GROUND MOTION MEASUREMENTS IN EARTHQUAKE ENGINEERING

by

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Abstract. The special requirements of ground motion measurements in the epicentral regions of destructive earthquakes are described, from the point of view of the determination of structural response to strong ground shaking. It is shown that for this purpose the true ground acceleration-time record is required. Based on the measured characteristics of past earthquakes, the basic specifications of transducer period, damping, sensitivity, range, recording speed, and other desirable accelerograph characteristics are given. The fundamental operating principles and properties of some existing strong-motion accelerographs are described, and some improvements are suggested. The design of certain simplified instruments is discussed by means of a consideration of response spectrum theory. Several seismoscopes of a simplified type are described, and it is shown how such instruments can be used to extend the areal coverage of recording accelerographs. Consideration is given to the design of networks of strong-motion instruments, and information is supplied on the current status of present coverage of important seismic regions.

Introduction. Any study of earthquake engineering which is to have a sound scientific foundation must be based on accurate knowledge of the motions of the ground during destructive earthquakes. Such knowledge can only be obtained by actual measurements in the epicentral regions of strong earthquakes.

The number of destructive earthquakes for which such measurements are available is unfortunately very small. It is perhaps not generally realized how slender our stock of accurate information really is in this respect. For none of the recent destructive earthquakes of the world such as Mexico (1957), Chile (1960), Agadir (1960), Iran (1962), Skopje (1963) and Alaska (1964) do we have even one record of strong ground motion. Of recent major earthquakes, only for Niigata (1964) were two important ground accelerograph records obtained. The available strong motion records are thus mainly limited to the several dozen accelerograms collected over the past thirty years by the U.S. Coast and Geodetic network in the Pacific Coast states.

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It is well to emphasize that typical seismological observatories with their sensitive seismographs are not intended to make measurements in the epicentral regions of strong earthquakes and cannot be adapted to do so effectively. Thus, although there are at present some thousand operating seismological stations distributed throughout the world, they cannot be expected to contribute directly to the special problem of the measurement of destructive ground motion.

Seismology and Earthquake Engineering

The instruments used by seismologists have, of course, been carefully designed for the specific research interests of geophysicists. This has resulted in devices that are unsuitable for direct engineering applications for the following reasons. (1) The seismologist desires to record small earthquakes occurring at any point in the earth. This requires sensitive instruments of high magnification. A strong earthquake near the instrument will usually displace the reading off-scale, or may even damage the instrument. The engineer requires a rugged device that will accurately record the heaviest shocks in the near vicinity of the instrument. (2) Since a study of the internal constitution of the earth has been a primary objective of seismologists, his instruments are founded if possible on solid bed-rock to eliminate the effects of local crustal irregularities. The engineer wishes to know the ground motion at the sites at which engineering structures are located, often on thick alluvium or at locations otherwise quite unsuitable for seismological observatories. (3) For seismological investigations, accurate timing of wave arrival times is essential, whereas the measurement of true ground motion is often of little importance. The engineer does not need absolute time, but true ground motion must be accurately known if the effects of the earthquake on structures are to be determined.

It will thus be seen that the fundamentally different objectives of the engineer will require a basically different instrumentation than that needed for seismological studies. Such instruments must be designed, developed, installed and operated by earthquake engineers who will be thoroughly familiar with the ultimate practical objectives of earthquake resistant design.

Types of Earthquake Ground Motions

Earthquake ground motions are of three types which should be carefully distinguished. (1) The earthquake may trigger landslides or simiilar local surficial movements which may destroy structures by simply removing their foundations. (2) The earthquake ground shaking may result in a large scale soil and subsoil consolidation or settling, which may damage structures through excessive foundation deformation. (3) The earthquake ground accelerations may induce inertia forces in a structure sufficient to damage it. The first two effects may almost be called "static" effects.

Although they are initiated by the earthquake ground vibrations, the large-scale earth motions themselves occur relatively slowly, and do not set up appreciable inertia forces in structures. In the following discussion, we shall be concerned exclusively with the third type of action, the dynamic forces associated with earth shaking, recognizing that landslides and consolidation require a different approach and a different instrumentation. We have only to remember the two great earthquakes of 1964 in Alaska and in Niigata, however, to appreciate that these relatively slow ground motions may be much more destructive than the ground shaking, and the need for a much m more thorough study of such phenomena must be continually emphasized.

Structural Response Determinations

In Fig. 1, two equivalent dynamic systems are shown. At the left is indicated schematically a four-storey building whose foundation has acquired a horizontal acceleration $\ddot{y}(t)$ as a result of earthquake ground shaking. From the right figure, it is seen that this situation is equivalent to a fixed base building with lateral forces applied to each floor having a magnitude equal to the product of the mass of the floor and the ground acceleration. The systems are equivalent in the sense that the same dynamical equations of motion describe each system. Such a replacement of ground acceleration by lateral inertia forces proportional to the acceleration is a generally valid procedure for all structures and leads to the conclusion that it is the ground acceleration that must be known if the equivalent forces acting on a structure are to be determined.

In principle it should be immaterial whether the displacements, velocities, or accelerations of the ground are measured, since there is a simple mathematical relationship between them. To obtain displacement from acceleration requires two integrations, whereas to obtain the acceleration from the displacement requires two differentiations. In practice, however, integrations can be carried out much more accurately than differentiations, since it is easier to determine accurately the way in which the area under a complicated curve varies with time than it would be to measure the slope of the curve with the required accuracy. The state of affairs for a typical earthquake may be seen in Figure 2, which gives the ground acceleration, velocity, and displacement for the Taft, California, earthquake (Ref. 1). It will readily be seen that to start from the displacement curve and to determine its slopes with a sufficient accuracy to produce the relatively complicated velocity curve and then to repeat the process to obtain the very complicated acceleration curve would be a practically impossible undertaking. The inevitable loss of accuracy in the differentiation process cannot be avoided, no matter how the process is carried out, be it by electrical, mechanical, graphical, or numerical techniques. We thus reach our first conclusion, which is that the basic measurement for earthquake engineering applications must be of the ground acceleration versus time. Once an accurate ground acceleration curve is available, the velocity and displacement curves can be obtained by integration with a satisfactory accuracy, as has been done in Figure 2. These velocity and displacement curves will reveal some features of the motion which are not so clearly indicated by the acceleration curves, particularly in the long period region.

The complexity of the typical acceleration curve of Figure 2 suggests that a wide range of periods is involved in the ground motion. This is illustrated more specifically by the Fournier Spectrum plot of Figure 3 for the same earthquake (Ref. 2). The individual sharp peaks in the low period range are to a certain extent fortuitous aspects of a particular earthquake, and are also partly the result of the data processing techniques. The general trend of such curves is clear, however, and indicates that a significant amount of energy might be introduced into a structure almost uniformly over a band extending from 0.1 seconds to 3 or 4 seconds. This is also the range of periods that is likely to be covered by typical engineering structures. Below 0.1 second a structure becomes so rigid that dynamic design is not ordinarily a significant factor. Above 3 or 4 seconds, a structure is so flexible that conditions of excessive deformation will likely limit design rather than strength considerations. We thus reach our second conclusion, which is that an accelerograph suitable for earthquake ground motion measurements should record accurately over a period range of from 0.1 second to at least 3 or 4 seconds.

Accelerograph Design Principles

We next inquire as to how to design an instrument that will measure the absolute ground acceleration over the required period range of any fixed reference point. The solution to this problem is indicated in Figure 4. (Refs. 3,4) The cross-hatched line in the upper left hand diagram represents the ground whose motion is to be determined. We attach to the ground a mass m by means of a linear spring k and a viscous damping element c. This constitutes the instrument, the output of which is the relative displacement between the mass and the groun d, which can be measured without any fixed reference point. It can readily be shown from the equations of motion of the spring-mass system that at any particular period of ground motion the instrument output is proportional to the ground acceleration. Unfortunately, however, the proportionality factor depends on the period of the gound motion, and the object of the instrument design is to make the response as independent of period as possible. The typical Fourier Spectrum of Figure 3 indicates that the ground acceleration waveform includes many period components covering the whole period range of structural interest. To reproduce the waveform accurately the instrument must record each component with the same factor of proportionality.

The instrument response curve of Figure 4 shows how well this can be done in practice. If the curve were a horizontal straight line, the instrument response would be independent of period. It will be seen that by a judicious selection of damping around a value of 0.6 - 0.7 of critical, it is possible to achieve an instrument characteristic which is approximately constant over a band of periods from zero to a period nearly equal to the natural period of the instrument spring-mass system. It thus appears that the design of an accelerometer transducer must satisfy two main conditions: (1) the natural period of the instrument should be smaller than the smallest period to be measured, and (2) the damping should be between 0.6 - 0.7 of critical record of the smallest period component, and all of the longer periods will be even more accurately measured.

Keeping in mind that the shortest periods of interest in earthquake ground motions are about 0.1 sec., it is evident that the accelerograph period should be if possible somewhat less than 0.1 sec. This is the consideration that has fixed the usual period setting of the standard USCGS Strong Motion Accelerograph in the range of 0.05 - 0.08 sec. The disadvantage of reducing the instrument period still further to give increased accuracy at shorter ground periods is that the sensitivity of the instrument would be reduced. The deflection per unit acceleration input of the instrument is proportional to the square of the period, so that shorter period would have a smaller deflection for a given ground acceleration.

In addition to the above amplitude response characteristics of accelerographs, it is also required that the phase shift between various period components is properly acccunted for. It fortunately happens that the optimum value of damping for period-independent amplitude response of 0.6 - 0.7 of critical is at the same time the best value to preserve phase relationships (Ref. 3,4).

Accelerograph Design Details

One way in which the spring-mass damping system of the theoretical accelerograph of Figure 4 appears in practice may be seen ny referring to the diagrammatic sketch of the horizontal transducer element from the USCGS accelerograph shown in Firgure 5 (Ref. 5). In this instrument, the moving mass is a rectangular loop of wire which swings like a door about a vertical torsion suspension axis along one side. The elastic restoring force is thus a torque in the torsion suspension rather than a rectilinear spring as in Figure 4. As the loop of wire rotates it moves in the magnetic field set up by a permanent magnet, and the induced eddy currents in the loop set up viscous damping forces. The advantage of a torsion rather than a rectilinear arrangement is that the angular displacements can be very easily amplified and recorded optically by mounting a mirror on the torsion suspension. It will be recognized that this transducer element is a form of the Wood-Anderson torsion seismometer which has been used for many years by seismologists for local earthquake recording (Ref. 6,7).

A modification of this same element is used in the recently designed AR240 accelerograph. In this instrument the single loop of wire forming the seismic mass is replaced by a rectangular many-turn coil of wire. By changing the external resistance in the coil circuit, the damping can be set to any desired value. An additional advantage of the coil system is that an external electrical signal can easily be introduced into the transducer element for calibration purposes.

As an example of a very different way of accomplishing the same end result, Figure 6 shows the basic transducer element of the Japanese SMAC Accelerograph (Ref. 8). The seismic mass is supported on the end of a rigid bar, which rotates about a flexure hinge. For the very small motions involved, the system performs essentially rectilinear motion. The seismic mass itself forms the piston of an air damping system, which is provided with sufficiently small clearances so that critical damping is achieved. The air damper has the advantage of relative independence of damping with temperature. The rectilinear motion of the mass is magnified 16 times by a mechanical lever system, and the final record is scribed on a waxed paper by a sapphire stylus. Although the record amplitude is small, the line is very fine so that considerable magnification of the record itself can be made if desired. In order to recude the battery power requirement, the record paper is driven by a mechanical spring motor which is hand wound.

Sensitivity Requirements

The first consideration involved in the required instrument sensitivity is that the largest possible earthquake ground acceleration should stay on scale. It is also required that the scale should be of such a size that acceleration-time data can be read from the record with an accuracy suitable for response calculations.

The maximum acceleration so far recorded for earthquake ground motion is that shown in Figure 7 for the El Centro earthquake of May 18, 1940 (Ref. 9). This maximum of 0.33g is not believed to be as high as might occasionally be expected. Detailed studies have indicated that this maximum possible ground acceleration caused by ground shaking is of the order of 0.5g, and that the time duration of heavy ground shaking is not greater than about 45 sec. (Ref. 10,11). Considerations involving the probable mechanism of the generation and propagation of earthquake waves suggest that it is unlikely that these values would be exceeded anywhere in the world. It is accordingly believed that a full-scale reading of 0.5g should be amied at, and the instrument sensitivity in unit deflection per g will then depend upon the configuration and size of the recording mechanism. Some instruments are designed to write a small record on a narrow recording paper with a fine line so that the record can be magnified for accurate reading. Other accelerographs employ a wide recording paper producing a large size record that can be directly measured.

The time duration of heavy shaking determines the length of record that must be provided for each earthquake. Some accelerographs are arranged so that a fixed time interval of several minutes is automatically recorded for each earthquake, while others are designed to record for a fixed time after the earthquake ground motion has subsided below the triggering level. In any event, it is very desirable that a supply of recording material sufficient for a number of individual earthquakes be available, and after each earthquake the instrument should automatically return itself to readiness for the next shock.

Recording Speed

The recording speed must be such that the complicated waveforms can be measured with an accuracy adequate for spectrum analysis and for response calculations. A speed of 1 cm/sec has been standard for several strong-motion accelerographs. It is now recognized that a somewhat higher speed would be desirable, and a speed of 2 cm/sec would simplify data analysis procedures.

At these recording speeds, a continuous 24 hr/day recording is, of course, completely impracticable, and hence some type of inertia starting switch activated by the earthquake itself is necessary. This starting device is perhaps the most critical component of the whole accelerograph, and is the part most difficult to specify and design. Since the very beginnings of the ground acceleration record may contain significant acceleration peaks, it is essential that the accelerograph be triggered as soon as possible, and that the delay times in the inertia element, relay systems, and motor drive be as small as possible. On the other hand, if the starter operates at too low values of acceleration-time excitation, it may be set off by extraneous non-seismic vibrations or by a series of small, non-destructive earthquakes, with the danger that the recording medium supply might be exhausted before a strong earthquake occurred.

The horizontal pendulum starter developed by the U.S. Coast and Geodetic Survey and used successfully for the past 25 years is shown schematically in the diagram of Figure 8 (Ref. 5). The pendulum has a period of one second, and the damping is approximately 30 per cent of critical damping. A displacement of the platinum electrical contacts of some 0.05 cm in any horizontal direction will start the recording cycle. It was found that more reliable operation was obtained with a break-contact start using a holding relay rather than a make-contact type.

The time required to start the recording process with the above system is of the order of 0.2 seconds. Any starting device will, of course, have its own dynamic characteristics, and various combinations of acceleration magnitude, time duration and wave shape may cause sufficient relative motions to cause operation. The optimum combination of characteristics for a given seismic area will need to be determined by experience. The desired operating characteristics of a starter can be expressed only in terms of transient response, and this is difficult to do in any generality. In Figure 9 are given curves which show the time required to close the pendulum contacts as a function of peak amplitude and time duration of a single half-sine pulse (Ref. 12). Another way of expressing these starting conditions is to say that if a constant amplitude sine-wave train of given amplitude and period starts at time t = 0 with the starter at rest, the curves will show the combination of peak acceleration amplitude and sine-wave period that will insure starter operation with the first on-half cycle of acceleration. These curves are calculated for the particular characteristics given above for the USCGS starter. This particular half-sine pulse is, of course, only a very approximate model for the actual state of affairs, since the operation of the starter would likely be preceded by a gradually increasing series of alternating acceleration peaks.

Although the starting time of the USCGS starter is not as short as might be desired for some purposes, the evidence from past accelerograms indicates that it has been adequate for Pacific Coast strong motion earthquakes. The major acceleration peaks have in practically all cases been preceded by a series of smaller peaks of a size sufficient to start the accelerograph, and it does not appear that significant information has been lost because of starting delays.

In the epicentral region, the arriving earthquake waves emerge almost vertically and hence the longitudinal P waves will have a motion that is predominately vertical while the shear waves will correspond to a horizontal motion. Since the longitudinal waves travel faster than the shear waves, the first arrivals would be expected to be vertical. An examination of past strong motion accelerograms does show that the vertical components are often of an appreciable magnitude when the horizontal starter operates. There would thus be a considerable advantage in using a vertical starter.

After a considerable amount of experimentation, the USCGS abandoned vertical starters because of long-term stability problems. A vertical starter is used, however, in the standard Japanese SMAC accelerograph. With careful adjustment, this vertical starter has given satisfactory service.

A different approach to the starting problem has been made in a recent New Zealand design (Ref. 13). In the M.O.1 accelerograph the starter system moves vertically and consists of a coil moving in a magnetic field which generates a voltage pulse. This velocity type device thus avoids the troubles of contact systems, and should solve the stability and drift problem for the vertical starter. Such a starter should offer definite advantages over any of the standard devices used in the past.

Another way of reducing the total system starting time is illustrated in the USSR Type UAR Accelerograph shown schematically in Figure 10 (Ref. 14). The recording drum (1) is wound up against the spring (2), and is held in this cocked position by the brake (9). The starting pendulum (7) releases the brake, and the high initial torque quickly starts the recording drum. The main difficulty in this device would be the provision of automatic resetting.

A number of attempts have been made to produce an instrument with a short memory, which would preserve intact the whole initial portion of the accelerogram. This could be accomplished, for example, by recording on a continuous tape loop, which would be also continuously erased. The starter and timer would then have only the function of arresting the erasing process and of stopping the recorder after one complete cycle of the loop. Although this would seem to be relatively simple to work out in practice, it does not seem to have as yet been used in the field for strong-motion measurements, although experimental devices have been built (Ref. 15). Another idea records the data continuously as a photo-luminescent trace which gradually fades out. The starter then serves the function of pressing an auxiliary recording paper against the trace at the appropriate time thus producing a permanent record (Ref. 16).

Timing and Power Requirements

Although an absolute time scale is not needed for strong-motion work, it is considered desirable to have accurate time marks on the record so that accurate data processing such as spectrum determinations and response calculations can be carried out. Most standard accelerographs contain an arrangement for making one or two marks per second on the record with a relative timing accuracy of the order of 1%. In a move towards simplification and reduced costs, a recent New Zealand design eliminates a separate timer, and retains accurate timing by the use of a precision D.C. drive motor of a type developed for analog computer applications (Ref. 13).

Any strong-motion accelerograph requires, of course, an internal source of power to provide for operation in the event an earthquake should knock out the local power system. This is often arranged for by using a storage battery as the main power source, which is continuously charged by a trickle charger energized from the local power supply. Since the Japanese SMAC accelerograph derives its main power from a mechanical spring wound motor, it requires only relatively long-lived dry cells for the starting circuits.

Summary of Existing Accelerographs

Table I summarizes the characteristics of a number of standard accelerographs that have been used for strong-motion recording (Ref. 17). A review of the table will indicate the extent to which the above requirements have been met by existing instruments, and will suggest possible future developments. Although several satisfactory devices are at present available on a commercial basis, there is a general feeling that these instruments are too costly for widespread application. The relatively high cost ($4000 per accelerograph) reflects mainly the limited market and the fact that the instruments have in the past been built in very small lots. There seems to be no question that if means could be found to acquire the numbers of accelerographs that are really needed to more adequately instrument the areas of strong seismicity, the costs of even today's complicated devices would go down considerably.

Simplified Instrumentation

Because of the relatively high cost of recording accelerographs of the type discussed above, there has always been a keen interest in the development of a simpler type of device which, although it might yield limited results, could be much more widely distributed. Such a device can be produced by adopting a different point of view in instrument design. The design philosophy behind the recording accelerographs described above produces a record from which the true ground motion can be derived. Once this true ground motion is known, any desired features can be analyzed, and the effects of such a motion on structures of any kind can theoretically be determined.

A second technique makes no attempt to determine the actual ground motion, but measures the effect of the ground motion on a particular system. The system is chosen in such a way that from its known behavior, certain significant features of the ground motion can be ascertained, and hence the behavior of other systems subjected to the same ground motion can be at least approximately determined (Ref. 18).

Perhaps the first systematic attempt to measure earthquake ground motions by their effects on very simple structures was made by Galitzin in 1911 (Ref. 19) who suggested that a series of rectangular blocks of various proportions could be calibrated in terms of which blocks would be overturned by a particular ground motion, an idea which was elaborated by a number of later investigators.

The first practical attempt to develop an instrument along the above lines was made in 1926 by Suyehiro (Ref. 20, 21). The "Suyehiro Vibration Analyzer" consisted of a series of cantilever beams of various natural periods, all having the same damping. The motion of these beams caused by the earthquake was recorded on a rotating drum. The instrument can be regarded as a series of dynamic models of structures, covering the range of natural periods likely to be encountered in actual buildings. Although the actual ground motion cannot be uniquely determined by such a device, something even more useful to the engineer is produced since the effects of the ground motion on typical structures are directly indicated.

Typical of later application of similar principles is the device developed by Medvedev as a means of attaching quantitative significance to earthquake intensity scales. Medvedev's "CBM Seismometer" (Ref. 22) consists of a conical pendulum of 0.25 sec period whose mass is free to to move in any horizontal direction. The pendulum mass is in the form of a copper disk which moves between the air gap of permanent magnets which give the system a damping of about 8% of critical damping. The motions of the pendulum are recorded on a smoked glass. A relationship has been established between the pendulum displacements and the grades of the earthquake intensity scale (Ref. 23).

Response Spectrum Theory

In order to understand more completely the full possibilities of simplified instruments of the above type, and how they are to be compared with recording accelerographs, it is useful to introduce the idea of a response spectrum.

To define the response spectrum, suppose that a given force or ground acceleration is applied to a single degree of freedom system. The behavior of the system as measured, for example, by its maximum displacement, will depend upon the exciting force, and upon the natural period and damping of the system. For a given excitation and a particular value of damping, the maximum displacement of the single degree of freedom system could be plotted versus the natural period of the system. A family of such curves, for various values of damping, would then form the response spectrum. Given the response spectrum, the maximum motion of any particular single degree of freedom structure of known period and damping can be directly determined.

The response spectrum reveals directly those aspects of the earthquake ground motion which are of primary concern to the structural engineer, and the preparation of such response spectrum curves is one of the main uses to which the recorded earthquake accelerograms are put (Ref. 24).

Calculation of Response Spectrum Curves

Response spectrum curves are in practice determined either by analog computation, or by the use of high speed digital computers. The main computation of U.S. earthquake response spectrum curves was based on a passive type electric analog computer system operating repetitively at a 10 cycle per sec rate (Ref. 25). The recent spectrum calculations made for Japanese earthquakes are computed on an electromechanical analog computer having a fixed frequency -responding element and a variable-frequency exciting function generator (Ref. 26). With the widespread availability of high speed digital computers, it is now becoming customary to make response spectrum calculations by this means (Ref. 2). In any event, the spectrum calculations, although simple in principle, are either laborious or expensive to carry out with the desired accuracy considering the present form in which the input data are available.

The USCGS Seismoscope

It will be recognized that Suyehiro's Vibration analyzer described above is one way of measuring the response spectrum directly, without the necessity of first measuring the true ground motion versus time and then carrying out a difficult calculation to get the response spectrum. By plotting the maximum deflections of each of the cantilever beam elements in the vibration analyzer versus its natural period, the response spectrum for the one damping value could be obtained. By providing similar instruments having various damping values, the whole set of response spectrum curves could be obtained.

In the same way, it will be seen that Medvedev's seismometer gives directly the one point on the response spectrum curve in the simplest possible way (Ref. 27). After an examination of many response spectrum curves calculated from recorded accelerograms of Pacific Coast earthquakes, it was decided that the single spectrum point which would give the maximum information would be a period of 0.75 seconds and 10% of critical damping. This decision was based on the fact that at periods above this value the velocity response spectrum curves tended to become constant independent of period, whereas at lower periods the response dropped off markedly. The 10% damping was sufficient to insure a relatively smoothly varying spectrum curve without local peaks, and yet was not so high that the response was reduced to a value difficult to measure. This seemed to be the single point around which the most informative extrapolations could be carried out, and in addition the values of period and damping were sufficiently close to those of many modern multi-storey structures so that the device preserved the useful physical concept of serving as a direct dynamic model of a structure. Figure 11 shows a schematic diagram of the final model of the seismoscope developed by the U.S. Coast and Geodetic Survey and the California Institute of Technology (Ref. 27(. This instrument was tested in the field by mounting it beside one of the USCGS recording accelerographs and recording simultaneously the same earthquake on each instrument. In Figure 12 is shown the velocity response spectrum curve for two components of the Montana Earthquake of 27 August 1959. On the same figure are shown the spectrum points as measured from the seismoscope record of the same earthquake. When it is considered how complicated are the instruments and calculations required to obtain the complete spectrum curves, it is remarkable that a seismoscope of such a simple form can produce so much information.

Multi-element Seismoscopes

A logical extension of the above ideas suggests the idea of several seismoscopes having various periods and damping so that a number of spectrum points can be obtained. One such instrument, developed by Nazarov, contains 12 elements in one instrument (Ref. 28, 23). Nine of these elements measure horizontal motions, and three of them vertical motions. The elements all have about the same damping and cover a period range of from 0.08 sec to 1.2 sec. Records are made on a smoked glass plate, as in the seismoscopes described above.

A similar idea has been developed by Krishna and Chandrasekaran, who have modified the USCGS Seismoscope so that they can be installed in sets of six having periods of 0.40 sec, 0.75 sec, and 1.25 sec at damping values of 5% and 10% of critical damping (Ref. 29).

It should, of course, be remembered that even if the exact response spectrum curve could be completely defined, the full information available in a true ground acceleration-time curve would not be at hand. The response spectrum curves, for example, give only maximum response magnitude and do not preserve the time differences at which these maxima occur. It is thus not possible to solve exactly from response spectrum curves alone the problem of the response of multi-degree of freedom systems. In view of the many uncertainties involved in all earthquake response calculations, however, a determination of the response spectrum may be considered as sufficient for most practical applications.

The big advantage of the seismoscope, of course, is the elimination of time recording, which much simplifies the device. Since it is possible to acquire about 50 seismoscopes for the price of one recording accelerograph, the attractive possibilities of the simple device for increasing coverage becomes very evident. It would seem that the optimum use of the instruments would involve one recording accelerograph surrounded in an area of 100 sq. mi. or so by several dozen seismoscopes. From the recording accelerograph the details of the response spectrum curves could be learned, and from the seismoscopes the way in which the magnitude levels are influenced by local geology and soil conditions could be ascertained.

Strong-Motion Instrument Networks

A strong-motion accelerograph must be located within some 30 mi. of the epicenter of a strong earthquake if useful information is to be obtained. Considering the seismic areas involved in the world, it would obviously be impossible to completely instrument such areas with an adequate network of strong-motion accelerographs. Past practice has been to concentrate such instruments near important cities or sites of major engineering works such as dams or power plants. The optimum location of available instruments to produce a maximum information is clearly a matter of many compromises, which deserves more special study than it has received in the past.

In Figure 13 is shown the distribution of strong-motion accelerographs in the U.S. Pacific Coast network maintained by the U.S. Coast and Geodetic Survey. The dotted circle shows roughly the area of useful information covered by a single instrument. Although there are many notable gaps in the coverage, the record of recovered data from California earthquakes has been very good since the first accelerogram obtained in the Long Beach earthquake of 1933, when the system was initiated. A notable recent exception is the Alaskan earthquake of 1964, for which no strong-motion records were obtained, as there were no instruments in that area prior to the earthquake. The accelerographs are, of course, heavily concentrated at Los Angeles and San Francisco where the largest population and structural investment is located.

Since 1960, about 120 of the simplified seismoscopes have been installed by the U.S. Coast and Geodetic Survey on an experimental basis. Figure 14 shows the distribution of these seismoscopes in the metropolitan Los Angeles area, to indicate how the seismoscopes are intended to fill in information on the bahavior of various local geological and soil situations.

The Japanese strong motion accelerograph network has expanded very rapidly since the formation of the "Strong Motion Acceleration Committee" in 1951. Figure 15 shows the 1963 distribution of instruments which has been significantly added to since that time. Japan is now the most completely instrumented seismic region for strong ground motion measurements and a number of interesting accelograms, including particularly those from the Niigata Earthquake of 1964 have recently been obtained (Ref. 30).

A number of other countries have installed a few accelographs, and are hoping to increase the coverage in the near future. Several useful accelerograms have recently been obtained, for example, in Mexico City.

Figure 16 shows the accelerograph network developing in Western Canada, according to information supplied by W. G. Milne of the Dominion Observatory. It is also expected that accelerographs will be located in the seismic zones in Eastern Canada, perhaps initially at Montreal, Quebec, and Three Rivers. The first Canadian accelerogram was that recorded at Victoria during the Seattle earthquake of 29 April, 1965. In addition to the recording accelerographs, 25 seismoscopes are now available for the Canadian network and 25 more are on order.

At present, no seismic region in the world can be said to be satisfactorily covered by strong motion accelerographs. This fact was recognized at the 1964 UNESCO Intergovernmental Meeting on Seismology and Earthquake Engineering, which recommended that increased numbers and improved distribution of strong-motion accelerographs should be provided for. UNESCO established a special working group having representatives from Japan, USSR, and U.S.A., to define suitable characteristics for such instruments. The instruments described in Table I all meet the general specifications set up by this working group.

In addition to the measurement of earthquake ground motion, the standard strong-motion accelerographs are useful to measure the earthquake response in tall buildings. By simultaneous measurements of ground motion and structural response during actual earthquakes, a great deal of information on the dynamic characteristics of structure under earthquake excitation can be derived. One opportunity to carry out calculations of this kind occurred during the San Francisco Earthquake of 1957 (Ref. 31). A similar situation existed in Akita, Japan during the Niigata earthquake of 1964, when excellent accelerograph records were simultaneously obtained of the ground motion and structural response of a modern structure.

Future Developments

Although existing instruments have been reasonably satisfactory, there are many obvious improvements which should be made, some of which have been suggested above. It must be concluded that none of the existing devices really exploits modern instrumentation developments to any significant degree. A major drawback is the form of analog record, which has been a major stumbling block to the introduction of modern data processing techniques. There would be a great advantage to a record which would directly produce an electric signal, such as a magnetic tape, since the data could then be easily transformed into any desired form. At present, a great deal of routine work is required to produce electric signals for analog computer studies or to produce digital data for digital computation. There is no basic reason why the instrument output itself should not be in a digital form as this would permit a maximum flexibility in data processing.

It is also clear that a good deal would be gained by the kind of cooperative program that would make it possible to increase the manufacture lot size of accelerographs. The high cost of past accelerographs has been in large part caused by the fact that many of them have been built on almost an individual basis. The number of such devices that can be economically justified for the seismic regions of the world is such that it should be possible to significantly reduce production costs.

Compared with the impressive network of teleseismic seismological stations distributed throughout the world, and the detailed studies of seismologists and geophysicists, the strong-motion earthquake measurement program must be considered to be a very rudimentary state. The potential importance of the subject makes it imperative that a much more energetic approach be made to the problem. It is hoped that the near future will see rapid and comprehensive developments in all phases of the subject.

References

1. Berg, G.V. and Housner, G.W., "Integrated Velocity and Displacement of Strong Earth quake Ground Motion," *Bull. Seis. Soc. Amer.*, vol. 51, no. 2, April 1961.

2. Hudson, D.E., "Some Problems in the Application of Spectrum Techniques to Strong-Motion Earthquake Analysis," *Bull. Seis. Soc. Amer.*, vol. 52, no. 2, April 1962.

3. Beckwith, T.G. and Buck, N.L., *Mechanical Measurements*, Addison-Wesley Pub. Co., Inc., Reading, 1961.

4. Bradley, W. and Eller, E.E., "Introduction to Shock and Vibration Measurements," *Shock and Vibration Handbook* (Harris, C.M. and Crede, C.E., eds.) McGraw-Hill Book Co., Inc., New York, 1961.

5. Heck, N.H., McComb, H.E. and Ulrich, F.P., "Strong-Motion Program and Tiltmeters," *Earthquake Investigations in California*, 1934-35, Special Pub. No. 201, U.S. Department of Commerce, Coast and Geodetic Survey, Washington, D.C., 1936.

6. Anderson, J.A. and Wood, H.O., "Description and Theory of the Torsion Seismometer, " *Bull. Seis. Soc. Amer.*, vol. 15, no. 1, March 1925.

7. Benioff, H., "Earthquake Seismographs and Associated Instruments," *Advances in Geophysics*, vol. 2, (Landsberg, H.E., Ed.), Academic Press, Inc., New York, 1955.

8. Takahasi., "The SMAC Strong Motion Accelerograph and Other Latest Instruments for Measuring Earthquakes and Building Vibrations," *Proc. World Conf. on Earthquake Eng.*, Berkeley, 1956.

9. Neuman, F., *United States Earthquakes*, 1940, Serial No. 647, U.S. Department of Commerce, Coast and Geodetic Survey, Washington, D.C., 1942.

10. Cloud, W.K., "Macimum Accelerations During Earthquakes," *Proc. Primeras Jornadas Chilenas de Sismologia e Ingenieria Antisismica*, vol. 1, Asociacion Chilena de Sismologia e Ingenieria Antisismica, 1963.

11. Housner, G.W., "Intensity of Earthquake Ground Shaking near the Causative Fault, "*Proc. Third World Conf. on Earthquake Engineering*, New Zealand, 1965.

12. Hudson, D.E., "The Measurement of the Ground Motion of Destructive Earthquakes," *Bull. Seis. Soc. Amer.*,vol.53, no. 2, February 1963.

13. Duflou, P.C.J. and Skinner, R.I., "New Strong-Motion Accelerographs, "Proc. Third World Conference on Earthquake Eng., New Zealand, 1965.

14. Shi-Yuan, E., Kirnos, D.P. and Solovyev, V.N., "A Simplified Recording Unit for Instrumental Observations in Epicentral Zones of strong Earthquakes," in Seismic Instruments, ed. Kirnos, D.P., and Borisevich, E.S., (Seysmicheskiye Pribory, No. 19:1-11, 1961, Trans. by Univ. of Mich. Inst. of Sci. & Tech.).

15. Fremd, V.M., "Installation with Memory for the Recording of Strong Earthquakes, "AN SSSR, Trudy Instituta Fiziki Zemli, No. 26 (193) Academy of Sciences, USSR, Moscow, 1963 (English Trans.).

16. Borisevich, E.S., Goldfarb, M.L. and Mosyazina, M.S., "Recorder with Luminescent Memory," in Seismic Instruments, ed. Kirnos, D.P., and Borisevich, E.S. (Seysmicheskiyi Pribory, No. 19:57-63, 1961, Trans. by Univ.of Mich. Inst. of Sci. & Tech.).

17. Halverson, H.T., "The Strong Motion Accelerograph," Proc. Third World Conference on Earthquake Eng., New Zealand, 1965.

18. Hudson, D.E., "Ground Motion Measurements in Earthquake Engineering," Proc. Symposium on Earthquake Eng., University of Roorkeem Roorkee, U.P., India, 1959.

19. Galitzin, B., "Uber Eine Skala zur Schatzung von Makroseismischen Bewegungen," St. Petersburg, 1911. Review and translated abstract by Wood, H.O., Bull. Seis. Soc. Amer., vol. 3, no. 2, June, 1913.

20. Suyehiro, K., "A Seismic Vibration Analyzer and the Records Obtained Therewith," Bull. Earth. Res. Inst., Tokyo, vol. 1, 1926.

21. Suyehiro, K., "Engineering Seismology - Notes on American Lectures," Proc. Amer. Soc. Civil Eng., vol. 58, no. 4, 1932.

22. Medvedev, S.V., Engineering Seismology, Moscow, 1962. (In Russian)

23. Savarensky, E.F., and Kirnos, D.P., Elements of Seismology and Seismometry, Moscow, 1955 (English Translation).

24. Hudson, D.E., "Response Spectrum Techniques in Engineering Seismology," Proc. World Conference on Earthquake Eng., Berkeley, 1956.

25. Caughey, T.K., Hudson, D.E., and Powell, R.V., "The C.I.T. Mark II Response Spectrum Analyzer for Earthquake Engineering Studies," Proc. Second World Conference on Earthquake Eng. Tokyo & Kyoto, 1960.

26. "Non-Linear Response Analyzers and Application to Earthquake Resistant Design," Response Analyzer Committee; Proc. Second World Conference on Earthquake Eng., Tokyo and Kyoto, 1960.

27. Cloud, W.K., and Hudson, D.E., "A Simplified Device for Recording Strong Motion Earthquakes," Bull. Seis. Soc., Amer., vol. 51, no. 2, April, 1961.

28. Nazarov, A.G., The Method of Engineering Analysis of Seismic Forces, Armenian Academy of Sciences, 1959 (in Russian).

29. Krishna, Jai, and Chandrasekaran, A.R., "Structural Response Recorders," Proc. Third World Conference on Earthquake Engineering, New Zealand, 1965.

30. "The Niigata Earthquake of 16 June 1964 and Resulting Damage to Reinforced Concrete Buildings," IISEE Earthquake Report No. 1, International Institute of Seismology and Earthquake Engineering, Tokyo, Japan, 1965.

31. Hudson, D.E., "A Comparison of Theoretical and Experimental Determinations of Building Response to Earthquakes," Proc. Second World Conference on Earthquake Eng., Yokyo and Kyoto, 1960.

TABLE I

CHARACTERISTICS OF SIGNIFICANT STRONG-MOTION ACCELEROGRAPHS
(Based on best information available June 1964)

CHARACTERISTIC	USC&GS-STANDARD	USC&GS - MARK II	AKASHI SMAC - B/SMAC-B2	HOSAKA DC-3	UED AR-240	NEW ZEALAND (NO MODEL NO.)	RUSSIA UAR
Components							
Accelerometers	2 horiz. and 1 vertical	2 horiz. and 1 vertical	2 horiz. and 1 vertical	2 horiz. and 1 vertical	2 horiz. and 1 vertical	2 horiz. and 1 vertical	2 horiz. and 1 vertical
Displacement Meters	2 horiz.	2 horiz.	None	None	None at present	None	None
Natural Period (in sec.)							
Accelerometers	Adjustable (0.001-0.15)	Adjustable (0.03-0.10)	0.10/0.14	0.10	0.055-0.065	0.03	0.05
Displacement Meters	Adj. 0.5-5.0 sec. (Carder) 10-sec. nominal (Coast Survey)	Adj. 5 sec. nominal	None	None	None at present		None
Sensitivity (in mm/0.1g)							
Accelerometers	Adjustable 6-20	Adjustable 6-20	4.0/8.8	4.0	Adjustable 5.0-7.5	1.25	1.6
Damping (% of critical)							
Accelerometers	Adjustable 60% nominal	Adjustable 65% nominal	100%	100% (silicone oil)	Adjustable 55-65%	Not known	70%
Displacement Meters	Adjustable 60% nominal	Approx. same as standard model	None	None	None at present	None	None
Damping Mechanism							
Accelerometers	Magnetic	Electromagnetic	Air Piston	Oil Piston	Electromagnetic	Not known	Electromagnetic
Displacement Meters	Magnetic	Electromagnetic	None	None	None at present	None	None
Recording Range	0.001-1.0g (usually 1.0 in California)	0.01-1.0g	0.01-1.0g/0.006-0.5g	0.025-1.0g	0.01-1.0g	0.01g to 1.0g	0.025g to 1.0g
Traces and Trace Width	12 total 5 fixed-x, y, z and displ. 5 variable-x, y, z and displ. 2 timing-each side Width: 0.05-0.075cm (depending on lamp current and development)	12 total 5 fixed-x, y, z and displ. 5 variable-x, y, z and displ. 2 timing-each side Width: < 0.003" on 70mm film	4 total 0 fixed 3 variable - x, y, z, 1 timing Width: Not known	4 total 0 fixed 3 variable - x, y, z, 1 timing Width: Not known	8 total 3 fixed-x, y, z, 3 variable - x, y, z 2 timing-each side Width: 0.010-0.015"	4 total 1 fixed 3 variable 0 timing Width: 0.003" on 35mm film	3 total 0 fixed 3 variable 0 timing Width: Not known
Time Marking	2 per second	5 per second ± 1%-5th mark acc. (115vac syn. motor and timing vane)	1 or 5 per second-clock with elec. cont.	5, 2, or 1 per second	2 per second ± 1%	None - dependent on precision paper drive	None
Recording Medium, Speed and Duration	Photo. paper roll at 1 cm/sec. (alternate drum) Duration: 1-1/4 min. and repeatable for 5 cycles	70mm film roll-50 feet at 1 cm/sec Duration: 1-20 sec. after last strong seismic shock and repeatable to end of film roll	Waxed paper roll at 1 cm/sec. Duration: 3 min. - able to start 5 times	Smoked paper drum at 1 cm/sec. Duration: 3 min. and repeatable for 3 cycles	Photo. paper roll 150 ft. at 2 cm/sec. Duration: 7 sec. after last strong seismic shock and repeatable to end of paper roll	35mm film 20 feet total 35mm film 20 ft. total duration: 45 sec. @ 1.5 cm/sec Starts 9 times	Photo paper on drum Photo paper on drum Duration: 60 sec. Not repeatable
Recording Drive	DC electric motor	115 vac synchronous electric motor	Hand-wound spring motor	DC electric motor (6 vdc)	DC governed electric motor (12 vdc)	Precision 12 VDC electric motor	

TABLE I

CHARACTERISTICS OF SIGNIFICANT STRONG-MOTION ACCELEROGRAPHS (Cont)

(Based on best information available June 1964)

CHARACTERISTIC	USC&GS-STANDARD	USC&GS - MARK II	AKASHI SMAC - B/SMAC-B2	HOSAKA DC-3	UED AR-240	NEW ZEALAND (NO MODEL NO.)	RUSSIA UAR
Built-in Calibration System	None	Electrical impulse to record damping and period information	None	None	Electrical impulse to record damping and period information	None	None
Starter							
Component	Horizontal-closed relay	Horizontal-closed relay	Vertical	Vertical	Horizontal-closed relay	Horizontal	Horizontal
Type	Pendulum-elec. contact	Pendulum-elec. contact	Pendulum-elec. contact	Pendulum-elec. contact	Pendulum-elec. contact	Pendulum-emf (no contact)	Pendulum-elec. contact
Period	1 sec.	Approx. 0.6 sec.	0.3 sec.	0.3 sec.	Approx. 1 sec.	0.2 sec.	Not known
Sensitivity	0.05 cm displ. of center	Adjustable-better than 0.01g	0.01g/0.006g	0.01g	Adjustable to 0.060" gap	Velocity approx. 0.01g	Not known
Damping	30% critical-oil type	50% critical-electro-mag.	Not known	Not known	100% critical-eddy current	Low	Not known
Misc.	------	------	Plus. aux. mech. starter	------	------	------	------
Starting Time	Approx. 0.2 sec.	Approx. 0.2 sec.	Not known	Not known	Approx. 0.1-0.15 sec.	Approx. 0.1 sec.	0.05 sec. to uniform rotational speed
Power Supply	12 vdc external wet storage batteries with 115 vac 60 cps ext. trickle charger	24 vdc external wet storage batteries with 115 vac 60 cps ext. trickle charger and ext. dc-ac inverter	12 vdc internal dry cells (4 cells at 3 vdc each) or alkaline cells auto-charged	Internal dry cells (3 No. 5) - 6 vdc	12 vdc external wet storage batteries 115 vac internal trickle charger	12 vdc internal dry cells	100 vdc and 6 vdc dry cells
Size (inches) HxWxL	13 x 20 x 45	10 x 14 x 21	15 x 21 x 21-incl. batteries	16 x 24 x 31-incl. batteries	14 x 16 x 16	12 x 12 x 24	Not known
Weight (pounds)	135 with cover	Approx. 60 with aluminum cover	220 with steel cover	440 with steel cover	60 with aluminum cover	35	Not known
Manufacturer or Designer	USC&GS-not commercially available	USC&GS-commercially available from United Electro Dynamics, Inc. Pasadena, California	Akashi Seisakusho, Ltd. Tokyo, Japan	Hosaka Shindo Keiki Mfg. Co., Tokyo, Japan	United Electro-Dynamics, Inc., Pasadena, California	Physics & Engineering Lab. - Department of Scientific & Industrial Research	Earth Physics Institute, USSR Academy of Sciences
Present Price	Has been fabricated for $4000 to $8000 depending on quantity and components desired	Price on request	$ 4000	Assumed $4000	$3950	Estimated $1000 commercial version under discussion	Not available commercially
Other Accelerographs	------	------	Ishimoto, SMAC-A, and Akashi IAS-P accelerographs	DC-2 and Ishimoto accelerographs	------	Horizontal accel. vector seismoscope - no time base - est. $25.00 price, about 95 installed in New Zealand Strong motion seismograph type EB - 2 horiz. components - range 0 to 0.5g	Can also be modified to provide velocity or displacement record

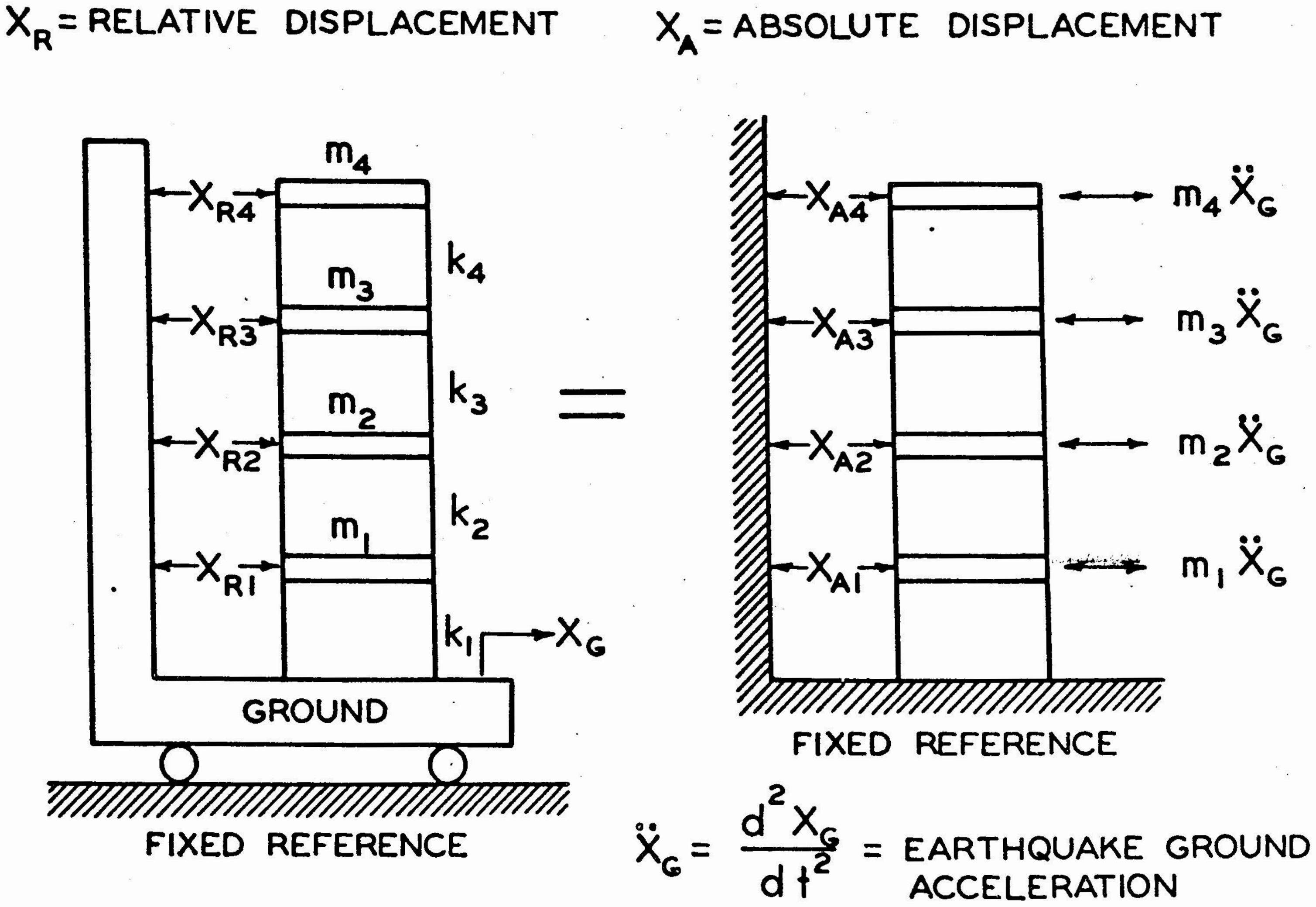


Figure 1. EQUIVALENT DYNAMIC SYSTEM FOR HORIZONTAL MOTION RESPONSE

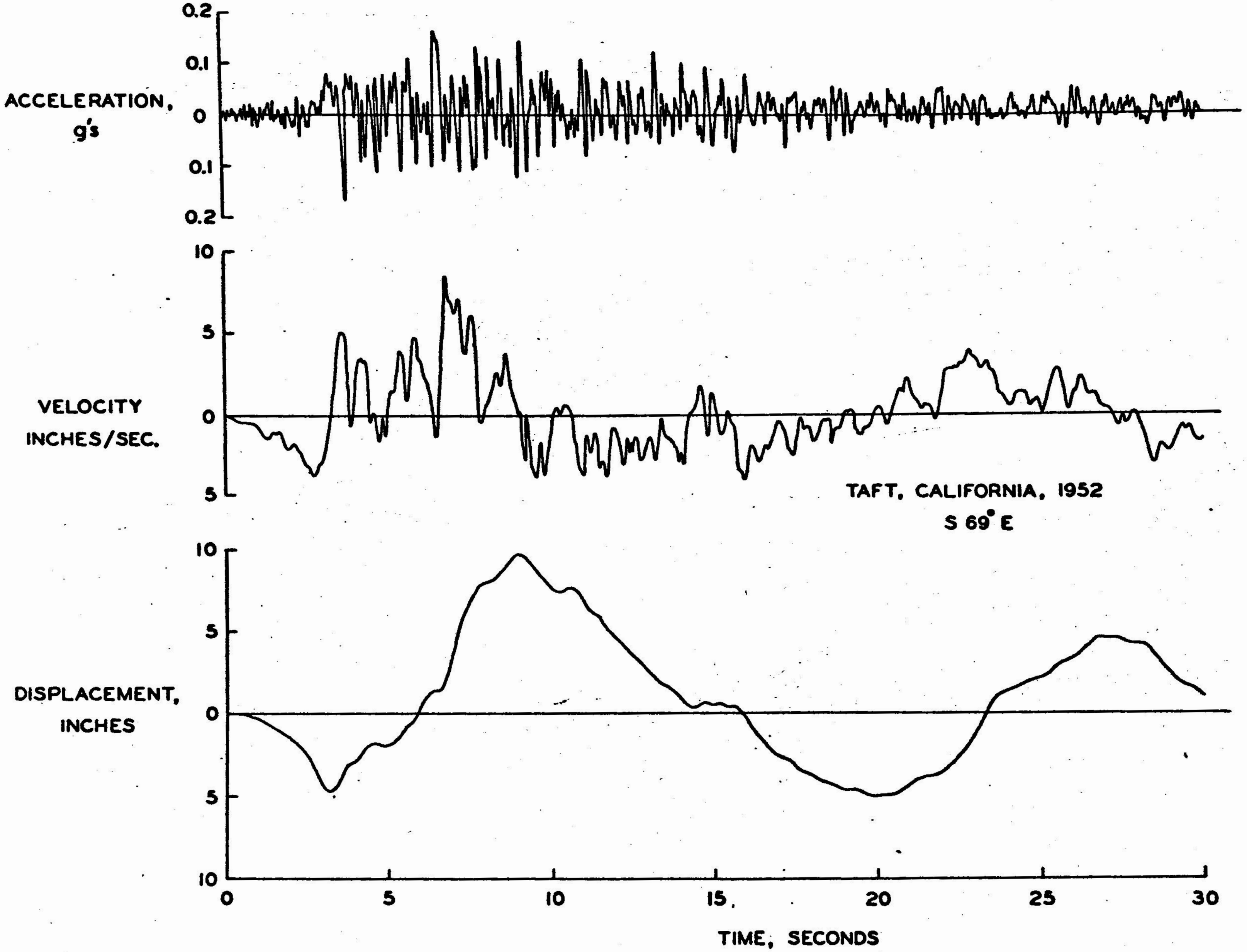


Figure 2. EARTHQUAKE GROUND MOTION

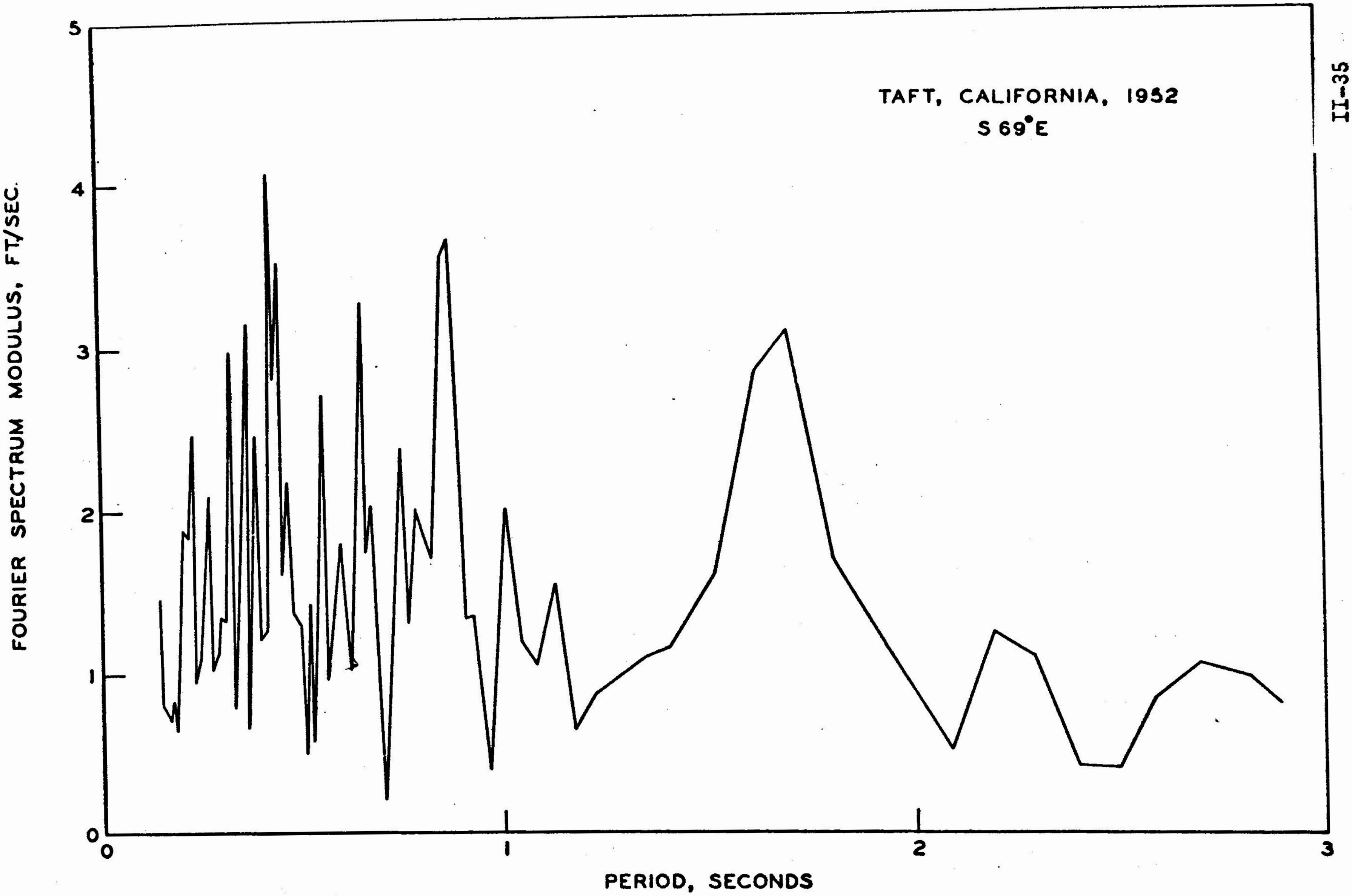


Figure 3. FOURIER SPECTRUM OF EARTHQUAKE GROUND ACCELERATION

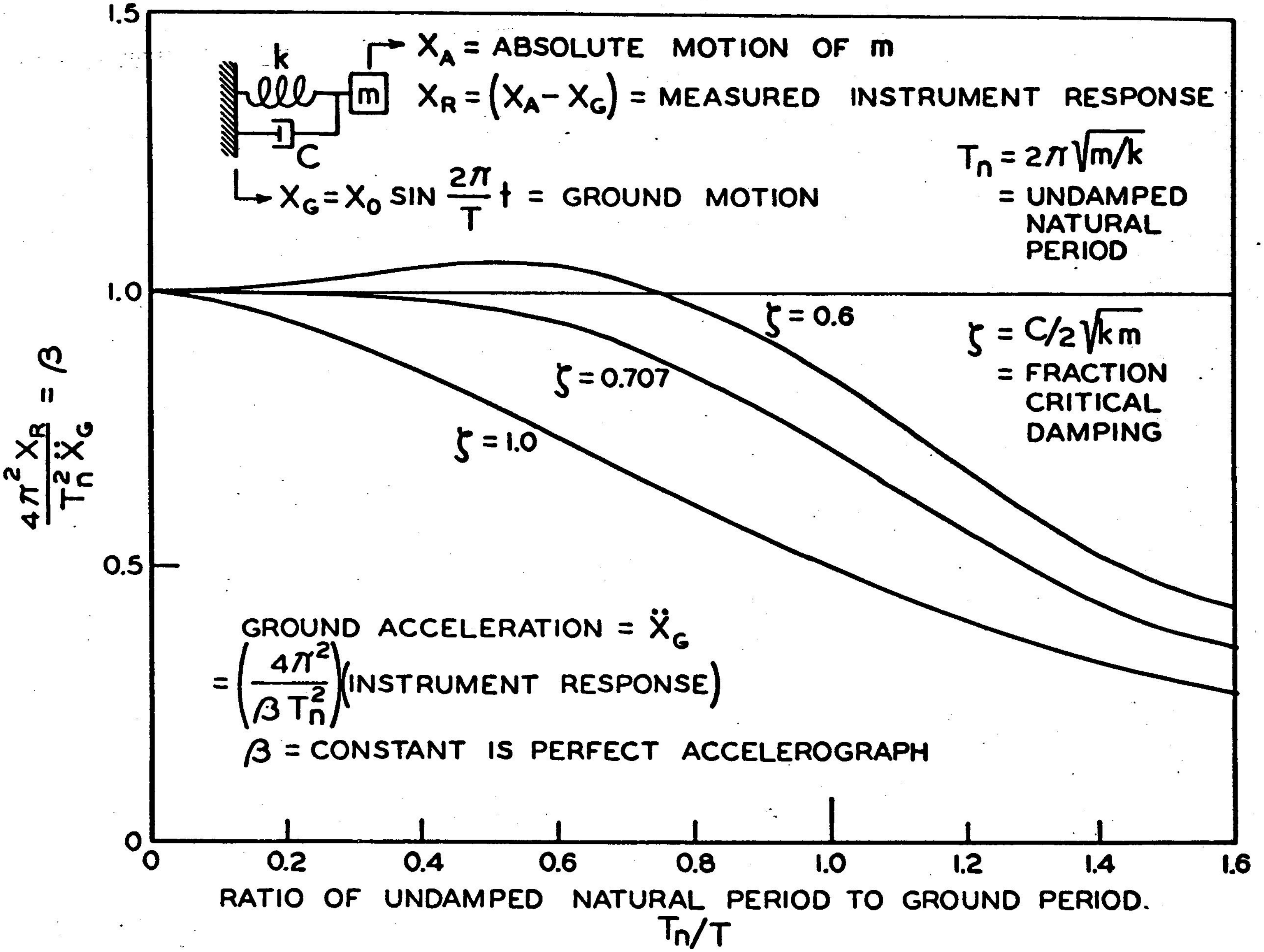
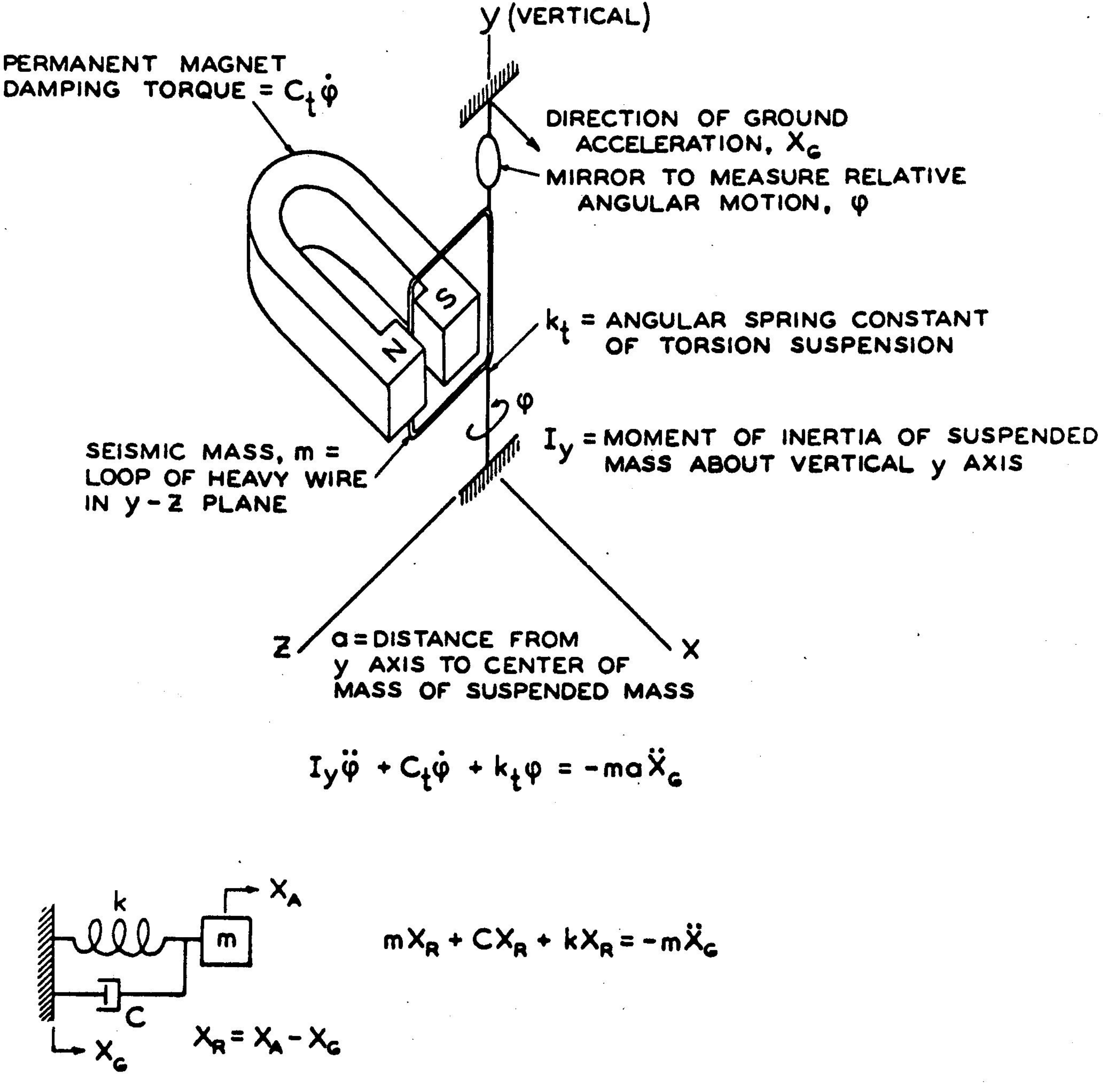


Figure 4. ACCELEROGRAPH RESPONSE CURVES



$$I_y\ddot{\varphi} + C_t\dot{\varphi} + k_t\varphi = -ma\ddot{X}_G$$

$$mX_R + CX_R + kX_R = -m\ddot{X}_G$$

Figure 5. BASIC SEISMIC TRANSDUCER OF STANDARD USCGS STRONG MOTION ACCELEROGRAPH

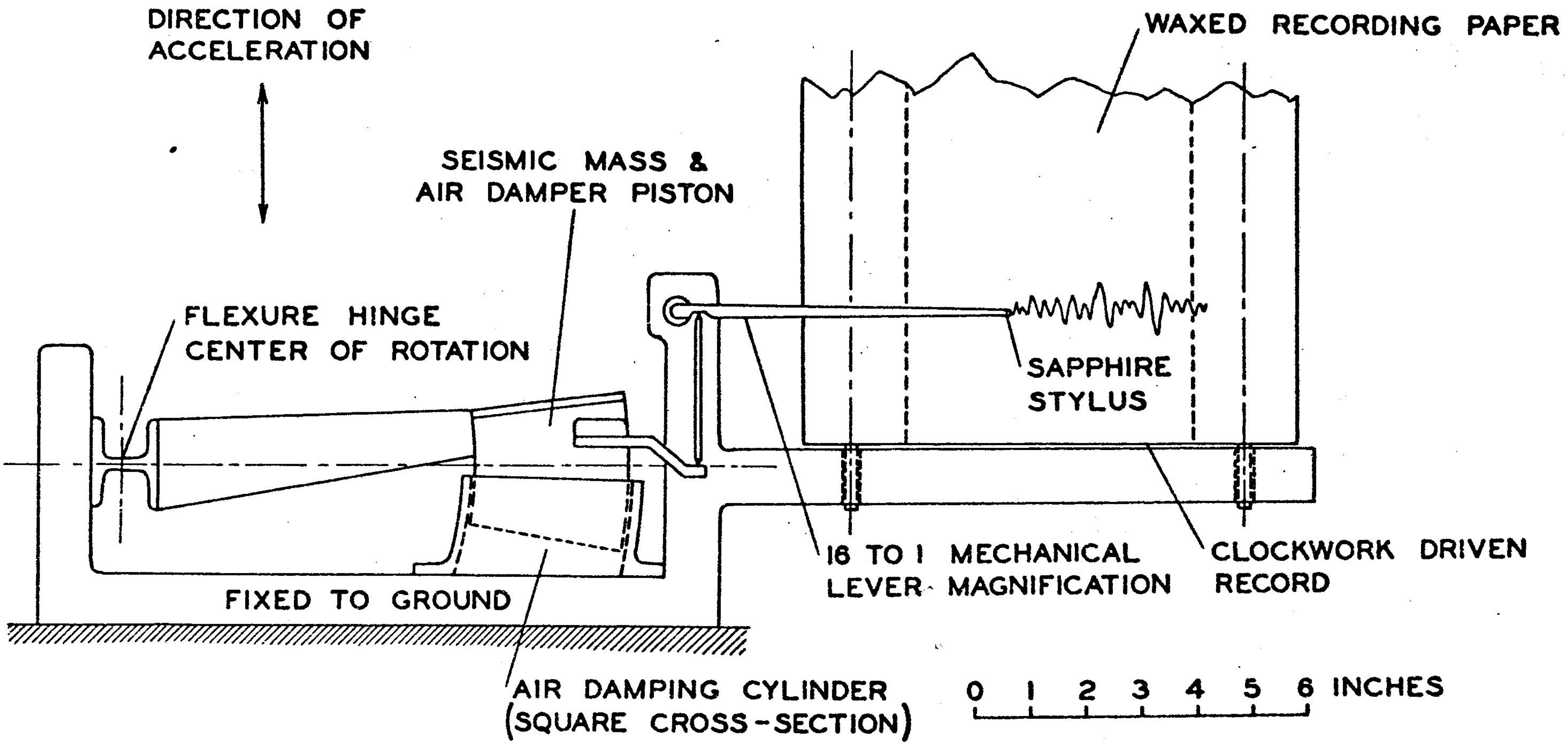


Figure 6. HORIZONTAL TRANSDUCER ELEMENT OF JAPANESE SMAC STRONG MOTION ACCELEROGRAPH

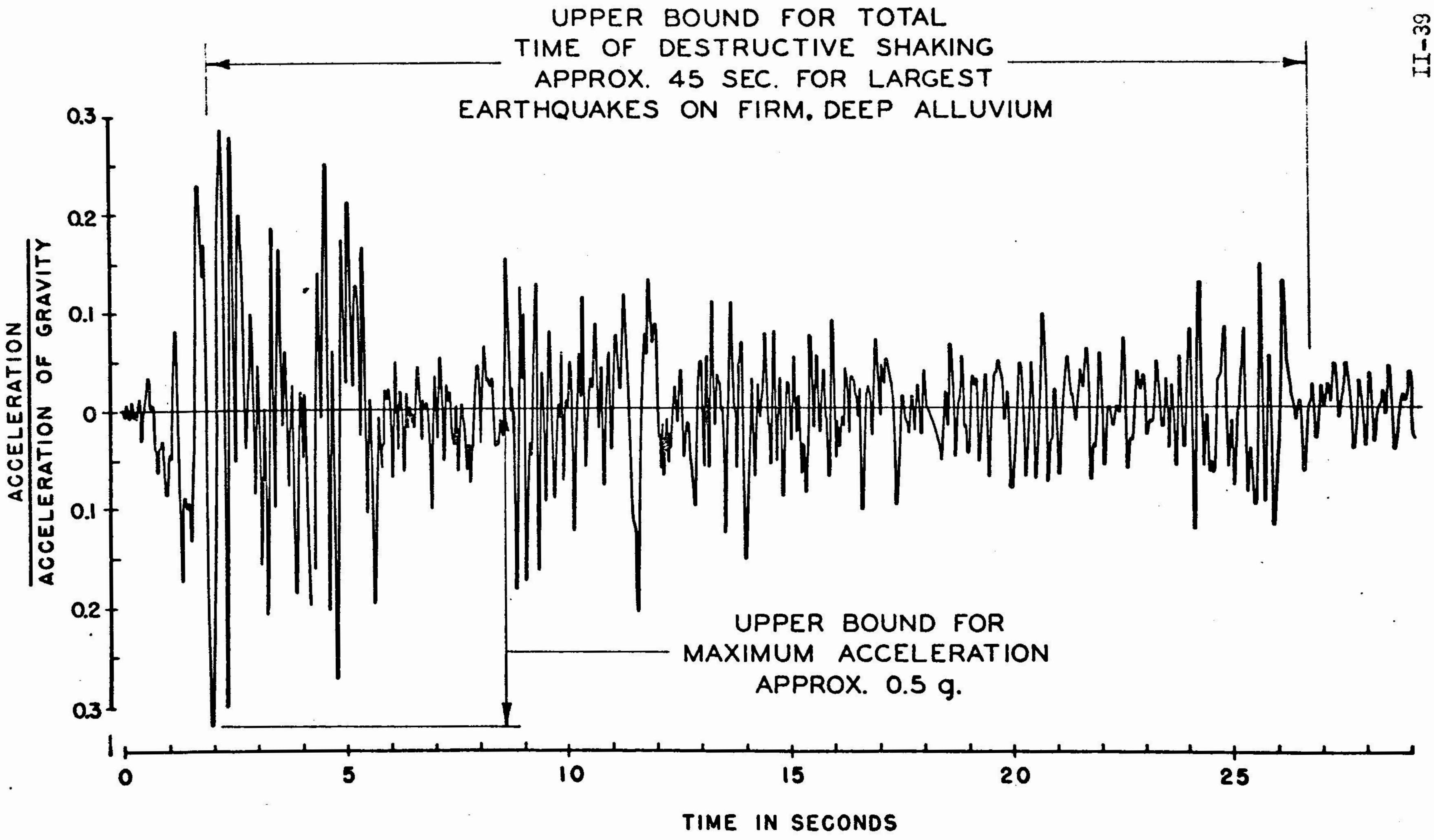


Figure 7. HORIZONTAL GROUND ACCELERATION-TIME RECORD FOR EL CENTRO EARTHQUAKE OF MAY 18, 1940, N-S COMPONENT

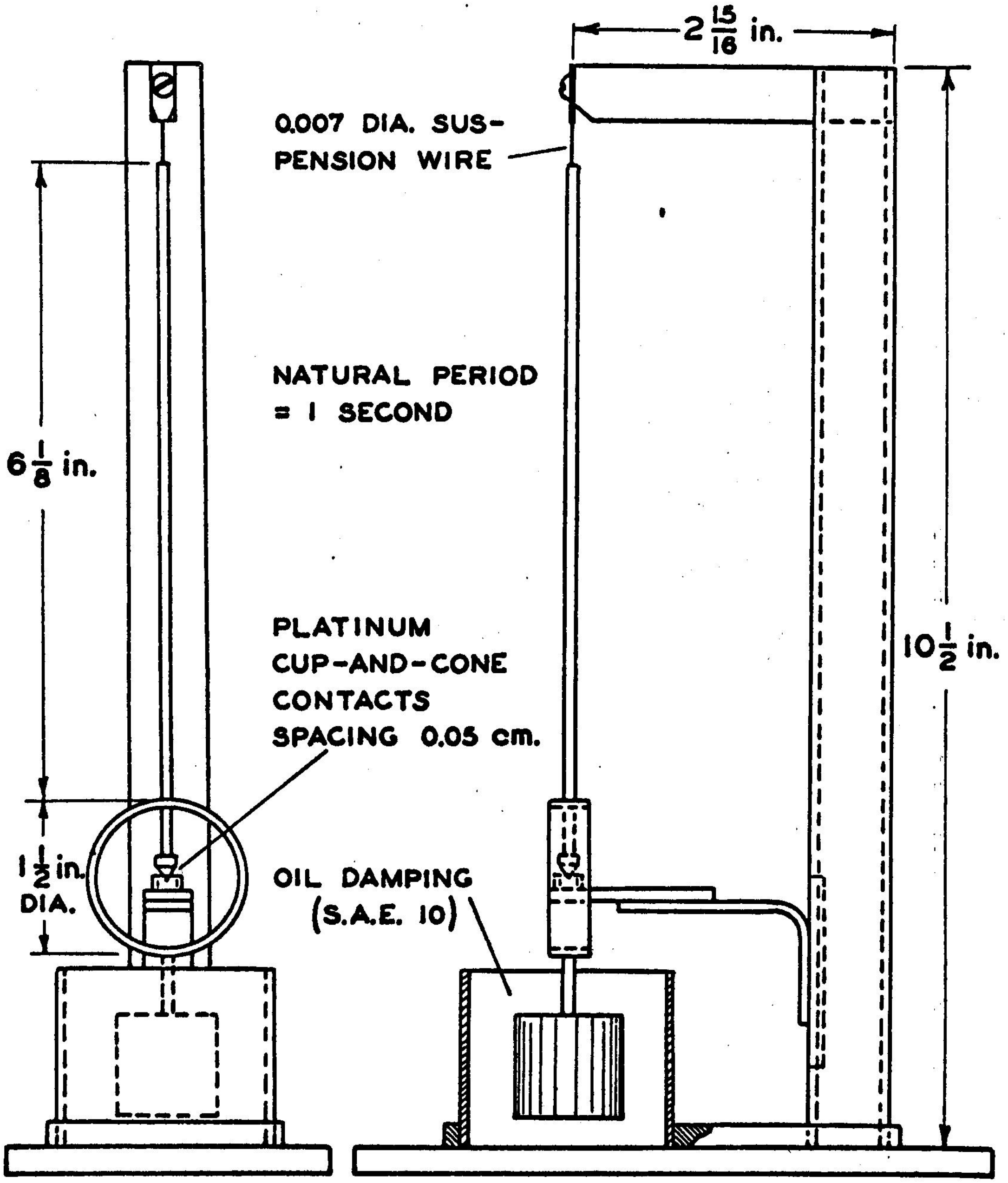


Figure 8. PENDULUM STARTER FOR U. S. COAST AND GEODETIC SURVEY STRONG-MOTION ACCELEROGRAPH

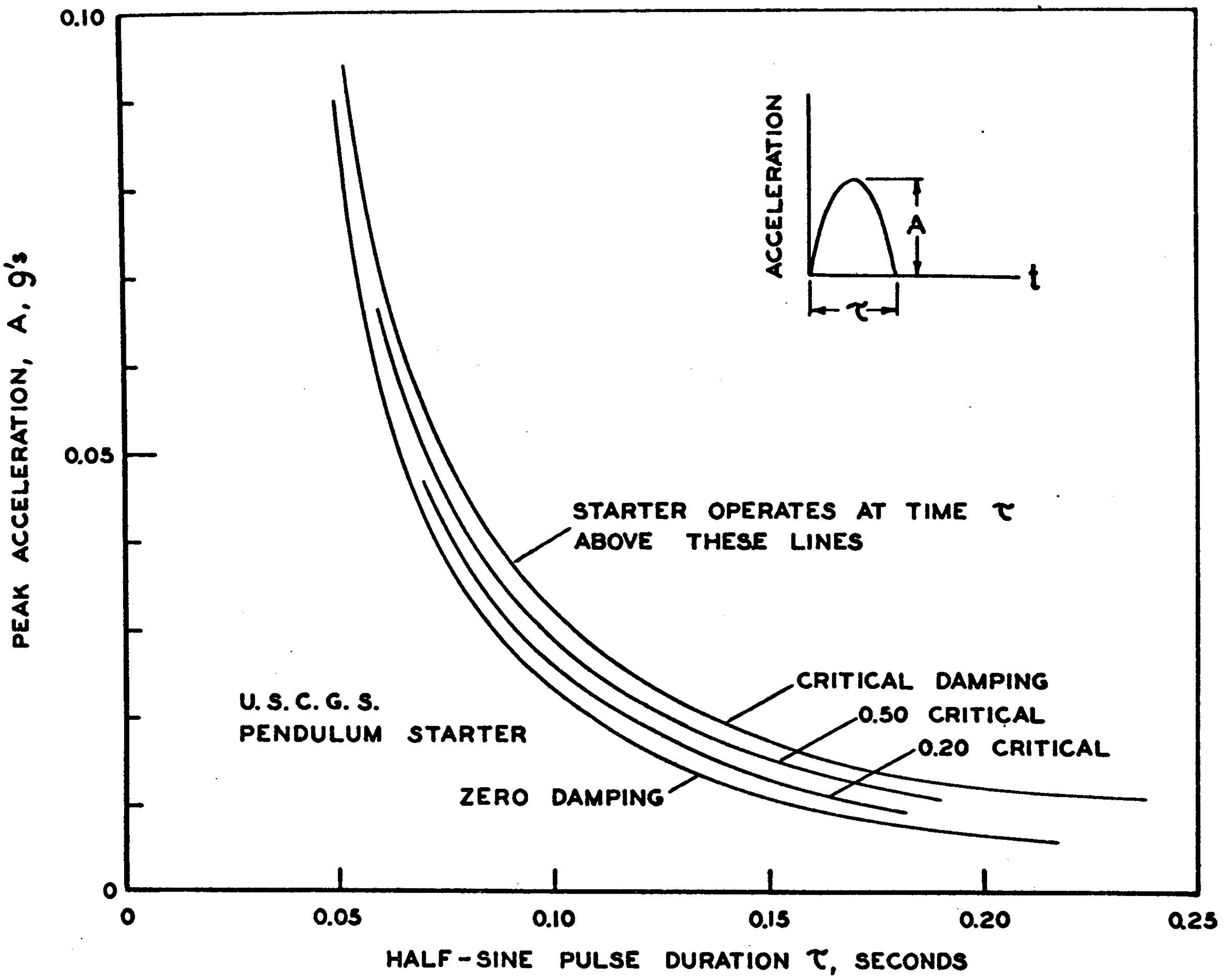


Figure 9. TRANSIENT RESPONSE CURVES FOR THE U.S. COAST AND GEODETIC PENDULUM STARTER

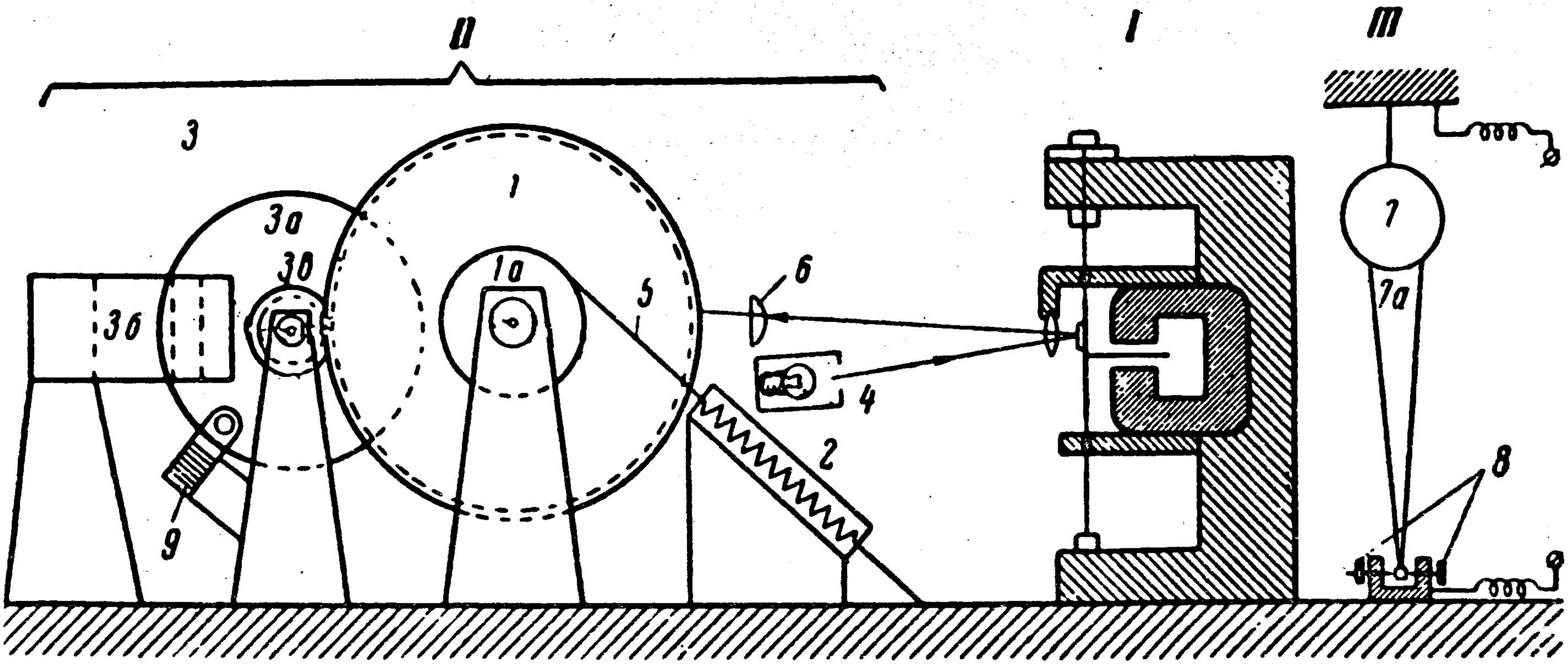


Figure 10. SCHEMATIC DIAGRAM OF USSR ACCELEROGRAPH

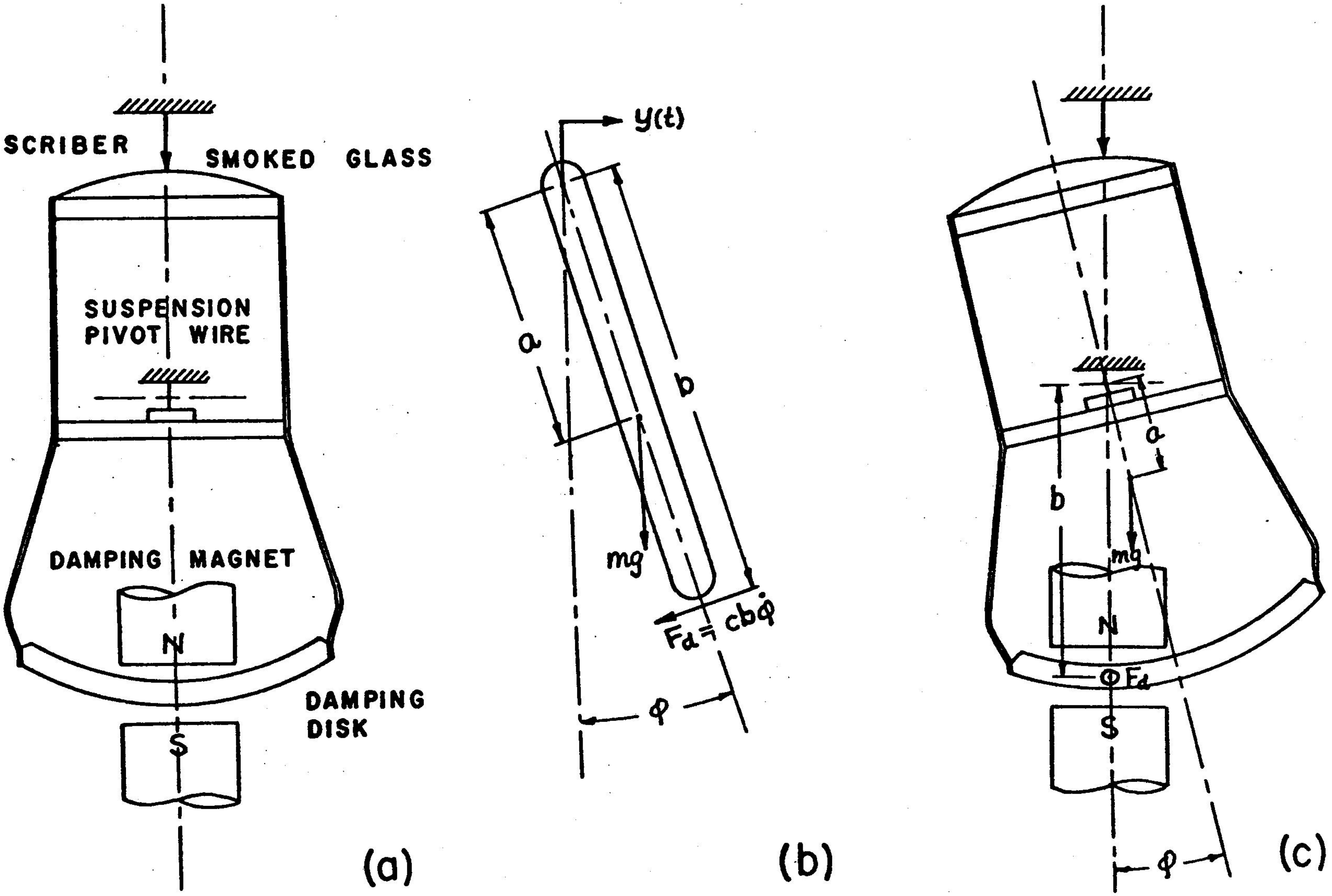


Fig. 11 Schematic Diagram of USCGS Seismoscope

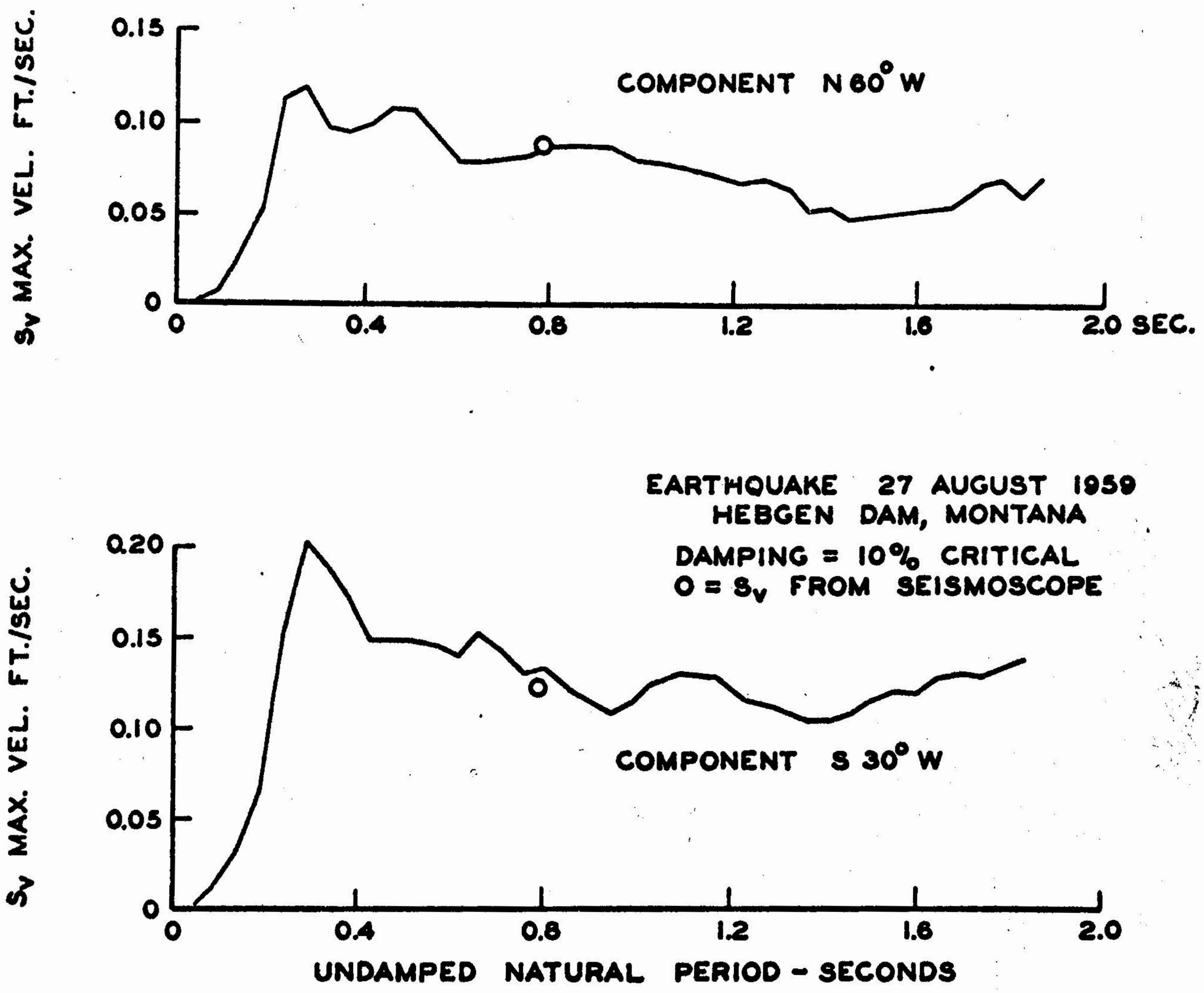


Figure 12.

COMPARISON OF SEISMOSCOPE READING AND RESPONSE SPECTRUM CALCULATION FROM ACCELERATION-TIME RECORD

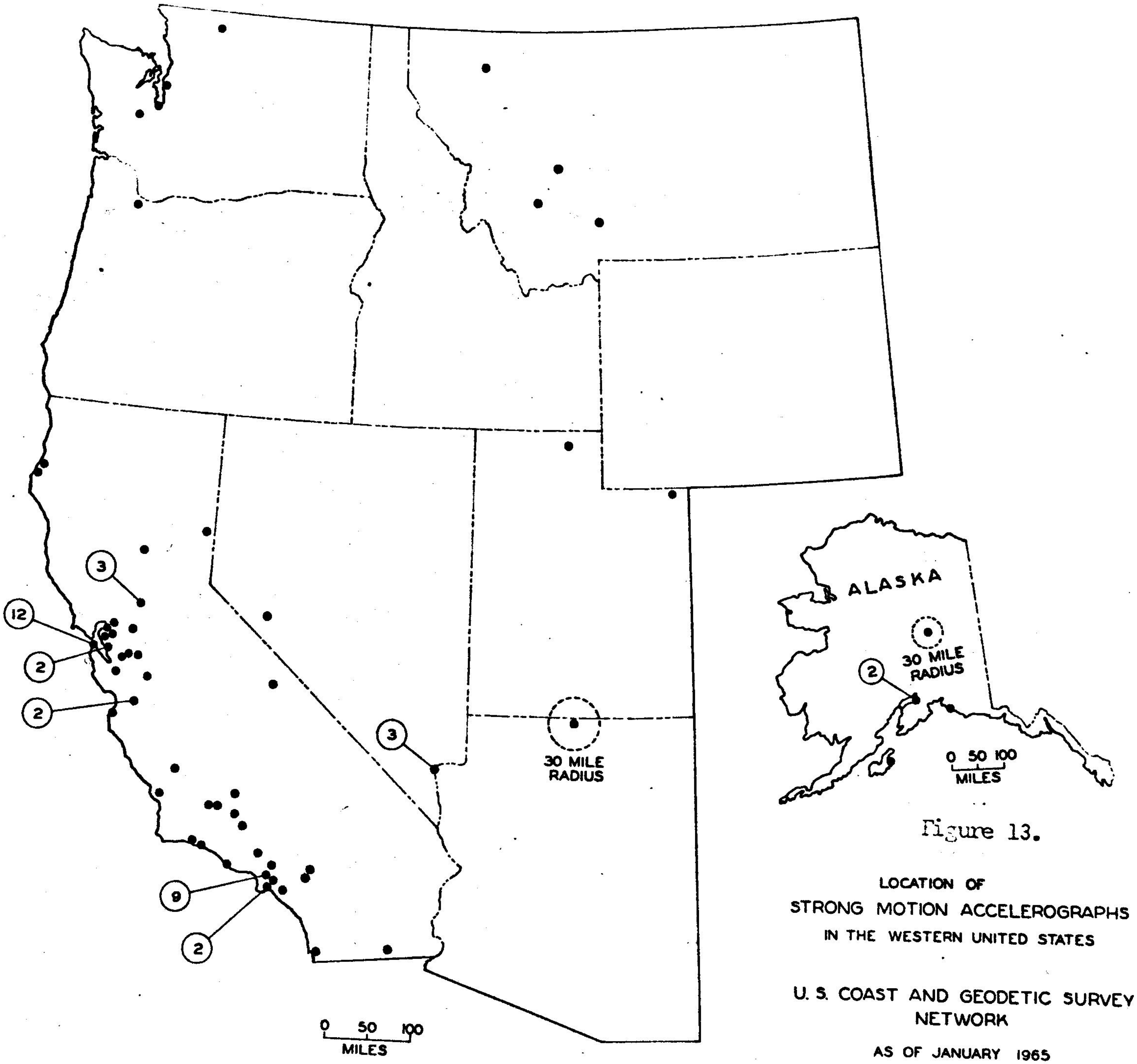


Figure 13.

LOCATION OF
STRONG MOTION ACCELEROGRAPHS
IN THE WESTERN UNITED STATES

U. S. COAST AND GEODETIC SURVEY
NETWORK

AS OF JANUARY 1965

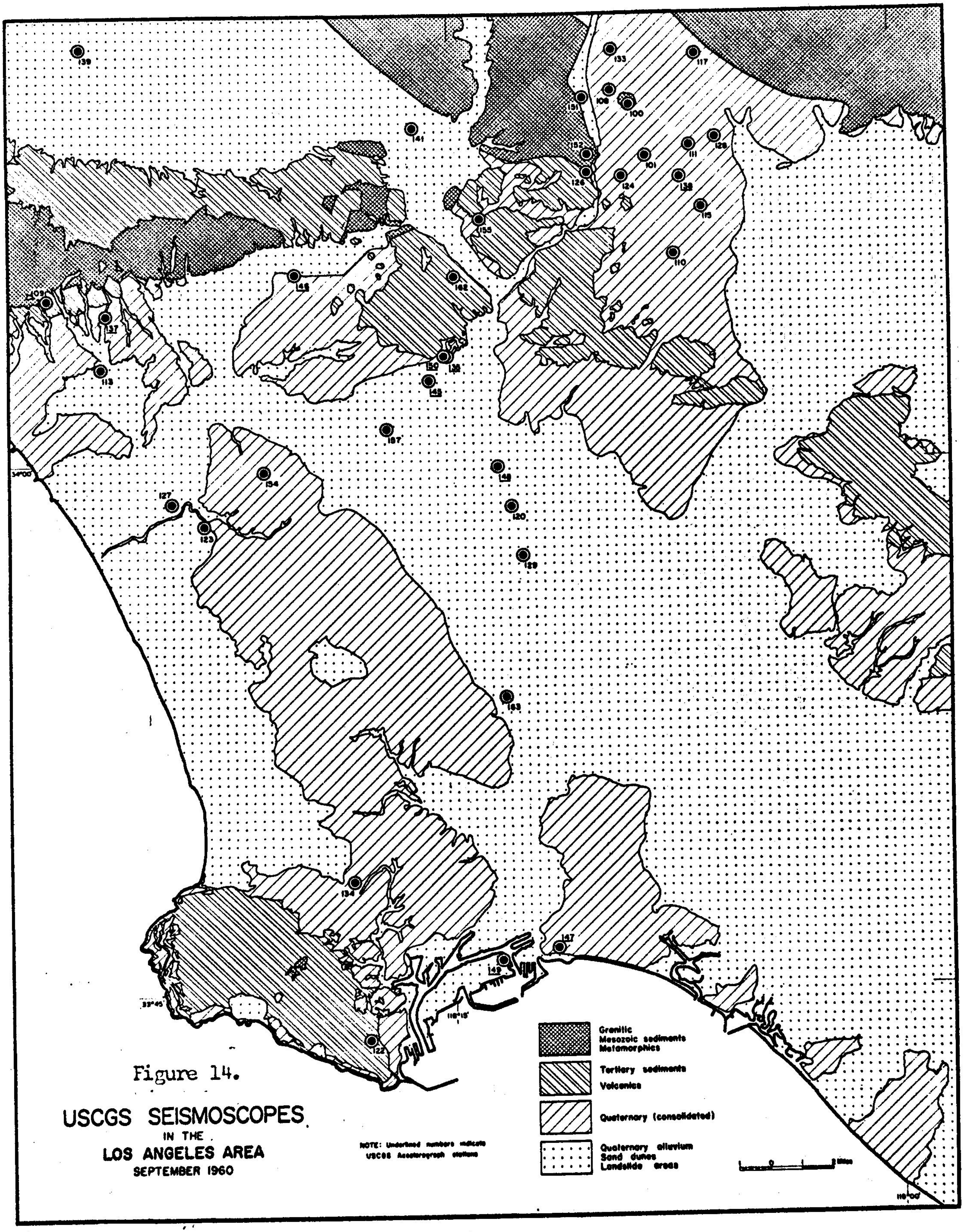


Figure 14.

USCGS SEISMOSCOPES
IN THE
LOS ANGELES AREA
SEPTEMBER 1960

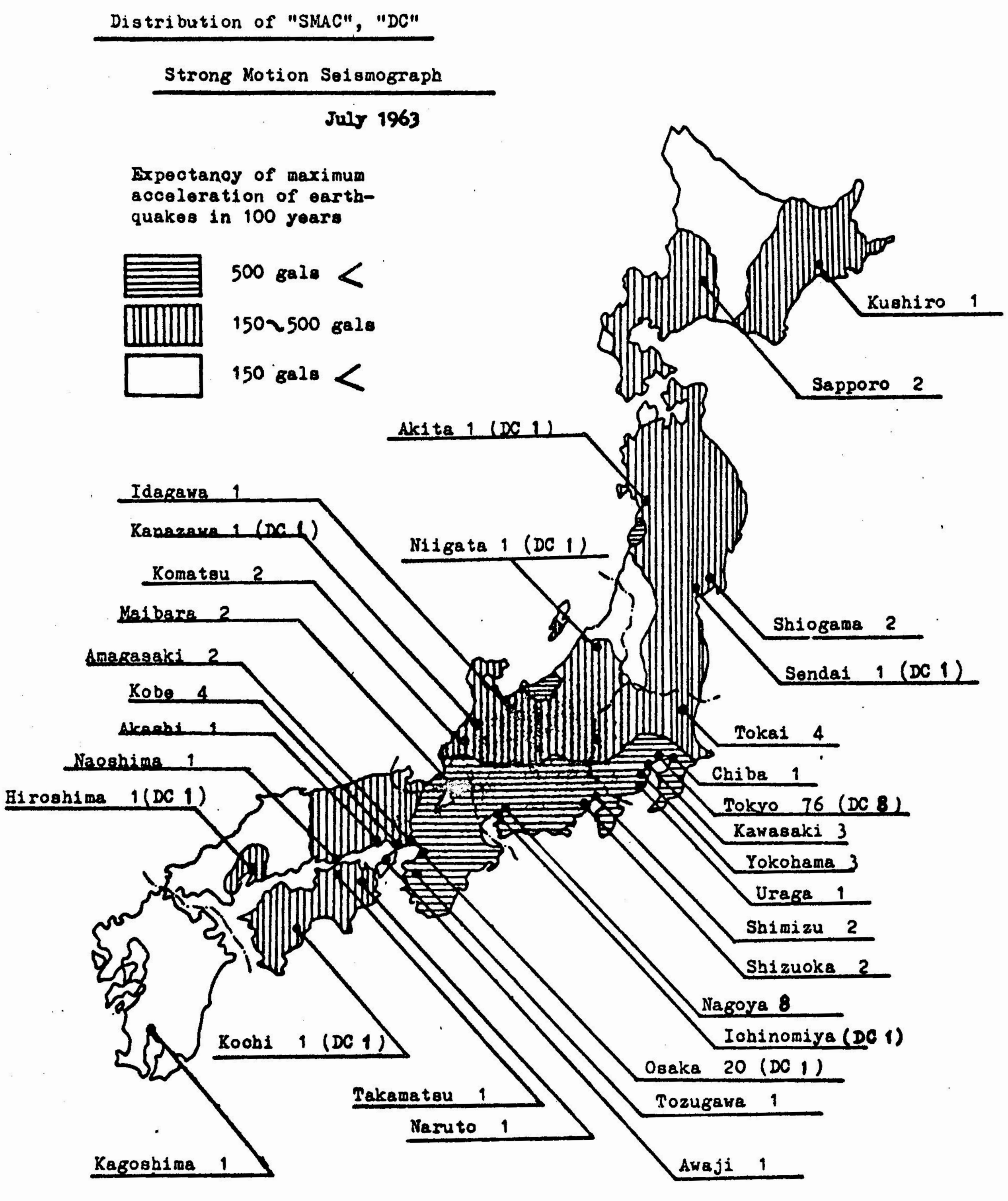


Figure 15. STRONG MOTION ACCELEROGRAPHS IN JAPAN

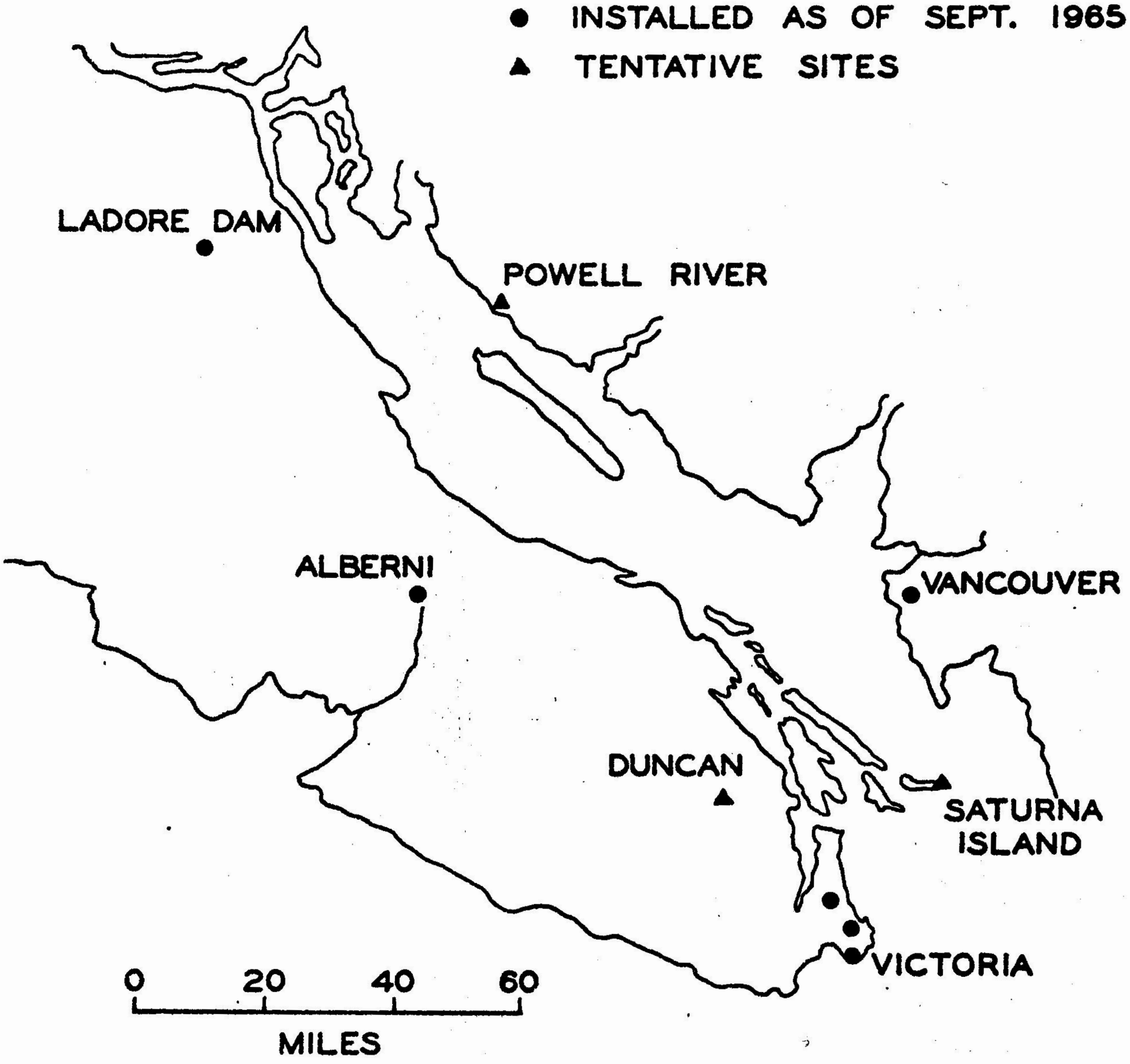


Figure 16. WESTERN CANADIAN STRONG MOTION ACCELEROGRAPHS