SEISMIC EXPERIMENTS

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CONTENTS.

INTRODUCTION.

The following paper is an account of a large number of experiments made at different times and in different places for the purpose of investigating phenomena connected with earth vibrations. The idea of making such experiments suggested itself to me in 1880.

In 1881 in conjunction with Mr. T. Gray formerly one of my colleagues at the Imperial college of Engineering, I commenced these experiments at the Engineering Works at Akabane in Tokio. Subsequently to this, eight other sets of experiments were undertaken the last being made on July 6 1883.

The earth vibrations which were studied were produced either by some explosive like dynamite or by allowing a heavy weight to fall from height. Each set of experiments involved several weeks preparation, and in some cases extended over several days. Among the chief difficulties which had to be overcome in connection with the experiments may be mentioned, that of obtaining dynamite from the government stores, its transportation, its storage, the difficulties of obtaining a piece of ground on which to experiment, manufacturing the necessary instruments, obtaining telegraph wire and its erection between the observing stations, the arrangement of firing apparatus, the manufacture of electric fuzes, the anxiety lest accidents should occur, putting down bore holes in which to fire dynamite, training assistants, the difficulties of contending against bad weather which had often to be encountered on days for which permission had been granted.

For the use of ground where the experiments were performed and for the loan of tents to cover the instruments at the different observing stations and for a body of attentive servants, my thanks are due to His Excellency General Yamada late Minister of the Interior, and Mr. Arai Ikunosuke Director of the Meteorological Department. For the loan of telegraph wire, firing apparatus and other instruments, I tender my thanks to the director and officers of the Public

Works Department, the Department of Imperial Telegraphs, the Naval and War Departments, to the officers of the Imperial College of Engineering and the Engineering works at Akabane. For much personal assistance I have to thank Mr. Denys Larrieu and Mr. John Reid who supplied me with dynamite, my colleagues at the Imperial College of Engineering, and many other residents in Tokio who from time to time came to witness the experiments.

In commencing my experiments the only data which I had for guidance were the results obtained by the late Mr. Robert Mallet and General H. L. Abbot. These gentlemen however only experimented on the velocity with which earth vibrations were propagated. In taking diagrams of earth motion I was therefore entering upon new ground and, as might be anticipated, continually encountered unexpected results. Sometimes for instance it was found that the instruments which were employed would require modification before satisfactory records could be obtained, at other times the records which were obtained gave indications of new lines of investigation to carry out which a new instalment of apparatus would be required, &c. For reasons like these many of the results given in the following pages can only be regarded as provisional, as for example those which relate to the velocities of normal and transverse vibrations. Should opportunity present itself for continuing those investigations there is no doubt that much of what is here recorded might be repeated, and by taking advantage of my experience more accurate results might be obtained.

As examples of investigations which have yet to be undertaken I may mention the following.

1. An accurate determination of the rate at which the velocity of transit decreases as a disturbance radiates from its origin.
2. The relationship between the velocity of transit and the intensity of the initial disturbance.
3. The determination of the rate at which the intensity of a disturbance decreases as measured at different distances from the origin. This might perhaps lead to

the construction of a curve of intensities from which the absolute intensity of the initial disturbance could be learnt.

4. A more complete investigation of vertial motion and free surface waves.
5. An investigation of the inward motion of shocks. In my experiments the movement of the ground from its neutral position *in* towards the origin of the disturbance has been performed so rapidly that I have been unable with the instruments at my disposal to accuratly measure its velocity. As this is probably the most destructive element of motion its investigation is exceedingly important.
6. Farther investigations on the relationship between earthquake diagrams and the overturning and projecting of various bodies.
7. A repetition of these and all other experiments on different kinds of ground.

&c. &c. &c.

Although in these and other respects my investigations are imperfect, many facts relating to the nature of earth motion have been collected. One striking result is the great differences between the results of observation and what would have been anticipated from theoretical investigations where it was assumed that the ground had behaved as a perfectly elastic body.

I may here call the attention of those who have occasion to refer to these experiments that with the exception of the tenth set, the remainder succeed each other in the order in which they were performed. This order becomes more systematic and the results which have been obtained appear more nearly consequential in their relation to each other, if the ninth set of experiments are placed before the fourth set. They ought certainly to be read before the seventh set. At the end of this paper I have summed up the different results which have been reached, indicating the experiment or experiments where the data on which such results are founded may be found. This has necessarily led to repetition but it has resulted in a systematic and convenient arrangement of results. In conclusion I may state that the nature of the experiments which I record are such that it is hardly just to expect them to be carried out satisfactorily by an individual. The trouble, the expense, the danger and I may add the magnitude of the arrangements which they involve make them fitter undertakings for an army corps rarther than for a private person. In addition to the field experiments, I also give an account of several laboratory experiments made for the purpose of determining the elastic moduli of rocks, the projection of bodies from springs &c. all of which it will be seen are fairly included in the title of this paper.

I. SERIES OF EXPERIMENTS.

The first experiments were made in January and Febuary 1881 by Mr. Gray and myself at the Akabane Engineering works in Tokio. An account of these experiments has been published in the Philosophical Transactions of the Royal Society. Part III. 1882.

The vibrations were produced by the fall of a ball weighing 1710 lbs, from varying heights up to 35 feet. In consequence of the blow which the ball gave, the surrounding ground, which was a hardened mud, was caused to vibrate for a distance of about 300 feet. A plan of the ground is shown in Fig. 1. The methods of observing the vibrations were various. A simple means of determining the relative amount of motion experienced at different stations was the observation of the number of seconds that the same quantity of mercury contained in similar vessels continued to move. These observations required a number of observers who, to equalize errors of observation, were interchanged between the different stations for each new experiment. In addition to simple contrivances like these, seismographs which gave a record of their movements on smoked glass plates were employed, as for instances Bracket seismographs similar to those employed by Prof: Ewing, Conical Pendulum seismographs, Rolling sphere seismographs &c. To record vertical motion, the can of liquid with a flexible bottom and Gray's vertical lever spring seismograph were employed. Descriptions of these instruments may be found in the Transactions of the Seismological Society of Japan.

The smoked glass plates on which the instruments wrote, were sometimes stationary and at other times by means of suitable contrivances they were drawn along horizontally beneath the writing indices. By means of electrical connections between the points of observation and a pendulum swinging across a cup of mercury, time ticks were made on the various plates. This furnished means to determine the velocity with which a disturbance was propagated, and facilitated exact comparisons being made between diagrams obtained at different stations. Independently of the time occupied in making the necessary preparations, the experiments extended over nine days, the ball being dropped four or five times each day.

The more important results which were obtained were as follows.

1. A partial determination of the effect of hills and excavations (like a deep pond) upon the transmission of vibrations. Small hills had but little effect in stopping vibrations, but a pond to a certain extent cut off both normal and transverse motion.
2. A complete graphical separation of normal from transverse vibrations. The existence of these two kinds of vibration was first observed in diagrams like Figs 2, 3 and 4 taken by means of a rolling sphere seismograph on a stationary smoked glass plate. At the commencement the needle of the pointer was resting near C. It first moved to A, then to B and back towards C at or about which point its motion was suddenly deflected. The direction in which the disturbance came is shown by the arrow. A more complete separation of the normal and transverse movement was obtained by placing two bracket seismographs at right angles, so that one recorded all motion in the direction of propagation and the other all motion at right angles to such a direction. It was observed that the former of the two seismographs invariably commenced to write its record before the latter.
3. A determination of the relative amplitudes of the normal and transverse motions as observed at points differently situated with regard to the origin of the shock. Near the origin the normal motion was much the greater, but in proceeding outwards from the origin the normal motion diminished the more rapidly of the two. Roughly speaking the amplitude of the normal vibrations was inversely as the distance from the origin.
4. There were usually about six vibrations per second. The normal vibrations had the quicker period.

5. The average velocity of the normal vibrations was 438 feet per second whilst that of the transversal movements was only 357 feet.
6. At a distant station (250 feet) four or five dissimilar vibrations would be recorded, and then the same four or five vibrations would be repeated in the same order as those first recorded.

II. SERIES OF EXPERIMENTS.

These experiments were made by myself and Mr. T. Gray at Yokosuka, a naval dockyard about 20 miles distant from Tokio. The ground was a horizontally stratified soft clay rock. The vibrations were produced by dropping a heavy weight from a height of about 40 feet. Although the weight was heavier than the one previously employed, on account of the nature of the rocks we found it impossible to create a disturbance which could be recorded at a distance greater than 20 feet, and even then the vibrations which were recorded had amplitudes too small to admit of satisfactory analysis.

For these reasons, after much time had been spent in making instruments, transporting them to Yokosuka, and obtaining the necessary permission to work, the experiments had to be abandoned. The negative result which was obtained is however worthy of record.

III. SERIES OF EXPERIMENTS.

In this series of experiments which were made in December 1881 the disturbances were created by the explosion of dynamite and other substances. Although many valuable results were obtained, owing to the heavy fall of snow which took place on the days for which permission had been granted to perform the experiments, the large number of visitors who assembled, the fact that the instruments which were employed had been hurriedly constructed and for other reasons, many of the diagrams which were obtained were imperfect. In consequence of these experiments however, experience was gained in properly proportioning charges of dynamite and in the general working of the apparatus which led to the satisfactory results obtained on subsequent occasions.

For the dynamite which was used and also for considerable assistance I have to thank Mr. John Reid agent of Nobel & Co. The charges employed varied from a few ounzes to 2 or 3 ℔s. They were fired near the place where in the first set of experiments the ball fell. Some of the charges were fired on the surface of the ground, some in the neighbouring pond, whilst others were exploded in bore holes from 3 to 12 feet in depth and 3^{in} in diameter.

The effect of an explosion in a bore hole was to produce a large cavity 4 or 5 feet in diameter at the top, and opening out downwards to a pear shaped form, the diameter below being double that at the top. For a given charge the greatest effect was produced when it was exploded in the neighbouring pond. The great advantage gained by using dynamite may be judged of from the fact, that the maximum displacement of an earth particle 50 feet distant from the place where the ball fell, was hardly more than $\frac{1}{5}$ of that produced by 2 ℔s of dynamite in a six ~~foot~~ feet bore hole acting at the same distance.

The charges were fired by means of a small electro-dynamo machine and tension fuses.

The instruments employed were three pendulum seismographs and three bracket seismographs. The former wrote their record on stationary plates whilst the latter wrote on plates which at the time of an explosion were drawn horizontally by means of falling weights beneath the recording pointers. There were three observing stations on the line AD Fig. 1. at distances from the scene of explosion of 50, 150 and 250 feet respectively. At each of these stations there was one of the above instruments. All the stations were electrically connected so that the swings of a small pendulum passing through a cup of mercury could be recorded on each of the moving record receivers.

The results of the experiments were as follows:—

1. EXPERIMENT.

Six oz. of gelatine (a new nitroglycerine compound) was exploded in a six foot bore hole. No effect was produced even at the 50 foot station.

2. EXPERIMENT.

6 oz. of gelatine together with 18 oz. of dynamite were exploded in a 7ft bore hole.

PENDULUM SEISMOGRAPH.

	Maximum Amplitude		
	Normal	Transverse	Remarks
At 50 ft. Station Fig. 5	3^{mm}	$.7^{mm}$	Three normal movements.
At 150 ft. Station Fig. 6	1.2	0	,, ,, ,,

3. EXPERIMENT.

18 oz. of dynamite exploded on the surface of the ground.

PENDULUM SEISMOGRAPH.

At 50 ft. Station. A maximum amplitude of $.4^{mm}$ at an angle of about 45° to true normal direction. Three or four complete vibrations.

BRACKET SEISMOGRAPH.

	Maximum Amplitude		
	Normal	Transverse	Remarks
At 50 ft. Station	$.01^{mm}$	$.01^{mm}$	The first motion compression.
At 150 ft. ,,	slight	slight	Two or three small ripples.

4. EXPERIMENT.

18 oz. dynamite fired in the pond near A. Fig. 1. The instruments being in the old position along the line AD were therefore not in one line with the origin of the disturbance.

PENDULUM SEISMOGRAPH.

At 50 ft. Station. A decided normal motion of .6^{mm}. The transverse motion was slight.

BRACKET SEISMOGRAPH.

	Maximum Amplitude		
	Normal	Transverse	Remarks
At 50 ft. Station	not well recorded	.5^{mm}	Altogether 11 vibrations.
At 150 ft. ,,	.25	.25	,, ,, ,,

The above movements are on account of the position of the explosion only approximately normal and transverse. The normal at the 150 ft. Station commenced as two slight ripples slightly before the transverse. The first movement was *in* towards the origin. The maximum movements consist of three large waves. The transverse movement commences irregularly. Fig. 7.

5. EXPERIMENT.

About 12 oz. dynamite were exploded in the pond near A.

PENDULUM SEISMOGRAPH.

At 50 ft. Station. Maximum amplitude of .4^{mm} intermediate to normal and transverse directions. (Record not good).

At 150 ft. Station. Maximum amplitude in a normal direction of nearly .4^{mm}. (Record not good).

BRACKET SEISMOGRAPH.

	Maximum Amplitude		
	Normal	Transverse	Remarks
At 50 ft. Station	$.21^{mm}$	not recorded	8 vibrations per sec.
At 150 ft. ,,	not well recorded	$.14^{mm}$	,, ,, ,, ,,

At the 50 ft. Station motion commenced with 2 small vibrations, the first movement being *inwards* towards the origin. The maximum movement is the fourth vibration. Motion continued for about half a second.

6. Experiment.

The ball (1710 lbs) fell 35 feet.

PENDULUM SEISMOGRAPH.

At the 50 ft. Station, there was motion in a normal direction of $.7^{mm}$ and a motion in a transverse direction of $.4^{mm}$. The movements in the two directions are not distinctly separated.

At the 150 ft. Station, the motion in a normal direction was $.3^{mm}$.

BRACKET SEISMOGRAPH.

At the 150 ft. Station. Both the normal and transverse motions were very slight.

7. Experiment.

The ball (1710 lbs) fell 35 feet.

PENDULUM SEISMOGRAPH.

At the 50 ft. Station. Maximum amplitude $.6^{mm}$.

BRACKET SEISMOGRAPH.

At the 150 ft. Station. The normal motion has a maximum amplitude of $.5^{mm}$ and a duration of about 1^{sec}. The first movement was outwards. There are 8 or 9 vibrations per second. The transverse motion has a maximum amplitude of $.14^{mm}$.

8. Experiment.

2½ lbs of dynamite exploded in the pond.

PENDULUM SEISMOGRAPH.

	Maximum amplitude		
	Normal	Transverse	Remarks
At 50 ft. Station	2^{mm}	slight	Three or four decided motions.
At 150 ft. ,,	$.6^{mm}$	,,	

BRACKET SEISMOGRAPH.

	Maximum amplitude		Frequency of vibrations per sec.	
	Normal	Transverse	Normal	Transverse
At 50 ft. Station	$.42^{mm}$	$.57^{mm}$	4 or 5	3 or 4
At 150 ft. ,,	not taken	.28	not recorded	3 or 4
At 250 ft. ,,	.14	.14	too small to measure	

The above directions are only approximately normal and transverse. At the 50 ft. at 250 ft. stations the first motions were distinctly those of compression or in a direction outwards from the origin. At the 50 ft. station the first two normal motions have ripples superimposed upon them. Fig. 8. The duration of motion is 2½ sec. The duration of the transverse motion is 4 sec. The first vibrations have ripples superimposed on them. The duration at the 150 ft. station of the transverse component is 1.5 sec. At the 250 ft. station the motion although decided is irregular. The transverse component reaches its maximum after the normal has become very small.

9. EXPERIMENT.

3½ lbs of dynamite exploded in a 9 ft. bore hole. At the distance of 100 feet the motion felt like that of a small earthquake.

PENDULUM SEISMOGRAPH.

	Max. amplitude	Remarks
At 50 ft. Station	about 5^{mm}	The pointer was driven off the plate
At 150 ft. ,,	1.7^{mm}	In a direction intermediate to Normal and Transverse

BRACKET SEISMOGRAPH.

	Maximum amplitude		Frequency of vibrations per sec.	
	Normal	Transverse	Normal	Transverse
At 50 ft. Station	7^{mm}	not recorded	5 or 6	not recorded
At 150 ft. ,,	$.56^{mm}$	$.6^{mm}$	5	5
At 250 ft. ,,	$.4^{mm}$	$.4^{mm}$	5 or 6	4 or 5

In all cases as the motion dies out the frequency of waves decreases to about 3 per second.

At the 150 ft. station normal motion commences with a movement of $.28^{mm}$ inwards. This is followed by an outward motion of $.36^{mm}$ which is succeeded by three large vibrations each about $.56^{mm}$. Transverse motion commences with a small movement of $.07^{mm}$ which is followed by two large motions each $.64^{mm}$.

At the 250 ft. station the normal motion commences outwards as is always the case at this station. The 3rd, 4th and 5th movements are the largest. The transverse motion commences gently.

At the 150 ft. station normal motion commences to be recorded .26 to .29 seconds before the transverse motion.

10. EEPERIMENT.

2 lbs of dynamite exploded in hole 5 ft. deep.

PENDULUM SEISMOGRAPH.

	Maximum amplitude		
	Normal	Transverse	Remarks
At 50 ft. Station	3.3^{mm}	.7^{mm}	There are 3 or 4 decided normal motions. The transverse motions are oblique to them.
At 150 ft. ,,	1^{mm}	.7^{mm}	These motions are at right angles to each other but each is inclined at 45° to a true normal direction.

BRACKET SEISMOGRAPH.

	Maximum amplitude		Frequency of vibrations per sec.	
	Normal	Transverse	Normal	Transverse
At 50 ft. Station	2.1^{mm}	1^{mm}	7 or 8	7 or 8
At 150 ft. ,,	.35	.35	8	6
At 250 ft. ,,	.21	.25	—	—

At the 50 ft. station the normal motion commenced with .5^{mm} of motion outwards followed by 1.6^{mm} motion inwards. After this come 4 of the largest waves. The motion then quickly dies out. The duration is 1½ seconds. Fig. 9.

The transverse motion consists of 4 almost equal vibrations described in .33 sec.

At the 150 ft. station motion commenced by a very slight inward motion after which the motion is .21^{mm} outwards. After 3 large vibrations which follow, the motion rapidly dies out. The transverse motion commences with 2 gentle vibrations each about .05^{mm}. From the appearance of the diagram it is evident that the period of the normal motion is shorter than that of the transverse motion.

At the 250 ft. Station 6 large normal vibrations are distinctly visible. The transverse component which commences as a ripple is slightly larger than the normal motion.

At the 50 ft. Station both normal and transverse motion commence at the same instant.

At the 150 ft. Station the normal motion is .19 to .24 sec. ahead of the transverse movement.

The velocity of the normal motion between the 50 ft. and 150 ft. Stations lies between 265 feet and 294 feet per second. The velocity of the transverse motion between the same stations was 176 feet per second.

11. EXPERIMENTS.

The Ball (1710 lbs) fell 35 feet.

PENDULUM SEISMOGRAPH.

At the 50 ft. Station the maximum amplitude was $.7^{mm}$ The direction of motion was at 45° to the true normal direction. The disturbance commenced with a slight normal motion.

BRACKET SEISMOGRAPH.

At the 50 ft. Station the maximum amplitude of the normal motion is $.21^{mm}$. The first motion was outwards. The general appearance of this diagram is very like that of experiment 10, only smaller. First there are two large waves after which the motion rapidly dies out. The duration of the disturbance is $.5^{sec}$.

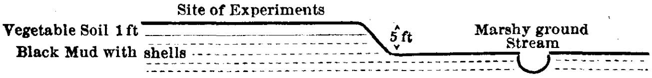
The transverse motion is also like that of experiment 10, only differing from it in being smaller Fig. 10.

At the 150 ft. Station. The normal motion is only represented by a straight line. The transverse motion shews 2 or 3 small flat ripples.

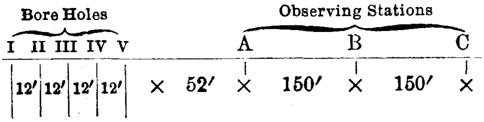
IV. SERIES OF EXPERIMENTS.

These experiments were made on December 26th 1881 in a field opposite the Kobusho (Public Works Department)

On the surface, the ground was dry but a few feet down it was very wet. A cross section on the line of operations is shown in the accompanying figure.



A section along the line of operations is follows.



The Bore Holes I II III IV and V were from 8 to 9 feet in depth. They were naturally filled with water to within 3 feet of the surface. This water together with a quantity of loose earth which was poured into the holes about the charges of gun powder and dynamite which were exploded, acted as tamping. The distances that A B & C were from the origins of the successive explosions were as follows,

	A	B	C
For the 1st Explosion	100 ft	250 ft	400 ft
„ „ 2nd „	88 „	238 „	388 „
„ „ 3rd „	76 „	226 „	376 „
„ „ 4th „	64 „	214 „	364 „

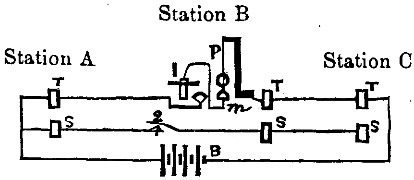
At A B and C bracket seismographs were employed. The multiplication of these instruments was 12. At B, Gray's lever spring seismograph for vertical motion wrote a record side by side with that of the bracket seismograph. At A and B pendulum seismographs with a multiplication of 10 were placed.

The indices of the bracket seismographs rested on the surface of a smoked glass plate which at the time of the shock was moved horizontally in the same manner as in the experiments at Akabane. The electrical arrangements by which the record receivers were set in motion and as they moved had time intervals recorded on their surface, will be understood from the following diagram.

T and S in the diagram represent two electro-magnets at each of the three stations. T is a magnet which deflects a small pointer on the moving plate to mark time intervals whilst S is a magnet which withdraws a catch and sets the record receiving carriages free.

By closing the key 2 and completing the circuit 2 S B S S the carriages are set free. By closing the key 1 and allowing the pendulum P to swing through the mercury *m*, the circuit *m* T B T T is continually opened and shut. With each swing of the pendulum the magnets T deflect a lever and record a time interval on the moving plates.

The operations were as follows. First the carriages were set in motion by means of key 2. Next key 1 was closed and time ticks were recorded on the moving plate. Immediately after this by means of a separate battery and an Induction coil the charge was exploded. Some 10 seconds later the motion of the record receivers was stopped, and remained at rest until a second charge had been prepared. In this manner experiment succeeded experiment without any alteration in the adjustment of the various instruments.



1. EXPERIMENT.

Three lbs of dynamite exploded in bore hole Number I.

PENDULUM SEISMOGRAPH.

	Maximum extent of motion		
	Normal	Transverse	Remarks
At Station A (100 ft.)	2.1^{mm}	.5^{mm}	
At Station B (250 ft.)	1.1^{mm}	.3^{mm}	The transverse was irregular.

BRACKET SEISMOGRAPH. (Fig. I. last plate.)

	Maximum extent of motion		Maximum frequency of vibrations	
	Normal	Transverse	Normal	Transverse
At Station A (100 ft.)	2.1^{mm}	$.53^{mm}$	4 per sec.	4.5 per sec.
At Station B (250 ft.)	$.5^{mm}$	$.23^{mm}$	3 ,, ,,	3 ,, ,,
At Station C (400 ft.)	$.15^{mm}$	$.1^{mm}$		

At Station A. The normal disturbance commenced by a slight motion outwards. The largest wave is the third one from the commencement. On the heads of each of the large waves a small ripple is superimposed. The amplitude of motion is greatest on the side of the origin or inwards. Motion extends over 3. 5 seconds, in which period there are 10 vibrations. At the end of the disturbance there are only 2 complete waves per second.

The transverse motion rapidly dies out after the second vibration which is the largest. At the end of the disturbance there are only 2 vibrations per second. Altogether there are 11 vibrations in 4 seconds.

At Station B. The normal motion commences as three gentle ripples, the first being in the direction of compression or outwards. After that come three large but slow vibrations.

The Transverse motion commences with two gentle vibrations.

At Station C. The first normal motion is inwards. There is no marked distinction between the different waves like that recorded at Station A.

The transverse motion has about the same period as the normal.

Vertical motion. This was recorded at station B. It apparently commences before the normal motion. At the commencement there are 6 waves per second but at the end only 2 per second. The quickly described waves have an amplitude of $.16^{mm}$ whilst those which were slower have an amplitude of $.44^{sec}$.

If we take the *smallest* of these measurements and combine it with the *largest* normal motion at this station ($.46^{mm}$) to obtain the tangent of the angle of emergence, we can calculate the least possible depth of the origin. The depth so calculated is 86.75 feet. We however know the depth to have been about 8 feet. The conclusion arrived at is therefore that the vertical motion is not due to a direct shock but to a surface wave. Farther it may be added that persons standing near Station B at the time of the explosion could feel the ground rising and falling as if such waves were passing beneath their feet.

2. EXPERIMENT.

Three pounds of dynamite exploded in bore hole Number II.

PENDULUM SEISMOGRAPH.

Maximum extent of motion.

At Station A 88 ft.	Motion oblique to normal and transverse 2.6^{mm}
At Station B 238 ft.	Normal 1.3^{mm} Transverse $.4^{mm}$. No distinct separation of normal and transverse.

BRACKET SEISMOGRAPH. (Fig. II. last plate.)

	Maximum extent of motion.		Maximum frequency of vibrations.	
	Normal	Transverse	Normal	Transverse
At Station A 88 ft.	3^{mm}	$.9^{mm}$	4 per sec.	4 per sec.
At Station B 238 ft.	$.5^{mm}$	$.2^{mm}$	3 ,, ,,	3 ,, ,,
At Station C 388 ft.	$.2^{mm}$	$.1^{mm}$	3 ,, ,,	3 ,, ,,

At Station A. The normal disturbance commenced as a slight compression followed by an irregular tremor. The largest wave is the third having a range of 3^{mm} after which the motion rapidly dies down to $.4^{mm}$. At the commencement of the motion there are 4 vibrations per second but afterwards only 3.

The transverse motion commences irregularly. At the end of the disturbance there are only 2 vibrations per second. Altogether there are 11 vibrations extending over 4 seconds.

At Station B. The normal motion practically consists of 4 large vibrations of nearly equal extent. They extend over about 1.5 seconds.

The transverse motion also consists of 4 nearly equal large vibrations executed in about $1.5^{sec.}$. The period is rather slower than that of the normal motion.

At Station C. In the normal motion two or three little ripples are to be observed at its commencement corresponding in time to two or three similar ripples in the transverse motion. These may possibly be due to a vertical component. They may also be traced in the diagram of the previous experiment.

About 7 vibrations appear in this diagram. They were executed in 2.5 seconds.

In the transverse motion the amplitude of motion is slightly less than in the normal. There are about 8 vibrations executed in about 2.5 seconds.

Vertical Motion. This was recorded at station B. It commences before the normal motion. At the commencement there are 6 small waves each having a range of $.15^{mm}$ performed at the rate of 8 per second. These are followed by a series of large vibrations with a range of $.4^{mm}$ performed at the rate of 2 waves per second.

Calculating as in the previous experiment, with a vertical motion of $.22^{mm}$ and a normal motion of $.38^{mm}$ we obtain 87 feet as a minimum depth for the origin of the disturbance. This we know to be incorrect. The vertical motion can not therefore be regarded as the result of a direct shock.

3. EXPERIMENT

Five pounds of gunpowder exploded in bore hole Number III.

PENDULUM SEISMOGRAPH.

	Maximum extent of motion.		
At Station A 76 ft.	Normal motion about	.2$^{\mathrm{mm}}$	Very irregular
At Station B 226 ft.	Motion about	.2$^{\mathrm{mm}}$	

BRACKET SEISMOGRAPH. (Fig. III. last plate.)

	Maximum extent of motion.		Frequency of vibrations.	
	Normal	Transverse	Normal	Transverse
At Station A 76 ft.	.6$^{\mathrm{mm}}$	.2$^{\mathrm{mm}}$	5 per sec.	3.5 per sec.
At Station B 226 ft.	No motion			
At Station C 376 ft.	,,	,,		

At Station A. In a normal direction the first movement is a very slight extention. The fourth wave is the largest. At the end of the disturbance there are only 4 vibrations per second. Altogether there are 6 vibrations performed in 1.25 seconds. The transverse motion commences with one or two very small ripples. These are followed by 4 waves each having a range of about .2$^{\mathrm{mm}}$.

At Stations B and C. No motion observed.

4. EXPERIMENT

2½ lbs of dynamite exploded in bore hole number IV.

PENDULUM SEISMOGRAPH.

	Normal	Transverse	Remarks
At Station A 64 ft.	3$^{\mathrm{mm}}$	1.5$^{\mathrm{mm}}$	
At Station B 214 ft.	1.2$^{\mathrm{mm}}$		Also an oblique motion

BRACKET SEISMOGRAPH. (Fig. IV. last plate.)

	Maximum extent of motion		Frequency of waves	
	Normal	Transverse	Normal	Transverse
At Station A 64 ft.	3.5^{mm}	1.2^{mm}	4 per sec.	3 per sec.
At Station B 214 ft.	.5^{mm}	.25	4 ,, ,,	
At Station C 264 ft.	.15	.1	3 ,, ,,	

At Station A. The normal motion commences with a decided compression of .4^{mm}. This is followed by three or four irregular back and forth motions of small amplitude. These are followed by the largest wave in the series. The whole of the motion was not recorded.

The transverse motion is characterized at its commencement by its irregularity.

At Station B. The normal motion commences irregularly. At the end of the disturbance there are only 2 waves per second. Altogether there are 11 vibrations performed in 4.5 seconds. The transverse motion commences irregularly with small waves. After this there are four well defined waves. Altogether 8 vibrations are described in 6 seconds.

At Station C. Both the normal and transverse motions are small and irregular. The transverse appears to have the quicker period.

Vertical Motion. This was observed at station B. It commences with a series of ripples each having a range of about .11^{mm}. Seven of these are described in a second. Next follow a set of larger waves with a maximum range of .7^{mm}. These recur in sets of three. These latter have a frequency of 3 per second. The periods of these waves it will be observed are quicker than those in the first experiment which were recorded 36 feet farther distant from the origin of the explosion.

AMPLITUDE.

Hitherto the only measurements which have been given are those of maximum extent of motion or the length of a semi-vibration. The halves of these quantities may be taken as maximum mean amplitudes of wave motion. Another value for amplitude would be the quarter of the sum of two succeeding semi-oscillations.

An inspection of the diagrams, especially those of the normal motion as observed at the station nearest to the explosion, shew that instead of taking mean amplitudes, absolute amplitudes may be measured with regard to a line which would have been drawn by the pointer of the seismograph had no explosion occurred. Examining the diagrams in this way it is clear that a point has not oscillated with equal amplitudes on either side of its normal position. At the station nearest to the origin the amplitude of normal motion has almost invariably been much greater in the direction of the origin than in the opposite direction. The general result of an explosion has been to compress the ground by an outward impulse, after which it has recoiled inwards through a greater range than it moved outwards.

This peculiarity of motion is also observable at the second station in the fourth experiment. At the third station the motion has become so small and irregular that measurement of outward and inward motion from a neutral line are impossible. In the following table showing the outward and inward amplitudes of normal motion for the first three prominent waves at each station, those for the third station are therefore only approximate.

The first outward impulse at Station A which in the diagrams has the appearance of a quarter wave, subsequent investigations have shown to be a semi-oscillation. To represent a true amplitude its values .4 .5 and 1.3 as given in the following table require to be halved.

AMPLITUDE OF NORMAL MOTION.

	Number of Wave.	Station A.		Station B.		Station C.	
		Outwards.	Inwards.	Outwards.	Inwards.	Outwards.	Inwards.
1. Experiment.	1	.4	.8	.25	.15	.05	.05
	2	.62	1.5	.35	.15	.05	.05
	3	.4	1.0	.25	.1	.05	.05
2. Experiment.	1	.5	1.5	.30	.2	.1	.1
	2	1.1	2.0	.4	.1	.1	.1
	3	.1	.7	.2	.2	.05	.05
4. Experiment.	1	1.3	1.7	.2	.4	.1	.1
	2	1.7	1.1	.12	.3	.1	.1
	3	.8	.2	.12	.3	.1	.1

When inspecting the above table it must be remembered that the distance of the three stations from the explosions was the smallest in the first experiment and greatest in the fourth experiment.

Another point of interest which may be obtained either from the table just given or from the values for the maximum extent of motion, is an approximate determination of the rate at which the motion dies out as a disturbance radiates.

From figures already given, the mean value in millimeters for the maximum semi-oscillation at stations A B and C in Experiments I II and IV are as follows.

Normal Motion.			Transverse Motion.		
A	B	C	A	B	C
2.8^{mm}	$.5^{mm}$	$.16^{mm}$	.85	.23	.1

or if we call the range of motion at A = 100, these numbers become.

100 18 6 and 100 27 12.

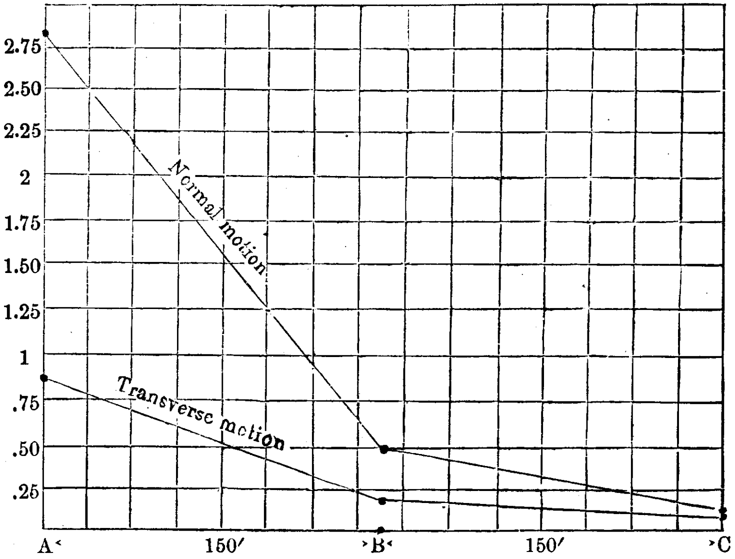
From this as from a direct inspection of the diagrams it is evident that the normal motion dies out very much more rapidly than the transverse motion.

Considering the transverse motion at each station as being equal to unity, then the ratio of the normal motion to the transverse motion is at each station as 3.3 : 2.1 : 1.6.

That is to say as the disturbance radiates the range of normal motion rapidly decreases until it is practically equal to the transverse motion.

These ratios together with the rate at which normal and transverse motion decrease are graphically shown in the accompanying diagram.

RANGE OF MOTION IN MILLIMETERS.



In connection with the discussion of amplitude it is interesting to observe the manner in which motion dies out at any particular station. The most interesting examples are those of the normal motion at the first station. From the second or third wave which in these diagrams are invariably the largest, the decrease in amplitude for the three succeeding waves is exceedingly rapid. From this point however the decrease is relatively slow. The dying out in amplitude is more rapid on the inward side of motion than on the outward side.

PERIOD.

The following table shows the time taken in seconds to describe the principal waves indicated in the four diagrams (see last plate.)

The times indicated were obtained by direct measurement of the distance between crests of successive waves.

		Normal				Transverse			Vertical	
Experiment	Station	1st wave	2nd wave	3rd wave	near the end.	1st wave	2nd wave	near the end.	small waves.	large waves.
I	A	.24	.44	.3	.5	.4	.37	.5	.12	.5
	B	.46	.63	.4	..	..	.36	..	..	..
	C	..	.36	..	..	..	.43	..	..	..
II	A	.25	.5	.32	.5	.4	.4	.5	..	..
	B	.37	.61	.4	..	..	.38	.4	.14	.5
	C	..	.3	..	..	..	.34	..	..	..
III	A	.21	..	..	..	..	.32	..	..	..
IV	A	.25	.4	.27	..	.3	.35	..	..	..
	B	.33	.33	.33	.5	.33	..	.41	.12	.38
	C	..	.3	.3	..	.27	.3	..	..	..

From an examination of the above table we see that—

1. As a disturbance dies out at any one station the period increases.
2. As a disturbance radiates the period increases.

These laws are the most clearly marked for the normal motion. It may here be pointed out that the measurements made on the diagrams obtained at station C on account of their smallness and irregularity, are not so accurate as those made on the diagrams obtained at stations A and B.

3. The vertical motion commences with a series of waves with an unusually short period. These are suddenly followed by a series with a long period.
4. Near to the origin of the disturbance, the transverse motion has at the commencement a period nearly double that of the normal motion.
5. At the end of a disturbance observed near the origin, or in diagrams taken at a distance from the origin, the period of normal and transverse motion approximate to each other.
6. The second wave obtained at station B in I and II with the unusually long period of over .6 second is in all probability a double wave due to the breaking up or elongation of the notched wave between the sinuses 1 and 2 which can be seen in Figs. I and II, last plate.

7. When we examine a diagram where there is a distinct movement of "shock" as for instance any of the diagrams of normal motion taken at the station (A) nearest to the origin, it is evident that the time taken to describe a half wave inwards is much less than to describe the preceeding or succeeding half wave outwards. To estimate these differences, measurements can be made of the time taken to describe quarter waves or amplitudes of wave motion. In making such measurements allowances have to be made for the arc which would be described by the pointer of the seismograph on the recording surface had the same been at rest.

Analyzing the normal motion obtained at station A in the different experiments we obtain the following results.

		1st wave			2nd wave				3rd wave			
		1st quarter out	1st quarter in	2nd quarter in	2nd quarter out	3rd quarter out	3rd quarter in	4th quarter in	4th quarter out	5th quarter out	5th quarter in	5th quarter out
Experiments.	I	.13	.1	0	.2	.12	.08	.03	.2	.05	.05	.03
	II	.19	.02	0	.26	.2	.03	.03	.31	.02	..	..
	III	..	..	..	..	..	..	.02	..	..	..	..
	IV	0	.07	.07	.07	.2	.04	.07	..	..	..	..

It is evident that the sum of the times (which are given in fractions of a second) taken to describe the different quarters of any particular wave, ought to equal the time given as the period of the same wave in the previous table. However advantage has been taken of any little irregularity in the character of a wave to reduce the various measurements to their least possible value in consequence of which slight discrepencies between the two tables may here and there be detected. The object of obtaining minimum values will be seen when speaking of intensity. Comparing the inward movements or movements towards the origin with those described in the opposite direction, we see that the former are very much the quicker.

In the first wave the second quarter inwards is in two cases noted as having occured in an interval of time too small to admit of measurement. As measured on the diagram this movement has the anomalous appearance of having been described in less than no time. The only explanation which I am able to offer for this peculiarity is that the post on which the seismograph was fixed did not synchronise with the movements of the record receiver,—whilst the stand was moving forwards the receiver was moving backwards. Experiments on the relative motion of two neighbouring points will be spoken about later on. The quarter waves here referred to have been measured to the right and left of a line which would have been drawn by the pointer of the seismograph had there been no disturbance. It is evident that they might also have been measured as halves of each semi-oscillation.

MAXIMUM VELOCITY.

If we assume that the motion of the ground has been simple harmonic then the maximum velocity $V=\frac{2\pi a}{T}$ where

a = the amplitude of motion and
T = the time taken to describe a complete wave.

In the adoption of this formula we are met with difficulties as to the manner in which a and T are to be measured. From the diagrams as already has been shown, either a mean amplitude or an absolute amplitude with regard to a certain line might be taken. A third value for amplitude would be quarter of a whole wave. Similarly T may be obtained by taking from the diagram the period of a complete wave, by doubling the time of a semi-oscillation, or by quadrupling the time of a quarter oscillation. Now as succeeding quarter or semi-oscillations have been described in different times, it is evident that three values for T may be obtained.

If therefore maximum velocities are calculated on the assumption that the motion has been simple harmonic it is possible to obtain nine different values for V.

A conclusion which the analysis of the diagrams here presents to us, is that the vibrations are in all probability not strictly simple harmonic motions, and whatever calculations respecting maximum velocities and other quantities are made on such assumptions, at the best can only be regarded as approximate.

The following table of maximum velocities in millimeters per second has been calculated for the normal motion at station A on the assumption that

a = the amplitude measured from the neutral line (see table p. 26.)
T = four times the time taken to describe a (see table p. 30.)

	1st wave			2nd wave				3rd wave			
	1st quarter out	1st quarter in	2nd quarter in	2nd quarter out	3rd quarter out	3rd quarter in	4th quarter in	4th quarter out	5th quarter out	5th quarter in	6th quarter in
Experiments. I	4.6	6	90*	6	7.5	11.2	75	1.1	12	12	50
II	4.7	37.5	225*	8.6	8.2	55	100	10	7.5	7.5	52
III	..	..	..	..	..	..	22.5	..	..	..	..
IV	10	28	36	36	12	64	24	..	..	..	..

The velocities marked with an asterisk are probably too great owing to the assumption made with regard to the value of T. This assumption was that $\frac{T}{4} = \frac{1}{100}$ second.

At station B the maximum velocities calculated on similar assumptions are as follows.

	1st wave			2nd wave				3rd wave			
	1st quarter out	1st quarter in	2nd quarter in	2nd quarter out	3rd quarter out	3rd quarter in	4th quarter in	4th quarter out	5th quarter out	5th quarter in	6th quarter in
Experiments. I	1.6	4	3.2	4.5	3.5	5.2	3.5	2.2	2.3	3.7	2.3
II	2.5	1.2	4.5	3	6	6	5	2.3	2.3	3	5
III	17	28	7.5	4	4	4	3	2.7	1.3	3	2

At station C the maximum velocities are approximately as follows:

I Experiment	.7 to 3^{mm}	per second
II ,,	1.5 to 10^{mm}	,, ,,
III ,,	3^{m}	,, ,,

In addition to these calculations of maximum velocities, calculations have been made of the same quantities by a method pointed out by Mr. T. Alexander in which there is no assumption made as to the nature of the motion (see Trans: of the Seis: Soc. Vol. VI. p. 13.)

The data on which these calculations are based, are the path traced by the pointer of the seismograph by the unknown motion of the pointer, the known linear velocity of the plate, and the length of the pointer.

As the construction to obtain maximum velocities by this method is chiefly dependent on the accuracy with which tangents can be drawn to the slope of the waves at their neutral point, the greatest accuracy has been obtained from the waves which were described slowly. In the case of the normal motion at A, the inward motion was described so quickly, as has already been pointed out, that calculations of maximum velocity in this direction have been neglected.

The waves which have been calculated are as follows.

MAXIMUM VELOCITY OF NORMAL MOTION IN MILLIMETERS PER SEC.

No of Experiment	1st wave	2nd wave	3rd wave	4th wave	
	1st quarter out	2nd or 3rd quarter out	4th or 5th quarter out	6th or 7th quarter out	
1st	3.6	6.5	6.5	3.	at A.
2nd	3.4	8.5	7.6	5.4	
4th	9.5	11.	10.4	7	
1st	1.2	3.5	2.4	..	at B.
2nd	2.	4.	1.8	..	
4th	1.4	4.4	2.6	1.1	
1st	.8	.6	..	..	at C.
2nd	.7	1.4	1.	..	
4th	.8	1.2	1.5	..	

In comparing these results with the results given in the three previous diagrams, it will be observed that if not absolutely identical, they are practically so when compared with mean values for each of the two corresponding quarters given separately in preceeding tables.

For the outward motion of the ground such comparisons, afford a means of estimating the amount of error which has entered into the numerous calculations which have been repeatedly made on earthquake diagrams, the assumption made in such calculations being that the motion was simple harmonic.

INTENSITY OF MOVEMENT.

In obtaining a value for the intensity of an earthquake many methods 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 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 I am 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 by adopting methods such as those here indicated it would seem that the intensity of an earth disturbance may be best 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 center 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 note on this subject was given to me by my colleague Mr. C. D. West.

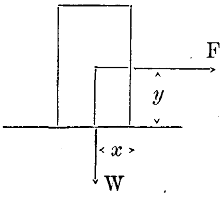


Fig. 17

Let the surface of the earth at any instant be undergoing an acceleration of velocity of f feet per sec. per sec. Let M be the mass of a column (see Fig.) resting on the ground, y the height of its center 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 center 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,

$$Wx = Fy = Mfy = \frac{W}{g} fy$$

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

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

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

If V is the maximum velocity of an earth particle as determined from an earthquake diagram, or by the projection of balls &c, 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 (see Ninth set of experiments).

In the following table the maximum acceleration $\frac{V^2}{a}$ has been calculated for prominent normal motions. The ratio of this to the mean time acceleration is $\frac{\pi}{2}$.

TABLE OF MAXIMUM ACCELERATIONS.—IN MILLIMETERS PER SEC. PER SEC.

No. of Experiments.	At Station A			At Station B			At Station C		
	1st quarter out	2nd or 3rd quarter out	4 or 5 quarter out	1st quarter out	2nd or 3rd quarter out	4 or 5 quarter out	1st quarter out	2nd or 3rd quarter out	4 or 5 quarter out
1	32	60	47	5	49	22	12	7	
2	23	55	57	13	53	20	4	19	10
5	69	71	108?	9	64	33	6	14	22
Mean Values	41	62	70	9	55	25	7	13	10

Owing to the difficulties in making the necessary time observations it is impossible to make calculations of maximum acceleration for inward motions, which are evidently very much greater than the ones just given. From an inspection of the accompanying diagram Fig. 11. which represents mean values for the intensity of the three waves given in the preceeding table, it would appear that for the area experimented on, the energy of motion varied inversely as some function of the distance from the origin.

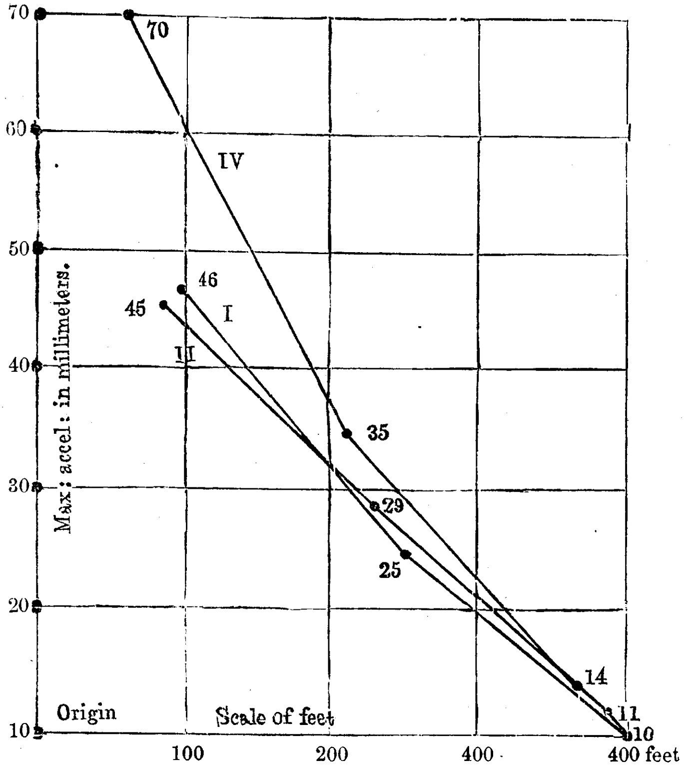


Fig. 11.

From the difference in the results obtained at the first station, which was at varying distances from the origin, it is probable that the rate at which energy was dissipated was greater between points near to the center of explosion than it was between points which were farther removed. Mr. T. Alexander has suggested that the total energy of the disturbance might be considered as proportional to the area enclosed between a curve of intensities and its axes, and having obtained such a curve for a unit disturbance produced for example by the explosion of a pound of dynamite we should have the means of giving absolute values for earthquakes providing their intensities had been measured at a sufficient number of stations.

RELATION BETWEEN NORMAL AND TRANSVERSE MOTION.

From an inspection of the diagrams it is evident that the normal motion has in all cases appeared on the recording surfaces a short interval ahead of the transverse motion. Unfortunately owing to irregularities in the diagrams we are unable to make accurate measurements of these intervals. One class of irregularities are probably due to displacements produced by sudden thrusts parallel to the length of the recording brackets, whilst another class may have been produced by sudden alterations in level accompanying the transit of surface waves. Evidences of such disturbances appear to exist in the diagrams.

For these reasons the results contained in the following table must only be regarded as approximate.

The time in seconds that the normal motion was recorded before the transverse motion is as follows.

	Distance from origin to			Time in seconds that the normal motion was recorded before the transverse motion.		
	A	B	C	A	B	C
	ft.	ft.	ft.	sec.	sec.	sec.
Experiment 1.	100	250	400	.23	.39	.51
,, 2.	88	238	380	.12	.33	.51
,, 3.	76	—	—	.1		
,, 4.	64	214	364	.03	.38	.5

On the assumption that these four records may be regarded. separately, the accompanying curve has been drawn (Fig. 12). The actual points, for which it may be regarded as a mean value, are shewn by dots. From this diagram it would appear, that at a certain distance from the origin the normal motion outraces the transverse motion at a rapid rate, but as the disturbance radiates this rate decreases. It would seem that

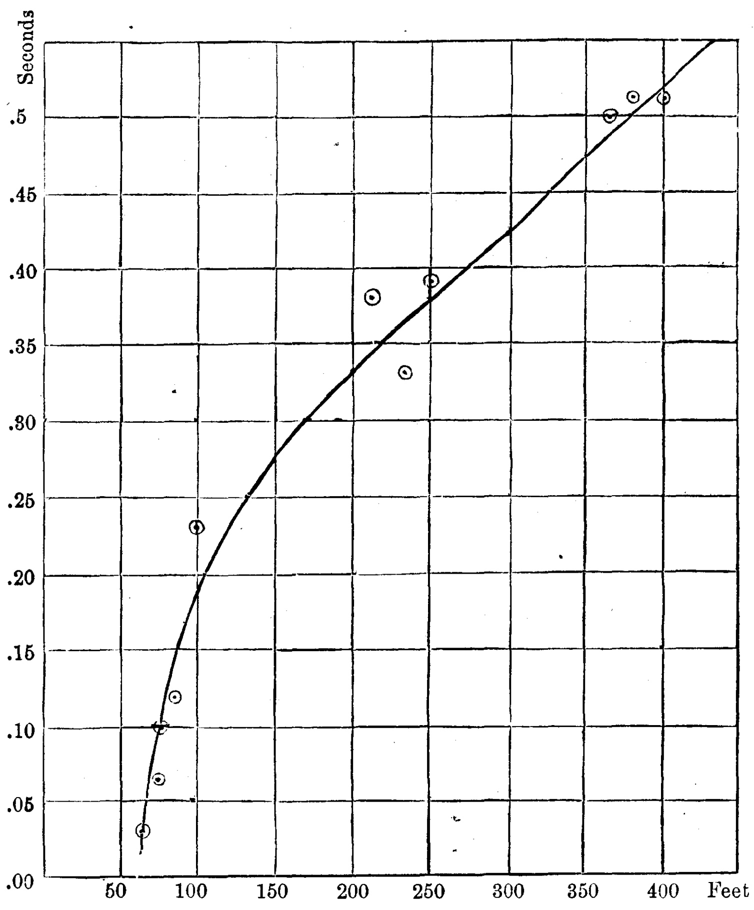


Fig. 12.

Time relation between Normal and Transverse Motion.

the curve ought if produced to pass through the *real* origin of the disturbance. The origin referred to in the figure is the *epicentrum* of the shock.

For reasons already stated, as it is possible that there may be inaccuracies in these results, the above table and diagram yet require confirmation by farther experiments.

VELOCITY OF PROPAGATION.

In determining the velocity with which different vibrations were propagated, it is necessary to make measurements similar to those referred to in the last section, in consequence of which individual determinations are open to considerable error. The results most nearly correct are probably those determined as averages.

1. Horizontal motion.

	Normal Vibrations. Velocity in feet per sec.			Transverse Vibrations. Velocity in feet per sec.		
	A to B	B to C	A to C	A to B	B to C	A to C
1. Experiment	357	333	344	258	263	260
2. ,,	357	405	380	238	272	257
4. ,,	357	272	309	193	224	208
Average.	357	336	344	229	253	241

From the above table we see that the normal vibrations have been propagated at a greater rate than the transverse vibrations, the velocity ratio of the two between A and B being as 1.5:1. It will also be observed that for the normal motion the velocity is greater between stations near the origin, than between stations at a distance. This rule is apparently reversed for the transverse motion. It is quite possible that this result is due to errors in time measurement due to irregularities in the diagrams.

2. Vertical motion.

An inspection of the diagrams clearly indicates that vertical motion was always recorded at station B a considerable interval before there was any trace of either normal or transverse motions. In experiments 1, 3 and 4 the intervals between the appearance of vertical and normal movements were respectively .14 .25 and .29 seconds.

These numbers are calculated on the assumption that the first tremor observed in the normal record is due to the horizontal normal component. The intervals between the appearance of vertical motion and the first *decided* normal motion are respectively .53, .76 and .64 seconds. A mean value for these measurements is $.22^{sec}$ which may be taken as the time by which the free surface wave outraced the normal component of horizontal motion in a distance of 234 feet. (the mean of 250, 238 and 214 feet).

Assuming that the normal motion had a velocity of 357 feet per second, the time taken to traverse 234 feet would be .65 seconds.

From this it follows that the vertical component travelled this distance in .43 seconds and therefore had a velocity of 544 feet per second.

Other results may be obtained by discussing the above data separately or by basing calculations on time measurements made between the first *decided* normal and vertical movements.

The most interesting point connected with this section of the subject is the observation that the preliminary tremors of a disturbance are due to a surface wave outracing the horizontal components of motion. Previous observers have determined the velocity of transit by observing the instant at which the surface of a vessel of mercury was set in vibration. By working in this way Mr. Gray and myself determined an average velocity of transit in hard mud (see first set of experiments) as 630 feet.

Mr. Mallet determined a velocity in sand as 824 .915 feet and in solid granite as 1664.576 feet per second.

General Abbott for like determinations in hard rocks obtained velocities of 3,000 and 8,300 feet per second. All high velocities like these usually accredited to the transit of earthquake motion, may possibly be due to the observers having recorded the surface wave.

Another phenomenon which the relatively high velocity of the surface wave may perhaps account for, are the preliminary tremors which have so often been observed to accompany large earthquakes. As one example of such tremors I will refer to the earthquake of March 11th 1882 where I recorded such tremors extending over a period of 10 seconds before the arrival of any decided earthquake motion (see Trans. S.S. Vol. VII Pt. 2 p. 42) These preliminary tremors may also be connected with the sound phenomena which usually preceed earthquake motion by a short interval.

GENERAL OBSERVATIONS ON THE CHARACTER OF THE RECORDS.

In looking at the diagrams of the various explosions it will be observed that the majority of waves which have been recorded are characterized by their smoothness in outline.

A notable exception to this is to be observed in the first two or three waves of transverse motion recorded at station A. These are invariably irregular. The greatest irregularity occurs when the normal motion has been the greatest, as in the experiment No. IV, and least when the normal motion has been least as in experiment No. III.

This would appear to indicate that the source of the irrgularity must be traced to the earlier commencement of the normal motion which had disturbed the transverse bracket. Theoretically such a disturbance could not occur, but as has already been indicated p. 38., there are reasons for believing that such disturbances have an existence.

Another peculiar character to which attention may be drawn are the slight but sudden changes or notch like marks which are superimposed on several of the later waves in the normal record.

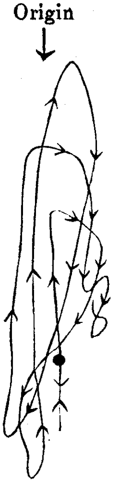
In experiments I, II and IV such notches may be observed on the left hand side of the first large wave. In experiment I, the notch occurs near the top of a wave, in experiment II about half way down the wave, whilst in experiment IV it occurs near the base of the wave.

By comparing the normal motion at A with that of the same explosion at B we see that by the time it has travelled to B the notches have been so far elongated that they practically constitute a second wave. In experiments I and II, a notched wave at A is included between the figures 1 and 2. The double wave at B resulting from this is included between corresponding figures. With this exception it may be said that it is practically impossible to recognize the same wave at two neighbouring stations. As a disturbance travels it appears to totally change in character. This observation appears also to hold good for actual earthquakes.

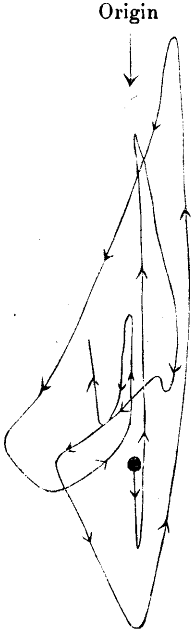
A third point to which attention may be drawn is, with the exception of the records taken at A, the indefinite manner in which the normal or transverse disturbance has commenced. This as already pointed out, may be explained on the assumption that the quickly transmitted vertical vibrations have affected the brackets recording horizontal motion before the actual arrival of the horizontal motion. To account for vertical motion affecting horizontal brackets we may suppose that the vertical waves caused slight tips in the soil.

The greatest irregularity in the character of the waves appears at station C where they are smallest. In experiments I and II attention may be directed to a series of small ripples appearing near the third time-interval.

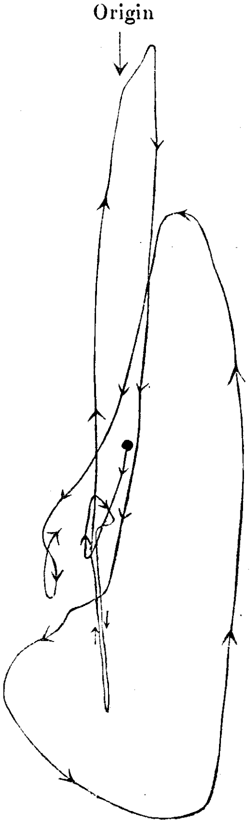
The best idea of the actual motion which took place at any particular station, may be obtained by the inspection of a figure resulting from the combination of the normal and transverse motions. Three figures have been drawn for the first three waves at station A in experiments I II and IV (see Figs. 13, 14, 15.). To draw these figures the original diagrams were enlarged three times. The point from which motion commenced is shown by a black dot. The direction which the motion followed is shown by arrows on its path. From these diagrams it would appear that the first motion at station A, although characterized by many irregularities has a general direction in the line of the origin. The loops and irregularities in these figures are very similar to the irregularities, observed in the diagrams taken by seismographs with single indices writing on stationary plates (see Figs. 2. 3. 4. 5. 6.)



Experiment I.
(Fig. 13)



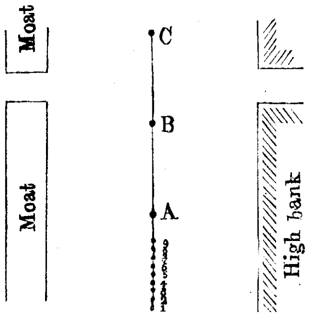
Experiment II.
(Fig. 14)



Experiment IV.
(Fig. 15)

V. SERIES OF EXPERIMENTS.

These experiments were a continuation of the experiments previously made at Akabane and Tameike. Both at Akabane and Tameike the ground on which the experiments were conducted was soft and wet. The special object of the experiments described in the present paper was to determine the velocity with which vibrations of various descriptions were propagated in ground which was dry and hard. They were carried out on the 19th of March, in the grounds of the Chirikioku (Survey Department) in the central part of Tokio. The preparation for these experiments occupied several months,—much time being spent in making the required instruments, obtaining dynamite, telegraph wire, firing instruments, but above all in finding a locality for which permisson could be obtained to carry out the experiments.



The general arrangements for the experiments will be understood from the accompanying sketch. At A, B and C which are in a straight line, stakes were driven in the ground on the tops of which seismometers were fixed. The distance between A and B, and B and C was 200 ft. In a continuation of the line C B A commencing 30 ft distant from A, at the point 9, a bore hole 3 in. in diameter was sunk ten feet. Similar bore holes were sunk at 8, 7, 6, 5, 4, 3, 2 and 1, each 10 ft apart. From these bore holes which were dry, it was seen that the soil consisted of a few inches of vegetable mold, there 5 or 6 feet of a reddish earth containing pebbles and fragments of tile, and lastly at the very bottom of the hole a stiff blackish clay. The chief part of the bore hole was through the reddish gravelly soil.

To the left of this line at a distance of from 200 to 300 ft. was a moat running along the base of the high ground upon which the Shôgun's castle was formerly situated. About 100 ft. away upon the right was a high bank which on the far side descended to the flat ground on which the greater portion of the city of Tokio is situated.

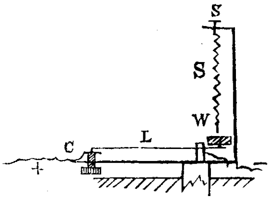
The first explosion was made in hole number 1, the second in number 2 and so on, each explosion in this way being 10 ft nearer to A than the one which proceeded it. The holes were tamped with loose earth. The dynamite which was employed was kindly given to me by Mr. Denys Larrieu a member of the Seismological Society.

The charges which were employed for the different experiments and the distances of A B and C from the explosion will be seen from the following table. Eighteen cartridges and six primers weighed 5 lbs.

					A ft	B ft	C ft	
I	8	Cartridges &	2	primers	110	310	510	
II	10	,,	6	,,	100	330	500	(missed fire)
III	10	,,	1	,,	90	290	490	
IV	7	,,	1	,,	80	280	480	(hole 5 ft deep)
V	5	,,	0	,,	70	270	470	
VI	10	,,	0	,,	60	260	460	
VII	12	,,	3	,,	50	250	450	
VIII	12	,,	3	,,	40	240	440	
IX	0	,,	13	,,	30	230	430	No result, the charge being too small

The first five of these explosions were employed to determine the speed of vertical vibrations. Numbers VI and VII for the speed of normal vibrations and VII and IX for the speed of transverse vibrations.

The instruments employed to record vertical vibrations were as follows.



S is a brass wire spring 2.5 cm. in diameter stretched by a lead weight W (about 1 lb.) to nearly double its length, and making about 27 oscillations in 20 sec. By means of the supporting screws this was so arranged that a pointer on the under side of W justs rested on the short arm of the lever L, the longer arm of which was a straw. This lever almost balances on its fulcrum. From the fulcrum a very thin wire passes down the straw to its end where it makes contact with a small copper plate C fixed on the head of a screw. The whole of this arrangement is carried on the frame shown in thick lines, which in turn is carried on a stake driven in the ground.

It is very evident that any upward motion of the ground will tend to leave the weight W at rest. The fulcrum of the lever having been raised, the short end being in contact with W and therefore at rest, the longer end must be caused to move upwards a distance which will be some multiple of the actual upward motion of the ground. This multiplication of the upward motion of the ground will be as the short arm of the lever is to the total length of the lever. In the instruments employed the multiplication was 12.

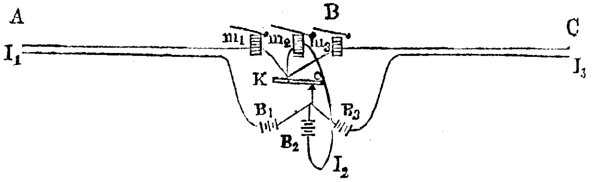
By this arrangement it is evident that a very slight upward motion would be sufficient to break the contact between the copper plate and the wire at the long end of the lever.

An instrument like the one described covered by a small tent was placed at each of the stations A B and C.

Each of these instruments was placed in an electric circuit, the current passing from the fulcrum down the straw to the copper plate C.

In each of these circuits an electro-magnet was placed which so long as the circuit was closed deflected a lever at the end of which these was a needle point resting on a smoked glass plate. This smoked glass plate just before the explosion took place, was caused to move by being placed on a carriage drawn by a falling weight. The motion of this carriage was regulated by a string wound upon an axle to which was attached a fan revolving in a vessel of oil. To measure the speed of the carriage, a small pendulum was so arranged that at each of its swings it made a tick upon the moving glass.

The electrical connections will be understood from the accompanying sketch.



I_1 I_2 and I_3 are the three instruments each of which has its own circuit, battery (B_1 B_2 and B_3) and magnet (M_1 M_2 M_3).

The batteries, magnets, moving carriage &c. were arranged on a table in a large tent close to B.

The order of proceeding was as follows.

The instruments I_1 I_2 and I_3 were all carefully adjusted by the same person. This adjustments was in all cases so delicate that it was impossible to walk on the ground in the neighbourhood of the instruments without breaking the contact as was seen by the movements of the lever connected with the magnet. All being adjusted, the key K was depressed and all the levers deflected, the pendulum was set swinging, the carriage with the glass plate set in motion, and shortly afterwards by depressing the lever of one of Breguets electrical exploders the explosion took place.

The result obtained was, that when the instrument at A was affected the circuit was broken and the straight line being drawn by the lever of M_1 was broken. Shortly after this when the disturbance reached B_2, the line being drawn by M_2 was broken and finally M_3 was broken.

For normal and transverse motions, bracket seismographs having a multiplication of about 12 were used.

These instruments were so arranged that a fine wire was carried down the writing index as one terminal of an electric circuit, this rested on the apex of an inverted V shaped piece of wire as the other terminal. A slight motion of this index to the right or to the left sufficed to break the circuits.

The remainder of the apparatus in connection with these bracket seismographs was similar to that employed with the instruments for vertical motion.

The results which were obtained are shown in the table on the next page. Numbers II and IX of these experiments are omitted, the first because the explosion missed fire and the second because the disturbance produced by the explosion was too small to produce an effect at the stations B and C.

The table of numbers proportional to the intensity of the shock at A were obtained by dividing the numbers proportional to the charge of dynamite by the distance from the bore hole to station A., it being assumed that the intensity of a disturbance is proportional to the quantity of the explosive which produces it, and inversely proportional to the distance from the scene of explosion. The reason for this latter assumption will be seen by reference to page 37.

When examining this table, attention may be drawn to the following facts.

1. It is extremely probable that the so called Normal vibrations are in reality vertical movements which caused the circuit to be broken by producing a tip in the soil and throwing the pointer of the bracket seismograph out of contact. The Transverse vibrations may really be transverse motions, inasmuch as the pointer of a bracket would not be thrown out of contact by waves advancing parallel to its length. For farther evidence for such suppositions see the fourth series of experiments.
2. For experiments VI VII and VIII two velocities are given for the same time intervals. The reason for this is that after the fifth experiment all the electrical connections had to be rearranged with the change of instruments. In doing this confusion appears to have arrisen between the wires leading to A and B, in consequence of which the recorded time intervals may refer to A C or to B C. The latter is more probably correct.

		Velocity in feet per second.			Charge of Dynamite in lbs:	Distance from bore hole to A.	No. proportional to intensity at A.
		1st 200 ft. A—B	2nd 200 ft. B—C	1st 400 ft. A—C			
Vertical Vibrations	I	350	186	243	2.25	100	.022
	III	..	211	..	2.50	90	.027
	IV	352	234	281	2.	80	.025
	VI	343	232	277	1.25	70	.017
Normal or Vertical Vibs:	V	..	203 or 407		2.50	60	.041
	VII	..	238 or 476		3.25	50	.065
Transverse Vibrations	VIII	..	172 or 344		3.25	40	.081

The general results obtainable from the above table appear to be as follows.

1. The velocity of transit is greater for the first 200 feet than it is for the second 200 feet. In other words as a disturbance radiates its velocity decreases. For the first 200 feet the average velocity was 348 feet per second whilst for the second 200 feet it was 213 feet per second.
2. For the first 200 feet the velocity of transit varies directly as the intensity of the disturbance at A,—the greater this intensity the greater the velocity. For the second 200 feet this law is not so marked.
3. The average velocity over the whole range from A to C may be taken as a mean of experiments I IV and V. It equals 267 feet per second.
4. The lowest record is that for transverse motion.

These results can only be looked upon as confirming results obtained by General H. L. Abbot, of the United States Corps of Engineers (see American Journal of Science and Arts Vol. XV No. 87 p. 178).

Thus to show that rate varies with the intensity of the initial shock General Abbot quotes from his observations the following.

400 lbs. of dynamite gave	8814 ft. per second
200 " " " "	8730 " " "
70 " " " "	8415 " " "

And to show that the velocity of the wave decreases with its advance the followng is quoted.

200 lbs. of dynamite give for 1 mile	8730 ft. per second
" " " " " " 5 "	8280 " " "
50,000 " " " " " 8 "	8300 " " "
" " " " " " 13½ "	5300 " " "

It may be objected that some of these observations were made upon disturbances propagated through different media all the stations not being in the same line. Also the experiments were made at different times by different observers.

The late Mr. Mallet also raised many objections to the results obtained by General Abbot. From the results of my own experience I am inclined to agree with the results obtained by General Abbot inasmuch as the objections even if valid can by their correction only make slight differences in the general results. The low velocities which I have recorded are almost as much below those obtained by Mr. Mallet as General Abbot's are above. This appears to be due, partly to the media in which I made my experiments, partly to the feebleness of the initial shock and partly to the instruments which I employed not been sufficiently delicate to record the small surface waves which outrace the movement of shock. It will be observed that in the experiments which I have described personal error, in observation have been avoided.

Measurement of Maximum Vertical Motion.

In three experiments the maximum vertical motion was approximately measured by fixing at right angles to the straw pointer of the instruments for vertical motion a short piece of very thin wire. After the instruments had been adjusted a glass plate standing vertically was gently pushed into contact with this so that if the pointer were pushed upwards, it would remain at its highest position in consequence of the friction of the wire against the glass.

The result was that the upward motion at A as composed with B was about as 7 : 3

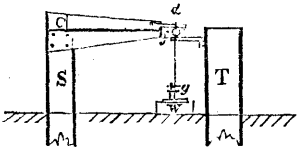
The actual upwards motion at A was in the III experiment about 3^{mm} in the IV experiment about 1.4^{mm}. At C the motion was too small to be measured.

Experiment to see how far two points near to each other synchronised in their motion.

In putting up seismometers especially those which give their records as two components it is usually assumed that we may support our apparatus on the heads of two posts driven in the ground at a short distance apart, the results obtained being the same as if we had supported our instrument upon one large post.

If however it could be shown that at the time of an earthquake the heads of two such posts did not synchronize in their motions, not only should we establish an important physical fact but also obtain information of practical value to the working seismologist.

With this object in view, in conjunction with the experiments which have been described, the following experiment was made. Near to the station A in a line parallel to A B C, two strong stakes S, T, were driven in the ground at a distance from each other of about 82^{cm}. From the head of S and projecting in the direction of T a light stiff board C was fixed. Down the middle of this there was a rib to give stiffness. The cross section of C was therefore thus +. On to the end of this there was screwed a piece of brass with a small hole in it at *d*. Immediately under this hole 1^{cm} below, there was a hole in a piece of brass attached to the stake T. Passing through these two holes was a piece of stiff wire with a small brass ball upon it. This ball which acted as a universal joint held the wire suspended in the lower piece of brass. The wire was continued downwards with a light bamboo index terminating at its lower end with a needle sliding through two small holes. This rested on a plate of smoked glass resting on a block of wood W.



If S and T syncronized on their movements then it was assumed that *d* and *f* would always keep in the same vertical line. If however there was a want of synchronism then the difference in motion of these two points would be magnified about 20 times by the pointer *f g* which was 21^{cm} long.

The results which were obtained were as follows.

I Explosion. A mark was made on the glass about 15^{mm} long in a direction at right angles to the line A B C.

III Explosion. Several lines were made. At right angles to A B C about 10^{mm}, and inclined to this at about 45°, a line of 15^{mm}.

IV Explosion. Irregular markings about 3^{mm} long.

V Explosion. A line of about 4^{mm} long almost parallel to A B C, and also an irregular mark.

For remaining explosions the line of the two stakes S T was placed at right angles to the line A B C, and the movements were very much more definite. They were as follows.

VI Explosion. A line 10^{mm} long parallel to A B C.

VII Explosion. At least three large oscillations parallel to A B C, the largest being 29^{mm} long.

VIII Explosion. At least four large oscillations parallel to A B C, the largest being 38^{mm} long.

IX Explosion. Two or three small oscillations parallel to A B C at least 7^{mm} long.

The results obtained in these experiments would indicate that notwithstanding the lightness and stiffness of the arm C, it had not synchronized in its movements with the post to which it was attached in consequence of which the point *d* had not remained vertically above *f*. If such were the case, in the first two experiments *d* must have suffered a displacement relatively to *f* in consequence of the transverse component of motion whilst in the 6th, 7th, 8th and 9th experiments the displacement would be due to normal motion.

That the latter may be an explanation of the last four records is quite possible. To explain the existence of the first two records having been produced by a switch like movement in the arm C by a transverse motion is more hazardous. Certainly the result recorded in the third experiment can not be explained by such an assumption. Although these experiments when taken by themselves do not prove that there was a difference in phase in the movement of two neighbouring points, they are weighty evidence in favour of such movements having occurred when taken in conjuction with the peculiar characters observed in the diagrams of the fourth series of experiments, which characters could only be explained on the assumption that during a disturbance the stake on which a seismograph rested must have approached and receded from the plate on which the record was being written.

Experiments on the production of Earth Currents.

From near the scene of the explosions a telegraphic communication was established across a deep moat up to a hill, where the mechanical disturbances were practically not observable. Each end of this circuit was put to earth by means of two long crowbars, and in the circuit on the hill one of Clark's differential galvanometers was arranged. As either of the crow-bars was raised or depressed it was found that the current passing through the galvanometer varied, sometimes being positive and sometimes being negative. At a certain depth which was found by trial, the needle of the galvanometer remained at zero, and it was in this way that the adjustment to 'no current' was made previous to an explosion.

When an explosion took place, one earth bar being at distances of from 10 to 50 ft., a considerable current was always produced, and the needle of the galvanometer swung with violence until it reached a stop. The direction of swing was, in the few experiments which were made, always constant. Sometimes the needle remained permanently deflected, and at other times it gradually fell back towards zero.

These currents I regard as being due to a mechanical disturbance of one of the earth bars, causing a difference of contact with the soil; and, in consequence of this, an alteration in the moisture, oxidation surface, &c., at one end of the circuit, thus giving rise to a difference of potential relatively to the other end of the circuit.

No doubt actual earthquakes act upon the earth plates of telegraphic lines in a similar manner, but the currents which are in this way produced at the time of an earthquake are due to different causes than those which appear sometimes to have *preceded* earthquakes by considerable intervals of time.

Since making the above experiments Mr. T. Gray informs me as a result of a laboratory investigation, that there appears to be a difference in potential between two sides of a slab of rock when it is bent.

VI. SERIES OF EXPERIMENTS.

These experiments were made at the latter end of May 1882, on the same ground where the fifth set of experiments were carried out. The object of the experiments was to obtain the velocity of transit between five stations. Owing to the severity of the weather on the day for which permission had been obtained to carry on the explosions, many of the experiments unfortunately failed. Such results as were obtained are however of sufficient value to be recorded. The general arrangement of apparatus with the electrical connections was practically indentical with the arrangement employed in the last series of experiments. To record the passage of a disturbance at the different stations for the first two explosions "circuit closers" were used as breakers. This was done by pushing the mercury dish so that it came to contact with the index, on the side of the explosion. For a description of the "circuit closer" referred to, see Trans: Seis: Soc. Vol. IV p. 98. For the remaining experiments vertical spring instruments similar to those described on page 47 were employed.

The five stations A B C D and E were each 150 ft. apart and in the same straight line with the bore holes where Dynamite was exploded. The charges which were employed, together with the distance of station A from the different bore holes, and the general results which were obtained are given in the following table.

No. of Explosion.	Velocity in feet per sec.				Charge of Dynamite in lbs.	Distance from Bore hole to A.	No. proportional to intensity at A.
	A B	B C	C D	D E			
I	306	....	....	....	2	115 ft.	.017
II	260		264	....	2	105	.019
III	....	264	....	....	3.5 ?	75	.046 ?
IV	....	256	....	....	2.25	55	.040
V	....	....	....	288	2.5	45	.055
VI	397	....	....	357	2.25	35	.064
VII	...	285	....	....	2.25	35	.064

The deductions to be made from the above table are evidently similar to those made from the table of results given for the previous set of experiments. They are briefly,—

1. The velocity of transist is greater between points near to the origin of a disturbance than between points farther removed.
2. The velocity of transit varies directly with the intensity of the initial disturbance.

The actual velocities which have been recorded, it will be observed accord fairly well with those determined in previous experiments.

VII. SERIES OF EXPERIMENTS.

On May 28th 1882 I suddenly received notice that His Imperial Majesty the Mikado would on the 30th of the month visit the Meteorological Department (Chirikioku) where amongst other things he was desirous of witnessing the effects of dynamite in blowing up earth.

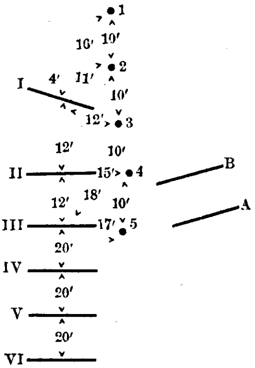
As the interval for preparation was so short I had not the time which was necessary to organize experiments which would require the use of seismographs or special instruments. The result was that the only advantage which could be taken of these explosions was to make observations requiring arrangements of a very simple kind. The ground selected for the experiments had in many places been very must cut up by trenches and other military works in consequence of which it was much drier and looser than that which had been previously employed.

The explosions were three in number, the charges being placed in 8 ft. bore holes each ten feet apart and in a straight line. In the first two explosions about 4 lbs. of dynamite was used. In the third, about 6.75 lbs. was employed.

Before a mine was exploded, three cylindrical blocks of deal each 6 inches in length and 6 inches in diameter were placed on the surface of the ground about 2 ft. 6 in. distance from the top of the hole and equally distant round it. A fourth block was placed above the hole. These blocks were marked A, B, C and D. At various distances from the bore hole heavy planks of wood were placed as stands for groups of wooden cylinders. Each group consisted of four cylinders the dimensions of which were as follows.

	Length	Diameter
No. of cylinder 1.	12^{in}	4^{in}
,, ,, ,, 2.	10^{in}	4^{in}
,, ,, ,, 3.	8^{in}	4^{in}
,, ,, ,, 4.	6^{in}	4^{in}

The arrangement of the planks and groups of cylinders of which there were six will be understood from the accompanying figure.



In the diagram 5 bore holes are shown by black dots. Only the first three of these were employed. After the first explosion plank VI was moved to A, which was 42 ft from bore hole 2 and 15 ft from bore hole 5. After the second explosion, plank V was moved to B, which was 15 ft from 3 and 12 ft from 5. These measurements were made from the center of each plank.

The result of an explosion was to leave a conical hole about 15 ft in depth.

The shallowness and probably the form of the hole is due to the falling debris which at the time of the explosion had been shot upwards in a fountain like column.

There is no doubt but that many of the columns were overturned by the falling materials.

The horizontal velocity of "shock" necessary to overturn a column is calculated from the following formula used by Mallet (see "The Admiralty Manual of Scientific Enquiry" p. 312)

$$V^2 = \tfrac{4}{3}\, g \sqrt{a^2 + b^2} \times \left(\frac{1 - \cos\theta}{\cos^2\theta}\right)$$

where a = height of the column
b = diameter of base of column
θ = the angle formed by the edge of base and a line drawn through the center of gravity.

For observations on the applicability of this formula see remarks at the end of the ninth set of experiments. The values given by this formula which are probably far below the true value, and the value for f or $\frac{V}{t}$ (see page 35.) also in feet are given in the following table.

If we assume a value for t say $\frac{1}{10}$ second, then values for V or the maximum velocity of the ground which corresponds to the velocity of projection are given in the last column of the table.

	Velocity of shock (Mallet.)	Acceleration to cause overturning. (Page 35)	Maximum velocity of ground.
Column 1	1.55 ft.	10.7 ft.	1.07
„ 2	1.75	12.8	1.28
„ 3	2.07	16.1	1.61
„ 4	2.49	21.3	2.13

I Explosion.

At plank I. Column 1. was just overturned and remained on the plank.
„ 2. was projected 2′. 3″.
„ 4. was slightly projected.

Of these columns it may be assumed that column 1 was overturned by the shock indicating a maximum velocity of about 1.07 ft. Columns 2 and 4 were probably overturned or projected by the falling debris.

Owing to the haste with which the second hole had to be fired no time was allowed to measure the distance to which the blocks were projected.

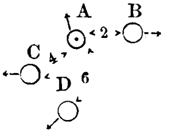
II Explosion.

At plank I. Column 1 was projected inwards 1 ft.
„ 2 „ „ „ 3 in.
„ 3 „ „ outwards 10 in.
„ 4 „ „ „ 4 in.

Columns 3 and 4 may possibly have been overturned by their inertia and would indicate a maximum velocity of at least 1.28 ft.

Projection.

The position of the blocks and their direction of projection with regard to the bore hole which is shown as a black dot will be seen by reference to the accompanying diagram.



A was projected 46 ft. horizontally.
B „ „ 24 „ „
C „ „ 27 „ „
D „ „ 14 „ „

The horizontal distances were measured from the bore hole. Assuming that the angles of projection for A B C and D were respectively 85, 70, 52 and 40 degrees then the initial velocity communicated to A B C and D must have been approximately 93, 33, 27 and 18 feet per second. The angles of projection were determined from the known depth of the charge, and the position of A B C and D with regard to the bore hole. From the form of the hole resulting from the explosion, and from the directions in which the blocks were thrown it is probable that the initial directions of projection were along a line joining the charge and the blocks. If the angles of projection which are taken as small as possible be increased, the resulting velocities for the given ranges will also be increased.

III Explosion.

At plank I Column 1 was projected 7.5 in. outwards.
At plank II „ 2 „ „ 11 in. „
„ „ „ „ 3 „ „ 8.5 in. „
At plank V „ 1 „ overturned „

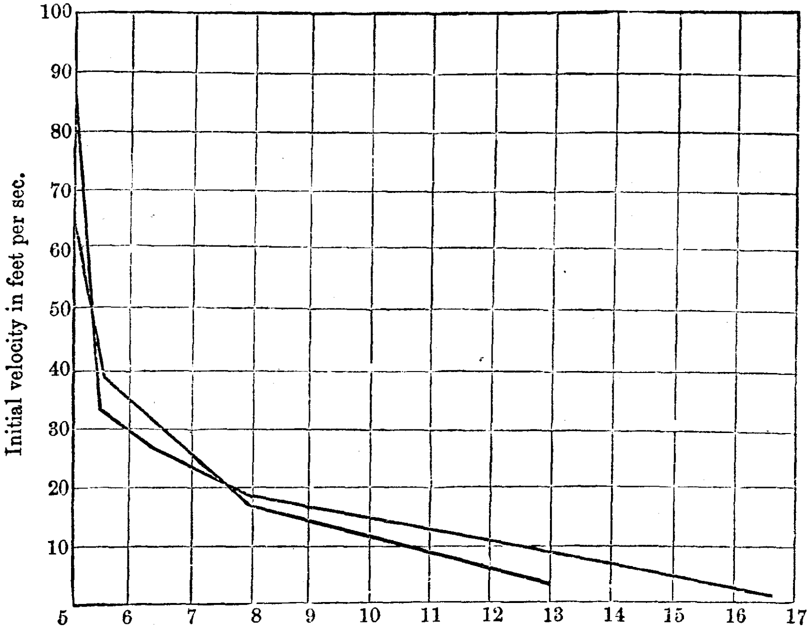
As all the columns which were projected or overturned were practically at the same distance from the explosion, we may take the maximum velocity as having been that necessary to overturn column 3, or 1.61 ft. per second.

Projection of Blocks.

A was projected 25 ft. horizontally
B „ „ 30 ft. „
C „ „ 34 ft. „
D „ „ 14 ft. „

The measurements were made from the bore hole. Taking the angles of projection as before, the initial velocities of A B C and D would be approximately 69, 38, 31 and 16 feet per second.

The few results which were obtained from these experiments are shown graphically in the accompanying figure. The horizontal distances are measured from the true origin of the explosion and not from the epicentrum.



Distance from the Origin in feet.

As these experiments are few in number, and as they were performed under circumstances which precluded exactness in observation the value of the results which might be obtained from them by a close analysis is very doubtful. A general inspection of the above diagram however shews the enormous difference in the intensity of shock between points which are near the origin and points like those where observations were made in previous experiments which were relatively at a distance from the scene of explosion. Another fact to be observed is the exceedingly rapid decrease in the intensity of the disturbance between the epicentrum and points only one or two feet distant from it, these points like the epicentrum being within the area of excavation.

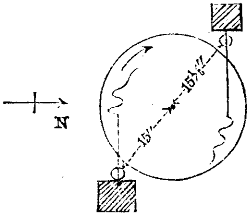
VIII. SERIES OF EXPERIMENT.

These experiments were made on July 6th 1883 in the grounds of the Chirikioku, near to the place where the seventh series of experiments were carried out.

The principal object of these experiments was to test different methods of determining the intensity of an earth disturbance. The disturbance was produced by the explosion of a charge of dynamite in a bore hole.

The general nature of the observations which were made was as follows.

1st. The record of the normal motion of the ground. This was obtained by a bracket seismograph on a revolving plate. To avoid the chance of error two brackets each placed to record normal motion were employed. These were so arranged that they wrote these records on two concentric circles as indicated in the accompanying plan.



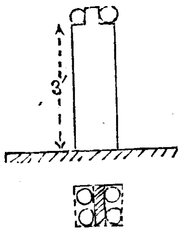
During the experiments the pointer of the East Bracket was slightly broken so that its record was somewhat irregular.

At the time of the explosion a pendulum making 22 marks in 10 seconds was caused to tick upon the edge of the plate.

The total length of the pointers from the back pivot to the describing points = $8\frac{5}{8}^{in}$. Multiplication of the pointers = 13.

2nd. Recording the distance to which small lead and wood balls were projected from the top of a post.

The balls were one inch in diameter. The post were 4^{in}. square and 6 ft long. They were driven three feet into the ground. At the top they were notched and the balls were



rested in the notches as shewn in the accompanying sketch.

A lead ball and a wood ball was in each notch.

It was assumed that the projection was due to a horizontal shock. The formulæ employed to calculate the intial velocity of projection on this assumption was $V^2 = \frac{a^2 g}{2b}$

where a = the horizontal distance of projection
and b = the vertical height or 3 feet.

If we introduce into the calculations a value for ε or the angle of projection, based on the assumption that the post was struck by a shock coming direct from the origin, the resulting values for V would be increased.

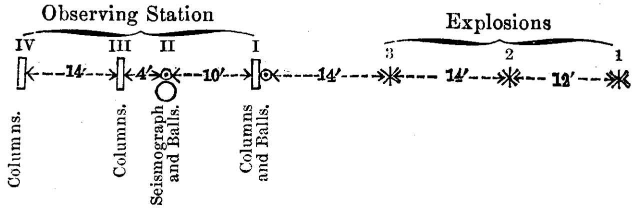
3rd. Observations on the overturning of wooden columns. The dimensions of these columns together with the calculated accelerations and velocities of "shock" necessary to overturn them are given in the following table. For methods of calculating these quantities see seventh set of experiments.

No. of Column.	Length in inches.	Diameter in inches	Acceleration to cause overturning. (Page 35.)	Velocity of shock to cause overturning. (Mallet.)
			ft mm	ft mm
1	24	1	1.34 or 407	.121 or 36.3
2	18	1	1.79 or 544	.300 or 90
3	12	1	2.68 or 814	.409 or 120
4	10	1	3.22 or 978	.442 or 132
5	8	1	4.01 or 1219	.479 or 143
6	6	1	5.36 or 1629	.520 or 156

Groups of these columns were arranged in lines on narrow planks, bedded in the soil.

The ground was very dry and contained large stones.

The relative position of the explosions and the instruments will be understood from the accompanying plan

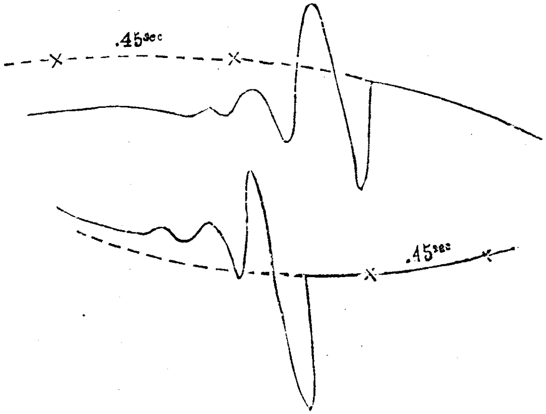


The explosions took place in holes about 8 ft deep so that from the surface to the center of the charge would be about 6 ft. In both the first and second explosion 5 lbs of dynamite was used, whilst in the third explosion only 3 lbs was employed.

The result of an explosion was to make a flat conical or saucer shaped hole about 8 or 9 feet in diameter and about 3 feet deep.

An example of the diagrams is shewn below. It represents the East and West records for the third explosion. To place them side by side one of them has been reversed.

East Diagram.



West Diagram.

RESULTS OBTAINED.

1. *Explosion.* (5 ℔s dynamite in a 6 ft. bore hole).

Station I. (40 ft. from the origin)

A lead and a wooden ball were each projected 6 inches in the direction of the origin. This would indicate a maximum velocity of 350 millimeters per sec. No columns fell.

Station II. (50 ft. from the origin)

A wooden ball was projected 14 inches away from the origin. This would indicate a maximum velocity in an outward direction of 795 millimeters per sec.

Records from seismographs.

The record given by the seismograph on the east side was not good, its pointer having been accidentally damaged. The records obtained from it have therefore not been analyzed. The record given by the seismograph on the west side furnished the following results.

	t	a	V
1st quarter out	.053	8	20
1st quarter in	.0053	8	184
2nd quarter in	.053	10	23
2nd quarter out	.026	5	23
3rd quarter out	.026	5	23
3rd quarter in	.039	6	17
4th quarter in	.039	6	17

"*out*" and "*in*" respectively refer to motion outwards and motion inwards towards the origin.

t is the time in seconds to describe a quarter wave. For the 1st quarter *out*, t is the time and a is the range of a *semi* oscillation. The smaller the value for t the greater has been the difficulty in making measurements. a is 13 times the true amplitude. V is the maximum velocity in millimeters per second. This was calculated as before, the assumption being that the motion was simple harmonic.

Stations III and IV (54 and 68 ft from the origin)

No columns fell.

2. *Explosion.* (5 lbs of Dynamite in a 6 ft bore hole)

Station 1. (28 ft. from the origin).

A lead ball was thrown 2 ft towards the origin, indicating an intial velocity of 1397^{mm}. This ball evidently rolled after touching the ground and the calculated velocity is therefore too high. A wooden ball was thrown 7^{in} towards the origin indicating a maximum velocity of 396^{mm}.

The lead and wooden ball on the other side fell at the base of the stake. All columns were upset by debris.

Station 2. (38 ft from the origin).

A lead ball fell 5^{in} and a wooden ball 9^{in} to the south or away from the origin, indicating initial velocities of 291^{mm} and 519^{mm}.

Records from Seismographs.

Here again the record obtained from the seismograph on the east side was not good. The results obtained from the seismograph on the west side are given in the following table. The letters have the same meaning as before.

			t	a	V
1st	quarter	out	.035	18	58
1st	,,	in	.008	18	235
2nd	,,	in	.096	20	24
2nd	,,	out	.017	20	135
3rd	,,	out	.063	9	16
3rd	,,	in	.087	9	12
4th	,,	in	.052	4	9
4th	,,	out	.043	4	10
5th	,,	out	.013	3	26
5th	,,	in	.013	3	26
6th	,,	in	.035	3	10

Stations 3 and 4. (42 ft. and 56 ft. from the origin)
No columns fell.

3. *Explosion.* (3½ lbs of dynamite in a 6 ft. bore hole)

Station 1. (14 ft. from the origin)

A lead ball fell 9in and a wooden ball fell 11in towards the origin, indicating maximum velocities of 519mm and 645mm. A lead ball fell 18in and a wooden ball fell 15in away from the origin, indicating initial velocities of 1038mm and 850mm. Columns 1, 2 and 6 were overturned. Number 6 may have been knocked over by debris. The velocities indicated are respectively 36mm and 156mm (Mallet).

The overturning accelerations are 407, 544 and 1629mm per second per second.

Station 3. (24 ft. from the origin)

A lead ball was projected 4in towards the origin, indicating an initial velocity of 234mm. The wooden ball from this side was found on the opposite side of the post.

A lead ball was projected 2^{in} and a wooden ball 5^{in} away from the origin, indicating velocities of 117^{mm} and 291^{mm}. Columns 1 and 2 fell away from the origin indicating velocities of shock of 36^{mm} and 90^{mm}. The overturning accelerations are 407^{mm} and 544^{mm} per second per second.

Records from Seismographs.

The notation is as before

	t	*a*	V
1st quarter out	.007	18	300
1st ,, in	.12	18	17
2nd ,, in	.12	15	14
2nd ,, out	.015	7	54
3rd ,, out	.015	7	54
3rd ,, in	.09	4	5
4th ,, in	.09	4	5

The maximum velocity calculated from the seismograph on the east side gave results rather greater than the above.

Station 3. (28 ft. from the origin)

Here columns 1 and 2 fell, indicating velocities the same as those determined by the overturning of columns at station 2. It is possible that these columns at station 3 may have been knocked over by debris.

Station 4. (42 ft. from the origin)

No columns fell.

CONCLUSION.

Although all ordinary precautions were taken when making these experiments, it is clearly evident that they have yielded the most discordant results. The only case in which the maximum velocity deduced from a diagram has agreed with the initial velocity of projection has been in the third experiment, the former being 300$^{\mathrm{mm}}$ and the latter 291$^{\mathrm{mm}}$ per second. In all other cases the maximum velocity obtained from a diagram has been very much lower than that obtained by projection. One source of error in working on the diagrams has been the impossibility of accurately making the necessary measurements for time. When these are small neither they nor the quantities dependent on them like maximum velocities can be relied upon. In future experiments this might be obviated by having a record receiving surface moving at a higher velocity. The high velocity of initial projection probably arises from a want of rigidity in the post from which the balls were thrown, in consequence of which at the time of projection the post had a switch like motion. Assuming this conclusion to be correct, it indicates to us the caution which has to be observed in making calculations respecting earthquake motion as deduced from the positions in which bodies are found after having been projected. It also shews that the upright post of simple seismometers intended to indicate by projection must have great rigidity.

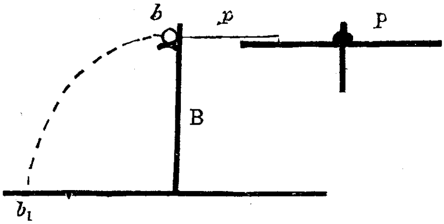
The "maximum velocity" given by Mallet for overturning is as might be anticipated not identical with the "maximum velocity" of projection. It is evidently a quantity dependent on the suddenness with which the column receives momentum. These quantities are farther discussed in the next series of experiments.

IX. SERIES OF EXPERIMENTS.

These experiments which were carried out in the workshop of the Imperial College of Engineering were made with the object of testing the accuracy of the methods which had been followed in analysing the records obtained in previous experiments.

They were as follows.

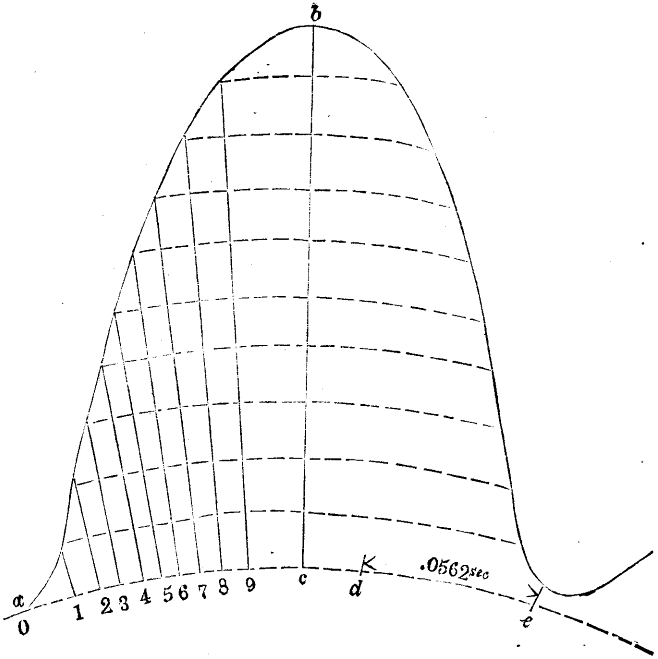
I. Experiments on Projection.



A flexible board B was clamped in an upright position. On the side of the board near to its end a small shelf was fixed on which a small wooden ball *b* could be rested. On the opposite side from the ball a light pointer *p* was hinged so that its outer end rested on the surface of a circular glass disc. The disc which was covered with smoke could be rotated at a known rate. An experiment consisted of the following operations.

First the board B was deflected and held in a deflected position by a small strut. The plate P was then rotated until it had acquired a uniform velocity after which the strut was suddenly removed. The result of this was to throw the ball from its shelf to some point b_1, whilst the pointer *p* described a series of waves on the revolving plate corresponding to the vibrations of the board.

From the horizontal distances, to which the ball was projected together with the vertical height through which it had fallen its initial velocity of projection might be calculated. This it was assumed would be equal to the maximum velocity of the board during its first swing, which quantity could either be taken directly by measurements made on the diagram drawn on the plate, or calculated from the diagram on the assumption of simple harmonic motion.



The above figure is a reproduction of the commencement of the diagram drawn in the second experiment. *a b* is the path of the pointer during the first swing of the board. *a c* represents the time taken to describe *a b*. *d e* is a unit of time given for the purpose of calculating a value for *a c*, or any fraction of it like 4, 5 or 5, 6. *a c d e* is a portion of the path described by the pointer before the strut was removed and the board was relieved from its deflected position.

1. *Experiment.*

In this experiment a board was used the vibrations of which had a period of $.16^{sec}$. It was deflected 72^{mm}. The ball was projected $2^{ft}.8^{in}$ from a height of $4^{ft}.6\frac{1}{2}^{in}$.

The maximum velocities obtained were,

1.	On the assumption of S.H.M.	1305^{mm} per sec.
2.	By direct measurement	1511^{mm} „ „
3.	By projection	1524^{mm} „ „

2. *Experiment.*

In this experiment a board was used the vibrations of which had a period of .20$^{\text{sec}}$. It was deflected 72$^{\text{mm}}$. The ball was projected 2$^{\text{ft}}$.3$^{\text{in}}$ from a height of 4$^{\text{ft}}$.6$\frac{1}{2}^{\text{in}}$.

The maximum velocities obtained were.

1.	On the assumption of S.H.M.	1056$^{\text{mm}}$ per sec.
2.	By direct measurement.	1142$^{\text{mm}}$ „ „
3.	By projection.	1285$^{\text{mm}}$ „ „

In making the calculation on the assumption of simple harmonic motion in the formula $V = \frac{2 \pi r}{T}$ the value for r was taken as $\frac{c\,b}{2}$ (see Fig. p. 71) whilst T was taken as twice the value calculated for $a\,c$.

Although the conditions under which the dynamite diagrams were obtained differ from those of the spring board, it would appear that the methods of calculation followed when analysing the latter are probably the more correct and therefore to be followed in analysing the former. For this reason the first motion of shock in the dynamite diagrams has been considered as a semioscillation and not as a quarter oscillation.

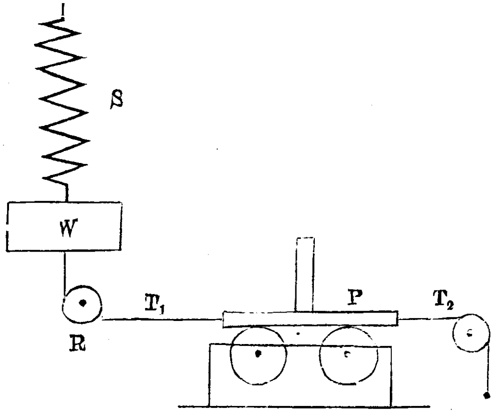
Another point which these experiments clearly indicate is that the initial velocity of earthquake motion as estimated by the range through which bodies have been projected, closely corresponds to the maximum velocity calculated or directly measured from a diagram.

The slight discrepency between these two quantities in these experiments partly arises from the fact that the ball was not projected horizontally from the top of the bent spring but was projected slightly upwards.

The difference between the calculated velocity and the velocity directly measured from the diagram may be due to the fact that the motion was not strictly simple harmonic.

II. EXPERIMENTS ON OVERTURNING.

These experiments were made as follows



S is a strong spring stretched by a 12 lb weight W.

A light strip of wood P resting on two large friction rollers is attached to W by means of a silk thread T_1 passing round a light pulley R. A second thread T_2 and a small weight balances the board P on the pulleys. When W is depressed and suddenly set free it oscillates for a considerable time, the board P moving with it back and forth about the same distance to the right and left of its neutral position. The columns overturned were placed on P as shewn in the figure. As the whole of the apparatus excepting the weight and spring was very light and the friction small, the free motion of the weight W, which made 14 complete vibrations in 10 seconds, was but little changed. The columns to be overturned butted against the edge of a strip of note paper pasted on the board P.

The object of this was to give sufficient friction to prevent the board suddenly moving beneath the columns without exerting any overturning effort.

An experiment consisted in finding out the distance to which W had to be depressed and then suddenly freed, to overturn a given column. Knowing the period of the spring and its amplitude, the maximum velocity V, the mean time acceleration $\frac{V}{t}$ and the maximum acceleration $\frac{V^2}{a}$ might be calculated. An acceleration f sufficient for verturning may also be calculated from the dimensions of the columns (see page 35). The relationship between these three quantities will be seen by inspection of the following table.

Dimensions of wood column		Overturning acceleration. (p. 35).	Deflection to cause overturning $= a$.	Acceleration $\frac{V}{t}$ due to deflection.	Maximum acceleration $\frac{V^2}{a}$
Length	Diam.				
2^{in}	1^{in}	16.1^{ft}	2.75^{in}	11.29^{ft}	17.73
3	1	10.7	2.25	9.23	14.49
4	1	8.05	1.50	6.15	9.65
6	1	5.36	1.375	5.64	8.85
8	1	4.01	1.125	4.61	7.24

Examining the above table it will be observed that the calculated acceleration sufficient to overturn the body is equal to the mean acceleration as calculated from the formula $\frac{V}{t}$ when the deflection is small. For larger deflections it lies between this value and the value calculated by the formula $\frac{V^2}{a}$.

These experiments show that the overturning power of an earthquake as determined from the dimensions of a body which has been overturned, are at the best only approximative. The maximum acceleration of an earth particle 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.

Mallets formula for the overturning of a column assumes either that the column is moving with a velocity V and is suddenly checked at the base, or else that the earth is moving with velocity V and the column is placed suddenly on it. As these conditions do not appear to exist in an earthquake the formula is inapplicable.

X. SERIES OF EXPERIMENTS.

These experiments were made in 1881 in the Physical Laboratory of the Imperial College of Engineering by me in conjunction with Mr. Thomas Gray who was then acting as Professor of Natural Philosophy.

The object of the experiments was to obtain data to calculate the theoretical velocity of earthquake waves through certain rocks. To obtain these data columns of rock 60 centimeters in length and 4 centimeters in diameter were subjected to cross bending and torsion from the results of which experiments Young's modulus and the modulus of rigidity were calculated.

Subsequently the modulus of rupture was determined and also the length modulus of crushing.

The following table gives the results of the experiments.

	Velocity of normal vibrations in feet per sec.	Velocity of transverse vibrations in feet per sec.	Ratio of normal to transverse.
Granite	12957	7185	1.80
Marble	12500	6824	1.83
Tuff	9350	6857	1.36
Clay rock	11417	8333	1.37
Slate	14796	9383	1.58

From an inspection of the above table it would appear that the ratio of the speed of normal and transverse motions is not constant. The softer and less elastic the rock is, the nearer do the two velocities approach each other.

It must be remembered that the rocks experimented on were nearly homogeneous whilst earthquakes are transmitted through rocks which may be extremely heterogeneous and fissured. Mallet who made experiments "on the compressibility of solid cubes of these rocks obtained the mean modulus of elasticity" with the result that "nearly seven eighths of the full velocity of transit due to the material if solid and continuous, is lost by reason of the heterogeneity and discontinuity of the rocky masses as they are found piled together in nature".

A fuller account of these experiments will be found in the Philosophical Magazine. 1881.

GENERAL RESULTS.

In reading these conclusions it must be remembered that they only refer to experiments performed in certain kinds of ground.

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1. Effect of Ground on Vibration.

1. Hills have but little effect in stopping vibrations (p. 8.)
2. Excavations exert considerable influence in stopping vibrations (p. 8.)
3. In soft damp ground it is easy to produce vibrations of large amplitude and considerable duration. (First, third or fourth set of experiments)
4. In loose dry ground an explosion of dynamite yields a disturbance of large amplitude but of short duration. (Diagrams of eighth set of experiments)
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. (Second set of experiments).

2. General Character of Motion.

1. The pointer of a seismograph with a single index first 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 which phases are in turn dependent upon the distance of the seismograph from the origin. (First set of experiments. p. 8. Figs. 2, 3, 4. also illustrated in records of other experiments.)
2. A bracket seismograph indicating normal motion at a given station commences its indications before a similar seismograph arranged to write transverse motion. (Diagrams of fourth set of experiments.)
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 (see p. 44.)

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 synchronize in their motions (pp. 52. 30.)
6. Earthquake motion is probably not a simple harmonic motion (p. 31.)

3. NORMAL MOTION.

1. Near to an origin the first motion is *outwards*. At a distance from an origin the first motion may be *inwards*. (Second and fourth experiments)
   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 outwards motion are practically equal (pp. 25. 26. 27.)
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 (p. 26.)
4. Roughly speaking the amplitude of normal motion is inversely as the distance from the origin (see pp. 26. 27.)
5. At a station near an origin the period of the waves is at first short. It becomes longer as the disturbance dies out. (see diagrams generally, also p. 29.)
6. The semi-oscillations *inwards* are described more rapidly than those *outwards*. (see diagrams generally, also p. 29.)
7. As a disturbance radiates the period increases. (see diagrams generally, also p. 29.) 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 (see table p. 28.)

8. Certain of the inward motions of "shock" have the appearance of having been described in less than no time. (for explanation see p. 30).
9. For tables shewing the maximum velocity of normal motion (p. 33.)
10. For diagram shewing the intensity of normal motion (p. 37.)
11. The first outwards motion which on diagrams has the appearance of a quarter wave must be regarded as a semi-oscillation. (p. 72.)
12. The waves on the diagrams taken at different stations do not correspond. (see diagrams for fourth experiments.)
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. (p. 42. 43.)
14. Near the origin the normal motion has a definite commencement. At a distance the motion commences irregularly the maximum motion being reached gradually. (for possible explanation of this see p. 43.)

4. Transverse Motion.

1. Near to an origin the transverse motion commences definitely but irregularly. (see diagrams.)
2. Like the normal motion the first two or three movements are decided and their amplitude slightly exceeds that of those which follow. (see diagrams.)
3. The amplitude of transverse motion as the disturbance radiates decreases at a slower rate than that of the normal motion. (p. 27.)
4. As a disturbance dies out at any particular station the period decreases. (p. 29.)
5. As a disturbance radiates the period increases. (p. 29.) 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 indefinite. (see diagrams)
7. It will be observed that the laws governing the trans-

verse 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.

5. 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. (pp. 26. 27.)
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. (see p. 27.) ✓
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. (p. 29.) ✓

6. MAXIMUM VELOCITY AND INTENSITY OF MOVEMENTS.

1. An earth particle usually reaches its maximum velocity during the first inward movement (p. 32.) A high velocity is however sometimes attained in the first outward semi-oscillation. (pp. 32. 33.)
2. The intensity of an earthquake is best measured by its destructive power in overturning, shattering or projecting various bodies. (p. 35.)
3. The value $V^2 = \frac{4}{3} g \sqrt{a^2 + b^2} \times \left(\frac{1 - \cos\theta}{\cos^2\theta}\right)$ 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 impulse. (pp. 58. 69. 74.)
4. In an earthquake a body is overturned or shattered by an acceleration f which quantity is calculable for a body of definite dimensions.

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 (pp. 35. 74.)

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, are not identical quantities.
   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. (pp. 70. 71. 72.)
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. (p. 61.)
8. A curve of intensities deduced from observations at a sufficient number of stations, would furnish the means of approximately calculating an absolute value for the intensity of an earthquake. (p. 37.)

7. VERTICAL MOTION.

1. In soft ground vertical motion appears to be a free surface wave which outraces the horizontal component of motion. (p. 40.)
2. Vertical motion commences with small rapid vibrations and ends with vibrations which are long and slow. (p. 29.)
3. High velocities 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. (p. 41.)
4. For amplitude and period of vertical waves as observed at the same or different stations see (p. 28. and diagrams.)

8. VELOCITY.

1. The velocity of transit decreases as a disturbance radiates. (pp. 40. 50. 56.)
2. Near to an origin the velocity of transit varies with the intensity of the initial disturbance. (pp. 40. 50. 56.)

3. In different kinds of ground, with different intensities of initial disturbance, and with different systems of observation I determined velocities lying between 630 and about 200 ft. per second. (First, fourth, fifth and sixth experiments.)

   Mallet determined a velocity in sand of 824 ft. and in granite of 1664 feet per second. General Abbot has observed velocities of 8800 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. (pp. 40. 50.)
5. The rate at which the normal motion outraces the transverse motion is not constant. (p. 38.)
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. (p. 40.)

   That the ratio of the speed of normal and transverse motions is not constant is shewn from a table of these velocities calculated for different rocks from their moduli of elasticity (p. 75.)

9. MISCELLANEOUS.

1. At the time of an earth disturbance currents are produced in telegraph lines. (p. 54.)
2. The exceedingly rapid decrease in the intensity of a disturbance in the immediate neighbourhood of the epicentrum is shewn by the diagram on (p. 61.)
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.
4. Many of the results enunciated above find direct or indirect confirmation in experiments others than those to which reference has been made.

Fig 2.

50FT STATION

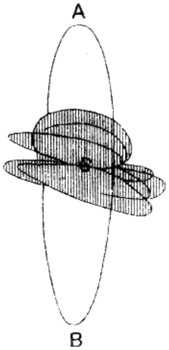


Fig 3.

100FT STATION.

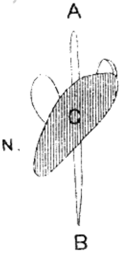
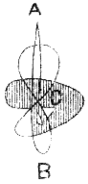


Fig 4.

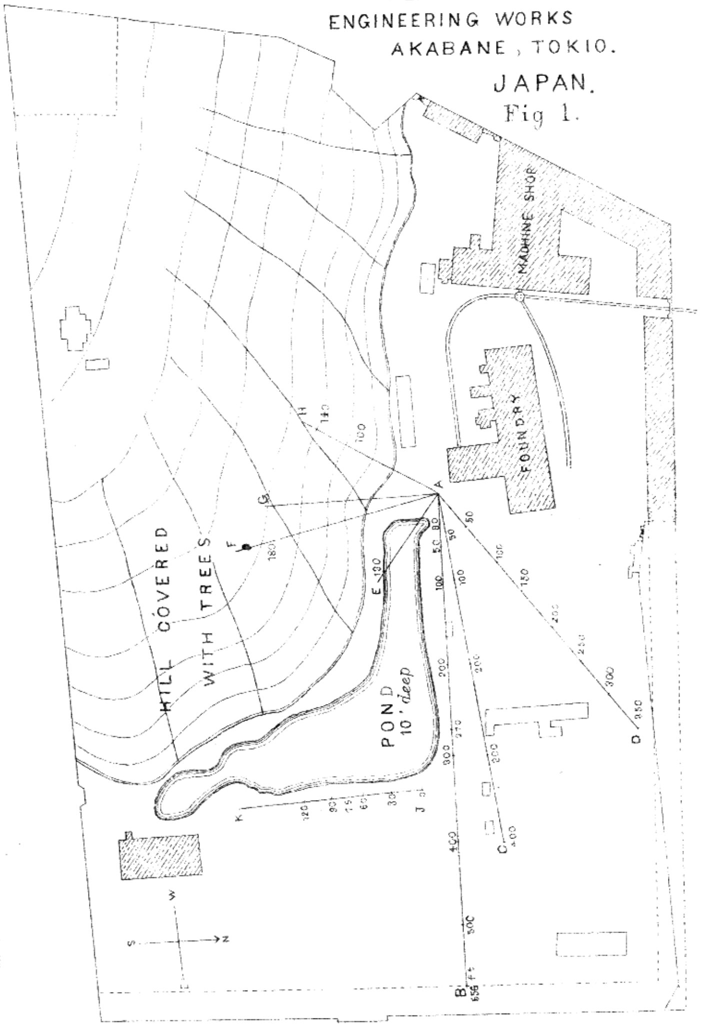
200FT STATION.



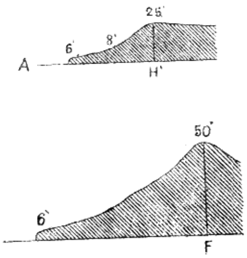
DIRECTION OF DIRECT VIBRATIONS

PLAN OF ENGINEERING WORKS AKABANE, TOKIO. JAPAN.

Fig 1.



SCALE: $\frac{3}{32}$ inches = 20 feet for Plan.
" " = 40 " for vertical Scale in Sections.



Section on A H. & A. F. on Plan.

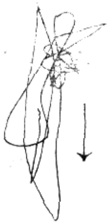


FIG 5

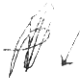


FIG 6

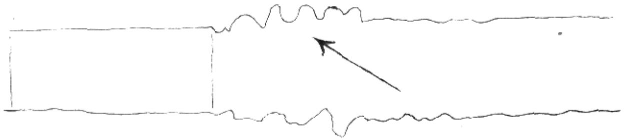


FIG 7

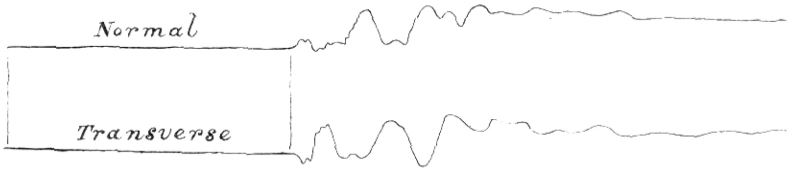


FIG 8

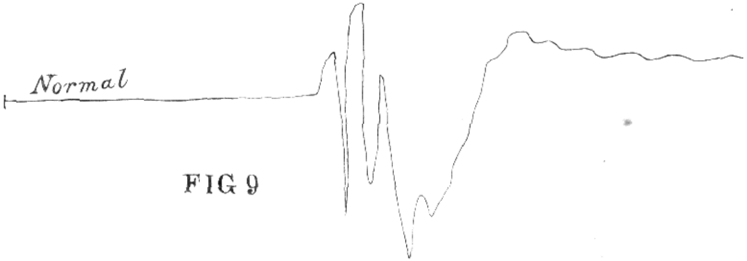


FIG 9

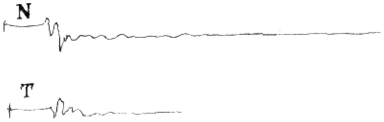


FIG 10

Time intervals = ½ Seconds.