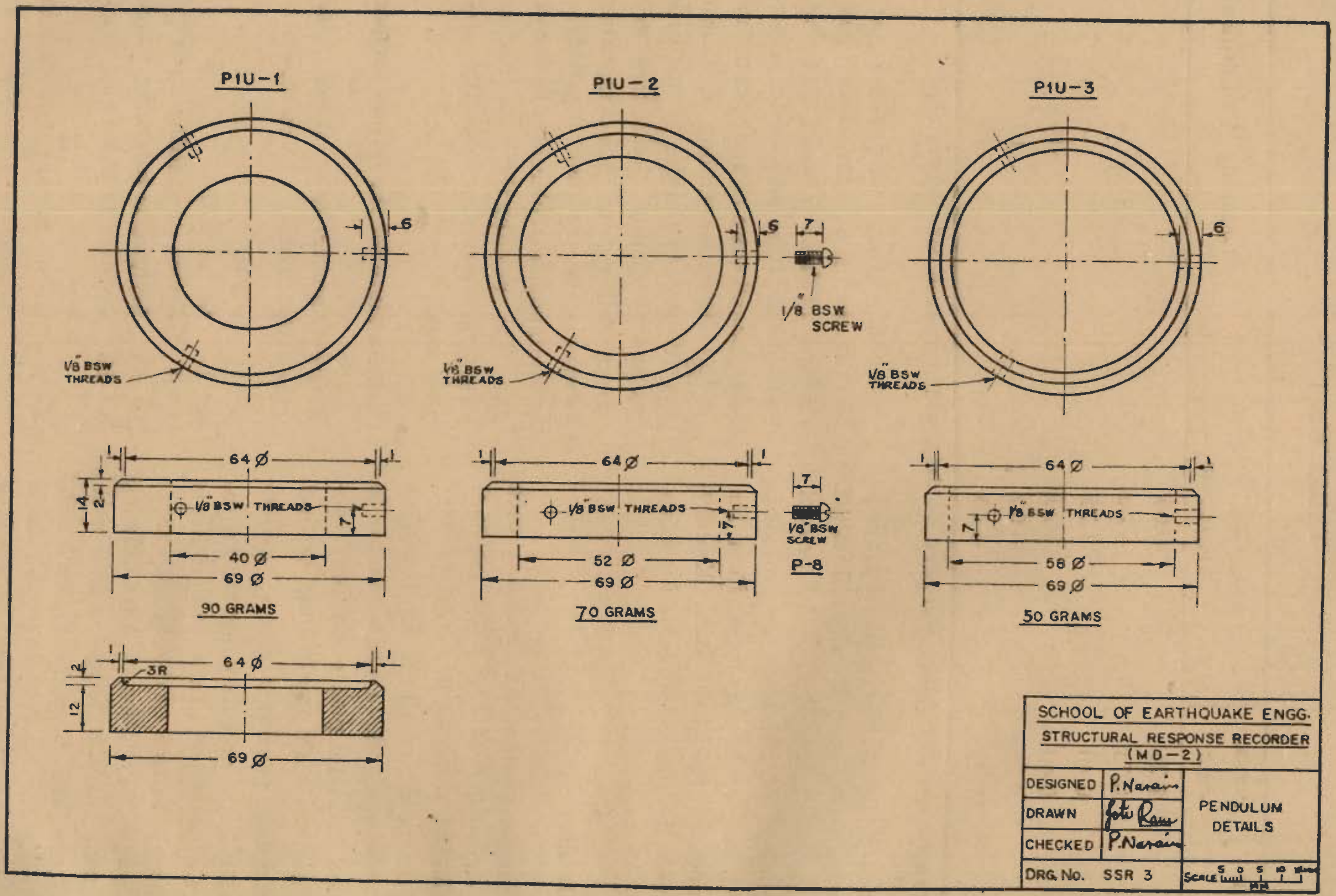

Fig. 4 Design drawings for upper weights of pendulum assembly.

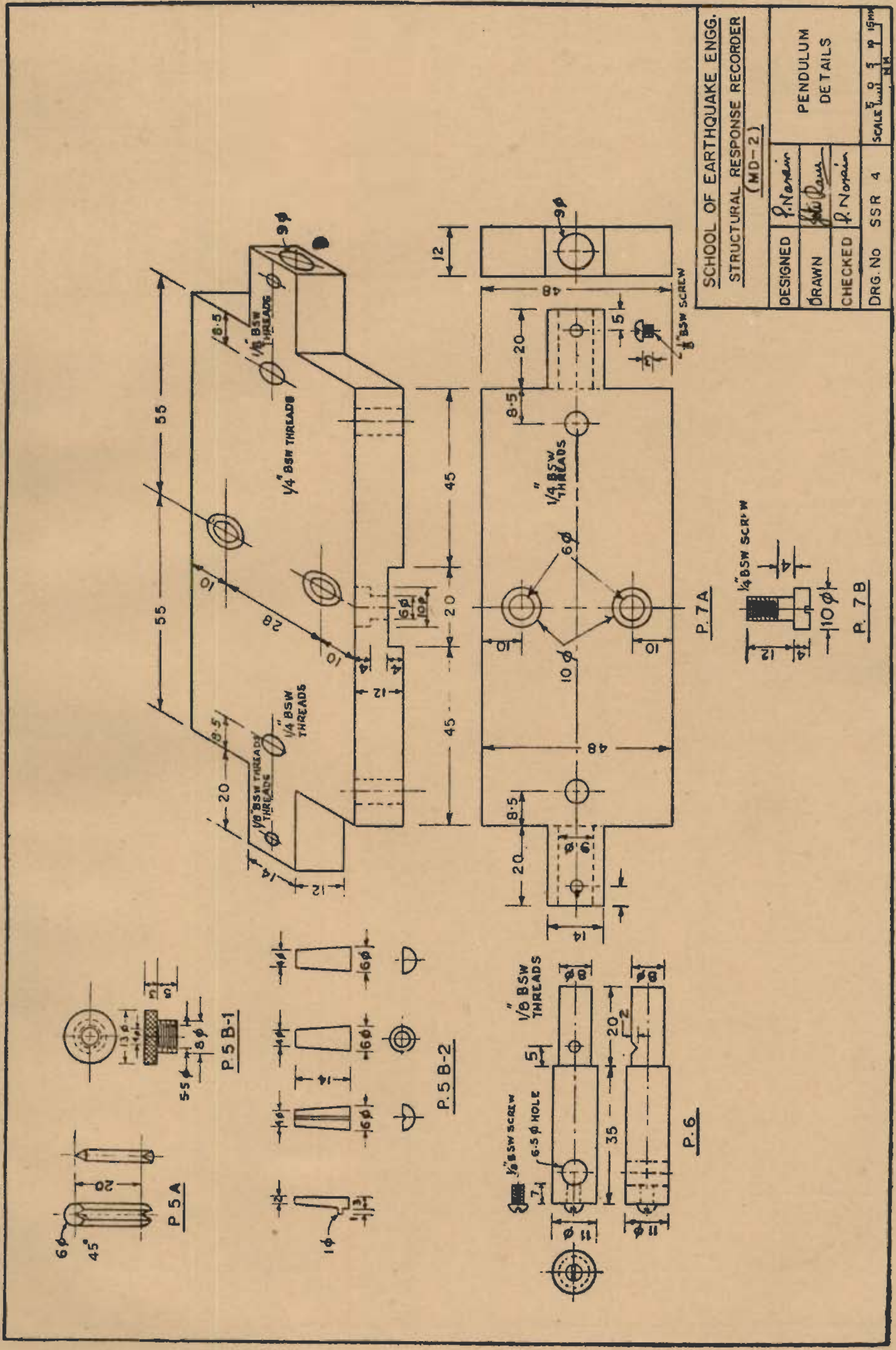

Fig. 5 Design drawings for remaining components of pendulum assembly.

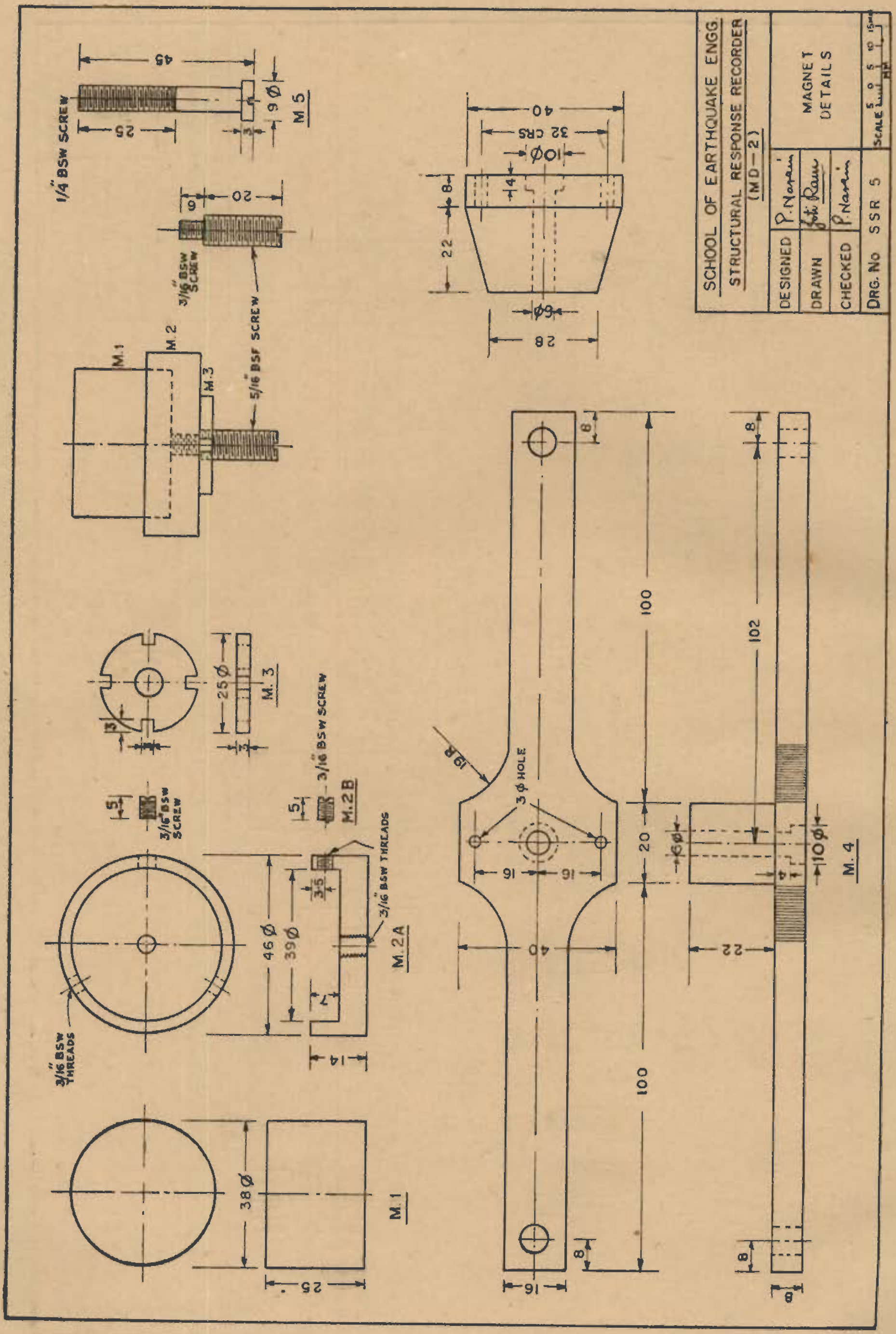

Fig. 6 Design drawings for componeuts of magnet assembly.

S—8A	Stylus arm pivot holding fish-plate.
S—8B	Fish-plate fixing pin.
S—9	Stylus arm pivot.
S—10	Screw (1/2″ BSW) 10 mm long.
P—1U1 1U2 1U3	Upper weights for 1.25, 0.75 and 0.40 sec period pendulums respectively.
P—1M	Middle pendulum weight.
P—1L	Lower pendulum weight (also acts as damping disc).
P—2	Pendulum strip.
P—3	Watch glass holding hinge.
P—4	Pendulum suspension.
P—5A	Upper suspension vice-jaws
P—5B1	Lower suspension vice-jaws
P—5B2	Lower suspension vice-nut
P—6	Removable pendulum support
P—7A	Support for a pair of pendulum and stylus.
P—7B	Pendulum and stylus support fixing screw.
P—8	Screw (1/8″ BSW 7 mm long)
M-1	Magnet
M-2A	Magnet holding socket
M-2B	Magnet tightening screw
M-3	Magnet socket locking nut
M-4	Support for a pair of magnet
M-5	Magnet support fixing screw
C-1	Base plate
C-2	Main support for recorders
C-3A1	Instrument cover frame with side fixed.
C-3A2	Instrument cover lid.
C-3B	Instrument cover fixing screw.

Conclusions :

The instrument has now been adopted for installation at new stations and is expected to yield spectral response values in a more effective and standardised manner. Also the bringing up of the instrument in to such a standardised form has enabled us to offer the same for supply to some of the countries facing earthquake problem and not yet making such instruments.

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