PRELIMINARY REPORT ON EARTHQUAKE MOTION.

By John Milne.

Kokadaigaku, Tokio, Japan.
February, 25th 1888.

To Hiromoto Watanabe, Esq.,
President of the Committee appointed to consider Construction in Earthquake Countries.

Sir,—I have the honour to submit for your consideration and for the consideration of the Committee appointed to report upon questions relating to construction in earthquake countries the following preliminary report upon the nature of earthquake motion. Diagrams of earthquake motion, together with details of instruments, observations, experiments, &c., which are referred to in the following papes may be found in the Transactions of the Seismological Society Vol., I—XII. To complete this report, illustrations of the phenomena referred to are required, criticisms and observations from the committee and others interested in these matters should be added, and finally to increase our knowledge respecting earthquake motion the results of numerous experiments yet to be carried out are required. Among the more important of those experiments attention is drawn to the following:—

1. The nature of earth motion as recorded on a rocky foundation. As many buildings in the Earthquake regions of Japan may be founded on rock, such experiments are of great importance.

2. A continuation of experiments in excavations such as might be made for foundations. To determine whether build-

ings with basements or foundations free from the surface receive less motion than similar structures with ordinary foundations, is an investigation the value of which is self evident.

3. Experiments upon different types of foundations such as piles, gravel, concrete, &c.

4. To determine the accelerations and maximum velocities necessary to destroy ordinary brick work, and to obtain such constants as may be required by engineers and others who have to construct to avoid the effects of earthquake motion. Should you or the committee desire that more detailed information be given as to the method of carrying out these, and I may add other experiments which have suggested themselves, it will afford me pleasure to do what I am able in order to comply with your wishes.

I have the honour to remain, Sir,

Your obedient Servant,

JOHN MILNE.

CONTENTS.

I.—Old Ideas Respecting Earthquake Motion.

A clear idea as to the actual nature of Earthquake motion is of cardinal importance to those who wish to construct so that they may avoid, or at least mitigate its effects, and it is for this reason that the nature of earthquake motion based on the hypothesis of its originating as a sudden impulse and being propagated through a perfectly elastic medium was first suggested by Dr. Thomas Young and Guy Lussac is here discussed. It was formally formulated by the distinguished seismologist, Mr. Robert Mallet, who wrote as follows:—An Earthquake is "*The transit of a wave or waves of elastic compression in any direction, from vertically upwards to horizontally, in any azimuth, through the crust and surface of the earth, from any centre of impulse or from more than one, and which may be attended with sound and tidal waves, dependent upon the impulse and upon circumstances of position as to sea and land.*" Investigations made in Japan have shewn that this dedefinition is insufficient in comprehensiveness. Not only may earthquake motion be due to the transmission of waves of elastic compression but it may be due to the transmission of waves of elastic distortion or even of waves of distortion and of compression at the same time.

Further it has been shown that in consequence of the imperfect elasticity of the materials composing the earth's crust the mode of transmission of earthquake waves is so altered that many of the laws established on the assumption of the perfectly elastic medium usually assumed are considerably modified. For example, the waves originating either from a strong impulse or a feeble impulse ought on the assumption of a perfectly elastic medium to travel with equal velocity. Investigations have shown the contrary. Near to an earthquake origin a disturbance travels quickly, but as it radiates its velocity apparently decreases. This is confirmatory of observations made upon disturbances produced by artificial means as for instance by explosions of gunpowder or dynamite which have in many instances shown that the greater the initial impulse the greater the velocity of propagation.

Not only is the definition of earthquake motion wanting in its completeness, but the assumption that the movement resulting from the initial impulse, is in itself an impulse or a blow has led to errors in calculations of a serious nature. For example: throughout Mr. Mallet's classical work upon the Neapolitan earthquake all problems relating to the overthrow or shattering of bodies, as for example monuments, chimnies, etc., are treated on the assumption that the destructive movement acted as a sudden blow. The same views are reiterated in Reports to the British Association, the Admiralty Manual of Scientific Enquiry, and many other works. It will be subsequently shown that these views do not coincide with the results of observations and experiments which have been conducted in this country, one conclusion arrived at in Japan being that destruction like overturning and shattering is the result of the rapidity with which bodies have motion communicated to them.

For reasons such as these it seems that earthquake motion discussed from a purely theoretical standpoint is of but little importance to those who wish to build so as to avoid its effects.

In the following pages the facts relating to Earthquake motion upon which greatest stress is laid are those of importance to builders, while those chiefly of interest to the scientific man, as for instance the velocity with which earthquake motion is propagated from point to point, will be omitted.

2.—Instruments used in Japan.

In speaking of earthquake motion as deduced from observation it would seem necessary that we should first describe the instruments by which the observations were made. To do this satisfactorily would necessitate a long description which in this report would be somewhat out of place.

The following are examples of instruments which have been used in Japan:—

SEISMOSCOPES.

Vessels containing liquids.

Of these the arrangements recommended by Mallet, Babbage, De la Bêche, and many others devised in Japan have been fairly tested but without success.

The "Cacciatore."

Palmieri's mercurial seismoscope and specially designed mercurial seismographs.

Bodies floating in liquid with masts attached to recording apparatus.

Columns like cylinders, cones, etc.

Columns standing on segments of small spheres.

Partially supported bodies like strips of glass, pins, etc.

These can be overturned by less motion than the finest columns which can be set on end.

Microphones ordinary and self-recording.

Compass seismoscope.

Tremor indicators consisting of a mirror which by the motion of a pendulum is permanently deflected.

Various forms of circuit closers, the simplest form of which is Palmieri's.

Pendulum instruments.

Pendulums intended to swing, usually short and with quick period. Some of these were in vacuo. Inverted pendulums of different periods arranged in series with apparatus to record their movements.

Pendulums intended to act as steady points.

Pendulums to mark in sand or with pencil on paper.

Pendulums to mark on smoked glass surfaces.

Pendulums controlled by friction to render them "dead" beat.

Pendulums with a great variety of multiplying indices.

Pendulums suspended by a spring to record horizontal and vertical motion.

These pendulums were from 2 or 3 feet to 40 feet in length the bobs being from 2 or 3 lbs. to 80 or 100 lbs. in weight. The supports of these pendulums were sometimes flexible sometimes extremely rigid. At the time of a severe earthquake nearly all the above were observed to swing.

SEISMOGRAPHS AND SEISMOMETERS.

Pendulums controlled by friction and the reaction of a balanced pointer writing their records on a stationary or moving glass surface. From these or from Gray's suggestion of an astatic pendulum seismograph a variety of duplex pendulums have been developed. These have been subjected to many tests and work satisfactorily.

Torsion pendulum seismograph.

Ball and plate seismographs.

Rolling cylinder seismograph.

Rolling sphere seismographs,—many varieties.

Parallel motion instruments of different forms like those of West, Ewing, Alexander, and Milne.

Bracket seismographs writing the earth's horizontal motion as two components on a moving surface. The forms of these which have been constructed by Chaplin, Ewing, Gray, Milne, and others are extremely varied.

Double bracket seismographs of several types.

Conical pendulums of various types.

INSTRUMENTS FOR VERTICAL MOTION.

Ordinary spiral springs.

Hydrometer seismographs.

Flexible bottomed cylinder seismographs.

The surfaces, moving and stationary, on which earthquake motion has been written and the time recording apparatus have been as numerous as the earthquake instruments themselves.

For detailed descriptions of the above instruments and examples of their performances see Trans. Seis. Soc. Vols. I-XII.

The above instruments are for convenience arbitrarily divided into seismoscopes, seismometers, and seismographs. The seismoscopes are those instruments which record the fact that an earthquake has taken place. The records yielded by these instruments which, it will be observed, are chiefly instruments of an old type are in nearly all cases unsatisfactory. For instance columns which have been made of various materials and of various shapes, if they stood upon a platform firmly fixed to the ground, are but rarely overturned, and even it they are overturned they may be found lying in all directions. If an earthquake commenced as a sharp blow, which, if such a condition exists, is of rare occurrence, the columns might fall in the direction from which the shock came. As earthquakes usually commence with a series of tremors it has been found that a column rocks before it falls and whilst rocking it changes its plane of oscillation. In consequence of this, coupled with the fact that the ground itself may describe elliptical or other curved paths and for other reasons it follows that a column may fall in any directions. Further, it follows that a small column may remain standing while a larger one may fall. Old fashioned pendulums writing with a pencil, or with a sliding pointer on a smoked glass plate are likewise unsatisfactory, the record which is obtained being but little better than a record of the *swinging* of the pendulum. Instruments of this sort tell us little about the actual amount or nature of an earthquake. They are described and the tests to which they have been subjected, will be found in the Transactions of the Seism. Soc. Vol. III.

In the group of instruments called seismometers we find contrivances which measure the maximum motion of an earthquake and at the same time record its direction. The most useful and trustworthy amongst which are the duplex pendulums.

The seismographs are for the most part seismometers which write the successive movements of the ground upon a moving surface, and in this way give a diagram which enables the observer to analyze any particular vibration.

The instruments most generally used amongst the latter class have been bracket seismographs or conical pendulums writing upon smoked glass plates or with ink upon paper, which at the time of an earthquake was in motion beneath the recording indices of the instruments. It will be observed that these various classes of instruments overlap each other and further that certain instruments may in one earthquake act as seismoscopes while in others they may be seismometers or seismographs.

The instruments which are now used in Japan and which have now been used for several years, like duplex pendulums, conical pendulums, and bracket seismographs are the results of a gradual development. The tests to which they have been subjected are numerous and severe. When any two of these instruments are placed side by side, even if they are different in their dimensions and in details of construction, for the same earthquake they give what is practically the same diagram. For diagrams see the Jour.: Science Coll., Imp. University, Vol. I. The most severe test to which the instruments have been subjected is to place them on a specially constructed shaking table and to take a diagram of the absolute motion of which is also recorded from outside. It is found that whether this motion is slow or quick, long or short, gentle or violent, so long as it is not greater in range than that for which any given instrument is constructed to record, the instrument placed on the table faithfully records the actual motion of the table; in other words when the instruments are shaken those portions of them intended to act as steady points are in reality for all practical purposes practically at rest. For tests diagrams see Trans. Seis. Soc., Vol. XII. and Memoirs of the Science Dep., Univ. Tokio, No. 9.

These preliminary remarks are made for the following two reasons :—

1st. To show that we have every confidence in the correctness of the earthquake records which have been obtained.

2nd. To show that what is said respecting construction is in great measure based upon a *knowledge of the actual nature of earthqnake motion rather than upon any hypothesis as to its nature.*

It may here be remarked that the earthquakes recorded in Japan have for the most part been small, but amongst them there have been several which have unroofed houses. The houses in Japan are mostly without an upper story and had the disturbances which have damaged these buildings occured amongst the tall buildings of a European city it is probable that the damage would have been excessive.

3.—The Nature of Earthquake Motion.

An earthquake of ordinary intensity consists of a series of preliminary tremors which may be the source of certain sound phenomena, a shock or vibration of considerable range, a series of irregular vibrations amongst which other shocks may occur, the whole disturbance terminating by a long series of irregular vibrations merging into a series of pulsatory movements of long period and small amplitude. In many earthquakes there are a series of vibrations each of approximately the same amptitude and without any well defined shock.

The total number of vibrations in these earthquakes may be from 10 or 20 to two or three hundred. The absolute number of vibrations in a disturbance has never yet been completely recorded, some of the preliminary tremors being lost on account of their smallness in amplitude, while the concluding pulsatory movements have been lost on account of their slowness in period.

The duration of an earthquake as recorded by a given instrument may be from 20 or 30 seconds to three or four minutes. Sometimes it may happen that disturbances have succeeded each other so rapidly that their vibrations have overlapped and a continuous trembling of the ground has occurred. In 1868, in the Island of St. Thomas, 283 shocks were felt in about 10 hours. And as a rule whenever a large and destructive earthquake has occurred, it has been succeeded by a long series of minor disturbances, which although irregular in their intensity and time of occurrence, may continue for several weeks, months, or even years. In Japanese history there are many examples of earthquakes of this description.

4.—Amplitude of Earthquake Motion.

The amplitude of a vibration, by which is meant the half of a semi-vibration or the quarter of a complete back and forth motion, may vary between the fraction of a milimeter and possibly a foot. Small earthquakes of which 4 or 500 are recorded every year in Japan, each having been felt by many observers may have amplitudes varying between the fraction of a milimeter up to 2 or 3 milimeters.

Earthquakes are occasionally recorded in Tokio or Yokohama having an amplitude of 20 or even 50mm. Such earthquakes are destructive; but earthquakes of much smaller amplitude are also destructive providing that the period of the movement is sufficiently short.

The following list of amplitudes in inches is taken from Mallet's account of the earthquake of 1857 which devastated Calabria :—

Station.	Polla.	La Sala.	Certosa.	Tramutola.	Sarconi.
Distance from seismical Vertical in geographical miles	3.45	11.60	16.50	20.60	26.7
Amplitude in inches	2.5	3.5	4.0	4.5	4.75

It may be remarked that the above table apparently shows that the amplitude increases as some function of the distance from the epicentrum or seismic vertical. The amplitude of a given vibration has often been observed to have been greater in one direction than in another, the side of greatest motion being that from which the disturbance originates.

5.—Period of Vibration.

The period of vibration means the time taken to perform one complete oscillation or back and forth movement. When this is long, it is not so likely that destruction should occur as when it is short. In a given earthquake different vibrations have different periods, the small vibrations being short and the large vibrations relatively long. The small vibrations have been recorded as having occurred at the rate of 5 or 6 per second. On rock it is probable that they are performed even more quickly. An average period for the ordinary vibrations of 24 earthquakes as recorded in Tokio on hard alluvium was .29 second, while the average period for a number of the same earthquakes recorded at neighbouring stations within 800 feet distance of each other on wet ground near a marsh, was .66 and .85 second. The period of a somewhat severe earthquake or March 1st, 1881, as recorded in Tokio was 1.2 second.

6.—Direction of Motion.

In earthquakes of small intensity and for the majority of vibrations in disturbances which may be destructive, the direction of motion is variable. In the Tokio earthquake of Sept. 5th, 1886, an earth particle described paths which were nearly circular and there were many which were elliptical. At other times the earth describes paths which are spiral or like a figure 8. The elliptical paths are, however, the most usual, and in the case of shocks the major axis of such ellipses indicate the direction from which an earthquake originated.

In any given earthquake, movements may occur in all azimuths, but in Tokio the direction of *shocks* is often approximately *E* to *W*.

That in a given district there may be one particular direction in which there is the most movement is a fact not to be overlooked.

7.—Vertical Motion.

Hitherto our remarks have referred to the horizontal components of earthquake motion. In Tokio appreciable vertical motion is relatively of rare occurrence. Occasionally in large disturbances we obtain a vertical component of from 1 to 3 milimeters, the vibrations constituting this movement being short in period so that two or three vertical vibrations are superimposed upon the large horizontal movement. Occasionally small earthquakes of short durations which are felt as sudden short jerks exhibit a small vertical component. The last of such disturbances occurred at 8h. 28m. a.m. in December, 1887.

The motion upwards appears to be greater than that downwards.

In large destructive earthquakes the vertical motion has been sufficient to produce waves which when of short period have resulted in a dancing-like motion of the grouud.

8.—The Intensity of Earthquake Motion.

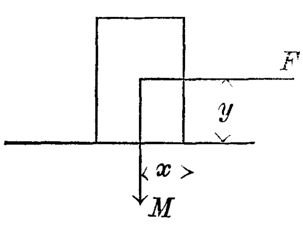
In obtaining a value for the intensity of an earthquake many method have been followed. Palmieri's seismograph indicates intensity by degrees. These degrees refer to the height up to which a certain quantity of mercury contained in a tube had been caused to oscillate. Inasmuch as this height is dependent on the depth of mercury in the tube, and the period and duration of the disturbance which causes its oscillation, it can only be regarded as a means of approximately estimating relative intensity.

Mallet in his reports to the British association divides earthquakes into different classes according to the area over which they were felt, but at the same time remarks that "area alone affords no test of seismic energy." As a result of many observations we are led to believe that the area over which an earthquake is felt is dependent not only upon the initial force of the disturbance, but also upon its focal depth, the form and position of that focus, the duration of the disturbance, and the nature and arrangement of the materials which are shaken.

Seebach considered the initial intensity of earthquakes as proportional to the square of the radius of the disturbed area, —a method of calculation practically identical with that suggested by Mallet.

Rather than adopting methods such as those here indicated, it would seem, at least for builders, that the intensity of an earth disturbance may be estimated by the work it is capable of doing, as for example in overturning, projecting, or fracturing various bodies. A column may fall by the ground being suddenly moved beneath it. This gives it an impulse at its base, the reaction of its inertia acting at its centre of gravity being equal to this. These two together produce rotation so that the column falls, or tends to fall, towards the side from which the impulse came according as the rotating moment is greater or less than its moment of stability.

The following is a note on this subject by Mr. C. D. West:



Let the surface of the earth at any instant be undergoing an acceleration of velocity of f feet per sec. Let M be the mass of a column (see Fig.) resting on the ground, y the height of its centre of gravity, and x its horizontal distance from the edge round which it may be supposed to turn.

Then the inertia of the column is equivalent to a force

$$F = Mf$$

acting horizontally through its centre of gravity and tending to overturn the column, the overturning moment being

$$Fy = Mfy$$

This moment is opposed by the moment of the weight of the column Wx, and therefore when the column is on the point of overturning

$$Wx = Fy = Mfy = \frac{W}{g} f y$$

$$\therefore \frac{x}{y} = \frac{f}{g}$$

$$\therefore f = g \frac{x}{y}$$

If f exceeds this value the column *may* go over, if less the column *may* stand.

A less acceleration than $f = g \frac{x}{y}$ *may* upset the column if the periodic time of the impulses so far agree with the oscillation of the column so as to get up in it a rocking oscillation; on the other hand, the same value for f may fail to upset the column if the period is too brief, the impulses then being more shattering than overturning.

If V is the maximum velocity of an earth particle as determined from an earthquake diagram, or by the projection of balls, etc., and t being the time of acquiring this velocity, or $t = \frac{T}{4}$ where T is the complete periodic time, then f in the above formula may be considered as

$$f = \frac{V}{t} = \frac{V}{\left(\frac{T}{4}\right)}$$

If V and t are both very small, this formula may be considered nearly correct, but if the amplitude is large then the upsetting value may be nearer to the maximum acceleration $\frac{V^2}{a}$ where a is half a semi-oscillation, and not the mean time acceleration.

The results of experimental investigations on this subject are given in a paper on Seismic Experiments, the results of which are quoted at the end of this report.

The conclusions are that the overturning power of an earthquake as determined from the dimensions of a body are at best only approximative. The maximum acceleration of an earth particle apparently lies above the value of f as calculated from the dimensions of a column which has been overturned, and the mean time acceleration lies somewhat below it.

Mallet's formulæ relating to overturning and shattering apparently depend upon conditions that do not exist in earthquake movement as recorded in Japan. They are therefore inadmissible.

In the formula for projection, as for instance

$$V^2 = \frac{ga^2}{2b}$$ for horizontal projection

where a = horizontal distance traversed by the body projected and b = height through which the body has fallen, the quantity V is apparently identical with the maximum velocity as measured directly or calculated from a diagram, and Mallet's calculations of these particular quantities are of considerable value.

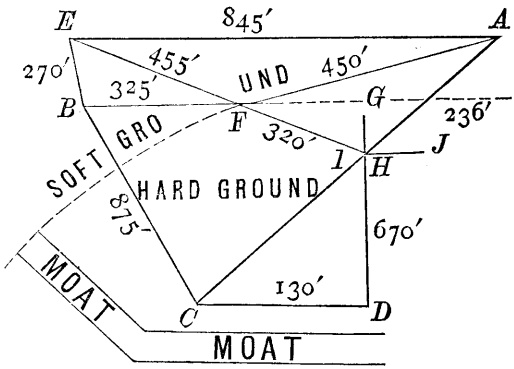
For the Neapolitan earthquake Mallet calculated from the distance to which bodies had been projected, maximum velocities of 9, 11, and even 21 feet per second.

In the great earthquake of Riobamba, February, 1797, it is said that bodies were projected vertically 100 feet. This would indicate a maximum velocity of 80 feet per second. Assuming the observations to be correct this disturbance so for as maximum velocity is concerned is the greatest we have on record.

9.—Earthquake Motion as recorded on different kinds of Ground.

(a). small earthquakes.

The following tables give the results of observations made at a number of stations situated on a plot of ground in Tokio about nine acres in extent. The relative positions and distances apart of these stations is shown on the accompanying sketch.



The instruments at *A*, *B*, *C*, &c., were similar in construction and similarly installed. Although they gave similar diagrams when placed side by side, two or three of them were occasionally interchanged as an additional check. The dotted line shows a gentle slope dividing the soft ground from the hard ground. The softest ground is in the middle of the triangle *B*, *E*, *F*, where it is quite marshy. A bore hole half way between *F* and *C* gave the following section :—

Earth and sand	78.0	feet.
Very hard ground	2.5	feet.
Fine gravel	2.0	feet.
Sand	6.5	feet.
Gravel	10.5	feet.
Tuff, a soft volcanic clay rock	—	feet.

The last material is probably the commencement, or very near the commencement, of the stratified tuff formation which at Yokohama and other places in and near to Tokyo is exposed in cliff-like sections. On the marshy ground water is met with at a depth of two or three feet.

For stations *G*, *H*, and *I* the number of observations are too few to give average results.

G refers to the record taken by an instrument placed inside a house specially constructed to mitigate the effects of earthquake motion. *H* is a station in a pit 10 feet deep. Special reference will be made to the records obtained at these stations.

The results of the observations were were as follows :—

NUBMER OF WAVES IN TEN SECONDS.

1884-85.	A	B	C	D	E	F	G	H	J
March 25th......	22	18							
March 31st......	30	32	23						
April 6th......	30	25	32						
May 6th......	32	26	35						
May 11th......	30	27	35						
May 19th......	37	33	21						
May 19th......	22	26							
May 30th......	28	21							
May 31st......	31	28							
June 11th......	32	26		26					
October 24th......	36	30							
November 16th......	34	32		38					
November 21st......	36	35		38					
November 27th......	36	28		38					
November 29th......	36	18		*					
December 7th......		34		†					
December 9th......	24			24					
December 16th......	30	28		40					
December 23rd......		26							
December 30th......	32			42	30 or 16				
January 2nd......		26		26	40 or 12	40			
February 1st......	28	20							
February 4th......	30	30			24				
February 12th......	30	28			14	34	72‡		
February 27th......	32	32			36				
February 28th......					50		48		
March 12th......	30	29			18				
March 20th......	30	30			14			12	26
Average..............	30	28	29	34	23 or 28	37	60	12	26

* At D too irregular to estimate. † At D too small to estimate. ‡ Ripples.

PERIOD OF LARGEST WAVE IN SECONDS.

1884-85.		A	B	C	D	E	F	G	H	J
March	25th......	·73	·85							
March	31st......	·30	· 4	·33						
April	6th......	·36	·61	·36						
May	6th......	·47	·70	·36						
May	11th......	·35	·47	·26						
May	19th......	·23	·36	·20						
May	19th......	·40	·50							
May	30th......	·36	·40							
May	31st......	·35	·30							
June	11th......	·36	·36		·36					
October	24th......	·32	·41							
November	16th......	·47	·47		·23					
November	21st......	·27	·45		·30					
November	27th......	·45	·36		·20					
November	29th......	·26	·56		·40					
December	7th......		·24		·24					
December	9th......	·40			·40					
December	16th......	·45	·54		·37					
December	23rd......		·40							
December	30th......	·32			·18	·75				
January	2nd......		·70		·18	·90	·18			
February	1st......	·45	·82			·50		·18		
February	4th......	·21	·30							
February	12th......	·39	·39			·72	·42	·39		
February	27th......	·24	·28			·25				
February	28th......					·18				
March	12th......	·18	·29			·64		·31		
March	20th......	·44	·53			1·40			·85	·55
Average	....	·29	·46	·30	·28	·66	·30	·44	·85	·55

MAXIMUM AMPLITUDE IN MILLIMETRES.

1884-85.		A	B	C	D	E	F	G	H	J
March	25th......	·10	·50							
March	31st......	·10	·14	·05						
April	6th......	·30	·80	·10						
May	6th......	·40	·10	·10						
May	11th......	·30	·90	·10						
May	19th......	·07	·15	·04						
May	19th......	·10	·20	·02						
May	30th......	·05	·10							
May	31st......	·05	·10							
June	11th......	·15	·25		·10					
October	24th......	·07	·10							

MAXIMUM AMPLITUDE IN MILLIMETRES.—(Continued.)

1884-85.	A	B	C	D	E	F	G	H	J
November 16th......	·25	·30		·05					
November 21st......	·10	·25		·05					
November 27th......	·15	·25		·05					
November 29th......	·20	·60		·05					
December 7th......	·10	·20		·05					
December 9th......	·07			·05					
December 16th......	·80	1·20		·25					
December 23rd......		·10							
December 30th......	·45			·20	1·90				
January 2nd......		·25		·05	2·50	·05			
February 1st......	·05	·07			·10	·01	·05		
February 4th......	·05	·10			·05	·02			
February 12th......	1·20	·80			2·20	·70	·50		
February 27th......	· 0	·12			·05		·04		
February 28th......					·05				
March 12th......	·10	·30			·60		·10		
March 20th......	1·30	1·40			1·90			·035	1·2
Average	·37	·40	·07	·09	·95	·19	·17	·035	1·2

MAXIMUM VELOCITY IN MILLIMETRES PER SECOND.

1884-85.	A	B	C	D	E	F	G	H	J
March 24th...........	·9	3·7							
March 31st...........	2·1	3·6	·9						
April 6th...........	5·0	8·0	1·7						
May 6th...........	5·3	9·0	1·7						
May 11th...........	6·0	12·0	2·4						
May 19th...........	1·8	2·6	1·2						
May 19th...........	1·5	2·5							
May 30th...........	·9	1·5							
May 31st...........	·8	2·0							
June 11th...........	2·7	4·5		1·80					
October 24th...........	1·3	1·5							
November 16th...........	3·3	4·0		1·30					
November 21st...........	2·2	3·5		1·00					
November 27th...........	2·0	4·4		1·50					
November 29th...........	3·4	7·0		·78					
December 7th...........		5·0		1·20					
December 9th...........	1·0			·70					
December 16th...........	11·0	4·0		4·20					
December 23rd...........		1·5							
December 30th...........	9·0			7·00	16·0				
January 2nd...........		2·2		1·70	17·0	1·7			
February 1st...........	·7	·6			1·2				
February 4th...........	1·5	2·0							
February 12th...........	19·0	1·3			1·9	10·1	12		
February 27th...........	2·6	2·7			1·2				
February 28th...........					2·0				
March 12th...........	3·4	6·0			5·8		2		
March 20th...........	18·0	16·0			8·0				
Average	4·4	5·3	1·6	1·40	9·7	5·7	7	·25	13

MAXIMUM VELOCITY IN MILLIMETRES PER SECOND.
INTENSITY.

1884-85.	A	B	C	D	E	F	G	H	J
March 25th		27							
March 31st	44	92	16						
April 6th	83	80	28						
May 6th	70	81	28						
May 11th	120	100	57						
May 19th	46	45	38						
May 19th	22	31							
May 30th	16	22							
May 31st	13	40							
June 11th	48	81		32					
October 24th	27	22							
November 16th	49	53		34					
November 21st	48	49		20					
November 27th	27	77		45					
November 29th	57	81		12					
December 7th		125		28					
December 9th	14			9					
December 16th	151	171		70					
December 23rd		22							
December 30th	180			215 ?	135				
January 2nd		19		58	116	58			
February 1st	10	5			14		?		
February 4th	45	40							
February 12th	300	210			170	145	128		
February 27th	67	60			28				
February 28th					80				
March 12th	115	120			56		40		
March 20th	249	182			34			1·7	140
Average	75	75	33	55	79	101	84	1·7	140

Some of the more important results to which the analysis of the above diagrams point are as follows :—

1. All stations have invariably given different records for the same earthquake. The principal differences relate to direction, period, amplitude, maximum velocity, and maximum acceleration.

2. On the hard ground, as at *C* and *D*, the amount of motion is very much less than at the remaining stations, like *A*, *B*, *F*, and *E*. Comparing together the average maximum velocities and maximum accelerations at *C* and *E*, we see that they have respectively been as 1 to 5 and 1 to 2·4 *A practical conclusion to be drawn from this is that a house at C might stand, whilst a similar house at E might be shattered.*

3. Similar waves only appear in the diagrams at different stations when an earthquake is strong.

4. As a disturbance passes from station to station the time interval between two similar waves suffers a change. This leads to uncertainty in determining the velocity with which a disturbance travels.

Details of the above observations may be found in Trans. Seis. Soc. Vol. X. "Seismic Survey," by J. Milne.

The shock of March 25th, 1884, was so slow in period that it was hardly observed in Tokio. That of November 16th was slightly destructive in Hakodate. The shock of December 16th was sufficiently strong to overturn lamps.

Diagrams of all these disturbances are given in the above-mentioned paper.

Generally in all large earthquakes the destruction has been greatest on the soft ground. (See next Report, Effects produced by Earthquakes upon Buildings.)

10.—Moderately Destructive Earthquakes.

The following few earthquakes are those which have been recorded in Tokio or Yokohama, and at the same time have been sufficiently intense to unroof a few buildings, shatter many chimneys, dislodge stones from the face of walls, crack brick-work and plaster, and create other damage.

February 22nd, 1880.[1]—This earthquake created considerable destruction in Yokohama. At that place very many brick chimnies fell. At many houses the tiles on the roof were shaken loose, while several were completely unroofed, one of which was a strong brick building. The main timbers in certain roofs were broken. Grave stones were rotated. Many windows were broken, and bodies like the tops of stone lanterns, corner stones of chimneys, etc., were projected.

In Tokio a few chimneys fell, tiles were dislodged from the eaves of buildings, and portions of a few walls were cracked or shattered. In some instances these latter fell.

In Yokohama the range of horizontal motion appears to

[1] Trans. Seis. Soc. Vol. I., Part II.

have been from 15 mm. ($\frac{5}{8}$ inch) to a maximum of 50 mm. (2 inch). Calculations of maximum velocity were made, but as the data on which there were founded do not appear to have been satisfactory they are here omitted.

In Tokio the amplitude (range of motion) observed at Surugadai was 21 mm. Assuming the larger vibrations to have been performed at the rate of one per second this would indicate a maximum velocity of 60 mm. per second and a maximum acceleration of 360 mm. per second. With a period of 2 seconds, which is probably a more correct assumption, the above quantities would respectively become 30 and 90 mm.

October 15th, 1884.—One or two chimnies fell in Tokio, plaster fell from ceilings, and several brick walls were cracked. In Tokio at Hitotsubashi-soto the greatest horizontal motion observed was 43 mm. and the period 2 seconds. This indicates a maximum velocity of 68 mm. and a maximum acceleration 210 mm.

January 15th 1887.[2]—This disturbance originated about 35 miles to the S.W. of Tokio. Near to its origin it destroyed many *kura* (fire-poof storehouses built of wood with a clay covering and a heavy roof of tiles) and opened fissures in the ground. In Yokohama, say 10 miles from the origin, it destroyed many chimnies and slightly shattered several buildings. In Tokio a few brick walls were slightly cracked.

In Yokohama a horizontal motion of 35 mm. was recorded.

In Tokio the following observations were made :—

	Range of motion in millimeters.	Period in seconds.	Maximum Velocity.	Maximum acceleration.	Vertical motion.	Period of vertical motion in second.
Hitotsubashi	21	2.5	26	66	1.8	9.8
Hongo	7.2	2.2	12	36	1.3	1.0
Chirikioku	19.2	2.3	24	64	5.5	0.8

Hongo and the Chirikioku (Imperial Metereological Observatory) are situated on moderately high ground which is dry and hard. At Hitotsubashi, which is low the ground, it is damp and soft.

[2] Trans. Seis. Soc. Vol. IX.

The above measurements of range of motion and period were made on solid foundations. The range of motion at the top of a building would be greater while the period might be less. It seems from these observations that when there is an earth movement of about 18 mm. ($\frac{3}{4}$ inch) or over, it is likely that the period will be sufficiently short to result in some form of destruction.

Earthquakes of this description, Professor Sekiya observes' occur in Japan about once a year and near to Tokio every few years.

11.—Destructive Earthquake.

The information that we have about the amplitude and period of motion in a destructive earthquake is extremely scanty.

In the Manila earthquake of 1880, eye-witnesses tell us that they saw the ground moving in the form of ripples. In many earthquakes, wave-like undulations of the ground have been rendered visible to the eye. In 1692 the sand in the streets of Port Royal is said to have risen like waves of a troubled sea. Examples of this nature showing that buildings at the time of a severe earthquake are not simply subjected to horizontal stresses but that they are actually tipped and rocked, may be derived from the accounts of almost all large earthquakes. (See note on Vertical Motion.)

For the Neapolitan earthquake of 1857, Mr. Mallet made many determinations of maximum velocity, many of which were based upon projection phenomena. The mean of these may be taken at about 12 feet per second. The amplitudes of motion, which we will assume were true amplitudes, varied from 2.5 to 4.7 inches, the mean of which may be taken at 3 inches.

With these data we can calculate that the period of a wave was 0.125 second, or that there were 8 waves per second. Inasmuch as observation in Japan has shown that the period of a wave increases with its amplitude, and that earthquakes in Japan have often been recorded with periods of over 1 second, it would seem that the above result must be received with caution. The chief source of error probably lies in the fact that the objects which were projected were thrown farther than they would have been thrown had the supports on which they rested been absolutely rigid. The result of this has been that the maximum velocity as calculated for the ground has been too high. In disturbances produced by the explosion of dynamite it has been shown that the maximum velocity determined by the projection of a ball from the top of a post has been much greater than that yielded by the analysis of a diagram taken by a seismograph at the foot of the post. (Seismic Experiments, Trans. Seis. Soc. Vol. VIII., p. 70.)

12.—Relative Motion of neighbouring Points of Ground.

Very little information exists as to how far two points of ground which are near to each other synchronize or disagree in their phase of motion. From a few experiments made in Japan it seems that the heads of two stakes 2 feet 6 inches apart have a considerable relative motion in the direction of the origin of a shock. These experiments, which are of importance to builders, inasmuch as they indicate that a building is not moved as a whole but possibly suffers considerable racking, require to be repeated and amplified. (See Report to British Association, 1881.)

13.—Rotation of Bodies.

After a severe earthquake it has often been observed that many bodies (like obelisks, grave-stones, chimnies, etc.) have been more or less rotated. Some have supposed that this phenomenon indicates a vorticose motion of the ground, others that the phenomena are due to reflected and direct shocks acting simultaneously on the body which has been rotated. Mallet offers the explanation that rotation is due to the centre of friction of the base of the body not coinciding with its geometrical centre. In certain cases no doubt these explanations, especially the latter, may be correct. If vorticose motion is the cause of the rotation we ought to find that all twisted bodies near the same place have been turned in the same direction; and if we take Mallet's view the rotation ought to follow no definite law. What we actually find is that they do follow a law, but not that which would be obtained on the supposition of vorticose motion. *The law is that all similar bodies such as grave-stones, having similar sides parallel are in the same district rotated in the same direction, while another set having their faces placed at an angle to these, may be rotated in an opposite direction.* This can be accounted for as the result of a series of direct shocks. If a shock comes broadside on to a body it only tends to throw it over, but if it comes obliquely to this direction (but not exactly in a diagonal) it tends to tilt it up on a corner. This shock may be resolved into two rectangular components. One along the projection of a line joining the centre of inertia and the corner tending to tilt it up on that corner, and the other at right angles tending to whirl it round. This explanation is vertified by observation after an earthquake and also by experiment. (Phil. Mag., November 1881, p. 377.)

14.—Earthquake Motion as Recorded in Buildings.

From our sensations and from many crude observations, like the swinging of lamps, the movements of liquids in vessels, etc., we know that the upper portions of buildings suffer greater motion than their lower parts.

From experiments made upon the projection of bodies from the top of stakes we find that the maximum velocity of the initial movement was greater than that of the ground beneath.

A number of experiments have been made with seismometers placed in the upper stories of wood and brick buildings and similar seismometers placed in the lower stories. Almost invariably the seismometers placed upstairs indicated a greater motion than those placed downstairs. In the buildings referred to, the vertical distance apart of the seismometers was about 13 feet and they were relatively in similar positions.

An average result obtained from the observation of about 27 small earthquakes was as follows:—

Brick house, Downstairs	1.8 mm.	range of motion.
Brick house, Upstairs	2.8 mm.	range of motion.
Wood house, Downstairs	3.5 mm.	range of motion.
Wood house, Upstairs	6.1 mm.	range of motion.
Outside, on the ground	2.5 mm.	range of motion.

The above movements taken in order are in the ratio of 1, 1.6, 2, and 3.4. (See Trans. Seis. Soc., Vol. XII.)

15.—Relative Motion of two Parts of a Building.

That all parts of a large building do not synchronize in their movement is a fact partly adduced from observations and partly by actual measurement of the relative movements at the time of an earthquake.

The following are examples of such observations and investigations:—

1. At the Imperial Palace partially constructed at Akasaka, Tokio, but now removed, a set of arches formed a connecting link between heavy brick walls. All the arches running in the same direction were, so far as could be learnt, simultaneously cracked across their crowns, the cause probably being non-synchronism in the horizontal vibration of the walls which they connected, the vibration being caused by a severe earthquake which occurred the night before the cracks had been observed. A like set of arches in a similarly constructed wall at right-angles to these, and at the same time at right-angles to the principal direction of the shock which had caused the damage, were not cracked.

2. The results of an examination of three hundred and thirty similarly built brick structures in the streets of Tokio showed that the upper windows of the houses had flattish arches meeting their abutments at an angle. Out of one

hundred and twenty seven cracks in these arches, no less than one hundred and thirteen ran from the angle. Out of two hundred and fifty cracks in the lower arches, one hundred and ten ran down from beams which supported a balcony, and one hundred and forty from some portion of the arch, usually near the crown. Not a single arch was observed to be cracked at the springing when the arch curved into its abutment. Another interesting point was that the number of cracks in walls running north-east to those in walls running south-east was as 1 to 1.3, and it is from south-eastern directions that statistics showed the principal shocks to have originated.

3. As another illustration of a structure weak in resisting horizontal vibrations not conicident in period, we may take the high wall of a factory or a church tower, which contains a series of openings like windows and doors vertically above each other. These openings constitute a line of weakness, and the wall may give away here at the time of an earthquake. This has been illustrated in may earthquakes.

4. In Yokohama after the earthquake of the 20th of February, 1880, a moderately high factory chimney was supposed to require support, and it was therefore connected by an iron band to the side of a neighbouring building. When the earthquake came, the band instead of giving the chimney support cut it in two.

5. Many similar examples of destruction due to difference in vibrational-period, could be seen in the chimnies at almost every bungalow, which in Yokohama have repeatedly been shorn of at their junction with the roof. By themselves, either the chimnies or the roofs of the bungalows would have been secure; but when in contact it is evident that they have been mutually destructive.

6. The pushing out of facing stones and brick-work from the walls of buildings with an internal framing may be taken as another illustration of non-synchronism in vibrational period. This is a common occurrence.

7. Among the experiments made to measure the relative motion of different parts of a building, a few were carried on at the Imperial College of Engineering, which is a heavy, solid structure of brick and stone. One set of experiments was made upon the archways of two corridors. These arches have a span of 8 feet 3 inches, a rise of 4 feet 1 inch, and rise from brick abutments 1 foot 11 inches thick, and 7 feet 1½ inch high. The voussoirs of the arch are made of a light grey volcanic tuff, and have a depth on their face of 12 inches. The width of the wall between the arches is 4 feet 6 inches. Across the springing-lines of these arches a light deal rod was placed. One end of this was spiked to the wall; the other end terminated with a fine steel wire, resting on the surface of a smoked-glass placed on a ledge at the top of the other abutment. If these two abutments approached to or receded from each other, a line indicating the range of motion would be drawn upon the smoked glass. A second record of motion was obtained on a glass plate fixed on the middle of the transverse rod, by a pointer hanging vertically from the crown of the arch. The result showed that in a severe earthquake there was sometimes a motion of from 1 milimetre (0.04 inch) to 2.75 milimetres (0.11 inch), the vertical movement of the crown being slightly in excess of the horizontal motion. In slight earthquakes there was either no motion in the arches, or else different parts of the arch had practically synchronized in their movements.

For a more detailed account of these experiments, together with other observations, the Transactions of the Seimological Society of Japan may be referred to.[3] Another interesting set of observations was made upon the cracks which exist in several of the buildings at the College of Engineering. At the basement of the buildings, which is constructed of a volcanic rock (andesite), the cracks follow the mortar-joints; but when they come to the brickwork above, they run up and down through the whole structure, sometimes along the mortar-joints but just as often through the bricks. Some of the cracks have a width of $\frac{1}{4}$ to $\frac{1}{2}$ inch. Across several of these, steel wire pointers were placed horizontally; one end of the pointer was fixed to the brickwork, whilst the other end rested on the face of a smoked-glass plate, in a frame nailed to the wall. In a severe earthquake it seems certain that the difference in phase of the portions of the building at the two sides of a crack sometimes reached 2 millimetres. In slight earthquakes no records were obtained. In addition to these experiments, the ends of a large number of cracks were marked and dated. After a strong shake, many of them were seen to have grown in length. It seems, therefore, that portions of a building which are not likely to synchronize in their vibrational-period ought either to be strongly tied together, or else, by means of joints intentionally left during construction, to be completely separated from each other.

DISTRUCTION DUE TO OVERLOADING.

The evil effects consequent on overloading the upper parts of walls, roofs, and chimnies have been mentioned at considerable length by Mr. Mallet in his clasical work upon the Neapolitan earthquake.[4] When a chimney with a heavy top is suddenly moved forwards, the upper part, by its inertia, tends to remain quiescent. The result of this, as with all other heavy superstructures, is to cause a fracture between the lower part which has been quickly moved, and the upper part which has tended to remain quiescent. In Japan many chimnies have been shattered by this cause. The last chimnies inspected by the writer were those of the British Legation, which partially fell, and were otherwise ruined, on the 15th of October, 1884. These were rectangular in section, half a brick thick, and loaded at the top with a heavy

[3] Vol., II., pp. 2-48.

[4] Great Neapolitan Earthquake of 1857. "The First Principles of Observational Seismology," 2 vols. 1862.

head. Chimnies much thicker, and without the heavy cap' have now been substituted. In Yokohama, experience has taught almost every householder to make his chimneys short, thick, and without heavy ornamental copings.

Weighty tile roofs act upon the supporting walls like heavy tops upon chimnies.

(For more details relating to this section see next Report, Effects produced by Earthquakes upon Buildings).

16.—Motion in a Building Resting on a Layer of Cast Iron Shot.

The building here referred to is 20 feet long and 10 feet wide. It is constructed of timber with a shingle roof, plaster, walls, and ceiling of laths and paper. It rests on six brick piers capped with flat cast iron plates. At first it rested on 10 inch shells, and inside it was placed an instrument similar to those used outside. Owing to the movements produced by the wind and other causes the 10 inch shells were replaced by 8 inch balls and subsequently by one inch balls. This was in 1883 and 1884. Since the middle of 1884 it has rested on a layer of cast iron shot each $\frac{1}{4}$ inch in diameter. By this means rolling friction has been so far increased that the building is astatic, and up to the present date although it has passed through several typhoons the wind has produced no appreciable effect. The records obtained from a seismograph placed inside the building are given in column G. (p. 17-19.)

The best idea of the motion experienced is given by reference to the diagram of February 12th, 1885, from which it is seen that only two small shocks A and B were recorded in the house, while at other stations not only were there many shocks equivalent to A and B, but there were many which were greater. (Trans. Seis. Soc., Vol. X., p. 1-36.)

17.—Observation in a Pit 10 Feet in Depth.

In the preceding tables (p. 17-19.) the numbers in column H refer to observations made in a pit 10 feet in depth. The bottom of the pit, which was dry, consisted of hard natural earth. Comparing the maximum amplitudes, maximum vibrations, and maximum accelerations obtained in the pit with those obtained at Station J, about 30 feet distant, for the earthquake of March 20th, 1885, they are in the ratios of 1 : 43, 1 : 52, and 1 : 82. In many earthquakes the diagram obtained in the pit was too small to admit of measurement, and it could only be detected by holding the plate on which the record was written up to the light and glancing along it length ways. In certain small earthquakes the record from the pit was equal in range of motion to that obtained on the surface, but the period was slower. As these results are of such importance to those who have to deal with foundations, it is advisable that they shouid be amplified. In mines, although earthquakes have often been felt, the ordinary experience is that they are passed by unnoticed. There is probably but little gained by sinking a pit in soft ground.

All large earthquakes appear to have been accompanied by the formation of fissures. In the Calabrian earthquake of 1783 one or two of the fissures which were formed were from a mile to a mile and a half in length, more than 100 feet in width, and 200 feet in depth. In the comparatively small earthquake of February 22nd, 1880, in Yokohama, cracks were formed near to the edge of cliffs overlooking the sea, two or three inches wide and 20 to 40 yards in length.

It has sometimes happened that the formation of fissures has been accompanied by elevation or depression and the surface of the ground has in consequence been broken up into steps.

Fissure phenomena are usually most observable in lines parallel to the face of free surfaces like cliffs, the banks of rivers, steep escarpments, etc. The reason that cracks have been formed, in such positions rather than in others is probably owing to the greater motion on the free surface which, being unsupported, tends to tear itself away from the material behind and form a fissure parallel to the face of the free surface.

It has often happened that water, mud, vapours, gases, and other materials have been discharged from fissures.

The falling of free surfaces has often resulted in the destruction of buildings standing upon their upper edges and the destruction of anything upon which they fell below. The materials dislodged from over hanging cliffs, which in magnitude have equalled ordinary land slips, have altered water courses, dammed up rivers, and created lakes.

Subterranean effects are also often produced by earthquakes. The flow of springs may be altered in the volume and character of their waters. Sometimes springs have been closed, and at other times new springs have been formed. Wells, artesian borings, and fumaroles, have been acted upon in the same manner as springs.

Closely connected with the above phenomena are the alterations which take place in vertical and horizontal directions of considerable tracts of land.

During the nineteenth century long tracts of coast in Chili and New Zealand have been suddenly elevated several feet, while in other districts, as the Delta of the Indus, and the State of Ohio whole districts have been sunk.

Mr. Forster, resident electrician in the island of Zante, has pointed out some remarkable instances where earthquakes have been accompanied by enormous submarine subsidences or landslips, resulting in the destruction of cables and the formation of depressions which, when new cables were laid, had to be avoided.

19.—Marginal Vibrations.

It has been frequently observed that cliffs, hill-scarps, and other free surfaces in similar situations, vibrate more than the level ground below or on the flat summit of the hill. Prof. Sekiya found by instrumental measurements that the steep edge of a loamy hill 38 feet in height moves twice as much as at its base. (Trans. Seism. Soc., Vol. XI., p. 87.)

20.—Earthquake Districts in Japan.

Between October, 1881, and October, 1883, 387 earthquakes were recorded in North Japan, that is between Tokio and Hokkaido.

Of these, 154 each shook an area of less than 50 square miles. The remaining 133 disturbances each shook an area with an average diameter of 45 miles. A few of the larger shocks shook an area the radius of which was at least 150 miles. The area where the most earthquakes were felt was along the seaboard, no less than 84 per cent. of the total number having originated beneath the Pacific Ocean or in land close to the seaboard. The district most shaken has been the flat ground forming the plain of Musashi, and Hitachi round the lower course of the Tonegawa. The mountainous districts and the immediate neighbourhood of the volcanoes have been singularly free from disturbances. Unless an earthquake is severe it grows feebler as it approaches the mountains and almost invariably dies out without crossing them. The mountains referred to have peaks from 6,000 to 10,000 feet high.

In 1885 the Imperial Meteorological Observatory received records of 492 distinct disturbances. The stations at which these were observed lie between Nemuro in the North of Yezo and Nagasaki in the South of Kiushiu.

The above records indicate that there were 40 earthquakes per month or 1.3 per day. Some idea of the intensity of these disturbances may be derived from the following table :—

Disturbances shaking more than	30,000 square miles	2
Disturbances shaking more than	18,000 square miles	6
Disturbances shaking more than	12,000 square miles	13
Disturbances shaking more than	5,755 square miles	9
Disturbances shaking more than	4,500 square miles	12
Disturbances shaking more than	3,000 square miles	17
Disturbances shaking more than	1,800 square miles	24
Disturbances shaking more than	1,200 square miles	27
Disturbances shaking more than	600 square miles	63
Disturbances shaking less than	100 square miles	319
		492

The largest shock disturbed an area of 34,700 square miles.

Out of the 492 shocks, 279 originated beneath the sea or near the sea shore. The district most shaken was the alluvial plain near Tokio. The eastern and southern portion of Japan is shaken very much more than the western side facing the Japan sea. The country north of Tokio is shaken very much more than that laying towards the south. In Kiushiu where volcanoes are numerous, earthquakes have not been so frequent as near the province of Kii where there are no volcanoes. In two instances, however, volcanoes and earthquakes appear to be related. Thus the earthquakes at the southern end of Satsuma, occur at or near the volcanoes of that district, while the shocks at the north-east extremity of Honshiu occur at or near Osoresan. In the former district 9 shocks and in the latter 24 shocks were recorded.

In the central district near Tokio where earthquakes are most frequent these do not appear to originate from the volcanoes but along and near a cast where there are evidences of elevation to be seen.

These observations show that there are certain districts in Japan where special precautions against earthquakes are hardly necessary, while in other districts precautionary measures are imperative.

20.—Disturbances in the Ocean.

The destructive movements in the ocean accompanying earthquakes are sea waves which have sometimes rushed inwards in upon the coast 60 to 100 feet in height. In South America the damage caused by these waves by destroying wharves, buildings, washing ships inland, and the like, has in many instances been greater than that produced by the actual earthquake.

In Japan many large waves have occurred, lists of which have been published by the Seismological Society. Among waves of late years may be mentioned those of 1854, 1868, and 1877.

In 1854 waves some of which were 30 feet in height inundated Simoda. Subsequently a sea wall was built to avoid similar disasters.

Some years ago a sea wave which *may* have had a seismic origin inundated and destroyed the shaft of a coal mine on the island of Hashima near Nagasaki.

In 1868 the waves originating on the South American coast, which with the accompanying earthquakes resulted in the loss of 25,000 lives, crossed the Pacific to the coast of Japan, where they rose and fell like a series of tides. In Hakodate where the ordinary tide is only 2½ feet the differences in sea level which occurred every 10 or 15 minutes sometimes reached 10 feet. Ware houses were inundated and considerable alarm was created.

Similar phenomena occurred at many places along the eastern coast of Japan.

In 1877 another South American earthquake inundated the coast of Japan. The velocity with which these waves travel to Japan depends upon the depth of the ocean. From their origin to Hakodate the waves of 1877 travelled 8,778 geographical miles in 25 hours 8 minutes or with a velocity of 512 feet per second.

As a wave approaches a coast near to its origin, the first observation is a receding of the water, after which as the wave advances it increase in height as the water shallows. The rear slope of such a wave is gentle, while the front slope may increase in steepness until it topples over. The destruction of places like Talcahuano and Callao has been in part due to this increasing height of waves, while places like Valparaiso on the edge of deep water have not suffered. Another cause affecting the height of waves is the configuration of the coast. A wave entering a bay with a wide opening and narrowing as it proceeds inland, will increase in height, while a wave entering a bay which is wider inland than at its entrance will decrease in height. In 1877 waves, which on many parts of the Japanese coast were 8 or 10 feet in height, did not exceed one foot in Tokio bay. The length of waves which have travelled a long distance from their origin may be one or two hundred miles so that these inundations appear on the coast like tides and visible waves are absent.

21.—Seismic Experiments.[5]

The following experiments were commenced in 1880. They were completed in 1885. The movements which were then recorded were produced by allowing a heavy ball, 1,710 lbs. in weight, to fall from various heights up to thirty-five feet. Subsequently many experiments were made by exploding charges of dynamite and gunpowder placed in bore-holes. The observations which were made upon the resultant vibrations of the ground were very numerous. As examples of these may be mentioned—the determination of the nature of earth vibrations as deduced from diagrams, the velocity of propagation of different kinds of vibrations, the relative motion of neighbouring points of ground, experiments on the production of earth currents, experiments on projection and overturning, &c.

I.—EFFECT OF GROUND ON VIBRATIONS.

1. Hills have but little effect in stopping vibrations.

2. Excavations exert considerable influence in stopping vibrations.

3. In soft damp ground it is easy to produce vibrations of large amplitude and considerable duration.

4. In loose dry ground an explosion of dynamite yields a disturbance of large amplitude but of short duration.

5. In soft rock it is difficult to produce a disturbance the amplitude of which is sufficiently great to be recorded on an ordinary seismograph.

II.—GENERAL CHARACTER OF MOTION.

1. The pointer of a seismograph with a single index first

[5] Trans. Seism. Soc. Vol. VIII.

moves in a normal direction, after which it is suddenly deflected, and the resulting diagram yields a figure partially dependent on the relative phases of the normal and transverse motion. These phases are in turn dependent upon the distance of the seismograph from the origin.

2. A bracket seismograph indicating normal motion at a given station commences its indication before a similar seismograph arranged to write transverse motion.

3. If the diagrams yielded by two such seismographs be compounded, they yield figures containing loops and other irregularities not unlike the figures yielded by the seismograph with the single index.

4. Near to an origin the first movement will be in a straight line outwards from the origin; subsequently the motion may be elliptical, like a figure 8, and irregular. The general direction of motion is, however, normal.

5. Two points of ground only a few feet apart may not synchronise in their motions.

6. Earthquake motion is probably not a simple harmonic motion.

III.—NORMAL MOTION.

1. Near to an origin the first motion is outwards. At a distance from an origin the first motion may be inwards.

As to whether it will be inwards or outwards is probably partly dependent on the intensity of the initial disturbance, and on the distance of the observing station from the origin.

2. At stations near the origin the motion inwards is greater than the motion outwards. At a distance the inward and outward motions are practically equal.

3.—At a station near the origin, the second or third wave is usually the largest, after which the motion dies down very rapidly in its amplitude, the motion inwards decreasing more rapidly than the motion outwards.

4.—Roughly speaking, the amplitude of normal motion is inversely as the distance from the origin.

5.—At a station near an origin the period of the waves is at first short. It becomes longer as the disturbance dies out.

6.—The semi-oscillations inwards are described more rapidly than those outwards.

7.—As a disturbance radiates the period increases. Finally it becomes equal to the period of the transverse motion. From this it may be inferred that the greater the initial disturbance the greater the frequency of waves.

8.—Certain of the inward motions of "shock" have the *appearance* on the diagram of having been described in less than no time.

9.—Tables have been calculated to the show the maximum velocity of normal motion.

10.—Diagrams have been drawn to show the intensity of normal motion.

11.—The first outward motion, which on diagrams has the the appearance of a quarter-wave, must be regarded as a semi-oscillation.

12.—The waves on the diagrams taken at different stations do not correspond.

13.—At a station near the origin, a notch in the crest of a wave of shock gradually increases as the disturbance spreads, so that at a second station the wave with a notch has split up into two waves.

14.—Near the origin the normal motion has a definite commencement. At a distance the motion commences irregularly, the maximum motion being reached gradually.

IV.—TRANSVERSE MOTION.

1.—Near to an origin the transverse motion commences definitely but irregularly.

2.—Like the normal motion, the first two or three movements are decided, and their amplitude slightly exceeds that of those which follow.

3.—The amplitude of transverse motion as the disturbance radiates decreases at a slower rate than that of the normal motion.

4.—As a disturbance dies out at any particular station the period increases.

5.—As a disturbance radiates the period increases. This is equivalent to an increase in period as the intensity of the initial disturbance increases.

6.—As we recede from an origin the commencement of the transverse motion becomes more definite.

7.—It will be observed that the laws governing the transverse motion are practically identical with those which govern the normal motion, the only difference being that in the case of normal motion they are more clearly pronounced.

V.—RELATION OF NORMAL TO TRANSVERSE MOTION.

1.—Near to an origin the amplitude of normal motion is much greater than that of the transverse motion.

2,—As the disturbance radiates, the amplitude of the transverse motion decreases at a slower rate than that of the normal motion, so that at a certain distance they may be equal to each other.

3.—Near to an origin the period of the transverse motion may be double that of the normal motion, but as the disturbance dies out at any given station, or as it radiates, the periods of these two sets of vibrations approach each other.

VI.—MAXIMUM VELOCITY AND INTENSITY OF MOVEMENT.

1. An earth particle usually reaches its maximum velocity during the first inward movement. A high velocity is, however, sometimes attained in the first outward semi-oscillation.

2. The intensity of an earthquake is best measured by its destructive power in overturning, shattering, or projecting various bodies.

3. The value $v^2 = \frac{3}{4} g \sqrt{a^2+b^2} \times \left(\frac{1-\cos\theta}{\cos^2\theta}\right)$ used by Mallet and other seismologists to express the velocity of shock

as determined from the dimensions of a body which has been overturned, is a quantity not obtainable from an earthquake diagram. It represents the effect of a sudden impluse.

4. In an earthquake a body is overturned or shattered by an acceleration, *f*, which quantity is calculable for a body of definite dimentions.

The quantity *f* as obtained from an earthquake diagram lies between $\frac{v}{t}$ and $\frac{v^2}{a}$, where v is the maximum velocity, *t* is the quarter period, and *a* is the amplitude.

5. The initial velocity given in the formula $v^2=\frac{2a^2}{b}$ (for horizontal projection), used by Mallet as identical with v^2 in 3, is not an identical quantity.

The velocity calculated from the range of projection when projection occurs is identical with the maximum velocity as measured directly or calculated from a diagram.

6. In discussing the intensity of movement I have used the values $\frac{v^2}{a}$.

7. The intensity of an earthquake at first decreases rapidly as the disturbance radiates; subsequently it decreases more slowly.

8. A curve of intensities deduced from observations at a sufficient number of stations would furnish the means of approximately caclulating an absolute value for the intensity of an earthquake.

VII.—VERTICAL MOTION.

1. In soft ground vertical motion appears to be a free surface wave which outraces the horizontal component of motion.

2. Vertical motion commences with small rapid vibrations, and ends with vibrations which are long and slow.

3. High veloctities of transit may be obtained by the observation of this component of motion. It is possibly an explanation of the preliminary tremors of an earthquake and the sound phenomenon.

4. The amplitude and period of vertical waves as observed at the same or different stations have been measured.

VIII.—VELOCITY.

1. The velocity of transit decreases as a disturbance radiates.[1]

2. Near to an origin the velocity of transit varies with the intensity of the initial disturbance.

3. In different kinds of ground, with different intensities of initial disturbance, and with different systems of observation, velocities lying between 630 and about 200 feet per second were determined. Mallet determined a velocity in sand of 824 feet, and in granite of 1,664 feet per second. General Abbot has observed velocities of over 20,000 feet per second. All of these determinations I regard as being practically correct, the great difference between them being due partly to the nature of the rock, the intensity of the initial disturbance, and the kind of wave which was observed.

4. In my experiments the vertical free surface wave had the quickest rate of transit, the normal being next, and the transverse motion being the slowest.

5. The rate at which the normal motion outraces the transverse motion is not constant.

6. As the amplitude and period of the normal motion approach in value to those of the transverse motion, so do the velocities of transit of these motions approach each other.

7. By cross-bending and torsion of cylinders of rocks the velocity with which normal and transverse vibrations would be propagated in such rocks has been determined. These determinations show that the ratio of the speed of these two kinds of motion is not constant. The softer and less elastic rocks are, the nearer do these velocities approach each other. That the ratio of the speed of normal and transverse motions is not constant is shown from tables of these velocities calculated for different rocks from their moduli of elasticity.

IX.—MISCELLANEOUS.

1. At the time of an earth disturbance, currents are produced in telegraph lines.

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[1] In the Flood Rock explosion General Abbot found an exception to this rule.

2. The exceedingly rapid decrease in the intensity of a disturbance in the immediate neighbourhood of the *epicentrum* has been illustrated by a diagram.

3. For the duration of a disturbance due to a given impulse in different kinds of ground, reference must be made to the detailed descriptions of the first four sets of experiments.