6. *Observations of Near Earthquakes on Mt. Tukuba with an Ishimoto Acceleration Seismograph.*

By Win INOUYE,

Earthquake Research Institute.

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1. Instruments.

A pair of Ishimoto acceleration seismographs[1] was installed at our station on March 10, this year, and has been working ever since in the constant observation of near earthquakes.

The constants of the instruments are as follows.

Component	Own period	Weight of the heavy bob	Sensitivity
E-W	0·114 sec.	15·3 kg	1 mm—1·77 gal
N-S	0·114 sec.	15·3 kg	1 mm—1·69 gal

Sensitivity in the above table means a deflection of 1 mm on the record correspoding to the acceleration of the ground. But the sensitivity of the instrument depends upon the ratio of the oscillation period of the ground to the period of the instrument itself. If this ratio is somewhat large, (say$>$2), the sensitivity of the instrument is constant for all values of the oscillation period of the ground. This is the sensitivity that is shown in the above table.

An example of calibration of the instrument, or the curve representing the extent to which the sensitivity of the instrument depends on the periods of the forced oscillations, is shown in Fig. 1.

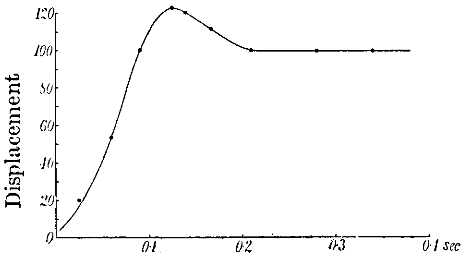

Fig. 1.

The sensitivity of the instrument moreover depens upon the damping of the instrument, so

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[1] M. ISHIMOTO, *Bull. Earthq. Res. Inst.*, 9 (1931), 316.

that the damper had constantly to be adjusted in order to modify the viscosity of the oil to keep the instrument under the same condition as shown in the figure.

To the auther's regrets, it was found in observing earthquakes with these acceleration seismographs that the periods of the ground motions, which consist in the main of acceleration, were generally shorter than the periods of the instruments themselves. The instrument is very sensitive to such short period vibrations, that is, readily affected by the period of the vibrations. For these reasons the instruments were frequently calibrated by a simple apparatus, designed to apply forces of varying frequency to the heavy bobs of both instruments by a rubber band stretched between the heavy bob and an eccentric point on a massive wheel which is controlled by hand. Every effort was made to keep the instruments under the same conditions throughout the period of investigation. Nevertheless, the results, particularly those concerning the magnitudes of the acceleration of the earthquakes obtained by these instruments, may contain some uncertainties. At any rate, it is very desirable to use instruments whose own periods are very much shorter than the periods of the seismic waves. We must bear in mind however that the sensitivity of an acceleration seismograph[2] is proportional to the square of its own period, so that the sensitivity diminishes rapidly as the period of the instrument becomes shorter.

2. The Periods of Earthquake Waves.

Authorities like the late Prof. F. Omori,[3] the late Prof. K. Suyehiro,[4] and Professor A. Imamura[5] agree that the dilluvial ground about Hongô, a part of the hilly district of Tôkyô, has a mode of free oscillation of a period of about 0·3 sec. They also showed that the alluvial ground in the lower section of Tôkyô has a mode of free oscillation of a longer period.

According to Professor M. Ishimoto,[6] the earthquake periods most frequently observed with acceleration seismographs at Hongô and Marunouti (the latter in the lower section) are 0·3 sec. and 0·6 sec. respecti-

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[2] M. ISHIMOTO, *loc. cit.*, 317.

[3] F. OMORI, *Bull. E. I. C.*, 2 (1908), *Pub. E. I. C.*, 11 (1902), 13 (1903).

[4] K. SUYEHIRO, *Bull. Earthq. Res. Inst.*, 7 (1929).

[5] A. IMAMURA, *Bull. Earthq. Res. Inst.*, 7 (1929).

[6] M. ISHIMOTO, *Bull. Earthq. Res. Inst.*, 10 (1932), 171.

vely. At Hongô, the period of acceleration of the ground motion is not constant throughout an earthquake, but lengthens as the earthquake continues, being about 0·2~0·3 sec. in the preliminary portion and about 0·3~0·4 sec. in the principal portion of an earthquake.[7] This suggests that the ground about Hongô is subject to free oscillations, somewhat resembling the longitudinal and transverse vibrations of a bar, during the preliminary and the principal portion of an earthquake. Moreover, it was observed by an ordinary seismometer that, at Hongô and Marunouti, the energetic portion of the movements of near earthquakes had the

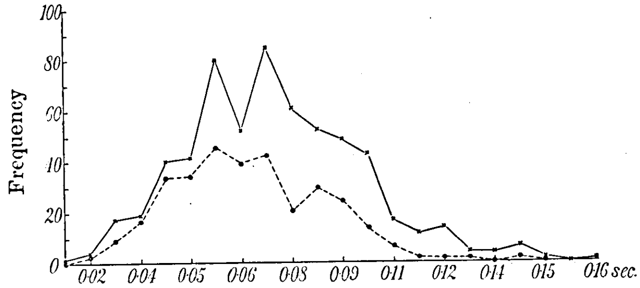

Fig. 2. The frequency distribution of the periods of waves in the earthquake of April 12, 1932.
● represent that of P-phase.
× represent that of S-phase.

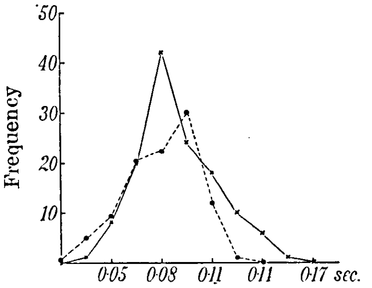

Fig. 3. The frequency distribution of the periods of waves in the earthquake of June 16, 1932.
● represent that of P-phase.
× represent that of S-phase.

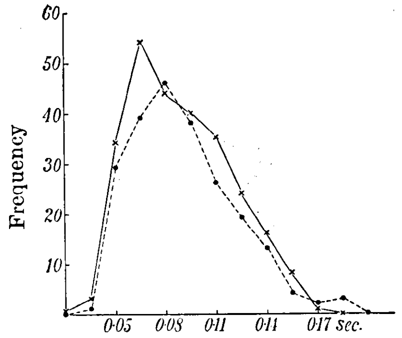

Fig. 4. The frequency distribution of the periods of waves in the earthquake of June 28, 1932.
● represent that of P-phase.
× represent that of S-phase.

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[7] M. Ishimoto, *Bull. Earthq. Res. Inst.*, **9** (1931), 480.

same period as that of the acceleration of those earthquakes.

Next, the frequency distributions of the periods of waves in some of the near earthquakes observed by acceleration seismographs at Mt. Tukuba are shown in Figs. 2, 3 and 4. As will be seen in these figures, the maximums in these frequency curves are at about 0·08 sec. in both the preliminary and principal portions of the earthquakes.

At Mt. Tukuba we heard earth-sounds[8] in most of the felt earthquakes and even in unfelt earthquakes of near origin, which is understandable by assuming that sound waves will be induced by refraction into the atmosphere by earthquake waves of high frequency, as above shown.

In this mountain again it is observed with ordinary seismometers in the case of near earthquakes that the period of the ground motions is about 0·16 sec., which is twice that of the acceleration of earthquakes. Waves with a period of 0·08 sec. are observed as ripples among the longer waves. See Fig. 5.

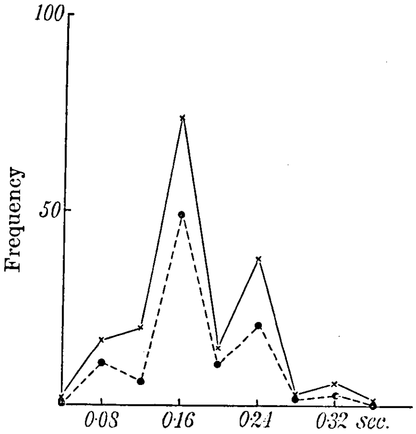

Fig. 5. The frequency distribution of the periods of waves in near earthquakes observed with an ordinary seismometer.
● represent that of P-phase.
× represent that of S-phase.

3. The Relation between the Magnitude of Acceleration and the Intensity of Earthquakes.

Comparing the maximum accelerations of earthquakes and the intensities to the senses of the corresponding earthquakes, Professor Ishimoto[9] found that at Hongô, Tôkyô, the limit of bodily sensation is 0·5 gal. The earthquake intensity scale under consideration is that adopted by the Central Meteorological Observatory of Japan. Professor Ishimoto also found that the limit of each scale of earthquake intensity, or acceleration is just 4 times that of the one that precedes it. He moreover found that Weber-Fechner's law of sensation, which is that the sensation increases in arithmetical progression as the stimulus increases in algebraical progression, applies here.

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[8] F. OMORI, *Pub. E. I. C.*, 22 A (1908), 1.

[9] M. ISHIMOTO, *Bull. Earthq. Res. Inst.*, 10 (1932), 614.

The relation between the magnitudes of maximum acceleration and the numbers in the intensity scale of near earthquakes at Mt. Tukuba is shown in Fig. 6. As will be seen in the figure, at Mt. Tukuba the shaking of the ground by an earthquake is noticed only when the maximum acceleration of the motion is greater than 1·7 gal. We also notice that the magnitude of acceleration defining the number in the scale of intensities becomes nearly as much as four times that of the number that precedes it as the number advances.

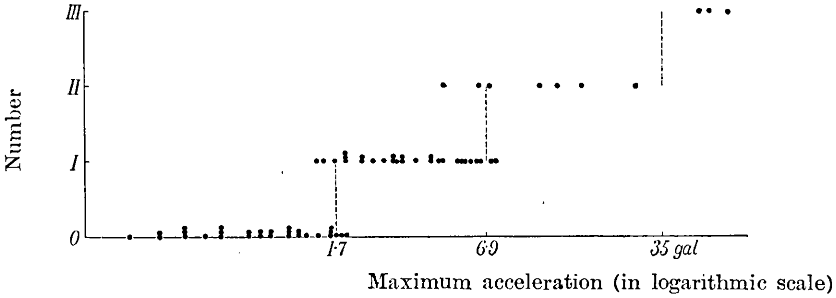

Fig. 6.

For reference, the magnitudes of acceleration for each grade of the intensity scale at Mt. Tukuba and at Hongô, Tôkyô, are shown in the following table.

Intensity	Acceleration of Earthquakes	
	at Mt. Tukuba	at Hongô, Tôkyô
0	0~1·7 gal	0~ 0·5 gal
I	1·7~6·9	0·5~ 2·0
II	6·9~35	2·0~ 8·0
III	35~ —	8·0~32·0

Not long ago the late Professor Suyehiro[10)] determined by experiment the minimum accelerations of oscillations of various period which are felt by the unaided senses.

The results obtained by him and also those obtained at Hongô and at Mt. Tukuba are plotted on the same figure, as shown in Fig. 7.

The late Professor Omori[11)] obtained 1·7 gal as the mean of the

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10) K. Suyehiro, *Proc. Imp. Acad.*, 5 (1929), 411.

11) F. Omori, *Pub. E. I. C.*, 11 (1902), 60.

lowest intensities felt of earthquakes, from seismometrical observations at several places in Tôkyô. With these data, the author studied the law governing the dependence of the limit of sensibility to earthquakes upon the periods of earthquake waves. The results are shown in Fig. 8.

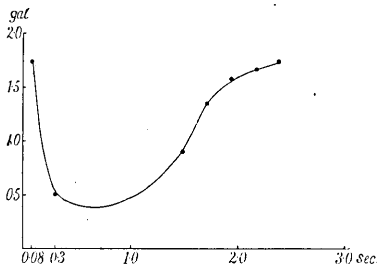

Fig. 7. Minimum accelerations of oscillations of various period which are felt by the unaided senses.

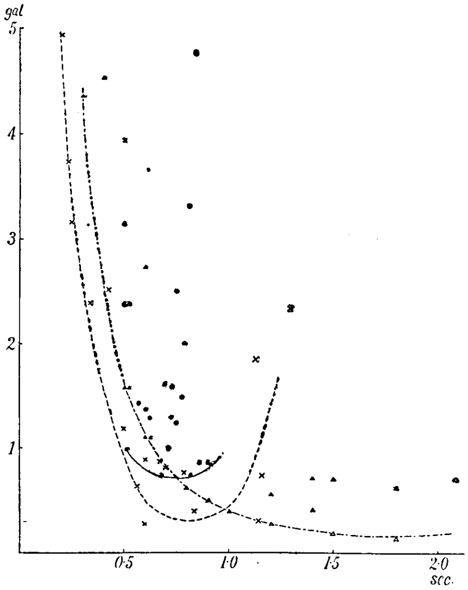

Fig. 8. × Hongô.
△ Central meteo. Obs.
● Hitotubasi.

As will be seen from these figures, the curve representing variations in the sensibilities to earthquakes according to the periods of the seismic waves, is the resonance curve of a pendulum with a period of slightly less than 1 sec., inverted.

4. Echoes or Internal Reflections of Seismic Waves.

From bodily sensation of earthquakes, it seems that the ground movements undergo somewhat periodic increase and decrease in their intensities several times.

As a matter of fact, in most of the records obtained by acceleration sesimographs at various places we can observe in several places the common phenomenon of repetitions of a periodic rise and fall of amplitudes of seismic waves, forming wave groups.

The mean periods of the wave groups for each of the two phases of earthquakes in three different localities are shown in the following table.

Locality	The mean period of the wave groups	
	in P-phase	in S-phase
Mt. Tukuba	0·80 sec.	0·97 sec.
Hongô, Tôkyô	2·8	3·1
Marunouti, Tôkyô	3·2	3·4

On the other hand, if we consider the frequency distributions of the periods of the wave groups at Mt. Tukuba, we shall find that the most frequent ones are 0·6 sec. in the P-phases and 1·0 sec. in the S-phases, so that the latter is 1·67 times larger than the former. See Fig. 9.

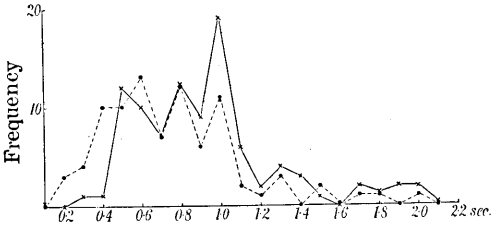

Fig. 9. The frequency distribution of the periods of the wave groups at Mt. Tukuba.
● represent that of P-phase.
× represent that of S-phase.

For earthquakes at the foot of Mt. Tukuba, the records obtained by acceleration seismographs are quite simple, consisting of a few wave groups in each phase, as will be seen in Figs. 16, 17, 18 and 21.

The durations of the main part of each of the two phases of earthquakes in the above cases are tabulated below.

Date of earthquake	Duration of the main part of the earthquake				The ratio T_2/T_1	
	in P-phase (T_1) (E-W)	(N-S)	in S-phase (T_2) (E-W)	(N-S)	(E-W)	(N-S)
April 9, 1932	1·38 sec	1·27 sec	2·43 sec	2·65 sec	1·76	2·08
April 21	0·69	0·64	0·95	1·06	1·38	1·66
May 20	1·22	——	2·02	——	1·66	——
June 22	——	0·90	——	1·54	——	1·70
June 23	0·54	——	0·85	——	1·58	——
June 28	0·95	0·95	1·59	1·59	1·67	1·67
July 1	0·74	0·85	1·27	1·27	1·72	1·49
July 5	0·85	1·06	1·38	1·70	1·62	1·60
Sept. 19	0·85		1·38	——	1·62	——
Sept. 24	1·17	0·85	2·22	1·59	1·90	1·87
Mean	$T_1=0·92$		$T_2=1·59$		$T_2/T_1=1·69$	

As will be seen in the table, the S-phase has a longer duration than the P-phase in the ratio 1·69.

We made a seismic wave analyser with a proper period of 0·09 sec. and a damping factor $\upsilon = a_1/a_2 = 2$, after the pattern of Suyehiro's seismic wave analysers, the instrument having been set up to record the NW-SE component of earthquakes. It is shown in Fig. 14.

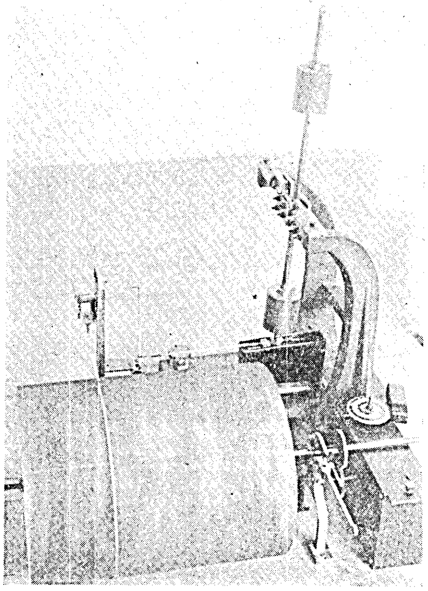
Fig. 14. A seismic wave analyser with a proper period of 0·09 sec.

Some examples of records obtained with this instrument are shown in Figs. 15, 17, 18, 19 and 20.

Well-defined wave groups of seismic waves may be observed in these figures.

In this case, the mean interval between the two successive wave groups in the P-phase is 0·82 sec. and that in the S-phase is 1·34 sec., the latter being longer than the former by as much as 1·72 in the mean. Moreover, in cases of near earthquakes at the foot of Mt. Tukuba, the mean duration of the main parts of the P-phases is 1·19 sec. (T_1) and that of the S-phases 2·01 sec. (T_2), and the mean ratio $T_2/T_1 = 1·69$.

As just stated, according to the results of observations made with acceleration seismographs and a seismic wave analyser at Mt. Tukuba, we know that an earthquake consists of many wave groups, the periods of these wave groups being different for the two phases of earthquake, those in the S-phase being longer than those in the P-phase by as smuch as nearly 1·69.

According to Professor K. Sezawa's[12] mathematical investigations, the period of the echoes of seismic waves at the boundaries of a layer of thickness H is expressed by the formula

$$T = 2H/V,$$

where T is the period and V is the velocity of the seismic waves.

By writing the periods of wave groups in the P-phase and in the

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12) K. SEZAWA, *Bull. Earthq. Res. Inst.*, **10** (1932), 1.

S-phase T_1 and T_2 respectively, they are expressed by the following formulae.

$$T_1=2H/V_1, \text{ and } T_2=2H/V_2,$$

where V_1 and V_2 are the velocities of the waves in the P-phase and in the S-phase. Consequently

$$T_2/T_1=V_1/V_2.$$

According to Professor Imamura, the velocities of seismic waves in the Kwantô district are as follows.

Layer	V_1	V_2	V_1/V_2
Upper Layer	5·0 km/sec	3·15 km/sec	1·59
Second Layer	6·1	3·70	1·65
Bottom Medium	7·5	4·45	1·69

As the ratio T_2/T_1 works out to 1·69 from our observations at Mt. Tukuba, it is highly probable that the wave groups of seismic waves are due to the echoes or multiple reflections at the boundaries of a layer in the earth's crust. The Poisson's ratio of this layer may be about 0·23.

As the mean period of the wave groups is about 0·7 sec. in the S-phase, and about 1·2 sec, in the S-phase, the thickness of the layer is about 2 km if we assume that the velocity of the dilatational waves in the layer is 5·0 km/sec.

According to observations made by the late Professor Suyehiro[13] with his seismic wave analysers at Hongô, Tôkyô, the analyser with a proper period of 0·3 sec. resonated many times with the wave groups of seismic waves. Since in this case, the magnifications of the instruments were small, they were only sensible to the S-phases in most of the earthquakes observed.

The frequency distribution of the intervals between the two successive wave groups in the records of earthquakes obtained by the 0·3 sec. analyser is shown in Fig. 10. The figure shows two frequency maxima

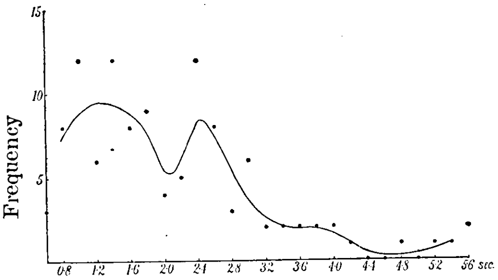

Fig. 10.

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[13] K. Suyehiro, *loc. cit.*

at 1·2 sec. and 2·4 sec.

It seems to the author that they are due to multiple reflections at the boundaries of two layers in the earth's crust, each having a thickness of several kms.

Moreover, in his paper on the seismic observations at Hongô with his acceleration seismograph Professor Ishimoto[14] noticed that solitary waves appeared repeatedly with a period of about five or six seconds, which he explained as multiple reflections at the boundaries of a surface layer.

It may be added that at Mt. Tukuba we heard earth-sounds when the earthquakes were near, especially at the P-phases. In the case of earthquakes at the foot of Mt. Tukuba, which earthquakes consisted of quite simple wave groups as will be seen in Figs. 17 and 18., we heard simple sounds like "boom," "boom, boom" (very short). On the other hand, in the case of an earthquake with many wave groups, as is shown in Fig. 15., we always notice rumbling noises like those of distant thunder.

5. The Scattering of Seismic Waves.

The late Professor F. Omori[15] studied the ratio of the magnitude of maximum amplitude of the principal portion to that of the preliminary tremor with respect to the focal distance of the earthquakes observed at Mt. Tukuba. Some of his data are plotted in Fig. 11. As will be seen in the figure, the S-phases were several times larger than the P-phases in their amplitudes, and the ratios increased as the focal distances decreased.

The author also after studying the same subject with earthquakes observed by ordinary seismometers at Mt. Tukuba, obtained identical results. It is shown in Fig. 12.

The author further studied the question of ratio, using the data obtained with acceleration seismographs. The result is shown in Fig. 13.

In contrast to the foregoing, we notice that, in the figure, the ratios of the magnitude of the main portions of earthquakes to their preliminary tremors are dispersed about a mean value of 3·5, independent of

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[14] M. ISHIMOTO, *loc. cit.*

[15] F. OMORI, *loc. cit.*

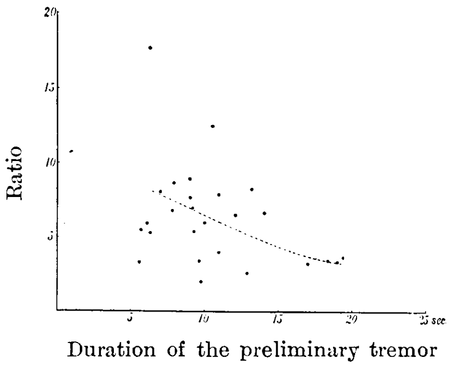


Fig. 11.

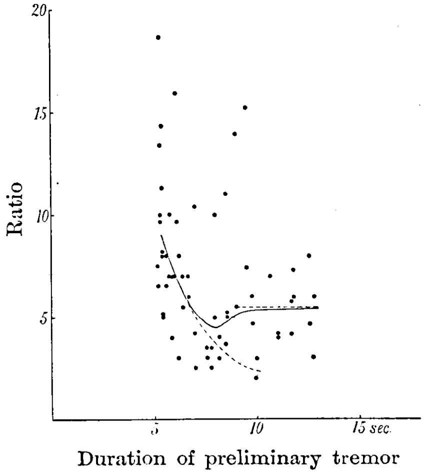


Fig. 12. The lower broken line represents the case of earthquakes of inland origin. The upper broken line represents mostly the case of earthquakes of oceanic origin.

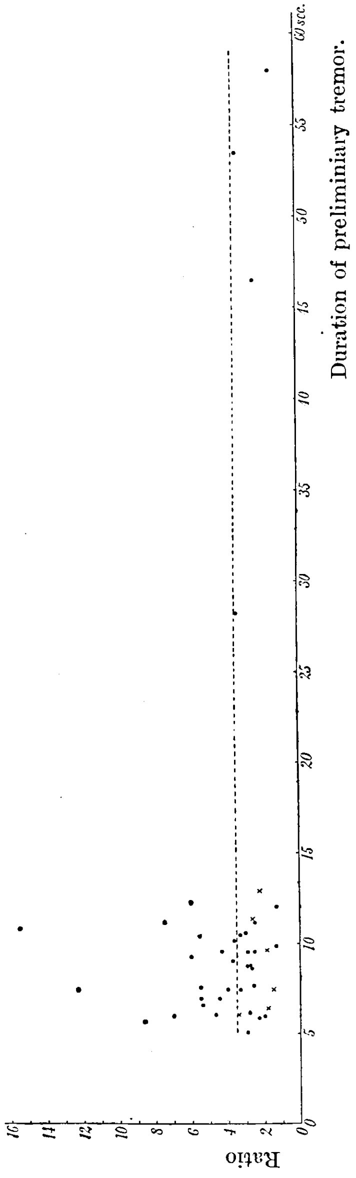


Fig. 13.

the focal distance.

The ratio in question is quite complex, depending upon the mechanism of the earthquake origin, the azimuthal direction of the station with respect to the origin, the bending of the seismic rays in the earth's crust, the reflections and refractions at the discontinuous boundaries, especially at the surface of the earth, and the direction of the oscillation of seimic waves.

Professor Ishimoto suggests that, just as in the case of scattering of solar rays by dust and other particles in the atmosphere, seismic waves are scattered by certain obstacles, differing in elasticity from the surrounding media and with dimensions comparable to the wave length of the earthquake waves, whether such obstacle be a cavity in the earth's crust, a magma pocket, hard rock masses, or crustal blocks.

The intensity of the scattered wave is inversely proportional to the fourth power of the wave length, so that its amplitude is inversely proportional to the square of the wave length.

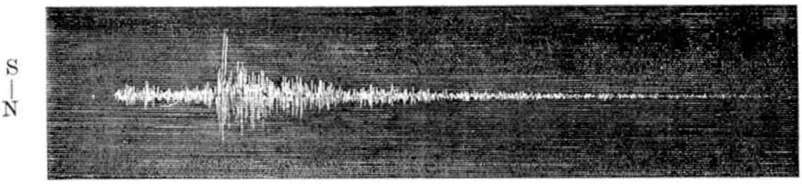
As above stated, in earthquakes observed at Mt. Tukuba, the periods of the dilatational and the distortional waves are the same, so that if we confine out attention to the effect of the scattering the ratio in question is equal to 3, assuming that Poisson's ratio $\sigma = 0{\cdot}25$. There are moreover characteristic features in the two different phases in the records of earthquakes, that is to say, the P-phases are fairly long with somewhat constant amplitudes, while the S-phases decay out logarithmically, especially in earthquakes about Tôkyô and under the Kastmanada (a part of the Pacific ocean on the *NE* side of the Kwantô district). This characteristic also suggests scatterings of seismic waves, since waves of short wave length may be reflected mostly from near objects and thus die away quickly, while waves of longer wave length return from near and distant objects and last longer.

Although records of earthquakes that have originated at the foot of Mt. Tukuba are very simple, those of earthquakes that have originated at Kasimanada and about Tôkyô are quite complex. In the former the ratios mentioned above are rather small as will be seen in the case of those marked × in Fig. 13. It seems to the author that the objects scattering the seismic wave may be densely or thinly distributed according to locality.

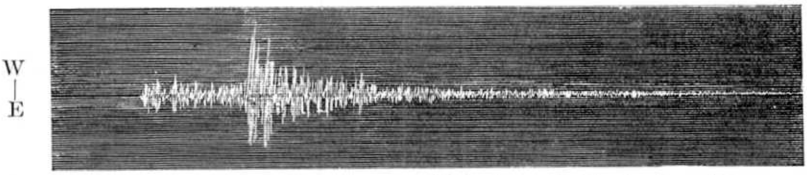
6. Conclusions.

a. The period of seismic waves most frequently observed with the acceleration seimograph at Mt. Tukuba is 0·08 sec.

b. The slightest acceleration of earthquakes which we can feel with the unaided senses at Mt. Tukuba is 1·7 gal. Our sensibility to earthquakes is in some respects like the sensitivity of a pendulum to external

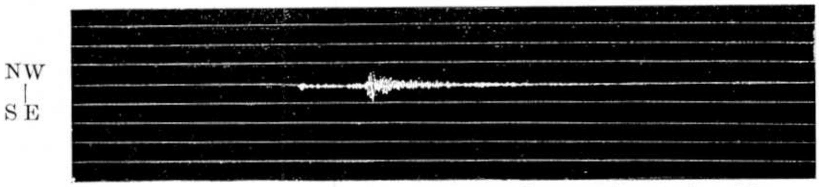


(1·2×the actual.)



(1·2×the actual.) 1 min.=151 mm.
1 gal=0·71 mm.

(Ishimoto Acceleration Seismograph Diagrams.)



(1·7×the actual.) 1 min.=98 mm.

(Wave Analyser Diagram.)

Fig. 15. The Earthquake of June 16, 1932.

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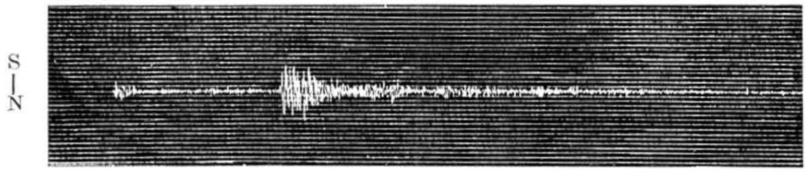
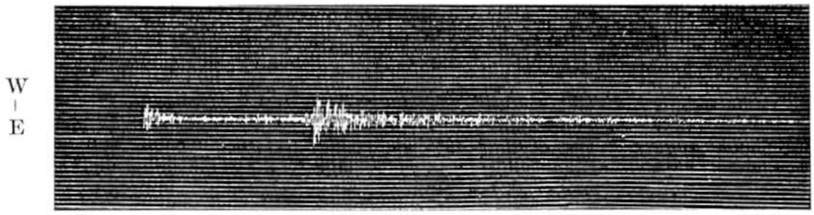
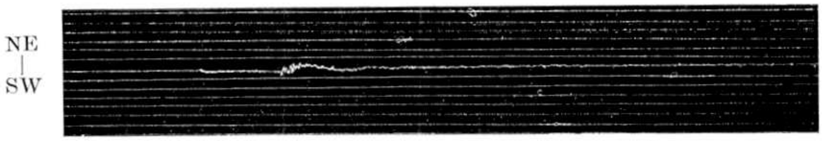


(1.9×the actual.)

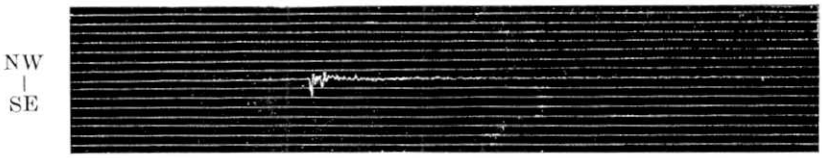


(1·9×the actual.) 1 min.=239 mm.
1 gal=1·12 mm.

(Ishimoto Acceleration Seismograph Diagrams.)



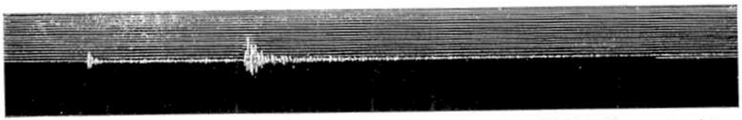
(1·7×the actual.)



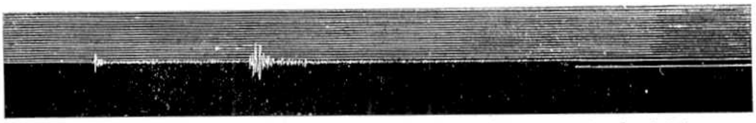
(1·7×the actual.) 1 min.=120 mm. magnification=50.

(Ordinary Seismograph Diagrams.)

Fig. 16. The Earthquake of June 22, 1932.

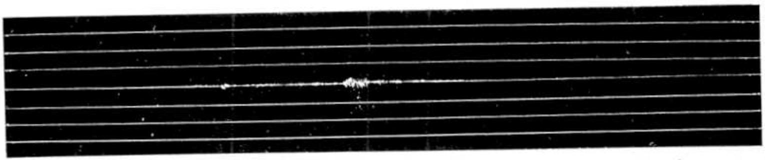


(1·08 × the actual.)



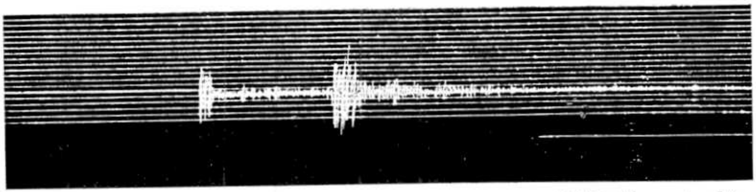
(1.08 × the actual.) 1 min. = 136 mm. 1 gal = 6·04 mm.

(Ishimoto Acceleration Seismograph Diagrams.)

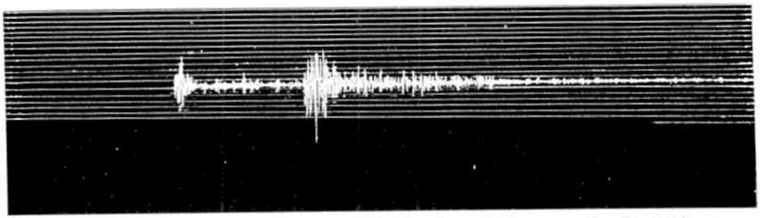


(Wave Analyser Diagram.) (1·6 × the actual.)
1 min. = 105 mm.

Fig. 17. The Earthquake of June 28, 1932.

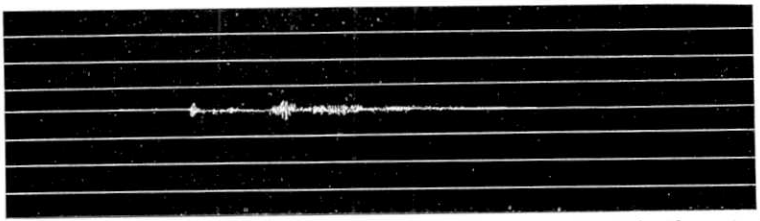


(2.35 × the actual.)



(2·35 × the actual.) 1 min. = 148 mm. 1 gal = 1·38 mm.

(Ishimoto Acceleration Seismograph Diagrams.)



(Wave Analyser Diagram.) (2·3 × the actual.)
1 min. = 88 mm.

Fig. 18. The Earthquake of July 5, 1932.

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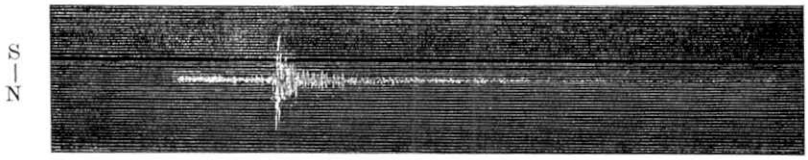
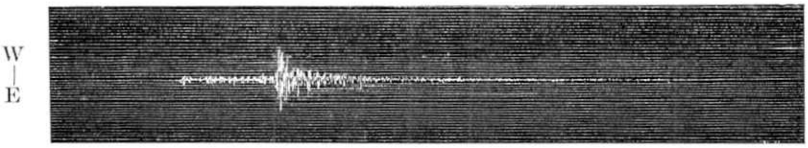
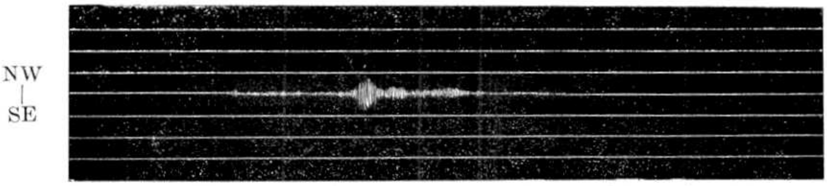


(1·2 × the actual.)



(1·2 × the actual) 1 min. = 75 mm.
1 gal = 0·71 mm.

(Ishimoto Acceleration Seismograph Diagrams.)



(1·9 × the actual.) 1 min. = 89 mm.

(Wave Analyser Diagram.)

Fig. 19. The Earthquake of Aug. 1, 1932.

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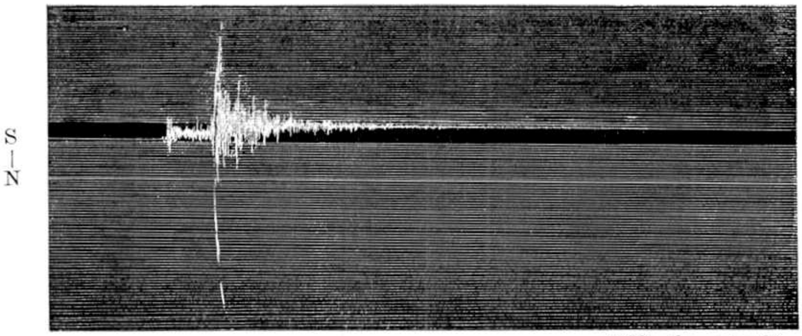
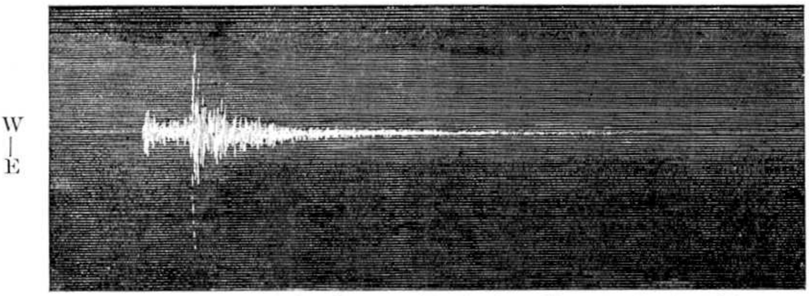
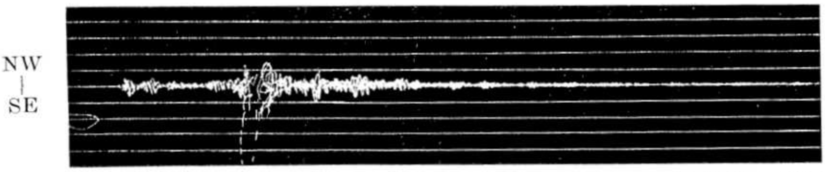


(1·08 × the actual.)



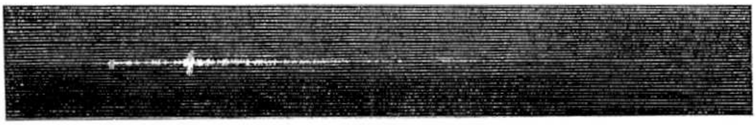
(1·08 × the actual.) 1 min. = 68 mm. 1 gal = 0.64 mm.

(Ishimoto Acceleration Seismograph Diagrams.)

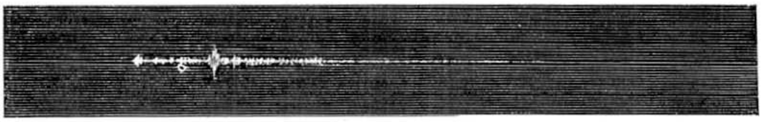


(Wave Analyser Diagram.) (1·4 × the actual.) 1 min. = 70 mm.

Fig. 20. The Earthquake of Aug. 7, 1932.



(1·2 × the actual.)



(1·2 × the actual.) 1 min. = 76 mm. 1 gal = 0·71 mm.

(Ishimoto Acceleration Seismograph Diagrams.)

Fig. 21. The Earthquake of Sept. 19, 1932.

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forces.

c. Earthquakes observed at Mt. Tukuba usually consist of many wave groups as the result of echoes or multiple reflections at the boundaries of layers in the earth's crust.

d. Some earthquake phenomena seem to be due to scattering of seismic waves by certain objects in the earth's crust or below it as already mentioned.

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 kind assistance in the course of these studies.

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6. 筑波山に於ける加速度地震計に依る地震觀測報告

地震研究所　井上宇胤

1. 筑波山に於ては加速度地震計に依つて觀測される地震波の最も優越せる週期は 0·08 秒である. 從つて筑波山地方に於て屢々經驗される鳴動の現象は此の種の地震波の大氣中への屈折に依つて生ずるものと考へられる.

2. 筑波山に於て人體に感じ得る地震波の最小加速度は 1·7 ガルである.

尙色々な異なつた週期の地震波に對する人體の感度は一秒に少し足りない固有週期を有する振子の外力に對する感度に類似する事を知つた.

3. 筑波山に於ては加速度地震計及び地震波共鳴器に依る地震記象に多數の波群が見られる。此等の波群は地殼內の層の境に於ける反響に依る事を知つた.

4. 地震波が地殼內の障害物に依つて散亂されて居ると考へられる場合のある事を示した.