16. Earthquakes and Earthsounds on Mt. Tukuba.

By Takahiro HAGIWARA,

Earthquake Research Institute.

(Read Dec. 19, 1933.—Received Mar. 20, 1934.)

1. Introduction.

Earthquakes are felt more frequently in the region of Mt. Tukuba than anywhere else in the Kwantô district. In 1933, for example, 141 sensible shocks and 597 insensible earthquakes were recorded by the acceleration seismographs in our station on Mt. Tukuba. These earthquakes have their epicentres chiefly near Mt. Tukuba, in the basin of the river Kinugawa, near Kasumigaura, and in Kasimanada (in the Pacific). The earthquake tremors in this region are distinguished by very rapid vibrations, while most of the sensible earthquakes are accompanied by peculiar earthsounds. The earthsounds, which are always low-pitched, are often characterized by the inhabitants with the sounds "goo" and "doo" (the "o" being pronounced as in "born" and held long), but the pitch of the sounds are so low that our vocal cords can never imitate them. The sounds begin simultaneously with the P-phase, that is, the initial motion of the earthquake tremor, continues with fairly equal intensity throughout the preliminary tremors and becomes louder at the S-phase, after which it gradually diminishes and fades away within several seconds after the S-phase.

Since March 1932, constant observations of near earthquakes were made by an Ishimoto horizontal acceleration seismograph, some of the results of which have been already reported by Mr. W. Inouye[1]. Since July 1933, however, continuous observations have been made with an Ishimoto vertical acceleration seismograph[2]. The details of these instruments are as follows.

Component	Self-period	Weight of the bob	Sensibility	Damper	Recording
Horizontal	0·115 sec.	15 kg.	(NW-SE) 1 mm—1·7 gal (NE-SW) 1 mm—1·8 gal	Oil damper	Smoked paper
Vertical	0·081 sec.	15 kg.	1 mm—4·1 gal	Air damper	Smoked paper

1) W. INOUYE, *Bull. Earthq. Res. Inst.*, **11** (1933), 69.

2) M. ISHIMOTO, *Bull. Earthq. Res. Inst.*, **11** (1933), 717.

The sensibility of an acceleration seismograph cannot be constant when the vibration periods of earthquake tremors are smaller than the period of the instrument itself. It was found that vibration periods of earthquake tremors on Mt. Tukuba were often shorter than that of these acceleration seismographs, so that the nature of earthquake tremors could not be sufficiently investigated from the records of those instruments. To overcome this difficulty, a new vertical acceleration seismograph with a period of 0·0155 sec. was equipped as an experiment, and observations with it have been made since October 1933. The details of this equipment will be given later.

This paper discusses the nature of the earthquake tremors on Mt. Tukuba[3] according to the results obtained by the above three instruments.

2. Durations of the Preliminary Tremors.

To find the epicenter and depth of every earthquake that occurs near Mt. Tukuba would indeed be very desirable, but much to the author's regret, quite a number of the earthquakes that are felt in this region are so local that, in many cases, the data from other stations are useless for determining the epicenters. At present therefore, epicenters are determined only for earthquakes of such magnitude as are sensible in Tokyo. Fig. 1 shows the epicenters that have been selected from the Seismological Reports of our Institute. In the figure, earthquakes accompanied by earth sounds and without are marked by ○ and ● respectively. As to the other earthquakes we shall only examine the durations of their preliminary tremors. Fig. 2 shows the maximum horizontal accelerations and the durations of the preliminary tremors

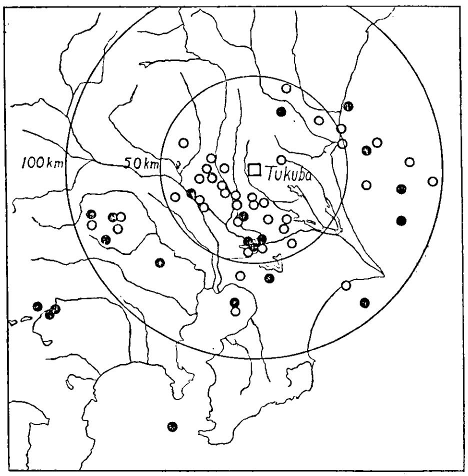


Fig. 1. Epicentral distribution of the earthquakes in the period from January 1932 to June 1933. Earthquakes accompanied by earthsounds and without are marked by ○ and ● respectively.

3) Mt. Tukuba consists of Gabbros and Granites, with none of the soft sedimentary layers that are seen in the Kwantô plains.

of sensible earthquakes on Mt. Tukuba (in the period from March 1932 to Dec. 1933). We see from the figure that the durations of the preliminary tremors largely range from 5 sec. to 7 sec., while tremors with shorter durations than 8 sec. are almost always accompanied by earthsounds. If the durations are longer than 8 sec., there is a decrease in the number of cases accompanied by earthsounds. Ordinarily, earthsounds are not heard when the duration of the preliminary tremors exceeds seventeen or eighteen seconds. But if the focus of an earthquake happens to be very deep, earthsounds occasionally accompany it, even though the duration of the preliminary tremors may exceed 1 minute. In that case, the sounds are heard twice; once at the beginning of the earthquake tremor and again at the S-phase.

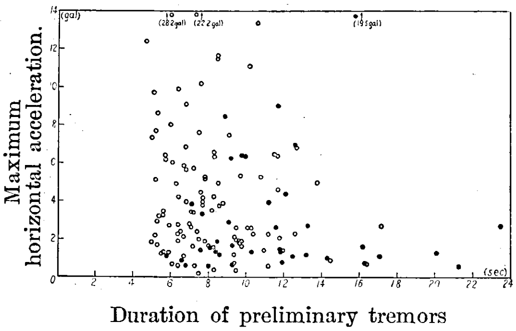


Fig. 2. The maximum horizontal accelerations and the durations of the preliminary tremors. Earthquakes accompanied by earthsounds and without are marked by ○ and ● respectively.

There are many earthquakes with durations of preliminary tremors of 5 and 6 sec., but none with tremors less than 5 sec., with the exception of only one. As these earthquakes with short preliminary tremors are generally local shocks, which are felt only near Mt. Tukuba, their hypocenters might be regarded as being under this region. The fact that we find no duration of preliminary tremors less than 5 sec., indicate that the seismic activities of this region occur at comparative depths. The constant "k" of Omori's formula[4] for determing the hypocentral distance of near earthquakes is usually taken as 9·3 for this station. If we assume that the hypocenter lies just under this station, the depth of the earthquake by Omori's formula becomes 46·5 km. for an earthquake whose duration of preliminary tremors is 5 sec. From this it would follow that the seismic activities near Mt. Tukuba occur at depths of about 40 to 50 km.

3. Maximum Accelerations.

Our next study is the accelerograms recorded by the Ishimoto acce-

4) $\Delta = kT$, where Δ is the hypocentral distance, k the constant, and T the duration of preliminary tremors.

leration seismographs, some of which are shown in Fig. 6. These two instruments were frequently calibrated by a simple apparatus designed to apply constant forces of varying periods to the bobs of the instruments by means of a rubber band stretched between the bobs and an eccentric point on a wheel that is turned by hand. By correcting the sensibilities of the instruments with this calibration, we obtained the maximum acceleration for each sensible earthquake. As the vibration periods of tremors with maximum accelerations are in fact comparatively large, this correction is not so large.

It will readily be seen that generally when the earthquake accelerations are large, the maximum acceleration is also large, and vice versa, so that maximum acceleration may express the magnitude of earthquake accelerations as a whole. Fig. 3 is a comparison between maximum horizontal acceleration and maximum vertical acceleration of sensible earthquakes. Taking the maximum horizontal acceleration as abscissa and the vertical for ordinate, the corresponding points are plotted. We see from this figure that both accelerations are generally of the same order of magnitude, but that the vertical accelerations of some earthquakes are conspicuously large compared with the horizontal accelerations, especially when the seismic scale is large. As to the earthsounds, it will be seen that in earthquakes accompanied by sounds vertical accelerations generally predominate.

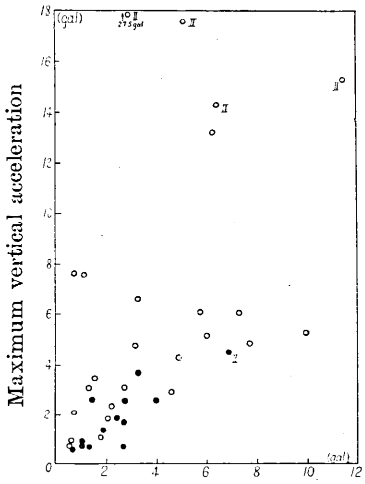


Fig. 3. Comparison between maximum horizontal acceleration and maximum vertical acceleration. Earthquakes accompanied by earthsounds and without are marked by ○ and ● respectively. The notation "II" represents seismic intensity of II.

4. Acceleration Seismograph by Photographic Recording.

As already mentioned, earthquakes on Mt. Tukuba are often accompanied by peculiar earthsounds. We may say that the vertical vibrations of the earth's surface cause wave motion of the air which becomes audible as earthsounds. Since the minimum frequency of air vibration that is audible to the human ear is believed to be from 16 to 20 per sec., if the earth's surface vibrates with greater frequency than this, and with moderate amplitude, the sound waves should be audible. From this standpoint it is interesting to examine with what frequencies actual earthquake tremors vibrate.

For recording rapid vibrations of the ground, the acceleration seismograph is most suitable. The reason for this is that, since its diagrams describe accelerations of earth movement, there is no fear of their being masked by other vibration of long period and of larger displacement-amplitude, as is so frequently seen in ordinary displacement seismograph records. But as already stated, the period of the acceleration seismographs themselves that were used for continuous observation, were not short enough for recording such rapid vibrations, so that no details can be discussed from the accelerograms of these instruments. In these circumstances a new vertical acceleration seismograph with a shorter self period was equipped as an experiment. The details of this equipment are as follows.

A brass cylindrical bob (M) which forms a pendulum is supported by two flat springs (F), as shown in Fig. 4. At the end of an aluminium arm (A) attached to the bob, a steel roller (R), whose axis lies horizontally, is supported on pivots. On this axis a small lens-mirror (L) is attached. A piece of slightly magnetized steel (P), which contacts with the roller, translates the motion of the bob into the rotation of the mirror. Through a slit (S) a lamp illuminates this mirror (a rectangular prism, which is fixed over the mirror, changes the direction of the rays). A recording drum (U), with a photographic film wrapped around it, is set at a distance of 1 m. from the surface of the mirror. By a cylindrical lens (C), the image of the slit is converged to a point on the film. An oil-damper (D) of piston type is attached to the arm.

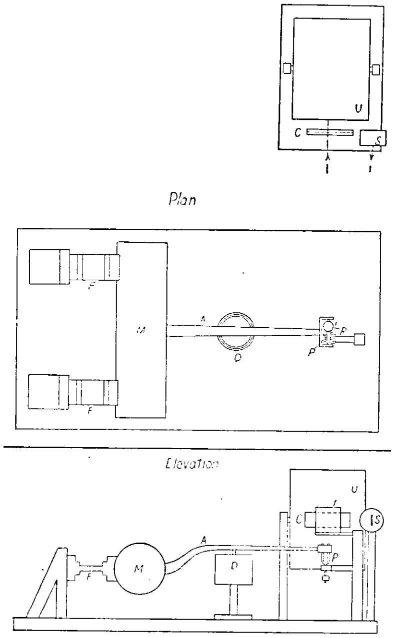


Fig. 4. Acceleration seismograph by photographic recording. M cylindrical bob, F flat spring, A aluminium arm, D oil damper, P steel piece, R roller, L lens-mirror, I rectangular prism, S slit, C cylindrical lens, U drum.

Known masses were placed on the bob and the corresponding deflections of the image on the drum were read off, and the sensibility of this instrument thus determined. Needless to say, in this case we added the correction due to the effect of the inertia of the pendulum as calculated from the geometrical figures of the bob and other parts. The elements of this instrument are shown in the following Table.

Component	Self-period (Frequency)	Mass of bob	Sensibility	Geometrical magnification	Damping ratio	Driving rate of recording film when steady.
Vertical	0·0155 sec. (65 per sec.)	1·4 kg.	1 mm. =3·3 gal	About 10,000	About 3	2·7 cm. per sec.

By means of a vertical pendulum with period of 1 sec., electric currents are sent at half second intervals to an electromagnet which closes the slit and marks the time on the record. Since the recording is optical and the driving rate of the film has to be large, continuous observation is practically impossible. We therefore adopted the following method. The moment a shock is felt or an earthquake sound is heard, we turn the switch and cause an electric circuit to be made, then, by the action of a relay, the lamp is lighted and the pendulum for marking the time begins to swing and the drum to revolve. The rotation of the drum becomes nearly steady about 2 seconds after starting. By this method, even were the circuit made simultaneously with onset of the earthquake, the tremors for a period of at least 2 sec. after the beginning of the earthquake cannot be satisfactory recorded, which however may be sufficient for studying the nature of earthquake tremors. Examples of photographic records obtained by this method are shown in Fig. 7.

5. Analysis of Photographic Records.

We shall now investigate what vibration-frequencies predominate in the earthquake tremors. For this purpose we usually describe frequency curves of the vibration-frequency. The earthquakes investigated were the following:

List No. in Seismological Report	Date	Duration of prel. trem. (sec.)	Epicenter	Epicentral distance (km.)	Depth (km)	Intensity	Earthsound
(57)	Nov. 20, 10^h35^m, 1933	8·8	Kasimanada	80	30	II	accompanied
(58)	Nov. 27, 16^h50^m, 1933	11·3	Kasimanada	80	40	I	accompanied
(60)	Dec. 4, 4^h28^m, 1933	7·0	Basin of Kinugawa	20	60	II	accompanied
(61)	Dec. 7, 4^h22^m, 1933	14·1	North of Kasimanada	140		II	not accompanied
(63)	Dec. 12, 2^h02^m, 1933	8·0	Near Mito	50	40	II	accompanied
(1)	Jan. 18, 11^h11^m, 1934	6·3	Basin of Tonegawa	30	50	II	accompanied

We drew a straight line (zero line) through the earthquake record and measured the time between each crossing and recrossing of this imaginary line by the vibrations (in the same direction), and in this way determined the period or frequency of vibrations. A frequency curve of vibration-frequencies was described for each earthquake with respect to (1) the total tremors measurable on the record, (2) with respect to tremors having double acceleration-amplitude larger than a certain magnitude, and (3) with respect to certain portions of the tremors. These results are shown in Fig. 5. In Figures 5, g, h, (P) is the portion of the preliminary tremors, (S) the portion of the principal tremors which, for the sake of convenience, represents the tremors after the S-phase in the interval of time that corresponds to the duration of the preliminary tremors, (T_1) represents the same interval of time after (S), and (T_2) the same interval of time after (T_1).

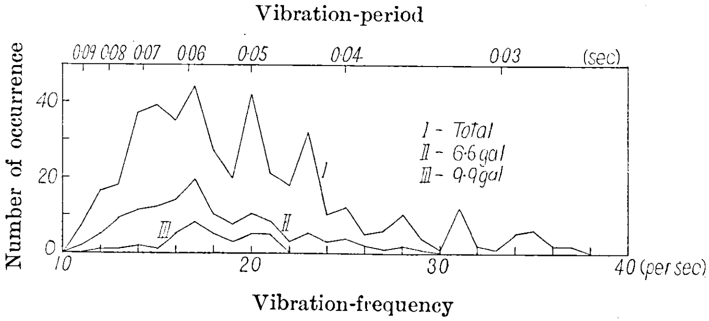


Fig. 5, a. The frequency curves of vibration-frequencies described with respect to tremors having double acceleration-amplitude largr than a certain magnitude. The earthquake of Jan. 18, 1934 (Dur. prel. trem. = 6·3 sec.)

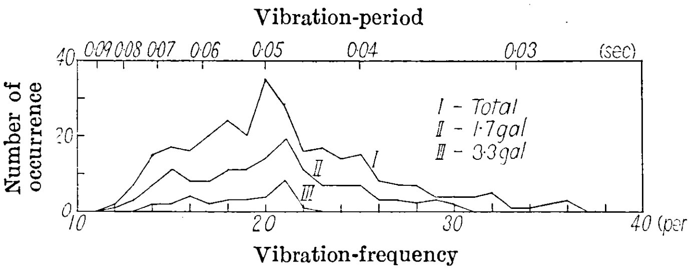


Fig. 5, b.
The earthquake of Dec. 4, 1933. (Dur. prel. trem. = 7·0 sec.)

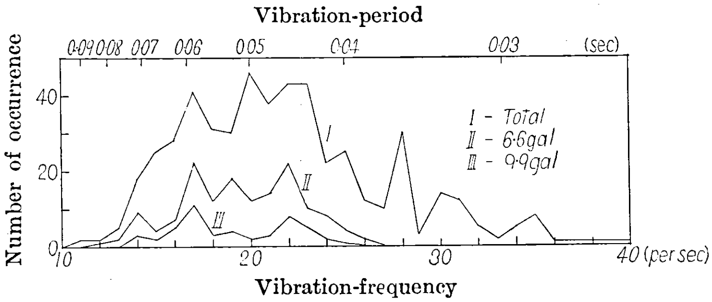


Fig. 5, c.
The earthquake of Dec. 12, 1933. (Dur. prel. trem = 8·0 sec.)

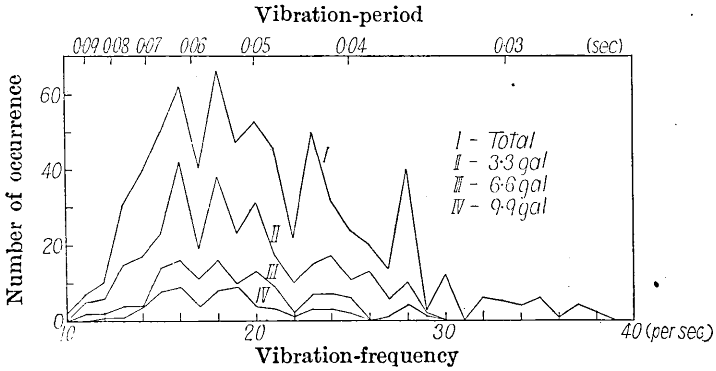


Fig. 5, d.
The earthquake of Nov. 20, 1933. (Dur. prel. trem. = 8·8 sec.)

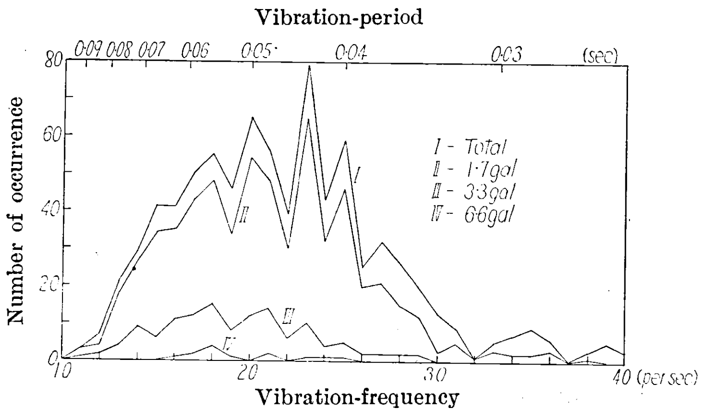


Fig. 5, e.
The earthquake of Nov. 27, 1933. (Dur. prel. trem. = 11·3 sec.)

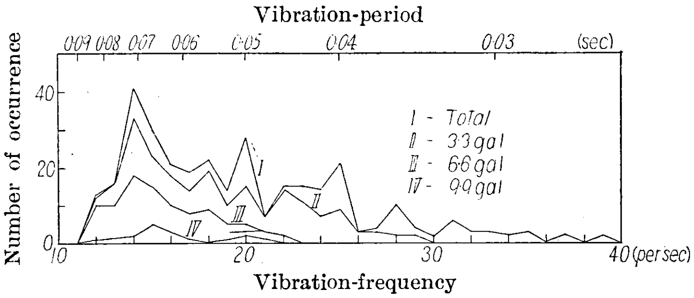


Fig. 5, f.

The earthquake of Dec. 7, 1933. (Dur. prel. trem. =14·1 sec.)

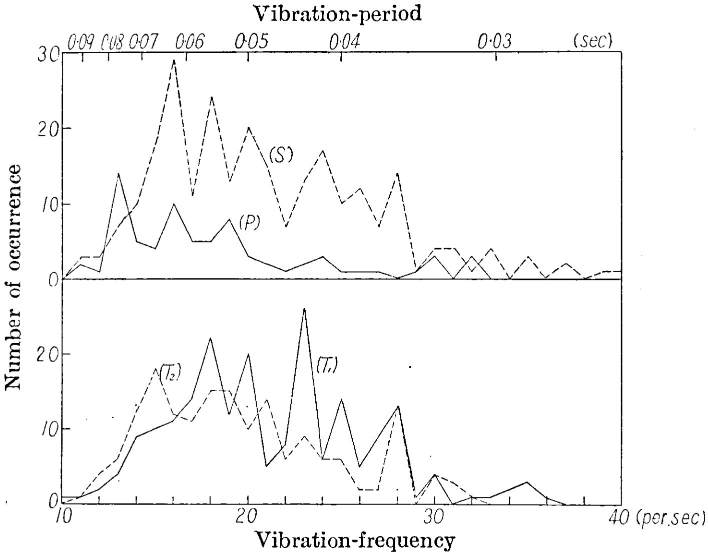


Fig. 5, g.

The frequency curves of vibration-frequency described with respect to various portions of the tremors.

(The earthquake of Nov. 20, 1933.)

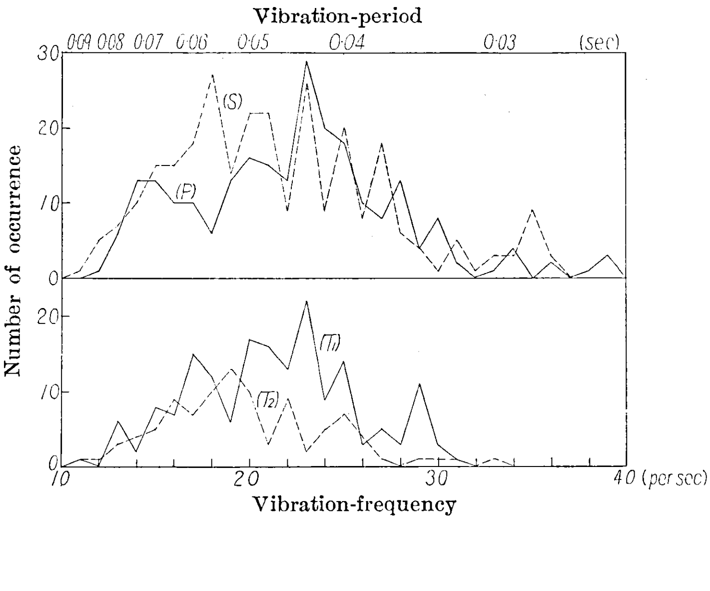


Fig. 5, h.

The frequency curves of vibration-frequency described with respect to various portions of the tremors.

(The earthquake of Nov. 27, 1933.)

We see from the figures that the number of vibration-frequencies in each earthquake range from 10 to 40 per sec., frequencies in the neighbourhood of 20 per sec. predominating. Beside this, other predominating frequencies are seen that are not common to all the earthquakes but vary with individual earthquakes.

As to different parts of the tremors, frequencies of 20 per sec. also predominate, but here too, we find other predominating frequencies that are not common to any particular portion of the tremors.

Tremors not accompanied by earthsounds abound in low-pitched vibrations, as shown in Fig. 5, f.

As to the relation between acceleration-amplitude and vibration-frequency, the latter has a tendency to decrease as the corresponding acceleration-amplitudes increase.

6. Earthsounds.

Earthsounds are believed to be sound waves in air, caused by the vertical component of rapid vibration of the earth's surface. The cubic elasticity of the air is very small compared with that of the ground; so that the ground may virtually be regarded as a rigid vibrating wall, so far as the vibration of the air is concerned. The pressure-amplitude of air sound P is expressed by the relation

$$P = a \cdot \frac{2\pi f}{c} \cdot \gamma \cdot p_0,$$

where a is the displacement-amplitude of the air particles, f the frequency of vibration, c the propagating velocity of sound in air, γ the ratio of the two specific heats of air, and p_0 the atmospheric pressure.

The acceleration-amplitude of the air particles A (which is identical with the acceleration-amplitude of the ground in vertical components) is expressed by

$$A = (2\pi f)^2 a.$$

Then

$$P = \frac{A\gamma p_0}{2\pi f c},$$

which may be written

$$p_0 = 74 \times 13{\cdot}6 \times 980 \text{ dyne/cm}^2,$$

$$\gamma = 1{\cdot}41,$$

$$c = 3{\cdot}3 \times 10^4 \text{ cm}.$$

Whence

$$P = 6{\cdot}6 \times \frac{A}{f}.$$

The minimum pressure amplitudes of sound to be audible to normal ears have been experimentally determined by several investigators[5], according to whom the lower limit of pressure-amplitude to be audible for sound with frequency in the neighbourhood of 20 per sec., is of the order of 1 dyne/cm^2.

If $P=1$ dyne/cm^2 and $f=20$ per sec, then $A=3$ gal, from which it follows that when the vertical vibrations of the ground have a frequency of 20 per sec. and the acceleration-amplitude is larger than 3 gal, then audible sounds are generated in the air. In our case the acceleration seismograph diagrams show that tremors with such frequencies are accompanied by sounds when the acceleration-amplitude exceeds about 1 gal, which is equal in its order of magnitude to the above value of 3 gal. Thus we can say that the earthsounds on Mt. Tukuba are caused by tremors with frequencies in the neighbourhood of 20 per sec.

In conclusion, the author desires to express his cordial thanks to Professor Ishimoto for his kind advice and encouragement and to Mr. Y. Inaba for his helpful assistance in the course of these studies.

---

16. 筑波山に於ける地震動並に地鳴

地震研究所　萩　原　尊　禮

筑波山地方は關東地方の他の場所に比較して地震を感ずる回数が甚だ多い. 是等の地震の大半は筑波山附近, 鬼怒川流域, 霞浦附近, 鹿島灘等に震央を有する. 筑波山地方の地震動は極めて急激な振動を特徴とし, 有感地震は此の地方特有の低音の地鳴を伴ふのを常とする.

筑波山に於ては, 昭和 7 年 3 月より水平成分石本加速度地震計 (週期 0·115 sec.), 昭和 8 年 7 月より上下成分石本加速度地震計 (週期 0·081 sec.) の觀測を行ひ, 更に昭和 8 年 10 月に週期 0·0155 sec. の光學的加速度地震計を實驗的に裝置した. 本文は是等 3 臺の加速度地震計に依る觀測結果に從つて, 此の地方の地震動の習性並に地鳴との關係を述べたものである. 結果の概略を例擧すれば次の如くである.

1) 初期微動繼續時間 8 sec. 以下の有感地震の大半は地鳴を伴ふ. 初期微動繼續時間が 8 sec. より長くなると地鳴を伴ふ場合は次第に減少し, 17〜18 sec. より長い初期微動繼續時間を有する地震では通常の場合地鳴は聞かれない. 然し深發地震に於ては, 初期微動繼續時間が 1 分を越えても地鳴を伴ふ場合がある.

5) For instance, see A. B. WOOD, "A Text-book of Sound," (1930).

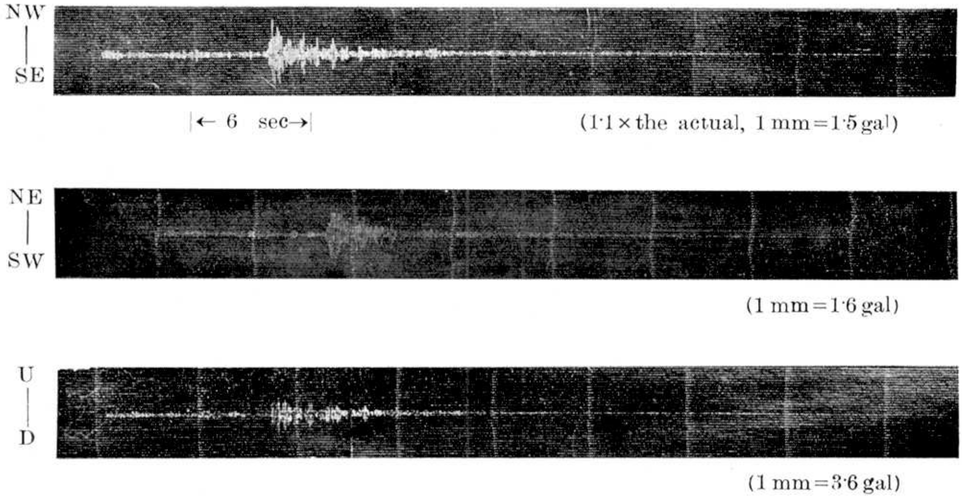


Fig. 6, a. Ishimoto acceleration seismograph diagrams.
The earthquake of Sept. 14, 1933.

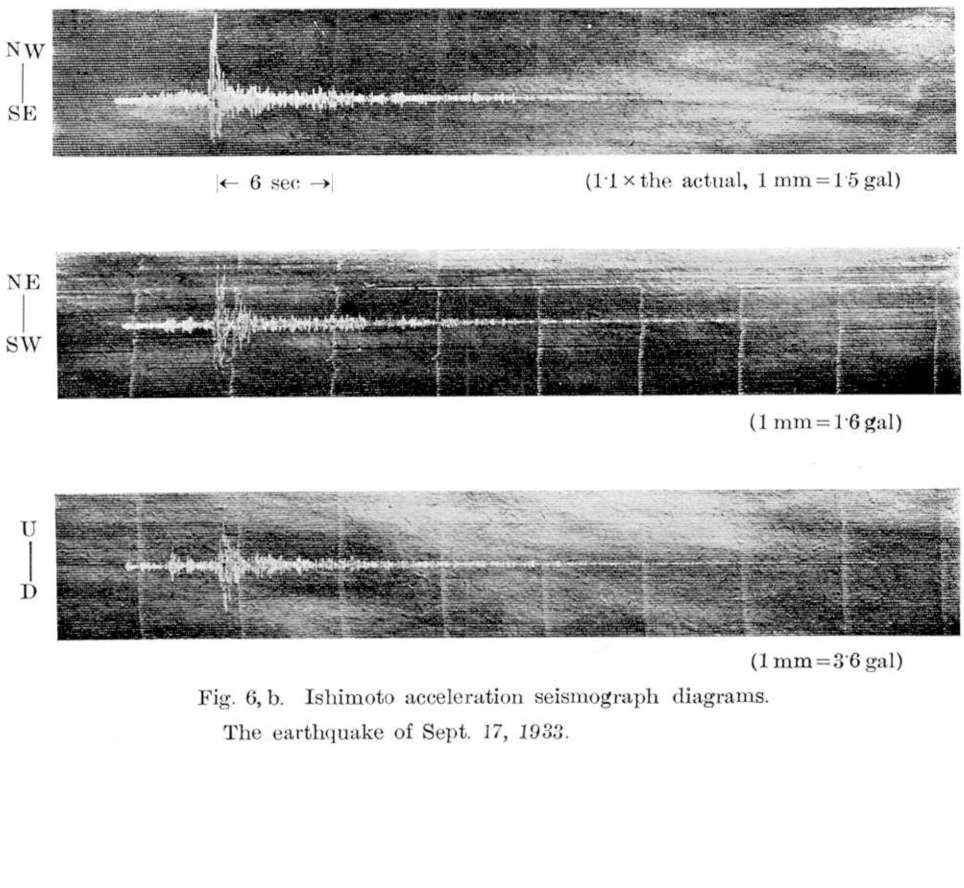
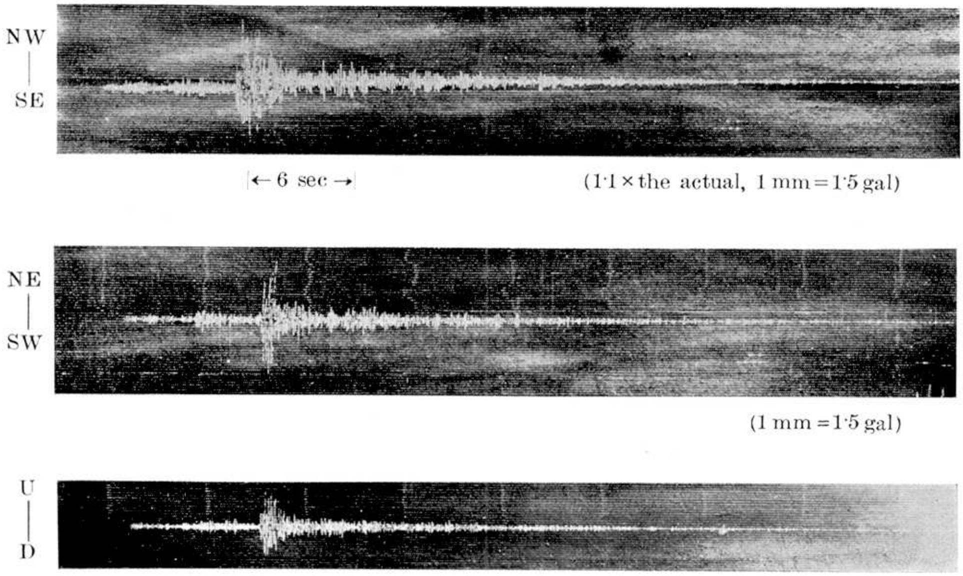


Fig. 6, b. Ishimoto acceleration seismograph diagrams.
The earthquake of Sept. 17, 1933.

（震研彙報、第十二號、圖版、萩原）

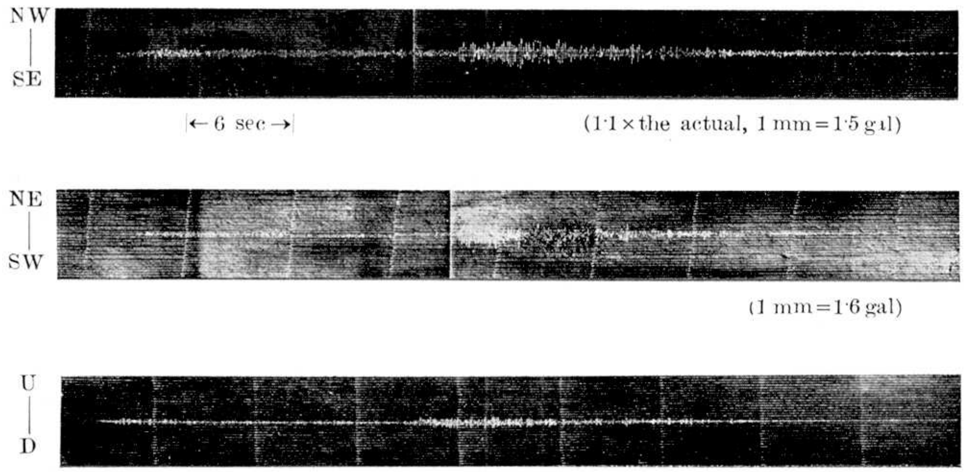


|← 6 sec →| (1·1 × the actual, 1 mm = 1·5 gal)

(1 mm = 1·5 gal)

(1 mm = 3·6 gal)

Fig. 6, c. Ishimoto acceleration seismograph diagrams.
The earthquake of Oct. 2, 1933.



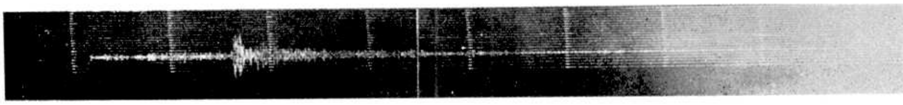
|← 6 sec →| (1·1 × the actual, 1 mm = 1·5 gal)

(1 mm = 1·6 gal)

(1 mm = 3·6 gal)

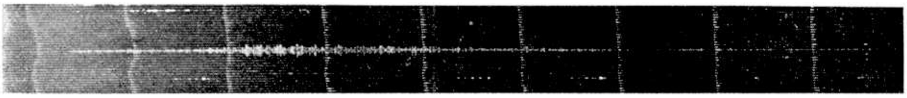
Fig. 6, d. Ishimoto acceleration seismograph diagrams.
The earthquake of Oct. 4, 1933.

(震研彙報、第十二號、圖版、萩原)



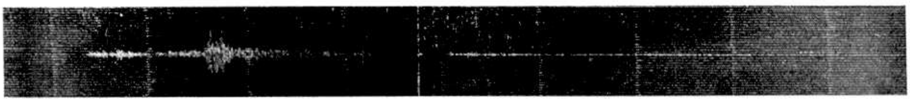
|← 6 sec →| (1·1 × the actual, 1 mm = 3·6 gal)

Fig, 6, e. Ishimoto acceleration seismograph diagram.
The earthquake of Nov 20, 1933.



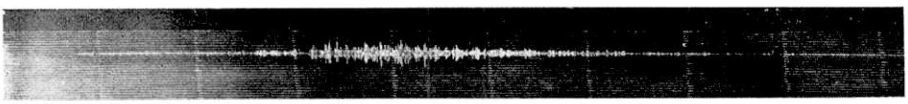
|← 6 sec →| (1·1 × the actual, 1 mm = 3·6 gal)

Fig. 6, f. Ishimoto acceleration seismograph diagram.
The earthquake of Nov. 27, 1933.



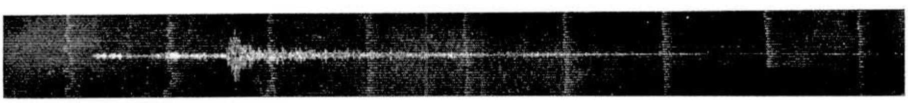
|← 6 sec →| (1·1 × the actual, 1 mm = 3·6 gal)

Fig. 6, g. Ishimoto acceleration seismograph diagrams.
The earthquake of Dec. 4, 1933.



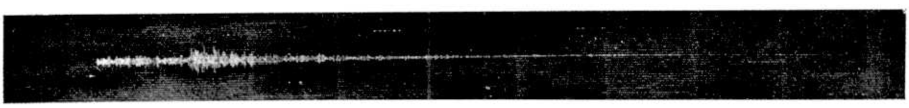
|← 6 sec →| (1·1 × the actual, 1 mm = 3·6 gal)

Fig. 6, h. Ishimoto acceleration seismograph diagram.
The earthquake of Dec. 7, 1933.



|← 6 sec →| (1·1 × the actual, 1 mm = 3·6 gal)

Fig. 6, i. Ishimoto acceleration seismograph diagram.
The earthquake of Dec. 12, 1933.



|←6 sec→| (1·1 × the actual, 1 mm = 3·6 gal)

Fig. 6, j. Ishimoto acceleration seismograph diagram.
The earthquake of Jan. 18, 1934.

（震研彙報、第十二號、圖版、萩原）

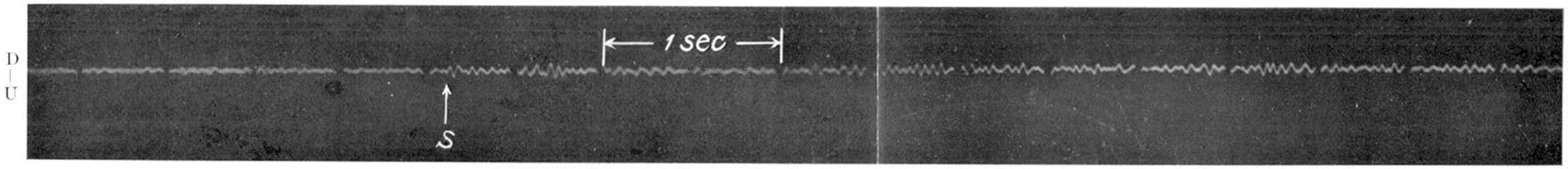


Fig. 7, a. Photographic record obtained by the acceleration seismograph with self period of 0·0155 sec. The earthquake of Nov. 27, 1933. (Full size, 1 mm = 3·3 gal)

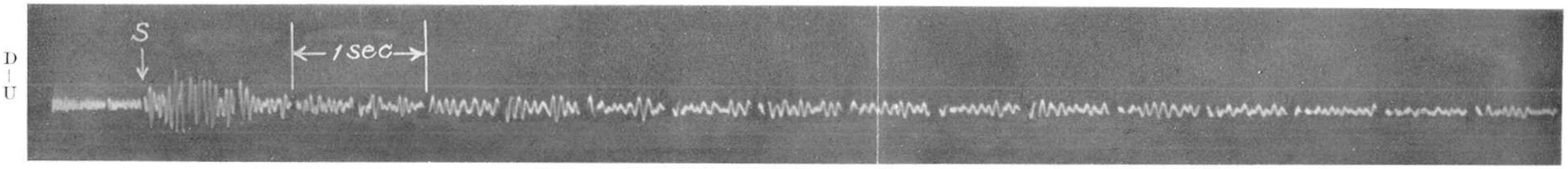


Fig. 7, b. The earthquake of Dec. 12 1933. (Full size, 1 mm = 3·3 gal)

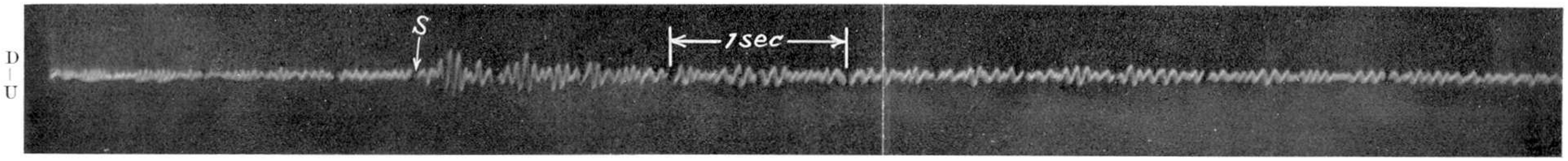


Fig. 7, c. The earthquake of Jan 18, 1934. (Full size, 1 mm = 3·3 gal)

（震研彙報、第十二號、圖版、萩原）

2) 初期微動繼續時間が 5 sec. より 7 sec. の地震の回数が甚だ多いが 5 sec. 以下のものは全く見當らない. 是等地震の中には筑波山附近に於てのみ感ぜられる局部的の地震が多く, 極く近似的には震源は筑波山の直下附近にあると見做し得るものが相當ある. 從つて初期微動繼續時間が 5 sec. 以下のものが見當らないと云ふ事實は此の地方の地震活動は相當に深い (少くとも 40 km.) 場所に起つて居ることを意味することになる.

3) 地震動の最大加速度は水平成分と上下成分とは概して同程度であるが, 目立つて上下成分の最大加速度が大きい場合がある. 此の現象は特に震度の大きい地震の場合に見られる. 地鳴に關しては, 地鳴の伴ふ地震は上下成分の最大加速度が比較的大きい.

4) 固有週期 0·0155 sec. の加速度地震計の記象から, 地震動の振動数の頻度曲線を作つた結果, 地鳴に伴ふ地震にあつては振動数は 10 per sec. より 40 per sec. のものが認められ, 其の中 20 per sec. 前後のものが卓越して居ることが確められた. 地鳴の無い地震では卓越振動数は小さい方に偏して居る. 又加速度振幅が増大すると之に相當する振動数は減少する傾向が見られる.

5) 地鳴は上に述べた如き 20 per sec. 前後の振動数を有する地表の上下振動に依つて發生せしめられる音波として定量的に説明し得られる.