

guages showing constant periods proper to different places of observation.*

20. *Remarks on the period of the earthquake motion.*—The average period in distant earthquakes remains constant throughout the end portion. Within certain limits, the period of the different types P_1 P_2 P_8 may depend on the distance between the earthquake origin and the place of observation. This and other questions shall be discussed on another occasion, but in the meanwhile I may state that long-period undulations also exist in earthquakes of near origin. Thus, for instance, in the Kiushiu earthquakes, Nos. 236 and 237, the periods of 31.3 to 35.4s were recorded in Tokyo. Different kinds of waves are probably originated simultaneously at the seismic origin, but quick-period vibrations are soon dissipated in consequence of the viscosity of the material forming the earth's crust, while slow undulations are less subject to such a dissipation and travel to great distances.

IV. ON THE NATURE OF THE LONG-PERIOD UNDULATIONS OF EARTHQUAKES.

21. About two years ago I expressed the view that the slow-period undulations of great earthquakes are probably *horizontal*, and not tilting, movements.† This supposition was based on the fact that, in the earthquake of Nov. 7th, 1898, the range of motion was equally large in the diagrams from two different horizontal pendulum apparatus, both in the E W direction, which ought to have been differently sensitive to the tilting of the ground, if any.

Recently I have observed a number of earthquakes simultaneous-

* See Vol. XXXIV of the Reports (Japanese) of the Earthquake Investigation Committee in which the present writer discusses in detail the tide gauge diagrams at different places in Japan, in reference to the causes of sea-waves.

† Jour. Coll. Sc. Imp. Univ. Tokyo. Vol. XI. 1899.

ly with the three horizontal pendulum apparatus A, B and C. (See § 7). A glance at their diagrams shows that the amplitude depends on the multiplication ratio of the writing pointer, and not on the sensibility of the pendulums to tiltings, in so far as the motion recorded is not confused by the proper oscillations of the heavy "steady mass" themselves. I shall next discuss, as an example of a seismic disturbance with very slow undulations, the diagrams of the earthquake of Oct. 29th, 1900.

22. *The earthquake of Oct. 29th, 1900 ; 6h 31m 52s.*

Total duration=4 h.

This was a very large earthquake at a great distance, and the ground continued more or less in a state of motion for several hours. The earthquake was satisfactorily recorded by the three horizontal pendulums A, B and C at Hongo as well as by the apparatus D at Hitotsubashi. The diagrams from the two pendulums C and D are reproduced in Pls. XII and XIII; *a* is the beginning of the earthquake; *ab* and *bc* are respectively the 1st and 2nd preliminary tremors; and *c* is the commencement of the principal portion.

The earlier part *cd* of the principal portion consists of very slow undulations, whose elements measured from the four diagrams are as follows :—

- | | |
|-------|---|
| (1) { | Hor. Pendulum A : EW component, Hongo ; |
| | $\left\{ \begin{array}{l} \text{max. } 2a=0, 26\text{mm.}, \\ \text{aver. period}=45,5 \text{ s.} \end{array} \right.$ |
| | Hor. Pendulum B : NS component, Hongo ; |
| | $\left\{ \begin{array}{l} \text{max. } 2a=0,31 \text{ mm.}, \\ \text{aver. period}=41,8 \text{ s.} \end{array} \right.$ |
| | Hor. Pendulum C ; EW component, Hongo ; |
| | $\left\{ \begin{array}{l} \text{max. } 2a=0,35 \text{ mm.}, \\ \text{aver. period}=45,3 \text{ s.} \end{array} \right.$ |
| | Hor. Pendulum D ; EW component, Hitotsubashi ; |
| | $\left\{ \begin{array}{l} \text{max } 2a=0,36 \text{ mm.}, \\ \text{aver. period}=47,0 \text{ s.} \end{array} \right.$ |

Then follows the *quick-period phase*, whose elements are as follows :—

- (2) {
- Hor. Pendulum A : EW component, Hongo ;
 $\begin{cases} \text{max } 2a = 1.15 \text{ mm.}, \\ \text{aver. period} = 31.0 \text{ s.} \end{cases}$
 - Hor. Pendulum B : NS component, Hongo ;
 $\begin{cases} \text{max. } 2a = 0.49 \text{ mm.}, \\ \text{aver. period} = 26.0 \text{ s.} \end{cases}$
 - Hor. Pendulum C : EW component, Hongo ;
 $\begin{cases} \text{max. } 2a = 1.15 \text{ mm.}, \\ \text{aver. period} = 31.0 \text{ s.} \end{cases}$
 - Hor. Pendulum D : EW component, Hitotsubashi ;
 $\begin{cases} \text{max. } 2a = 1.9 \text{ mm.}, \\ \text{aver. period} = 30.0 \text{ s.} \end{cases}$

In the above measurement, the ranges of motion, $2a$, have been obtained on the assumption that they were horizontal movements, that is, by dividing the recorded movements by the multiplication ratio of each instrument. With respect to (1), where the average period was about $45\frac{1}{2}$ s, the two EW component apparatus C and D thus gave practically identical results, while the apparatus A recorded a slightly smaller max $2a$. Considering, however, the extreme length of the period, these three results may be regarded as being very near to each other; since, in cases like this, a slight difference in the amount of friction between the writing index and the record receiver may easily produce a sensible error.

With respect to (2), where the period was somewhat quicker and equal to 31 s, the two EW component apparatuses at Hongo, A and C, gave exactly identical results. The Hitotsubashi apparatus D gave a larger max. $2a$, due probably to the proper period of the pendulum being very near to the period of the earthquake motion.

The periods of free oscillation of the three EW component horizontal pendulums at Hongo and Hitotsubashi, whose dimensions were already given in § 7, were in this case respectively 28,0 s, 60,0 s and 29,7 s. Let us denote by r_A , r_C and r_D the angular displacements of the ground corresponding to 1 mm. motion of the writing indices of the three apparatus. We have then, by equation (1),

$$r_A = 0,105$$

$$r_C = 0,0229$$

$$r_D = 0,112$$

Or if δ_A , δ_C and δ_D denote the displacements of the writing indices of the three instruments for the tilting of 1'', we have

$$\delta_A = 9,5 \text{ mm.}$$

$$\delta_C = 43,7 \text{ ,,}$$

$$\delta_D = 8,9 \text{ ,,}$$

Thus if the slow undulations under consideration had been due to the tilting of the ground, the apparatus C ought to give records of motion nearly 5 times larger than the apparatus A and D. Such, however, is very far from being the case.

23. Another point, which bears on the question of the nature of the slow earthquake undulations, was suggested to me by Dr. Charles Davison. This is the amount of the vertical amplitude which would exist according to the assumption that these slow movements are due to the tilting of the ground. As illustrative examples I shall take the severe Japan earthquake of Nov. 25th, 1899; the Java earthquake of Sept. 30th, 1899; the Alaskan earthquake of Sept. 4th, 1899; and the Indian earthquake of June 12th, 1897. The first three of these earthquakes are respectively Nos. 236, 207 and 193 of our list (Table I).

(a). *The Japan earthquake of Nov. 25th, 1899.*—The origin was off the eastern coast of Kiushiu at a distance of 840 km. from Tokyo.

Now the record from the horizontal pendulum C (Pl. X) shows, in the principal portion, two main series of waves, (1) and (2), whose respective maximum traces were as follows :—

(1) range*=64,0 mm., period=24,0 s ;

(2) range*=27,0 mm., period=8,0 s.

In this case, the period of free oscillation of the pendulum was 2 m, so that the sensibility to tilting was very great, as follows :—

1 mm. displacement of the writing index=0,"0057. Hence the above maximum traces of (1) and (2), if due to the tilting of the ground, would respectively correspond to the angular movements of

$$\delta_1 = 64 \times 0,"0057 = 0,"365,$$

$$\text{and } \delta_2 = 27 \times 0,0057 = 0,154.$$

If now the earth's surface be thrown, in consequence of the tilting into the form of a sine curve, each of the above δ 's may be supposed to represent the greatest angle of inclination of the surface during the passage of the particular wave in question, and we have

$$2A_1 = \frac{\lambda_1 \delta_1}{\pi} = \frac{24 \times 3,3 \times \sin 0,"365}{\pi} = 40,6 \text{ mm.},$$

$$2A_2 = \frac{\lambda_2 \delta_2}{\pi} = \frac{8 \times 3,3 \times \sin 0,"154}{\pi} = 6,3 \text{ mm.}$$

where $2A_1$ and $2A_2$ are respectively the double vertical amplitudes of the two waves under consideration, whose wave-lengths are denoted by λ_1 and λ_2 . In the above calculations the velocity of transit of the earthquake wave has been assumed to be 3,3 km. per sec. The maximum vertical accelerations would be respectively 1,4 and 1,9 mm. per sec. per. sec.

(b). *The Java earthquake of Sept. 30th, 1899.*—The record from

* These are the direct readings, not divided by the multiplication ratio of 10.

the horizontal pendulum A (Pl. VI) shows, at the commencement of the principal portion, the following large trace of motion :—

$$2a=54,0 \text{ mm.}, \text{ period}=38,0 \text{ s.}$$

In this case the period of oscillation of the horizontal pendulum was 28 s and 1 mm. displacement of the index corresponds to $0",105$ (§ 22), so that the above displacement would, if due to tilting, amount to the angular motion of

$$\delta=54 \times 0",105=5",7.$$

In this case we must take for the transit velocity the value of 4,8 km. per sec. (v_3 in the rotation of § 34), and we obtain, for the double vertical amplitude of the tilt wave,

$$2A=\frac{38 \times 4,8 \times \sin \delta}{\pi}=1610 \text{ mm.}$$

This would give the maximum vertical acceleration of 22 mm. per sec. per sec.

(c). *The Alaskan earthquake of Sept. 4th 1899.*—The record from the horizontal pendulum A (Pl. VII) shows, in the *quick-period phase* of the principal portion, a series of undulations of average period of 16,2s, whose maximum trace was 48,0 mm. The sensibility here was the same as in the preceding case, and therefore the corresponding tilting motion would be

$$\delta=48 \times 0",105=5",04.$$

Taking the transit velocity to be equal to 3,3 km. per sec. (v_5 of §§ 34,38), the double vertical amplitude would be

$$2A=\frac{16,2 \times 3,3 \times \sin \delta}{\pi}=416 \text{ mm.}$$

This gives the maximum vertical acceleration of 31,3 mm. per sec. per sec.

(d). *The Indian earthquake of June 12th, 1897.*—According to Prof. G. Agamennone, the period of large undulations as observed in Europe was about 20s, and the “maximum inclination” of the ground was 12’’.^{*} Taking here the velocity of transit to be the same as in the preceding case, namely 3,3 km. per sec., the double vertical amplitude would be

$$2A = \frac{20 \times 3,3 \times \sin 12''}{\pi} = 1220 \text{ mm.}$$

This gives the maximum vertical acceleration of 60 mm. per sec. per sec.

(e). *Summary.*—According to the calculations made above, it seems probable that in some cases, as with the Japan earthquake (a), the vertical movement of the supposed tilt wave amounts only to a few mm. or a few cm., with a corresponding maximum acceleration of only 1 or 2 mm. per sec. per sec. Such a motion could not probably be felt by us. But in other cases, as with the earthquakes of Java, Alasca and India (b, c, d), the vertical displacement, consequent to the tilt wave, would be considerable, ranging in the examples treated of, from 416 to 1610 mm; their maximum accelerations are accordingly very large and vary between 22 and 60 mm. per sec. per sec. Movements like these would be sufficiently intense as to be felt by us, and indeed a motion with an acceleration of 50 to 60 mm. per sec. per sec., may be classed as a strong earthquake shock. By way of comparison, I reproduce here from the late Prof. S. Sekiya’s work on the Tokyo earthquake measurement † the following elements of motion at Hitotsubashi:—

^{*} G. Agamennone:—*It terremoto dell’ India del 12 giugno 1897, registrato in Europa.* Rendiconti della R. Accademia dei Lincei. Vol. VII. 1898.

† S. Sekiya:—*Earthquake measurements, etc.* Jour. Coll. Sc. Imp. Univ. Tokyo. Vol. II.

Max. horizontal motion0,73 mm.

Period of max. hor. motion..... 0,96 s.

Duration of hor. motion..... 117 s.

These figures are the means deduced from 95 earthquakes observed with Prof. Ewing's seismograph at Hitotsubashi (Tokyo) during 1885—1887. From the above we see that the average maximum (horizontal) acceleration is

$$\frac{2\pi^2 \times 0,73}{0,96^2} = 15,6 \text{ mm. per sec. per sec.}$$

It may be remarked that earthquakes are felt always much stronger at Hitotsubashi than in other parts of Tokyo, and the value of the acceleration here deduced may therefore be taken as representing the intensity of motion of moderate strength. Thus it will be seen that the earthquakes of Java and Alasca observed in Tokyo, or the earthquake of India observed in Europe, ought to be felt as moderate or strong shocks, if their undulations be tiltings of the ground. Such, however, was certainly not the case. The conclusion is that the slow undulations of the earthquake motion can not, at least not generally, be regarded as tilting movements.

24. As an illustrative example of sensible slow oscillations, I may take ship's rolling motion. On board a German steamer *Prinz Heinrich* (gross tonnage about 6,000 tons), I found the lateral oscillations had a period of about 15s. When the up-and-down range of motion at the edge of the upper deck was about 1m, the movements were of course there very well felt, the maximum acceleration in the vertical direction being about 88 mm. per sec. per sec.

25. Let us next see what are the maximum accelerations of the slow earthquake undulations, supposed to be horizontal movements. For three of the earthquakes discussed in § 23, observed in Tokyo, we have the following results.

- (a). The Japan earthquake of Nov. 25th, 1899 :—
 (Slower wave) Max. acc. = 0,22 mm. per sec. per sec.
 (Quicker wave) Max. acc. = 0,83 „ „ „ „ „
- (b). The Java earthquake of Sept. 30th, 1899 :—
 Max. acc. = 0,074 mm. per sec. per sec.
- (c). The Alaskan earthquake of Sept. 4th, 1899 :—
 Max. acc. = 0,36 mm. per sec. per sec.

The maximum horizontal acceleration in each of these cases amounts to a mere fraction of one mm. per sec. per sec., an amount much too small to be felt by us, or even to be registered by ordinary seismographs.

26. *Conclusion.*—From the discussions in the foregoing § §, it will be seen that there are several difficulties in attempting to explain the slow earthquake undulations as tilting movements, while there are none in supposing them to be horizontal movements. I conclude therefore that *the slow earthquake undulations are horizontal movements.*

It must here be noted that equation (1), which I have used for calculating the sensibility to the tilting of a horizontal pendulum is strictly applicable only when the period of the earthquake undulation is sufficiently long in comparison to the period of oscillation of the horizontal pendulum itself. The estimation of the amount of tilting in the cases like the Alaskan earthquake (c) § 23, when the period of the earthquake movements was much shorter than that of the pendulum itself, is subject to a certain error. But this error causes the estimated amount of the tilting to be smaller than the actual value. Hence if properly corrected, the vertical displacement and its maximum acceleration would come out much greater than those given in § 23, which favours my argument still further.

27. With respect to ordinary *macro-seismic* movements, I have made at Hongo (Tokyo) a series of observations of earthquakes with

three sets of horizontal pendulum seismographs, whose sensibility to tilting and multiplication of horizontal motion were so arranged as to separate the horizontal motion from the tilting of the ground. The result so far obtained is that in the ordinary small and strong earthquakes, occurring so often in Tokyo, there is no tilting motion, or if any, not one sufficiently large to be recorded by means of ordinary seismographs.*

V. PULSATORY OSCILLATIONS.

28. *Pulsatory oscillations.*—Denote those small slow oscillations of the ground, whose origin is not seismic. Their average periods and ranges of motion in 70 cases between July 1898 and Dec. 1899 are collected in the following Table. These are not of course exhaustive, the measurements having only been made in so far as these movements occurred in the diagrams which contained earthquakes.

* A detailed account of these observations is given by the present Author in Vol. XXXII of the Reports (Japanese) of the Earthquake Investigation Committee.