ON CERTAIN SEISMIC PROBLEMS DEMANDING SOLUTION.

By John Milne.

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1. Sound Phenomena.

On January 26th, I read a short paper before the Seismological Society on the sound phenomena of earthquakes, in which there was an endeavour to show that the sounds which preceeded an earthquake were produced by short period vibrations of the ground forming the front portion of an advancing earthquake. Many earthquakes, like the solar spectrum, have extremities which are difficult to investigate. At the end of an earthquake there are vibrations which are so long in period, that the pointers and steady points of our seismographs do not give a relative movement, but follow these back and forth movements as a whole, and no record is obtained. At the commencement of a disturbance there are exceedingly rapid movements of small amplitude. With indices giving a large multiplication many of these short period movements have been recorded, but if the instrument has a small multiplication they are lost. In all probability these minute movements which have been recorded are the continuation of still smaller and more rapid movements, which on account of want of sufficient multiplication in our instruments have never yet been rendered visible. It is to these hitherto invisible motions that we are to look for an explanation of sound phenomena. Dr. C. G. Knott in his admirable paper on "Earthquakes and Earthquake sounds as illustrating the general theory of vibrations," while discussing the investigations of Lord Raleigh respecting elastic waves at a bounding surface, points out that certain of the formulæ indicate that short period vibrations have amplitudes proportionally small.

That period increased with amplitude *up to a certain point* is a fact which has been repeatedly observed, and that it should now be confirmed by theoretical investigation, inasmuch as it tends to harmonize earth motions with those of ideally elastic bodies, is extremely interesting.

It is to vibrations of this description that Dr. Knott looks for an explanation of sound phenomena. They are not so much due to the large movements recorded by seismometers as to minute vertical vibrations which are superimposed upon them or which outrace them. They are true elastic waves. As I understand Dr. Knott, the difference between his explanation and mine is extremely small. He defines the nature of the waves and makes them out to be a phenomenon which may quite be expected to precede the actual earthquake. I advanced the opinion that they were phenomenon with which the earthquake was continuous. In artificially produced disturbances, as in actual earthquakes, short period waves have formed the van of the advancing disturbance. The phenomenon is a curious one, and why it exists is difficult of explanation.

2.—Velocity of Propagation.

If in ordinary earthquakes the movements are beyond the limits of elasticity, it would appear to be a necessity that the disturbance should travel more slowly than if it consisted of true waves of compression or distortion. This is an opinion put forward by Dr. Knott in the above-mentioned paper, and it is an opinion which is probably shared by all scientific men who have thought about this subject.

When we turn to certain observations, and the observations chosen are those which we have every reason to rely upon as being practically accurate, we meet with results which are difficult to reconcile with the above assumptions. The following are examples of these observations :—

The Charleston Earthquake.

Professor Simon Newcomb and Captain Charles Dutton have subjected upwards of 400 time observations of the Charleston Earthquake to a most rigorous analysis. Many of these observations were obtained by clocks which had been stopped. Many of the clocks being used as regulators had been compared daily with a time signal. A number of the observations specify the time of the first tremors within seconds. The greatest distance over which a wave path was timed was 924 miles. The average distances appear to have been from 300 to 600 miles. According to their relative merits, the observations were divided into 3 groups, the first group containing the most reliable observations. The average results gave the following velocities :—

Group I.	5,205m.	± 168m.
Group II.	5,192m.	± 236m.
Group III.	5,171m.	± 116m.
Average result	5,184m.	± 80m.

(*American Journal of Science*, 30th January, 1888.)

The Destruction of Flood Rock.

In 1885 Flood Rock was destroyed by the explosion of 240,397 pounds of rack-a-rock and 48,537 pounds of dynamite. By specially arranged electrical connections the instant of explosion was noted on chronographs at a number of stations, the farthest being 181.68 miles distant. At each of these stations the arrival of the first tremors were recorded by observers, who watched the disturbance of an image reflected from the surface of mercury. After making various minute corrections to determine the absolute instant of explosion, &c., a series of velocities were obtained. Towards the east through drift, the velocity of the earth wave varied from .83 to 3.15

miles per second, but towards the north, through homogeneous gneiss, the velocity was practically constant, being about 3.88 miles per second, and this for distances of 175 miles. These latter velocities are equivalent to 6,258 meters per second.

The above are examples of the high rates at which earth waves have been observed to be propagated. The highest velocity for a sound wave, through piano steel of density 7.7, is given by Tomlinson at 5,198m. per second.

By cross bending and twisting columns of rock, the writer and Mr. T. Gray determined moduli necessary for calculating the speed with which compressional and distortional waves ought to be propagated. The highest speed calculated was, for a sound wave in granite of specific gravity, 2.63. This was 3,750 metres per second.—(*Quart. Journal, Geological Society*, May, 1883.)[1]

Looking at the four velocities just given, it would appear that the distortional waves of the Charleston Earthquake were propagated through the heterogeneous, and more or less fissured crust of the earth more quickly than a compressional wave is propagated through a specimen of homogeneous granite and practically as quickly as a similar wave is propagated through a piece of steel wire.

The tremors from the Flood Rock explosions, whatever their nature may have been, were propagated more quickly than any of the above waves were propagated.

Amongst other points connected with earthquake motion which are difficult to understand, the following may be enumerated :—

3. In artificial disturbances and apparently in earthquakes, the greater the initial impulse, the greater is the speed of propagation. General Abott showed this to be true in connection

[1] The data on which the above result was founded is unfortunately in England. On receiving the same is will be re-examined.—*J.M.*

with the explosions at Flood Rock, Hell Gate, and many other experiments carried out under his superintendence. The writer showed it to be true for small explosions produced in the alluvium of Tokio.

4. As a disturbance radiates the velocity of propagation decreases. Although many experiments made by General Abott in America and by the author in Tokio have confirmed this conclusion, in the Flood Rock explosion along an easterly course through the drift there was at first an increase in velocity.

5. In soft ground the large horizontal motions are preceded by a series of vertical surface ripples.

6. Near to an origin a normal motion is observed at a short interval before a transverse motion, but as the disturbance radiates the amount of separation between these two components of motion does not increase.

7. Near to an origin the motion inwards towards the origin is greater, and is performed more quickly, than the motion outwards. This may be explained on the assumption that the back swing of the earth is performed in the direction of the crater of explosion which may play the part of a free surface.

8. Near to an origin the amplitude of normal motion is greater than the amplitude of transverse motion, but as the disturbance radiates they rapidly approximate to each other.

9. At any given station the period becomes longer as the disturbance dies out.

10. As a disturbance radiates the period becomes longer.

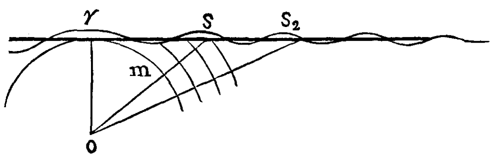
11. For *small* displacements the period increases with the amplitude.

12. As a given vibratory motion radiates from the origin it may split up into two waves.

For a detailed account of the observations which have led to the above conclusions see "Seismic Experiments," *Trans. Seis. Soc.* Vol. VIII.

RADIATION OF A DISTURBANCE IN THE EARTH'S CRUST.

The following remarks upon the manner in which an earthquake may radiate are chiefly based upon observations and the results of experiments :—



If an impulse originates at a centre O, the experiments of military engineers have shown that the radius rs of a crater which might be found never exceeds three times the line of least resistance ro. Providing the initial impulse at o is sufficiently great, inside the circle rs a direct shock resulting in projection may be experienced. A direct shock due to waves of compression might also be felt as far as some point s_2. Assuming o to be surrounded by spherical shells each the breadth of the vibration of a particle, the energy of a particle k_1 in a shell of radius r_1 will be to the energy of a particle k_2 of a particle in a shell of radius r_2, inversely as the cubes of the radius of the shells, or

$\frac{k_2}{k_1} = \frac{r_1^3}{r_2^3}$, and as energy is dissipated $\frac{k_2}{k_1} = f\frac{r_1^3}{r_2^3}$

when f is less than unity and represents the rate at which energy is dissipated.

From this it would appear that within the crust of the earth the energy of the initial impulse must be dissipated at a very rapid rate and the distance at which a direct shock is felt is probably very small. Whatever intensity may be recorded at a point s an equal intensity will be found for downward directions at points nearer to o than os, that is to say, owing to the movement of particles being more constrained in the interior of the earth than at the surface, energy is dissipated more quickly in the interior than along the surface.

Apart from these theoretical considerations, it has been found by experiment that the movement at points near to *r* but outside the crater of disruption, the vertical component of motion, cannot be accounted for as being due to a direct wave of compression. The vertical movements are free surface waves which can be felt. In large earthquakes they have often been seen, and for artificial disturbances if not also for actual earthquakes they have been instrumentally recorded. Their velocity of propagation is very great. They are probably produced by the outcrop of the waves of compression near the origin, and at a distance from the origin it may be only these waves which are sensible.

Mallet,* who speaks of such waves as probably forming the front portion of all earthquakes, refers to the experiment of Wertheim and Breguet on the linear and transversal vibrations of wire, which are propagated at values in the ratio of 3485 : 4634. (*Compus Rendus*, t. XXXII., p. 293.)

As these free surface waves apparently travel more quickly than compressional waves, it would seem that even at a station within the cone of direct shock, excepting at *r*, these free surface waves may be felt first and might be sufficiently large to mask the direct waves of compression.

Another point of importance is the fact that the amplitude of direct motion decreases very rapidly as a disturbance radiates, and therefore at a distance from the origin the direction of motion may be equally in any many azimuth.

* *Neapolitan Earthquake* Vol. II. p. 300.