THE "SMAC" STRONG MOTION ACCELEROGRAPH AND OTHER LATEST INSTRUMENTS FOR MEASURING EARTHQUAKES AND BUILDING VIBRATIONS

By RYUTARO TAKAHASI[1]

INTRODUCTION

In calculating the resistivity of a structure against earthquakes, the seismic force is usually represented as a static horizontal force. This static force should be such as would give rise to the same deflection as that due to the earthquake. It is therefore equal to the product of the local mass of the structure and the spatial acceleration of that mass. The spatial acceleration is the algebraic sum of the acceleration of the earthquake and the acceleration due to the deflection of the structure; so it depends both on the wave form of the earthquake and on the vibrational characteristics of the structure, such as the period, mode and damping.

The spatial acceleration, as analyzed to each mode, may be obtained directly by means of a response analyzer (1), (2) and (3). It is necessary, first of all, to have accelerograms of strong earthquakes. According to our opinion, the oscillatory properties of strong earthquakes may differ considerably according to the kind of the ground. For the study of earthquake resistant design, therefore, it is necessary to observe and record strong earthquake motions at various localities and on various grounds. Observations and recordings at various heights of a building are desirable also.

For these purposes, it has been planned to cover our country with an observation network in which each primary station is equipped with a SMAC Strong Motion Accelerograph or a DC Strong Motion Accelerograph. The secondary stations are to be provided with a Bellows Acceleroscope, or the like. Ten SMAC accelerographs have already been installed in the locations shown in Table 1.

According to our observations, earthquake vibrations in the ground depths are rather simple; although they become complicated at the surface. This is attributed mainly to the surface layers acting as resonators (4), (5) and (6). This fact has been ascertained by numerous observations of microtremors and earthquakes made by Kanai with his Microtremor Recorder. The resonant effect of the surface layers is to be expected also in the case of great earthquakes. In this respect, studies of microtremors cannot be neglected.

Microtremor recorders have also been applied to the shaking tests of buildings. For this purpose, however, a Direct-Reading instrument recently developed by Kawasumi is probably most convenient.

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In this paper, the author wishes to introduce these new instruments cited above, and explain briefly their construction, performance and applications.

THE "SMAC" STRONG MOTION ACCELEROGRAPH

This instrument was designed and constructed by the "Strong Motion Acceleration Committee" which was established in 1951 for the purpose of promoting research on the seismic horizontal force to be used in building design. SMAC stands for the name of this Committee (7) and (8).

The accelerograph consists essentially of: 1. Three accelerometer pendulums set at right angles to each other; 2. A spring motor for driving the record paper; 3. A time-marking clock; and 4. An electric starter. All of these parts are mounted on a rigid iron base which in turn is bolted to a concrete pedestal.

An outline of these vital components of this accelerograph is tabulated as follows:

1. Accelerometer proper.
   a. Type: Pendulum type accelerometer with its bob of 4.3 kg in weight acting as the piston of the air damper.

   b. Proper period: 0.1 sec.

   c. Sensitivity: 25 gals per mm. on the record.

   d. Damping: Critical.

   e. Working range: 10 to 1000 gals.

   f. Record paper: Special wax paper, 24 cm x 10 m.

   g. Recording speed: 1 cm. per sec.

2. Driving spring motor.
   a. Type: Hand-wound spring motor.

   b. Action: Starts 3 times. 3 minutes running time for each start.

   c. Governor: Centrifugal, quick-accelerating.

3. Time-marking clock.

   a. Type: Hand-wound clock with electric contacts.

   b. Time marks: Every one sec., or 1/5 sec., interchangeable.

4. Electric starter.
   a. Type: A vertical component pendulum with a period of 0.3 sec.

b. Action: Operate at 10 gals.

c. Electric contact: 3 pairs of platinum contact points in parallel.

This instrument starts automatically to record earthquakes when they are greater than 10 gals in acceleration and stops recording automatically after a three-minute running period. The time marking clock starts and stops at the same time. This automatic action will repeat itself for three successive earthquakes. Ordinarily, the action is started upon a signal from the electric starter, but in addition a mechanical starter is provided in the driving spring motor in case of electric starter malfunction. An elinvar spring is used in the electric starter to eliminate the effect of temperature change.

The recording is made by scratching a belt of wax paper by a sapphire-tipped needle. By this means, we can obtain a very sharp record which enables us direct printing upon photographic paper, or photographic enlarging up to ten times the original.

The instrument has a very strong air-tight cover to protect the mechanisms from dust, humidity and falling objects in case of disastrous earthquakes. Four FM-III and four FM-V dry cells are held in a pocket box of the cover and serve as the electric source for the starter.

The SMAC accelerograph with cover lifted is shown in Fig. 1. The overall dimensions of the instrument are 56cm x 74cm x 84cm.

We have not yet obtained any remarkable record by these instruments since no large earthquakes have occurred since 1952. We have obtained, however, the accelerogram for the earthquake on Feb. 14, 1956. This accelerogram is shown in Fig. 4. The SMAC accelerograph is used often in shaking tests of buildings or in testing vehicle vibrations. Records of such tests are shown in Figs. 2 and 3.

The special merit of this instrument is the ability to record as perfectly as possible the acceleration of earthquakes as large as 1000 gals with large recording speed; to continue operable; and to record automatically two more of the aftershocks. Ease of maintenance was considered in the design. The instrument requires a careful inspection by an expert only once a year together with additional bi-monthly attention of a less skilled mechanic.

THE "DC" ACCELEROGRAPH

In order that as many strong motion accelerographs be installed throughout Japan as is possible within the budgetary limitations of the program, the most reasonably priced instrument is desirable. Such an accelerograph has been designed with the financial aid of the Ministry of Construction. It has been named, "The DC Accelerograph". Originally, it was designed to be used in combination with a SMAC accelerograph to record the vibrations of the different portions of a building structure. In such a case, the vertical components of vibrations are usually small compared with the horizontal components. In this instrument, therefore,

the vertical component pendulum was eliminated to reduce the cost. For the same purpose, the instrument has no integral starter but starts recording in response to an electric signal transmitted from the starter of a SMAC accelerograph installed on a different floor level.

An outline of the vital components of this accelerograph is tabulated as follows:

1. Accelerometers.
   a. Type: Two horizontal component pendulum-type accelerometers.

   b. Proper period: 0.1 sec.

   c. Damper: Air dampers.

   d. Sensitivity: 12 gals per mm.

   e. Working range: 5- 500 gals.

   f. Magnifying device: Eden's twin strips.

   g. Record paper: Smoked paper.

   h. Recording speed: 1 cm per sec.

2. Driving device.
   a. Type: 1/50 hp., d.c. motor.

   b. Action: Non-repeating.

3. Electric source.
   a. Batteries: A 6-volt secondary battery.

The DC accelerograph is shown in Fig. 5. The overall dimensions of this instrument are 59 cm x 48 cm x 35 cm. In addition to the original use for which it was designed, this accelerograph is used often in shaking tests of such civil engineering structures as dams and bridge piers.

A MAXIMUM ACCELERATION SEISMOSCOPE

An inexpensive seismoscope to indicate the maximum acceleration of a large earthquake was developed recently for use as an auxiliary instrument for installation in secondary stations of the observation network.

This instrument consists of a cubic iron weight, 7 cm x 7 cm x 7 cm, and six bronze bellows, one attached to each of the cube surfaces of the weight. The bellows is 6 cm in effective diameter and 7 cm long. The assembly of the weight and bellows is supported by a framework made of iron angles. Each bellows is connected to a thin glass tube of 6 mm inner diameter by a vinyl plastic tube and is filled with kerosene colored with oil red. A part of the connecting vinyl tube is narrowed to give an adequate damping effect to the oscillation of the bellows and

weight system.

Each glass tube has a very thin branch tube which leads to a common flat oil-filled tank. This common tank is for the purpose of minimizing the change in the level of the kerosene in the glass tubes due to thermal expansion and also to equalize the kerosene levels in the glass tubes. The side tube has no effect on rapid fluctuation of kerosene level due to earthquakes. Any rise of the oil surface in a glass tube leaves a mark on a thin glass plate inserted into the glass tube. The glass plate is coated previously with a film of soap.

The instrument allows a record to be made of the maximum accelerations in six directions. The bellows and thin glass tubes provide the instrument an adequate magnification of 100, a suitable damping and a proper restoring force.

A prototype instrument is shown in Fig. 6. The proper period is 0.06 sec and the sensitivity is about 10 gals per mm for periods greater than 0.2 sec. The cost of the instrument is only $150.

DIRECT-READING INSTRUMENT FOR OBSERVING BUILDING VIBRATIONS

An instrument which permits the direct observation of the amplitude and mode of vibration of a building was developed recently by H. Kawasumi. This instrument consists essentially of eight D-type oscillograph vibrators, a light source and a slow-fade fluorescent screen. The light spots reflected from the vibrators are lined up vertically on this screen. Each vibrator is connected directly with a moving-coil type pick-up with a proper period of 1.0 sec. The total sensitivity of the system is about 3000 times at 10 cycles.

When the pick-ups are installed at various heights of a building structure, the light spots describe horizontal lines on the screen indicating the vertical distribution of velocity of the vibration. The period of vibration at each building height will be the same, provided a specific mode is dominant as is generally the case. Hence the lengths of the horizontal lines on the screen also are proportional to the amplitude. Moreover, the instantaneous positions of light spots show the approximate mode of vibration of the building.

Ordinarily, the screen observation is made visually. The instrument is capable of camera attachment for photographic recording, if desired. Fig. 7 shows the instrument setup with a camera attachment and also an example of the record obtained by this instrument. This instrument can be used conveniently for vibration observations of structures other than buildings.

THE MICROTREMOR RECORDER

This instrument assembly consists of a pick-up with a period of 1 sec., an amplifier, a moving-coil type recording head and a smoked paper recording drum driven by a Warren motor. The instrument is shown in Fig. 8. The alternating current for the amplifier and the motor is

obtained by an inverter which is driven by a 12-volt secondary battery. A voltage regulator is used. The magnifying mechanism in the recording head is simplified by the use of Eden's twin strips. The total magnification of the whole system is adjustable between 100 to 10,000 times.

The equipment can be installed in a car to obtain mobility which results in the ability to make observations at several different locations in one hour. This instrument was developed by K. Kanai and he has used it to measure microtremors as well as building vibrations (9).

Microtremor recordings on different types of ground are shown in Fig. 9. On base rock, the microtremors are very small, of short period, and simple as they are composed of waves of limited frequency band. On marshy ground, however, the microtremors are very complicated, being composed of waves of all periods. The microtremor curve in this case resembles that of random noise recordings. Microtremor recordings made on diluvial and alluvial soils show the intermediate nature of these two extreme grounds and show that the most frequent wave periods are 0.3 and 0.8 secs., respectively. Fig. 9 shows also the results of frequency analysis of these microtremor curves.

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(2) "Spectrum Analyses of Strong Motion Earthquakes", by J.L. Alford, G.W. Housner and R.R. Martel. First Technical Report under ONR Contract N6ONR-24425, Project Designation NR-081-095.

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(4) "Relation between the Nature of Surface Layers and the Amplitude of Earthquake Motions. Part II", by K. Kanai, Bull. Earthq. Res. Inst., Vol. 31 (1953), (English), p 219.

(5) "Earthquake Motions on Soft Grounds" by Ryutaro Takahasi, Bull. Earthq. Res. Inst., Vol. 19 (1941), (Japanese), p 534.

(6) "A Short Note on a Graphical Solution of the Spectral Response of the Ground", by Ryutaro Takahasi, Bull. Earthq. Res. Inst., Vol. 33 (1955), (English), p 259.

(7) "The SMAC Strong Motion Accelerograph", by Ryutaro Takahasi, Zisin, Ser. 2, Vol. 6 (1953), (Japanese), p 117.

(8) "The SMAC Strong Motion Accelerograph", by N. Nasu, Proc. 3rd Japan Nat. Congr. Appl. Mech., 1953, (English), p 371.

(9) "Measurement of the Microtremor. I.", by K. Kanai, T. Tanaka and K. Osada, Bull. Earthq. Res. Inst., Vol. 32 (1954), (English), p 199.

No.	Location	Date of Installation
1	Akashi Seisakusho Co. Ltd., Shinagawa Ward, Tokyo. Ground Floor.	Nov. 1952
2	Osaka First Life Insurance Building, Osaka. Basement floor.	Dec. 1953
3	Earthquake Research Institute, Bunkyo Ward, Tokyo. Underground vault.	Apr. 1954
4	Nagoya Culture Center, Nagoya. Roof.	May 1954
5	Daimaru Department Store, Chiyoda Ward, Tokyo. Basement floor.	Dec. 1954
6	Ditto. Second floor.	Dec. 1954
7	Ditto. Sixth floor.	Dec. 1954
8	Toyoko Department Store, Shibuya Ward, Tokyo. Old Building, 5th floor.	Apr. 1955
9	Ditto. Connect-bridge. 5th fl.	Apr. 1955
10	Ditto. New Build. 5th fl.	Apr. 1955

TABLE I.

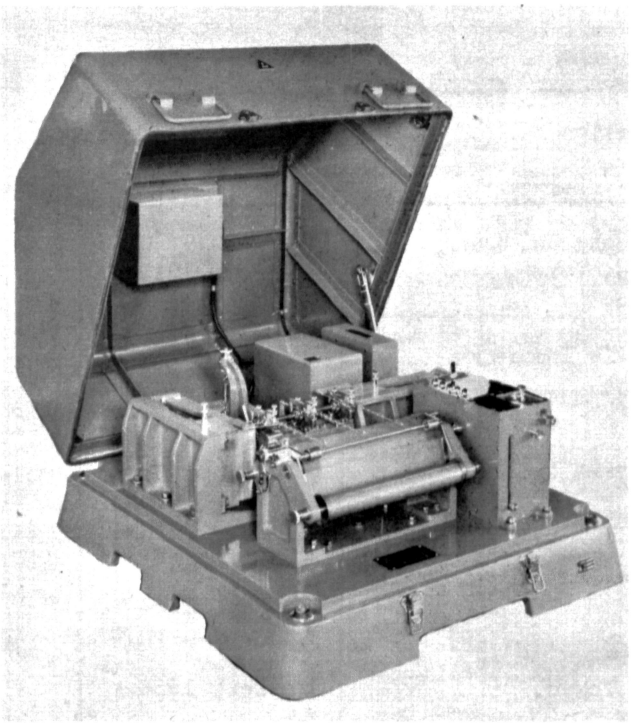


FIG. 1

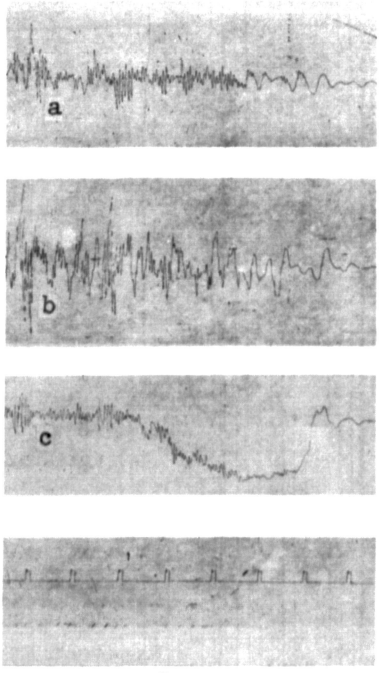


FIG. 2

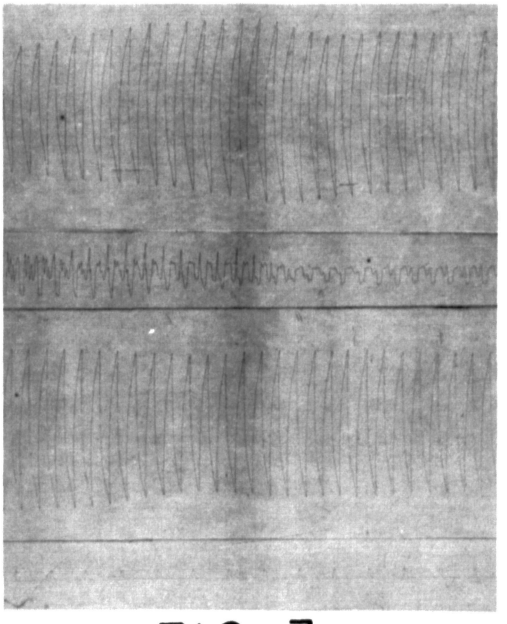


FIG. 3

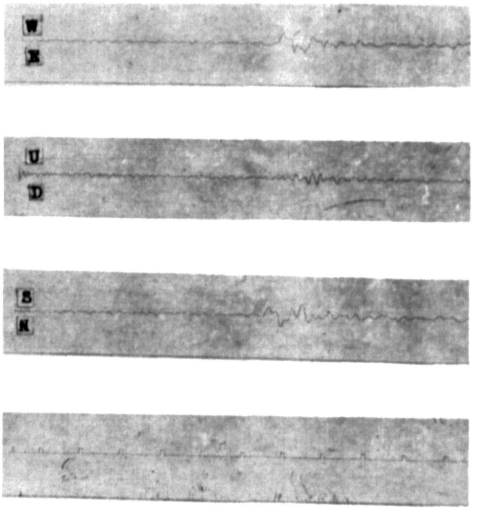


FIG. 4

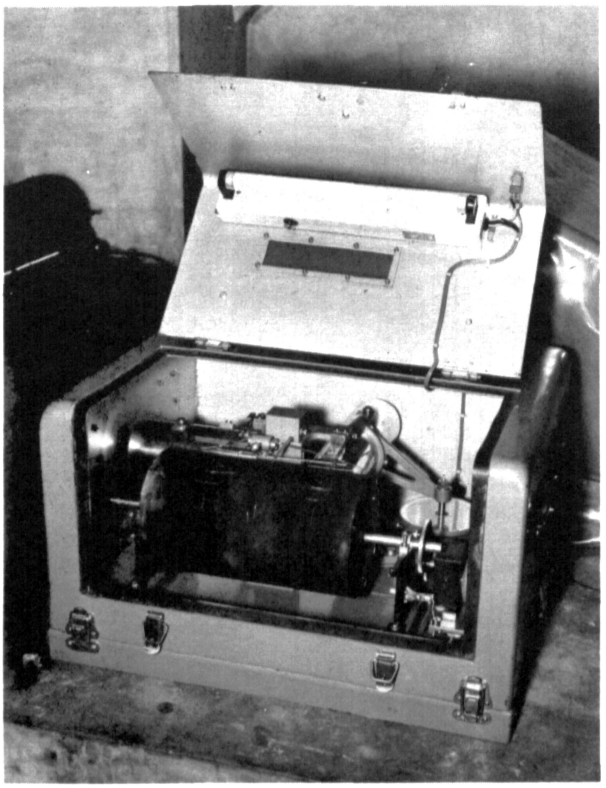


FIG. 5

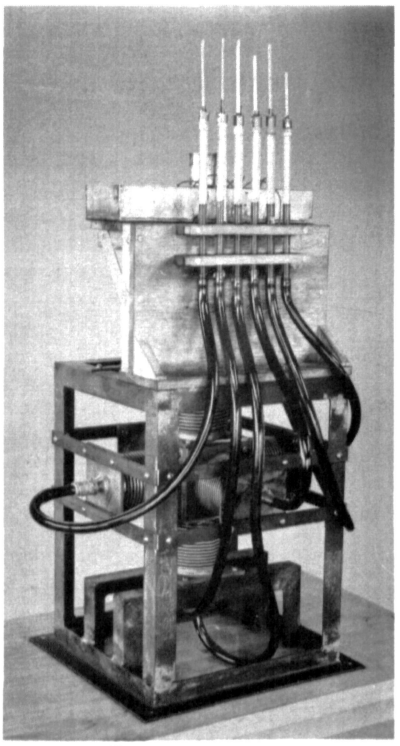


FIG. 6

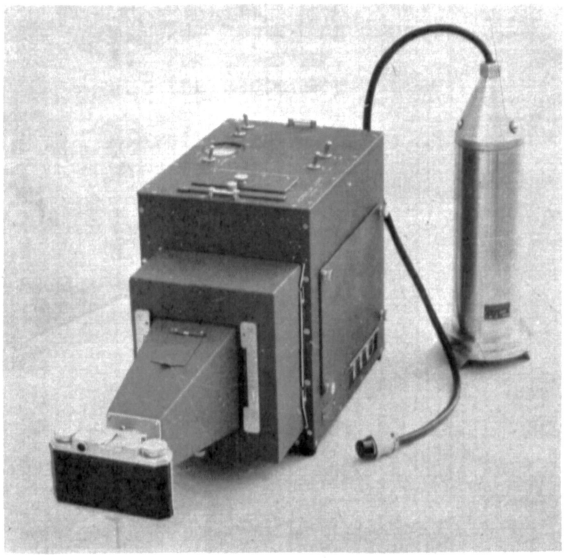
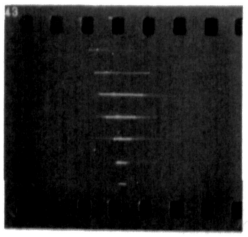


FIG. 7



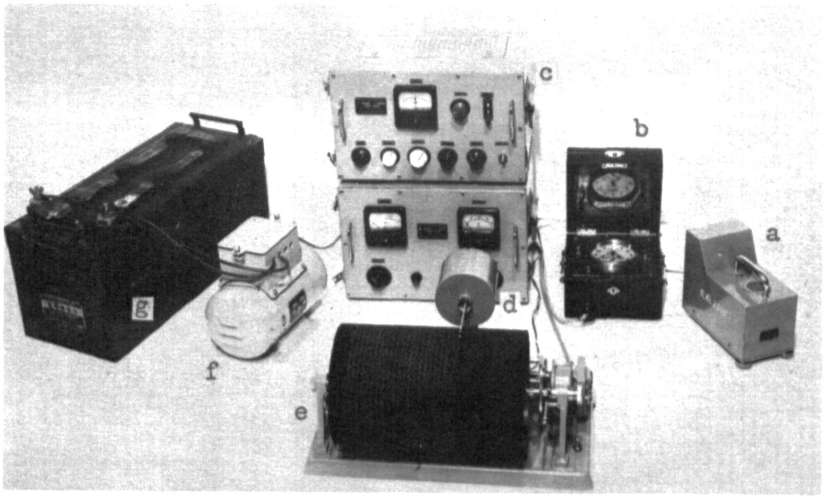


FIG. 8.

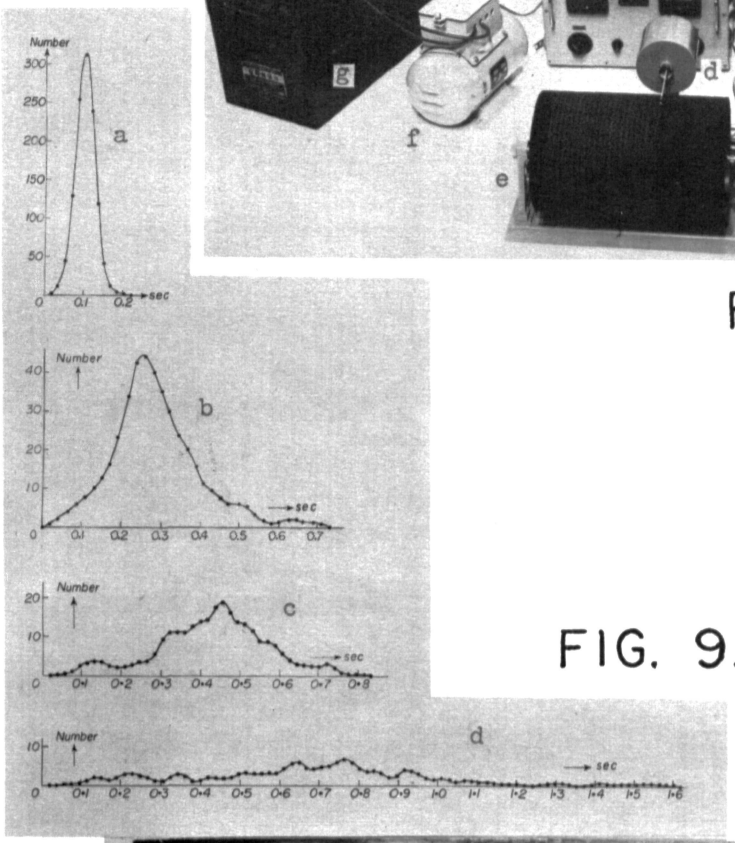


FIG. 9.

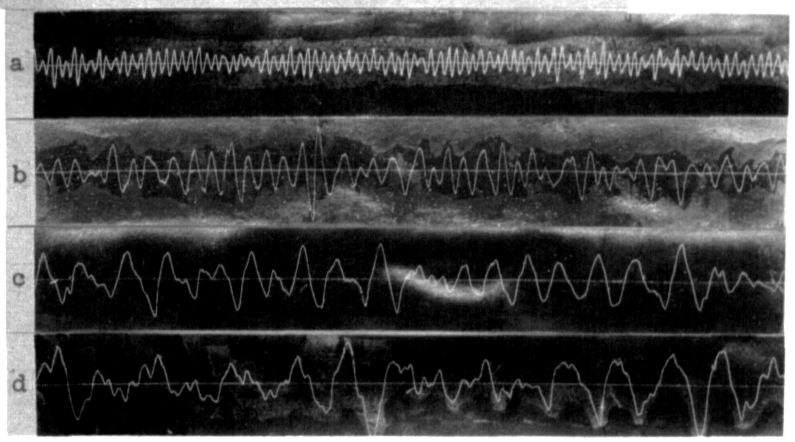


FIGURE CAPTIONS

Fig. 1 The SMAC accelerograph with cover open.

Fig. 2 The acceleration of a moving vehicle as recorded by a SMAC accelerograph.

a. Component in the transverse direction.
b. U-D component.
c. Component in the direction of vehicle motion. The remarkable deflection of the c. curve shows a sudden stop of the vehicle. Time marks: every 1 sec. 3/4 the original.

Fig. 3 Record of the vibration of a building in a shaking test, as recorded by a SMAC accelerograph. 3/5 the original.

Fig. 4 The accelerograms of the earthquake which occurred on Feb 14, 1956, as obtained by a SMAC accelerograph at the Earthquake Research Institute. Time marks: every 1 sec. 2/3 original.

Fig. 5 The DC accelerograph with the cover open.

Fig. 6 The Bellows type maximum acceleration seismoscope.

Fig. 7 The Direct-Reading instrument for measuring the amplitude distribution and the vibrational mode.

Fig. 8 Microtremor recorder assembly.

a. A pick-up.
b. The time marking clock.
c. The amplifier and voltage regulator.
d. The recording head.
e. The recording drum.
f. The inverter.
g. The secondary battery.

Fig. 9 Microtremors recorded on various type of ground by the microtremor recorder, with the corresponding frequency spectra.

a. Bed rock.
b. Diluvial ground.
c. Alluvial ground.
d. Marshy ground.

Table 1 The distribution of SMAC accelerographs as of Jan. 1, 1956.