MEASURING EARTHQUAKES[1]

II.—RESULTS.

In this paper a short account will be given of the chief results of two and a half years' observations in the Seismological Observatory of the University of Tokio. The first instruments to be successfully used were the horizontal pendulum, or rather a pair of horizontal pendulums writing a multiplied record of two rectangular horizontal components of the earth's motion on a revolving plate of smoked glass, and also a very long common pendulum. The duplex pendulum, an astatic vertical-motion seismograph, and other instruments which have been mentioned in the former article, were added later.[1]

The earliest records were those of five small earthquakes in November 1880.[2] In the first of these the vibration of the ground lasted continuously for 1½ minutes, and no fewer than 150 complete oscillations could be counted in the record. The shaking began feebly, speedily rose to a maximum, fluctuated irregularly, and died out very gradually. The greatest movement from side to side was less than one-third of a millimetre. Both

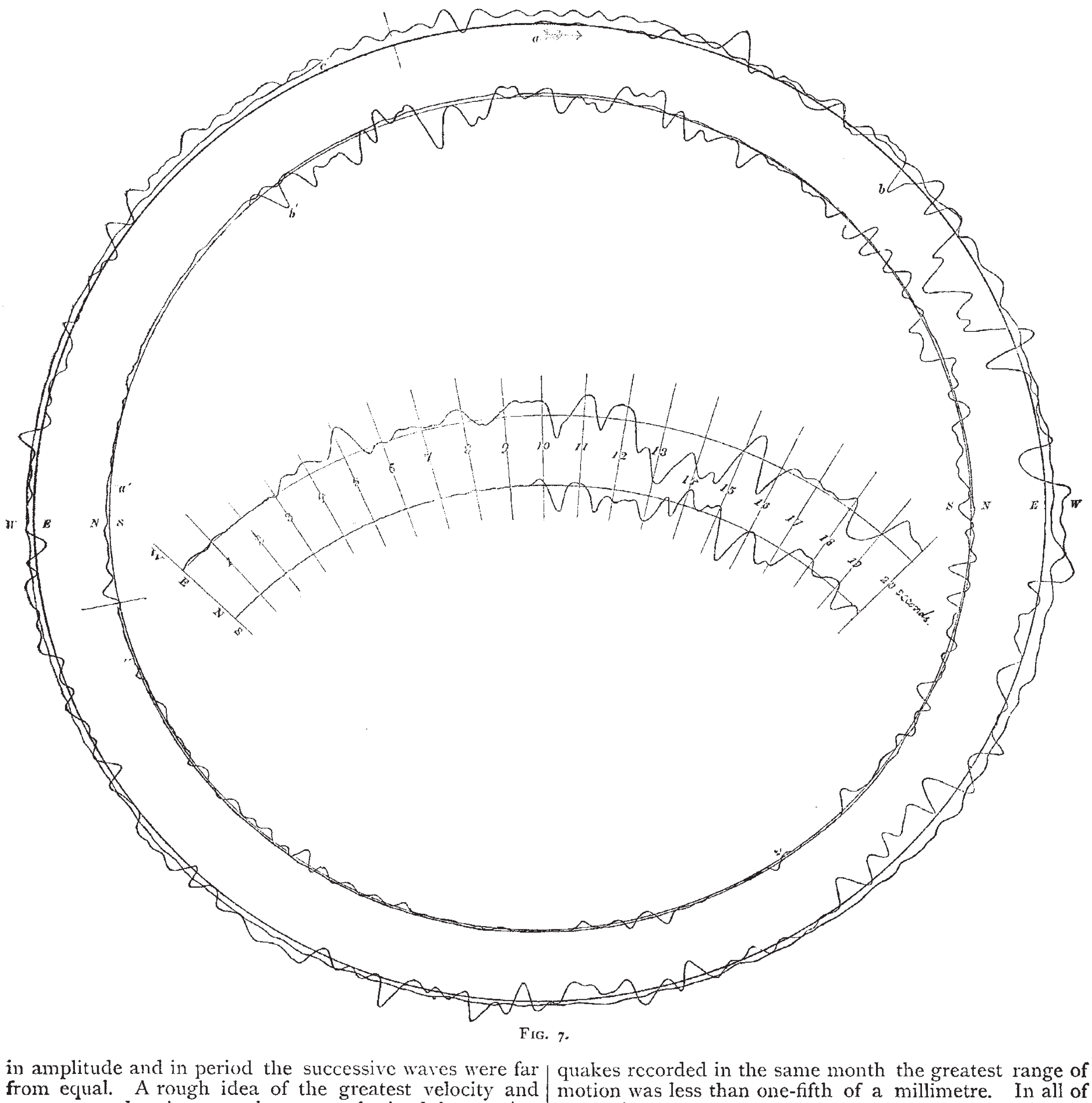

FIG. 7.

in amplitude and in period the successive waves were far from equal. A rough idea of the greatest velocity and greatest acceleration was, however, obtained by treating the greatest movement as a simple harmonic vibration, with a period of three-fifths of a second. This gave 1·6 mm. per second for the greatest velocity, and 16·4 mm. per second per second for the greatest acceleration, showing that bodies attached rigidly to the earth's surface must have experienced a horizontal force equal to about one-six-hundredth of their own weight. In three of the five earthquakes recorded in the same month the greatest range of motion was less than one-fifth of a millimetre. In all of them there were many and unequal vibrations, but in none was there any single impulse prominently greater than the other movements.

Later observations showed that these were fairly repre-

[1] Continued from p. 152.

[1] For a fuller account of the methods and results of these observations the writer may be permitted to refer again to his memoir on Earthquake Measurement, published as No. 9 of the *Memoirs of the Science Department of the University of Tokio.*

[2] Described in the *Transactions of the Asiatic Society of Japan*, vol. ix. p. 40.

sentative of a very large proportion of the earthquakes which occur so frequently in the Plain of Yedo. Earthquakes of this class do no damage to buildings, but they are strong enough to make their presence felt by the shaking and creaking of houses, and even, in the night, to startle residents out of sleep. Lamps and other pendulous bodies are frequently set into considerable oscillation through the long continuance of the disturbance, the period of some consecutive vibrations of the ground being nearly uniform and equal to the free period of the lamp. The shaking lasts rarely less than one and sometimes as much as ten minutes.

In some cases, however, the amplitude of the earth's motion is considerably greater; occasionally it rises to 5 and even 7 mm. With such an amplitude as this, and with the ordinary frequency which the earthquake waves have, the shock is more or less destructive—walls are cracked and chimneys are overthrown. The writer's observations do not include any earthquake of first-rate violence, but they show by several examples that in the alluvial soil of Tokio a sufficiently alarming and even damaging earthquake may occur, in which the range of horizontal motion is less than a single centimetre.

In the Yedo earthquakes the vertical motion is generally much less than the horizontal, and, as a rule, forms an unimportant part of the disturbance.

Fig. 7 is a copy, reduced to about half size, of the record of one of these more considerable earthquakes (on March 8, 1881), traced by a pair of horizontal pendulums on a revolving plate. The inner circle shows the N.S. component, and the outer circle the E.W. component of the displacement. The records begin simultaneously at the points marked *a'* and *a* respectively, and extend in the direction of the arrow over nearly two complete revolutions of the plate. At the point marked *c* in the outer circle, when the earthquake oscillations were slowly dying away, the writer (who happened to be present) withdrew the plate, to prevent the later portions of the record from confusing the earlier portions. By this time the earthquake had lasted for two minutes and a half, and some 200 vibrations had been registered. The motion, as recorded, was exaggerated in the ratio of 6 to 1; hence in the diagram as it appears here the displacements are nearly three times the natural size.

For the sake of exhibiting some interesting features of this earthquake more clearly, the records of the two components during the first twenty seconds of visible motion have been reproduced in the centre space of the diagram in such a manner that simultaneous parts of both are on the same radius. The short radial lines mark seconds of time. It will be seen that for three seconds the motions were very minute; then the E.W. seismograph became pretty sharply disturbed, but the other component was scarcely visible until the tenth second from the beginning.

During the tenth and eleventh seconds the phases of the two components agree in the main, but they soon diverge; and in the fifteenth second, when the motion is greater than at any other part of the whole disturbance, they differ by about a quarter of a period. Hence at that time points on the earth's surface were vibrating not in a rectilineal path but in *loops*. This is strikingly shown by Fig. 8, which shows the path (exaggerated in the ratio of 6 to 1) of a point on the earth's surface, during three seconds at this epoch in the disturbance. Starting from *p* at 13·7 seconds from the beginning of the earthquake, a surface particle described the tortuous path shown in the figure, and reached *q* three seconds later. Similar rapid changes of phase-relation occur throughout the rest of the disturbance, and in the slowly dying oscillations with which the earthquake drew to a close the writer noticed one of the pointers moving vigorously when the other was nearly at rest, and *vice versâ*.

The evidence, first clearly given in this earthquake, of the non-rectilineal character of the ground's motion, was confirmed by very many later observations. In fact in every case where the records were sufficiently large and well-defined to admit of a satisfactory comparison of the phases of the two components, the same thing was exhibited. And not only in those cases, but even in very minute earthquakes, instruments having two degrees of horizontal freedom, such as the duplex pendulum, showed in the most direct manner that the earth's movements consisted of a multitude of twists and wriggles of the most fantastic character.

An excellent example of a still sharper earthquake is given in Fig. 9—a record (reduced to half size) given by two horizontal pendulums with a multiplying ratio of four to one on a plate which was turning once in fifty-four seconds. The beginning of motion can be detected on the outer circle at *a*. At *b* and the corresponding point *b'* it increases somewhat suddenly, and during the next few seconds we have the principal motions, followed during many minutes by a long trail of lesser irregular oscillations, in which a marked lengthening of period may be detected towards the close. To allow the phase-relation during the principal part of the shock to be examined, lines (numbered 1 to 16) have been drawn by the aid of templates through corresponding points in the two records. An examination will show that the phase-relation changes: in fact when the two components are combined the movements are found to be loops, agreeing very closely with the larger loops of Fig. 10, which is a "static" record of the same earthquake given by the duplex pendulum. In a

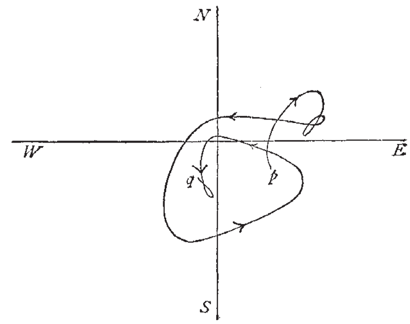

FIG. 8.

part of Fig. 10 the motions are so numerous and so much distributed over all azimuths, that the film of lamp-black has been completely rubbed away from a portion of the plate which received this record.

It frequently happens in the record of an earthquake that the motions which are first recorded are rapid vibrations, of short period and small amplitude, which are immediately followed by larger and less frequent movements. Sometimes, indeed, the former appear as a ripple of small waves superposed on larger ones. But in all cases where the short-period waves can be detected they die out early, and the later part of the earthquake consists of relatively long-period waves alone. Records of this class are exceedingly suggestive of the arrival of first a series of normal waves (that is, waves of compression and extension), constituting the rapid tremor, and then a series of transverse waves (that is, waves of distortion), forming the principal motions of the earthquake.

In fact it is difficult to explain the rapid changes of phase in the two components, or, in other words, the curved character of the horizontal movement, which most if not all the recorded earthquakes exhibit, otherwise than by supposing that the principal movements are transverse waves occurring in a plane not very much inclined to the horizon, and this conclusion is supported by the smallness of the vertical component.

It is true that the appearances presented by the diagrams could be accounted for by assuming the presence, together, of normal and transverse waves, with a nearly horizontal direction of propagation; but in that case we should expect to find normal waves occurring alone at the beginning of the earthquake with much greater amplitude than they actually have. Other still less probable solutions might be referred to; but it is safe to say that the evidence furnished by these observations goes far to prove that the earthquakes of the Plain of Yedo consist chiefly of distortions, not compressions, of the ground, and emerge at Tokio in a direction not very far from vertical.

In the older seismology it was generally assumed not only that an earthquake consists mainly of one impulse, but that the motion of the ground has a definite direction, and that that is the same as the direction of propagation of the wave. All three assumptions were false. An old piece of seismic apparatus, based on these ideas, was a group of columns of various heights standing on a plane horizontal base. These were intended to show the direction and "intensity of the shock" by falling over. It is clear enough, however, that no appliance of this kind can give intelligible results from earthquakes of such complexity as those described above. The very word

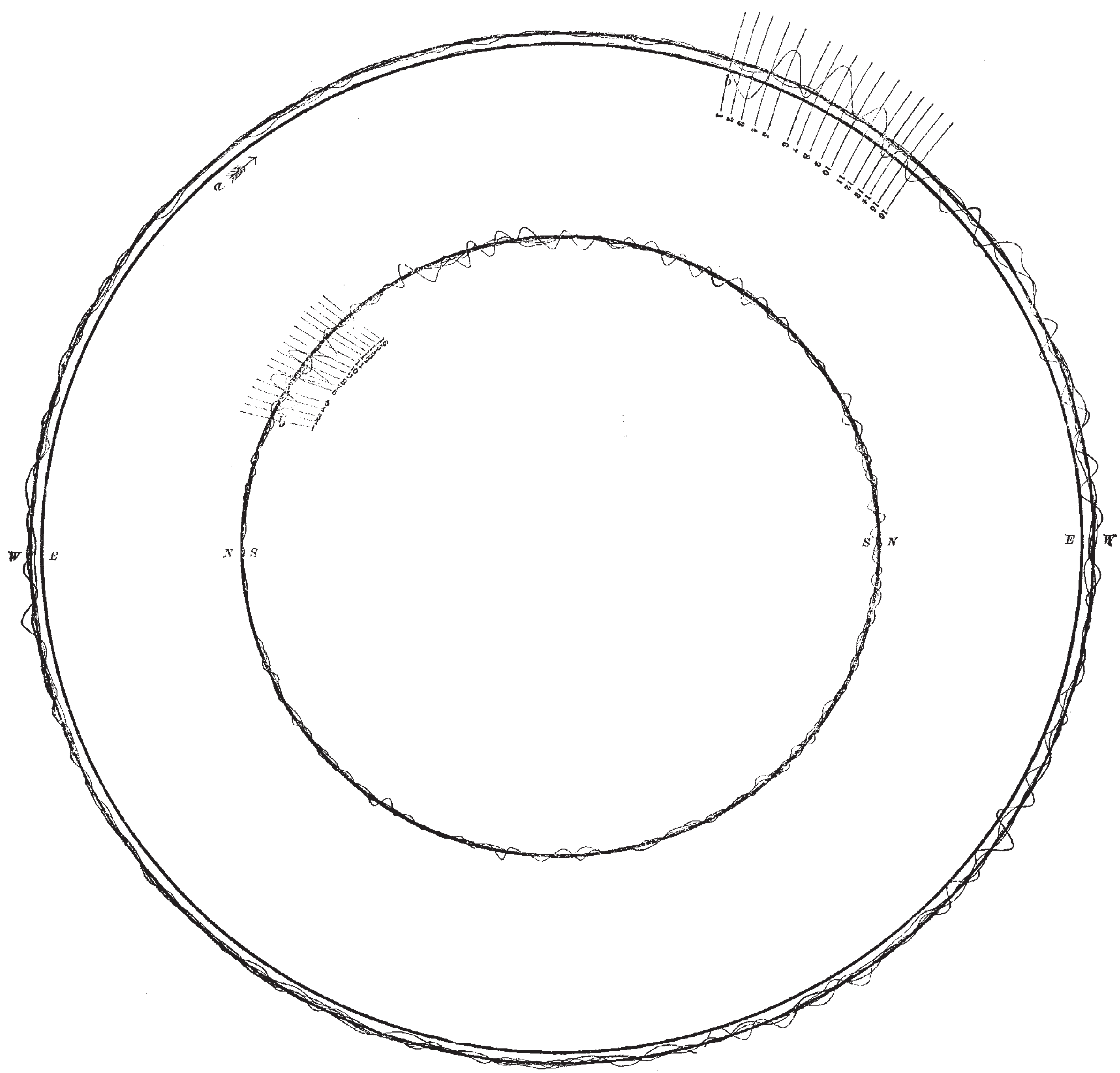

FIG. 9.

"shock," accurately as it describes the feeling produced by an earthquake, is a singularly inappropriate name for what an apathetic seismograph records.

As evidence of the accuracy of the apparatus by which the foregoing results were obtained, it should be mentioned that the records given at the same place by different instruments during the same earthquake were found to agree remarkably well. Further, the instruments were tested experimentally by placing them on a shaky table, and obtaining, side by side, two records of table-quakes, one from the so-called "steady-point" of the instrument, and the other from a point in a fixed bracket projecting from a neighbouring wall, and known to be truly steady. When the table was shaken in such a way as to give records resembling those of actual earthquakes, the agreement of the two showed conclusively that the steady-point of the instrument did remain very nearly undisturbed, and that the records were in all important particulars substantially correct.

We have then the means of accurately observing the nature of the surface motion at an earthquake observatory. But this of itself tells us nothing of the speed and direction of transit of the disturbance, particulars which are only to be learnt by connected observations made at several stations. Any one earthquake, as a whole, lasts far too long and begins too gradually to admit of the measurement of time-intervals between its arrival at different points, but if we can identify any single vibration in the records given at several stations—spread over a moderate area, and connected telegraphically with each other—the problem admits of a fairly easy solution. A recording seismograph at each station will give a complete record of the earthquake as it appears there, and if, during its progress, time signals be sent from one station and marked on all the revolving plates, it will be possible to

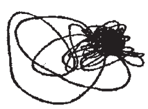

FIG. 10.

determine the differences in time of arrival of *the same phase of the same wave* at the successive stations in the group. From this, if the stations be sufficiently numerous, the speed and direction of transit, and even the origin of the disturbance, may be found with more or less precision. But all this depends on our being able to recognise at the various stations some one wave out of the complex records deposited at each, and, especially in view of the curvilinear nature of the motion, it would be hazardous to say without trial whether this can be done. To ascertain whether it can be done, and if so to organise groups of connected stations to carry out the scheme roughly sketched above, should be the next step in observational seismology.

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NOTES ON A FEW OF THE GLACIERS IN THE MAIN STRAIT OF MAGELLAN MADE DURING THE SUMMERS OF 1882-83 IN H.M.S. "SYLVIA"

THE western part of the main Strait of Magellan, to which my remarks are confined, lies between rugged and abrupt mountains, of rock mainly crystalline, but in parts of slate.

The highest peaks are not over 4500 feet high, and the height of the snow-line is about 2700 feet. The land is cut up into small areas by numerous and tortuous channels, and, on the southern side certainly, no large masses of land exist. The mountain ridges are mostly sharp and steep, and afford but little area for snow to lie in quantities, but wherever a mountain slope is moderate, there it accumulates, and forms *névé*, which may or may not descend to lower levels.

From this it will be seen that the glaciers spoken of are small, only one snow-field, the "Northbrook," being of any size. Much larger glaciers of course exist in these regions, but were not in my beat, lying either to the south about Mount Darwin and Mount Sarmiento, 7000 feet high, or to the north on the mainland bordering the western channels.

Some ice-masses are ridiculously small, one I remarked, at the end of summer, on a ledge a little below a very sharp ridge 2700 feet high, was not probably larger than 10,000 tons. It lay entirely bare of snow on the southern or shady side of the ridge, and was of blue ice.

It is evident that it is the enormous amount of the supply of material which accounts for the existence of glaciers from such small origins, and in fact the deposition of snow is going on all the year round for the majority of hours out of the twenty-four. The winds are eternally from the western quarter, are usually fresh, and, arriving moist from the Pacific against the rampart of mountains, rush up their western slopes into the colder regions, where constant condensation takes place. During my stay—about eight months—the summits of the higher snow-fields (3500 to 4500 feet) were only seen twice or thrice, so continually are the mists around them.

The daily duration of rain at the water-level during the *Sylvia's* stay of about eight months west of Cape Froward was eleven hours out of every twenty-four. The quantity corresponded to a yearly fall of 180 inches.

Though the mean temperature for the year is low, the range, summer and winter, is very small, so that flowering plants which grow on the borders of the glaciers and on exposed hills perish in England, from inability to withstand the sudden changes and lowness of the winter temperature.

The inference would seem to be that a Glacial period need not so much depend upon extreme cold as on an unlimited condensation with an equable temperature, low enough at moderate altitudes to form snow.

The glaciers are nearly entirely devoid of erratic blocks or surface moraines. Coming, as they do, over everything, down a hill-side, there is seldom an overhanging mountain to discharge blocks; where there is, the rock is so solid that the very slight changes of temperature (for the sun has no power here) is not sufficient to disintegrate it. Even the glaciers therefore that descend nearly to the sea are quite clean and spotless to the very end.

I could never make out any raised beaches, nor other signs of former lower level of the land; all the evidence is the other way. No beaches exist at the water-level of the present day. There is not enough sea in these confined channels to wash away the land, even if it was of a softer nature. The steep rocky mountain-sides dip clean into the water nearly everywhere. Thick moss covers the hill-sides wherever it can get a hold, so that it is not easy to see the true contours of them, and a more experienced eye than mine might perhaps detect a raised beach where I have failed to do so.

Glacier from Mount Wharton

Mount Wharton, 4400 feet high, on the south shores of Long Reach, sends down what I consider a rather remarkable glacier, despite its small size.

The upper part of the mountain, of a tolerably gentle slope, is of an area of about four square miles. This terminates everywhere in steep precipices, over which in different directions the blue ice, which can be seen lining the edge, tumbles, and forms *glaciers remaniés* in hollows at lower levels in several places. On the south-eastern side only is a steep slope, down which, after a series of ice-falls, a leg of glacier, one-third of a mile wide, and one mile and a half long, extends to within 150 feet of the sea-level, and a quarter of a mile from the shore. At its end it abuts against a hill, and from the fact of the ground sloping away on either side from this glacier leg, it appears that this slope is a ridge, down which the glacier comes, as it were, astride. Where it strikes the hill, it divides, and sends a final short leg towards the sea on either side of the peninsula formed by the hill.

The slope of the lower part of the glacier is 15°, and it is much crevassed, and squeezed into pinnacles and ridges, so that, when tolerably clear of snow, it looks like frozen waves.

There is no moraine on it, and, wherever I could see, it lies on the solid rock, but a few stones are carried along at the bottom of the ice, and, at its end, where it abuts against the hill, the latter is a mass of loose rounded stones (very few angular ones), up to the limit occasionally reached by the glacier, which is well and curiously marked by a narrow belt of trees, growing on the edge of the tumbled stone moraine. Behind them the hill is of solid rock, bare or moss-covered (see illustration).