THE STRONG-MOTION PROGRAM OF THE COAST AND GEODETIC SURVEY

*by W. K. Cloud and D. S. Carder

Until recent years one of the stumbling blocks to development of earthquake engineering on the most rational basis was lack of reliable information on earthquake motions against which structures should be designed. To obtain this information, strong-motion seismographs were devised and installed in seismically active areas of western United States. The present network of stations is shown in Fig. 1. As the records produced by these instruments are more and more being used as a basis for further research and as indicators of earthquake forces, a knowledge of the instruments and their product should be useful to engineers in evaluating results.

Generally speaking, the strong-motion program in the United States began at the 1929 World Engineering Congress in Tokyo. During the Congress American Engineers were afforded an opportunity to study work of the Japanese Earthquake Research Institute and of other organizations in applying earthquake knowledge to design of structures. As a result many returned home convinced that the United States should focus more attention on the engineering aspects of seismology, in particular on the development of suitable instruments for recording earthquake motions responsible for damage. Through speeches, writings, and personal contacts of engineers such as John R. Freeman, Federal aid was enlisted, and in 1931 Congress allocated additional funds to the Coast and Geodetic Survey for the work.

From the beginning, the program was a highly cooperative venture. In writing of meetings held at the time to determine criteria for instruments, N. H. Heck[1] stated, "The chief purpose of the work is for the benefit of architects and engineers. It has been felt that they should say what they want and the general consensus of opinion that has been obtained from them is that recording should start at the point where slight damage begins and such records should have sufficient amplitude for interpretation. The upper limit should be the recording of acceleration for as wide a range as the design of the instrument permits and the upper limit should exceed 2/10 of the acceleration of gravity. The information desired includes the acceleration, the period, and the amplitude of ground motion."

Guided by these criteria, employees of the Survey assisted by those of other Government agencies and of universities, developed the several types of strong-motion seismographs which, with relatively minor changes, are in use today. Pictures of these instruments in their present state of development are shown in Fig. 2 together with the names of persons who designed the prototypes.

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*Coast and Geodetic Survey
Old Mint Building, San Francisco 3, California
Department of Commerce Building, Washington 25, D.C.

(1) Chief, Division of Geomagnetism and Seismology, Coast and Geodetic Survey, 1920-1942.

EARTHQUAKE GROUND MOTIONS

Though differing in mechanical detail and thus in appearance, the seismographs are fundamentally alike. Each contains one or more pendulums, a starting device, a timing device, a recorder, and control relays. Of these component parts only the pendulums need be considered for an understanding of the results. The other devices merely insure that the differential motion between pendulum and earth is plotted instant by instant against time to form a permanent record.

If it were possible to view ground motion during an earthquake from a fixed point in space, a facsimile of displacement could be recorded and velocity and acceleration derived by methods of differentiation. Pendulums approximate such a vantage point, and in some ways improve the view. Ground motion is seen as from a movable point whose motion can be predicted and adjusted within certain limits. A theoretically perfect pendulum is one which is free to oscillate without friction about an axis fixed relative to the earth, and which is subjected to a restoring torque precisely proportional to the pendulum displacement at any instant and a damping torque precisely proportional to the pendulum velocity, both displacement and velocity being relative to the earth. Actual physical pendulums, to be of value as a means of recording earth motion, must closely approach the performance of theoretically perfect pendulums.

Though basically alike, pendulums may differ greatly in some of their characteristics. By properly choosing these characteristics, pendulums can be designed to record either the accelerations or the displacements of ground motion occurring at periods within selected limits. The limits selected for Survey instruments have been from about 0.1 sec. to 5 sec.--a range within which the natural period of most buildings fall.

To determine the response characteristics of pendulums used by the Coast and Geodetic Survey, a number of shaking-table tests have been made. The results, presented in the following paragraphs, will afford engineers a sound basis for judging the reliability of some of the instruments. Before proceeding, however, it is of interest to point out certain facts relative to shaking-table tests. In such tests, pendulum supports are subjected to known vibratory displacements. In sustained simple harmonic motion, elementary mathematical treatment will indicate how faithfully a pendulum records either acceleration or displacement. In random or irregular motion, records from a pendulum designed to record acceleration must be subjected to a detailed analysis to determine whether they show the actual accelerations corresponding to the known displacements. The accuracy of a pendulum designed for recording displacement is easily determined by comparing pendulum records with table motion.

Fig. 3 illustrates the response of a short-period Survey torsion-type pendulum, such as pictured in Fig. 2, to sustained simple harmonic motion. The theoretical magnification curve shows how a perfect pendulum with a damping ratio of 10 to 1 would record forcing motion having unit amplitude. The curve is derived from the fundamental equation of motion of a damped pendulum when subjected to an external acceleration, which for sustained

harmonic motion can be written in the form:

$$M_h = \frac{V}{\sqrt{\left[\left(\frac{T_e}{T_o}\right)^2 + 1\right]^2 + 4\left(\frac{T_e}{T_o}\right)^2\left(h^2 - 1\right)}}$$

where M_h = Harmonic magnification
V = Static magnification
T_e = Shaking-table period
T_o = Pendulum period
h = Damping factor
$\mathcal{E}$ = Damping ratio $= \dfrac{\text{Log}_{10}\,\mathcal{E}}{\sqrt{1.861 + \left(\text{Log}_{10}\,\mathcal{E}\right)^2}}$

The static magnification, also known as the lever or geometric magnification, is the ratio of the displacement of the recording point to that of the center of oscillation of the pendulum. The acceleration function shows how the amplitudes recorded by a pendulum must vary with variations in the forcing period, if the pendulum is to measure acceleration. Here the amplitude as recorded when the forcing period equals the pendulum period, is arbitrarily taken as unity. The points are derived from the equation for simple harmonic motion

$$a = \frac{4\pi^2 A}{T_e^2} \quad \text{in the form} \quad a \propto \frac{1}{\left(\frac{T_e}{T_o}\right)^2} A$$

where a = Shaking-table acceleration
A = Shaking-table displacement - (considered unity)
T_e = Shaking-table period
T_o = Pendulum period

The actual response of the pendulum under test closely approximates both the theoretical magnification curve and the acceleration function for all forcing periods longer than the pendulum period. Thus, it meets the requirements of an accelerometer and has been so named. The fact that it fails to meet requirements of a displacement meter for forcing periods shorter than 0.3 of its natural period, is immaterial to its use, but as a matter of interest, the large anomalous response here is caused by bowstring-type vibration of the single wire suspension system. Additional tests shown by the smaller dots were made after silicone jelly had been packed around the suspension wire in the hope of reducing the bowstring vibration. It is apparent that the effect was negligible. Some of the differences between the experimental curve and the theoretical curve may also be due to imperfections in the damping system, or to errors in evaluating the static magnification.

These test results demonstrate that the pendulum actually does record accelerations in sustained simple harmonic motion. In another series of tests a similar pendulum was subjected to irregular motions on a shaking table, and the actual motions of the table were accurately recorded.

The records made by the pendulum were then subjected to a double integration process which would give the original table motion within the accuracy of the processing, provided the pendulum had recorded actual accelerations. Fig. 4 shows the results of one such test. The middle curve (D) is a record of the actual table motion, the upper one (B) is the record made by the pendulum, and the lower one (E) is the integration result.

Though there are obvious differences between the recorded and the computed table motions, their similarity is still sufficient to show that the pendulum recorded very nearly the true accelerations of the motion. It can be shown that any significant departures from true acceleration in the pendulum record will usually result in larger departures from true displacement in the computed curves than those in Fig. 4. In Fig. 5, for example, the lower curve illustrates spurious displacement resulting from double integration of an accelerograph record when the acceleration axis shifts by small amounts.

A record from still another kind of shaking-table test is shown in Fig. 6. Here a pendulum with a much longer period (36 times as long as the one in the first test) was subjected to irregular motions, and again both the motion of the table and the response of the pendulum were accurately recorded. The upper curve in Fig. 6 is the response of the pendulum, while the lower one is the exact table motion. This test demonstrates the fact that a pendulum will serve as a reasonably accurate displacement meter for ground motions with periods considerably shorter than that of the pendulum.

From the foregoing it will be apparent that the period of a displacement meter pendulum needs to be long, while that of an accelerometer pendulum must be very short.

Referring again to the network of strong-motion seismographs shown in Fig. 1, 12 of the accelerographs are located in the basements and on the top floors of 6 buildings, and 3 are on different floors of the same building. Instruments indicated on the map include 11 which are considered substandard, 3 of which are on different floors of one building and 2 in the basement and on the top floor of another.

The map shows that there are wide gaps which have no instrumental coverage. This lack of coverage is a serious deficiency which still exists in the strong-motion program, and which it has not been possible to correct because of lack of funds. With only a limited number of seismographs available it has been necessary to try outguessing the earthquakes and to put the instruments where it was hoped they would give the most valuable information. This approach has met with fair success, as a considerable number of strong-motion records have been obtained, all of which are available for further research. However, twice within the past 4 years the Survey has been greatly chagrined by having the largest earthquakes since the program was started occur in localities where there was insufficient instrumental coverage. These were the Kern County, California, shocks of July 1952, and the western Nevada shocks of December 1954. For the Nevada shocks the nearest strong-motion station was sixty miles from the epicenter, well outside of the area of potential damage. For the Kern County shocks the nearest station, 25 miles from the epicenter, yielded a valuable record, but in an area of Modified Mercalli Scale intensity VII instead of in the area of maximum intensity IX or higher. Fig. 7, 8, and 9 illustrate the kind of records written by three types of pendulums during the earthquake.

A definite program is now underway to make significant improvements in instrumental design and to increase the coverage of potential earthquake areas with more instruments. This program will include:

(1) Design and distribution of simple oscillators with the damping and period characteristics of many common structures.

(2) Redesigned strong-motion seismographs for (a) single recording with a time record and (b) multiple recording with a time record.

(3) Plans for other instruments, not necessarily seismographs, that may furnish additional information or the same information in more usable form to earthquake engineering.

The simple oscillators are intended to leave records of maximum responses to earthquake motion, and thus measure intensity in a form physically related to structural dynamics. They will supplement, not replace, strong-motion seismographs.

The redesign of strong-motion seismographs is intended to accomplish several things. Many of the Survey's so-called accelerographs now in use are being remodeled to incorporate displacement meters. This is possible at reasonable cost. New instruments, however, cost $6000 to $8000 to build when let out on contract in small lots. It is believed that by simplifying the design an instrument can be constructed for much less than this to give the same information without sacrifice of precision, but perhaps of elegance. By additional sacrifice of the vertical component and re-cycling system it is believed that single-operation strong-motion seismographs may be mass-produced for even less. The latter instruments are intended for use at different levels in structures, and to replace substandard instruments now in use.

Other plans under consideration for future work include recording on magnetic tape, development of longer-period strong-motion seismographs, and utilizing a technique now being employed with success to forecast rock bursts in deep mines. Rock burst forecasting is based on a premise that rock is under excessive strain preceding rupture, and in this strained condition produces diagnostic sounds that can be detected by suitable geophones. The same technique applied to deep wells along active faults may conceivably result in eventual forecasting of earthquakes along these faults.

In summary, a brief history of the strong-motion seismological program in the United States has been given as background; type and accuracy of instruments used has been described to provide engineers with criteria for judging results; and the future program has been outlined as a matter of interest. Earthquake records obtained as a result of the program, except for illustration as to type, have been excluded, as they are normally published in "United States Earthquakes" for general information, and available in original form for further research. The Survey has, or soon will have, instruments capable of giving the kind of information that is needed. To date because of high cost it has not yet been possible to provide a sufficient number to give adequate coverage. However, the Survey is now endeavoring to correct this condition by developing instruments which can be mass-produced at a fraction of the cost of present instruments, but which will still give valuable information. If this can be accomplished it will

enable the strong-motion program to be greatly expanded and to more efficiently serve its purpose of providing the basic data on earthquake motions structures must resist.

The authors in closing wish to express appreciation to the many engineers, architects, and others whose continued interest and support have been largely responsible for such success as the strong-motion program has achieved. Both the authors and the Coast and Geodetic Survey officials invite suggestions for improving the program's value.

BIBLIOGRAPHY

Coast and Geodetic Survey, "Earthquake Investigations in California 1934-1935," Special Publication No. 201.

Coast and Geodetic Survey, "United States Earthquakes," Annual Publication.

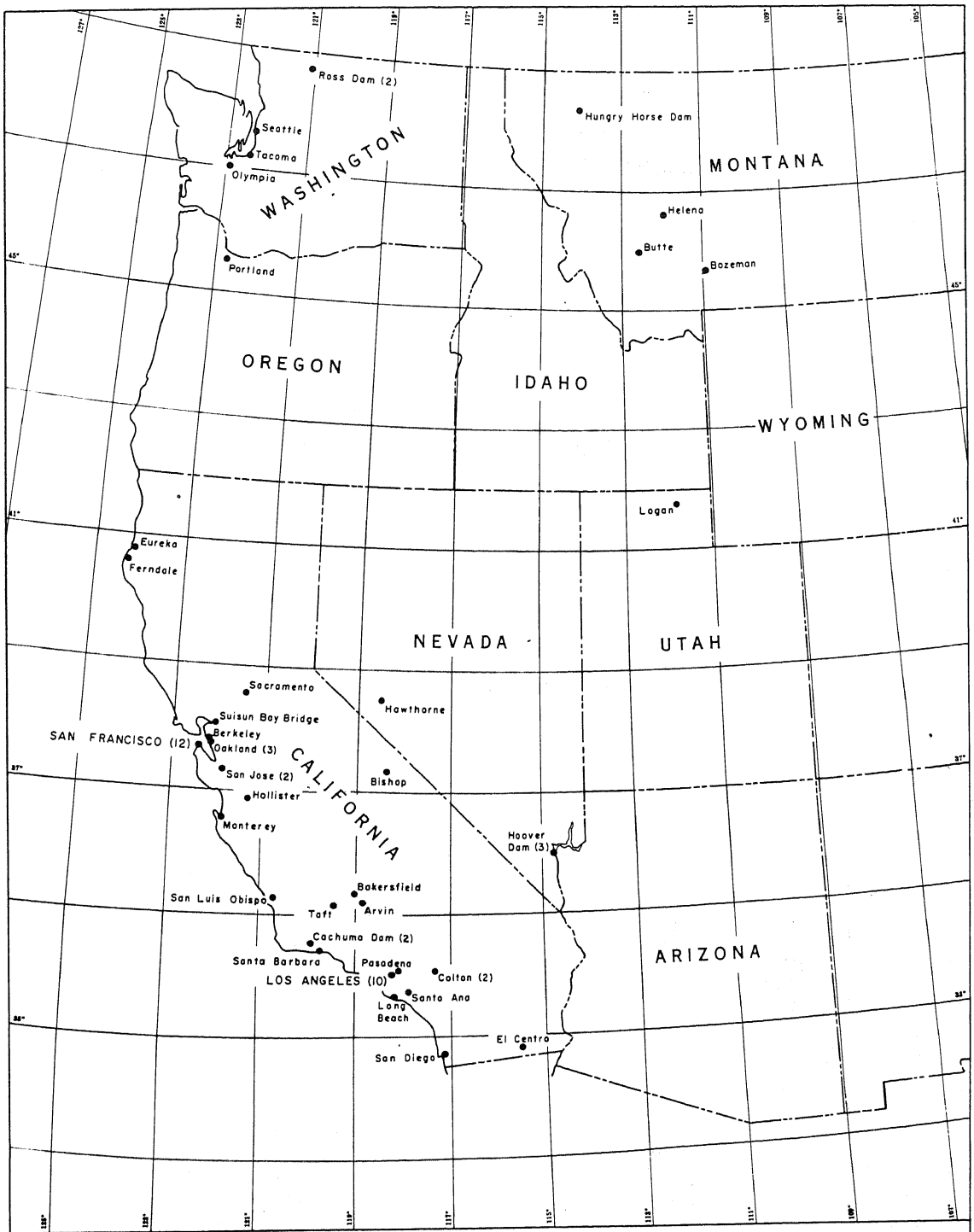
Coast and Geodetic Survey, "Earthquake Investigations in the United States," Publication No. 282.

Coast and Geodetic Survey, "The Determination of True Ground Motion From Seismograph Records," Special Publication No. 250.

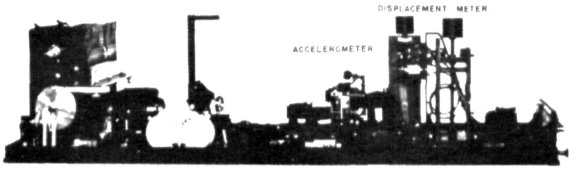
John R. Freeman, "Earthquake Damage and Earthquake Insurance," McGraw-Hill Book Co., Inc.

Coast and Geodetic Survey, "Seismological Activities of the Coast and Geodetic Survey," Yearly report published in the Bulletin of the Seismological Society of America.

Coast and Geodetic Survey, "Quarterly Engineering Seismology Bulletin," Mimeographed report issued on mailing list CGS-5.

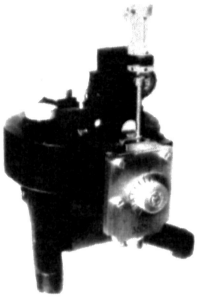


STRONG-MOTION SEISMOGRAPH STATIONS FIGURE 1



COAST & GEODETIC SURVEY STRONG-MOTION SEISMOGRAPH TYPE I

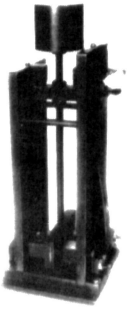
Prototype of components other than pendulums designed by H.E. McComb and Edward C. Robison, Coast & Geodetic Survey



WENNER ACCELEROMETER

Prototype designed by Frank Wenner, Bureau of Standards

PENDULUM PERIOD = 0.035 to 0.1 seconds
STATIC MAGNIFICATION = About 120
SENSITIVITY = 0 to 26mm per 0.1 gravity

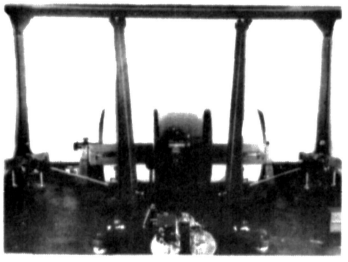


CARDER DISPLACEMENT METER

Prototype designed by D.S. Carder, Coast & Geodetic Survey

PENDULUM PERIOD = 2.5 to 6 seconds
STATIC MAGNIFICATION = About unity

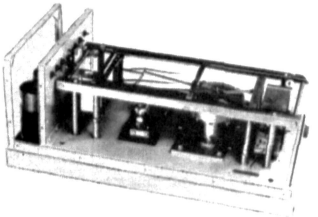
FIGURE 2



COAST & GEODETIC SURVEY
STRONG-MOTION SEISMOGRAPH TYPE 2

Prototype designed by
H.E. McComb and Edward C. Robison, Coast & Geodetic Survey

PENDULUM PERIOD = 10 seconds
STATIC MAGNIFICATION = About unity



WEED STRONG-MOTION SEISMOGRAPH

Prototype designed by Arthur J. Weed, University of Virginia

PENDULUM PERIOD = 0.18 seconds
STATIC MAGNIFICATION = About 7
SENSITIVITY = About 6mm per 0.1 gravity

FIGURE 2

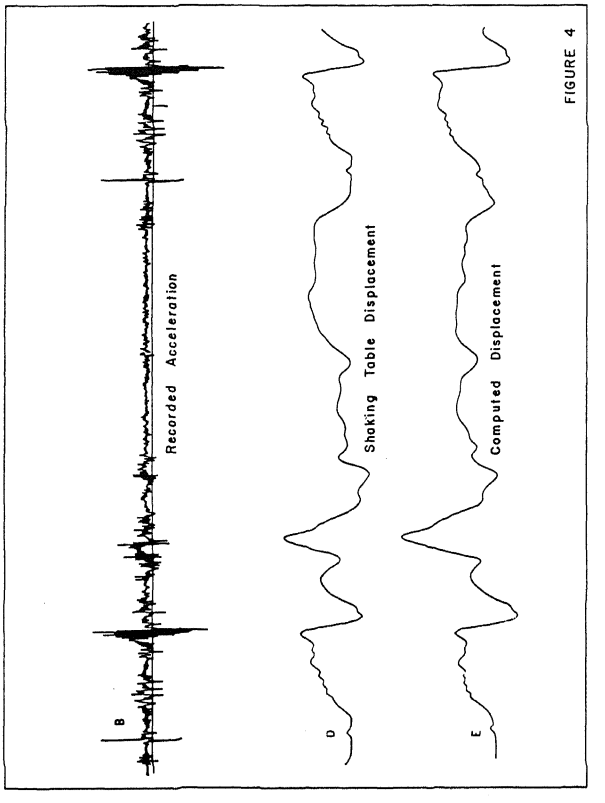


FIGURE 4

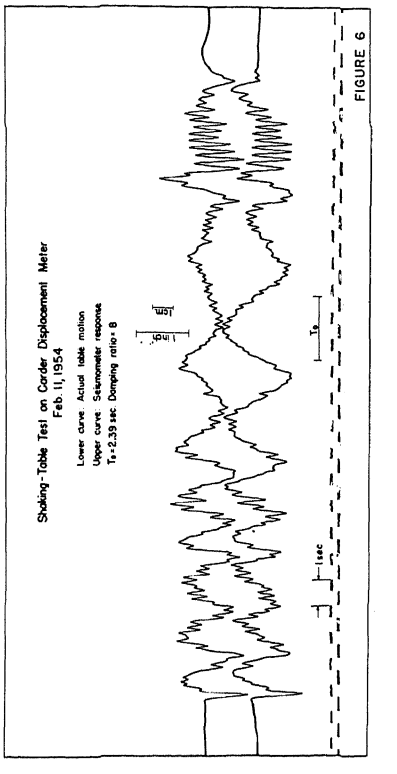


FIGURE 6

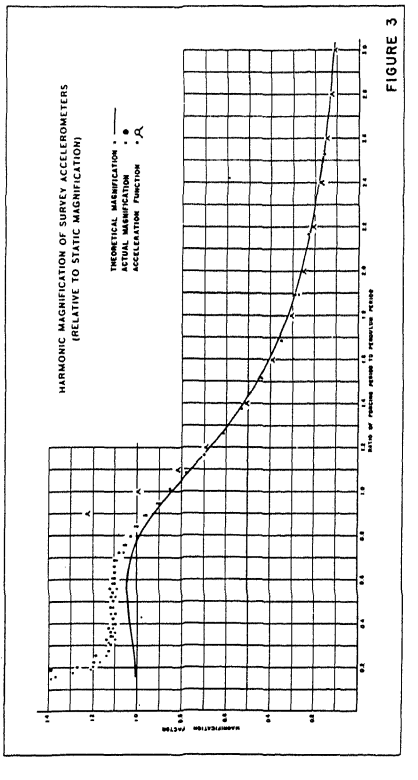


FIGURE 3

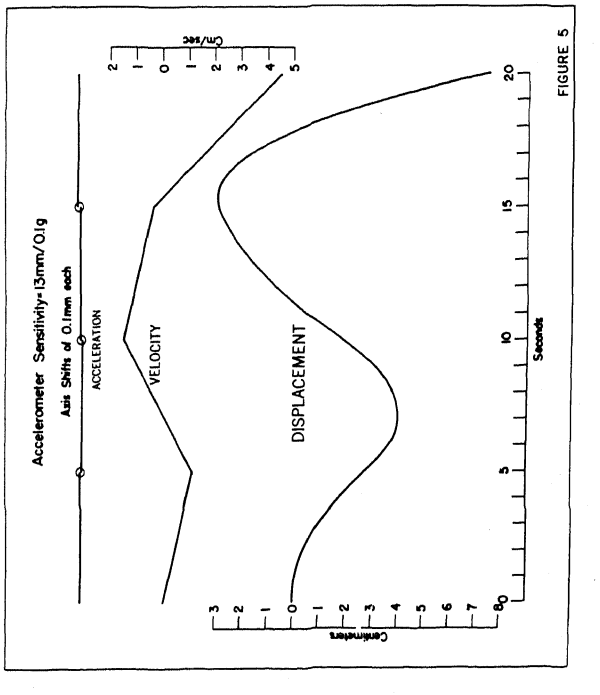


FIGURE 5

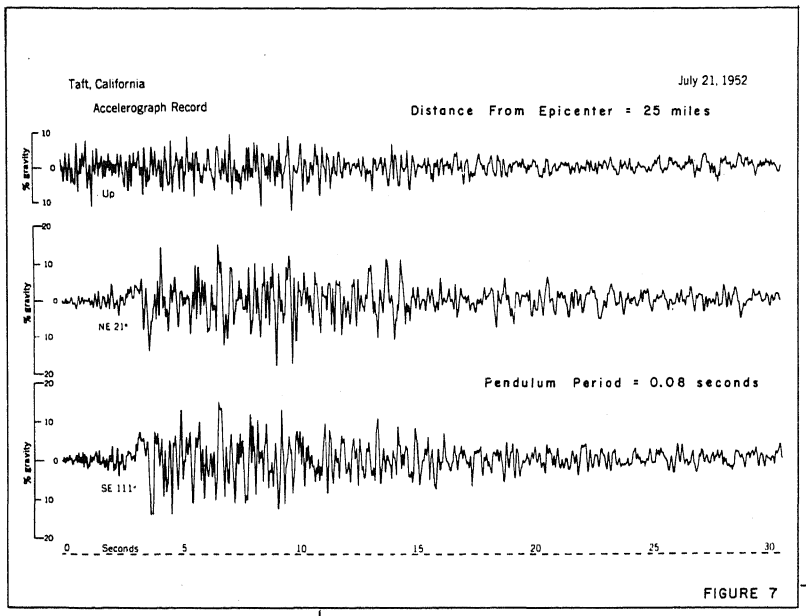


FIGURE 7

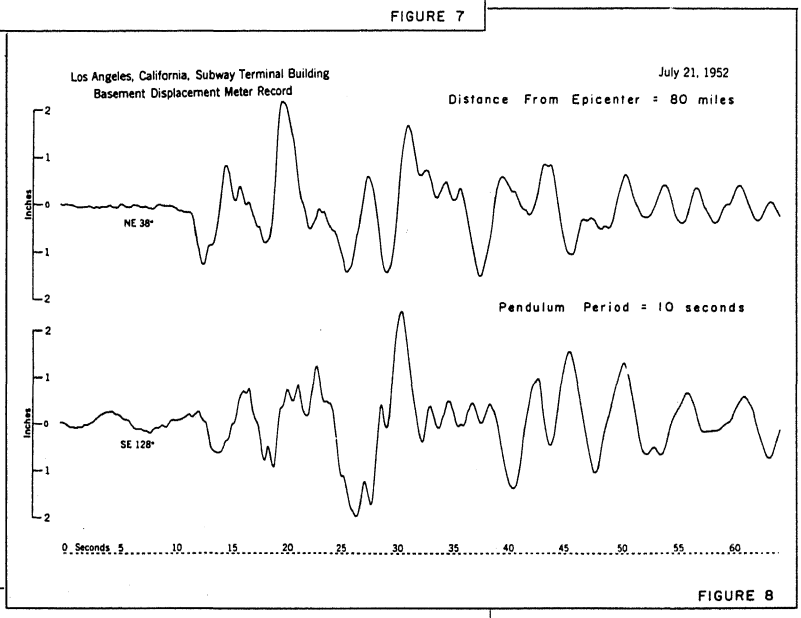


FIGURE 8

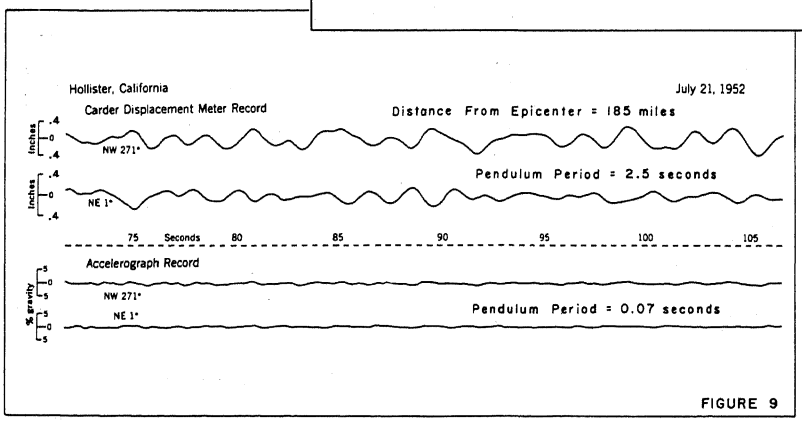


FIGURE 9