

THE GRAY-MILNE SEISMOGRAPH
AND OTHER INSTRUMENTS IN THE SEISMOLOGICAL
LABORATORY AT THE IMPERIAL COLLEGE OF
ENGINEERING, TOKIO.

BY JOHN MILNE.

[Read November 29th, 1887.]

The following instruments were exhibited :—

I.—GRAY-MILNE SEISMOGRAPH.

The following description of the Gray-Milne Seismograph is almost entirely a reproduction of the original description given by Mr. Gray in the *Philosophical Magazine* (April, 1887). The diagrams are taken from the same source, but are slightly modified. A few additional notes are added at the end.

The new form of apparatus has for its object the determination of the same elements as have been already enumerated with reference to an instrument previously constructed by Messrs. Gray and Milne. Provision is, however, now made for the whole of the record being obtained on a fresh surface, and for any number of earthquakes which may occur within a limited period, say a week, being recorded on the same sheet. The record-receiver is kept continuously in motion at a very slow rate, and time is marked on it at regular intervals by means of a good clock; the object being to secure with perfect certainty that most important element in earthquake investigation—the time of occurrence of the disturbance. In the most complete form of the apparatus the record-receiving surface is a long ribbon of thin paper, which is gradually unwound from one supply drum on to another, which may be called the hauling-off drum, by means of a

weight or spring and a train of wheelwork. The speed is rendered uniform by taking the paper in its passage from the one drum to the other round a third drum, which is kept continuously in uniform motion by a train of clockwork and a suitable governor. A somewhat simpler arrangement is obtained by using a single drum covered with paper, or a smoked glass or metal cylinder, and giving to this cylinder a slow motion of translation in the direction of its axis, so that the record takes the form of a spiral line round it. As, however, the rate of motion must be such as to give the time of occurrence with fair accuracy within a second of time, it is difficult to obtain a good record on a cylinder of moderate size, which will extend over more than twelve hours with this arrangement. It is of course easy to adapt the apparatus to be used either way, if that were desirable; but the continuous ribbon of paper is so much the better form of receiving-surface that the description given in this paper, in so far as it refers to earthquakes, only includes that form. The spiral record has some advantages in apparatus adapted to record slow changes of level of the earth's surface; and it will be again referred to in that connection. For such purposes the rate of motion may be made excessively slow; and hence the records for a considerable length of time may be written on one sheet.

At the time of occurrence of an earthquake, the rate of motion of the paper is automatically greatly increased, and a siphon pointer is simultaneously set into vibration, and made to mark seconds of time on the ribbon, thus showing accurately the rate of motion at any instant. The actual rate of motion of the paper on the slow speed may be varied from about a quarter of an inch to an inch per minute, and on the fast speed from about 25. to 50 inches per minute, with the present form of instrument. This change of speed is generally obtained by including in the driving clockwork two governors, one of which can be automatically thrown out of gear, either electro-magnetically or mechanically. The

latter method has been found the best and the simplest in practice. The arrangement commonly used is described below, and need not be more particularly referred to here than in a general statement of the operations it is intended to perform. At the time of an earthquake three operations take place simultaneously. One is the introduction in train with the clockwork of an adjusting mechanism which is intended to readjust the starting apparatus, whatever that may be, so that it may be in readiness for another earthquake should that occur. Another is to throw out of gear the slow-speed governor, or, if that method is adopted, to work a change-wheel lever, so as to shorten the train between the driving power and the governor. A third is to throw the siphon pointer into action so as to cause it to mark time on the record sheet. It will thus be seen that the instrument is intended to be absolutely self-acting, so long as its supply of paper lasts and the driving mechanism continues to go. The supply-drum can take as much paper as is required in a week on the slow speed.

The record is made in ink by means of fine glass siphons, in very much the same manner as that which was introduced by Sir William Thomson in his siphon-recorder for submarine telegraph-cable work. This is extremely well adapted for the continuous ribbon method of working, and, besides, gives an excellent clear record which requires no further preparation before it is filed for reference; and, what is of great importance, the record is obtained with exceedingly little disturbance from friction at the marking-point.

The siphons which write the horizontal components of the motion are controlled by two pendulums, the suspending wires of which are held out of the vertical by horizontal struts terminating in knife-edges which rest against the bottoms of flat V-grooves fixed to a cast-iron pillar rigidly attached to the sole plate of the instrument. These pendulums, when set in vibration, describe cones, and hence they have been called

"conical pendulums." The degree of deflection from the vertical can be varied from about one and a half inches to a foot, by sliding the pendulum-bob along the strut. The strut is made in two pieces, so that a part of it can be removed when high sensibility is required, and in consequence the mass is used near the knife-edge. The bob of the pendulum is suspended by a fine platinum or steel wire from an arrangement which permits the suspending wire to be lengthened and shortened, and also allows the points of suspension to be put in such positions above the knife-edges as causes the struts to place themselves in positions at right angles to each other, and at the same time provides the means of adjusting their periods of free vibration to any desired length.*

It is of great importance in apparatus of this kind that the mass which, through its inertia, enables the record of the motion of the earth to be written, should be as far as possible from the knife-edge or point fixed to the earth; a long period of free vibration can thus be obtained, combined with considerable stability of position, while the greatest motion to which the knife-edge is likely to be subjected does not turn the strut through a large angle. If this latter condition be not provided for, the interpretation of the record becomes exceedingly difficult; and this difficulty is likely to be greatly increased by the mass acquiring oscillations in its own free period of such large angular amplitude that the direction of the component which is being recorded becomes a variable quantity.

The siphon which writes the vertical component of the motion is controlled by a compensated horizontal lever instrument, on the same principle as that introduced by the present writer and exhibited to the Seismological Society of Japan, and described in the Transactions of that Society, vol. i. part I, p. 48, and vol. iii. p. 140, and also in the *Philosophical*

* This pendulum is a modification of one designed by Mr. Gray in the beginning of 1880, in which the weight was supported by a thin wire in line with a rigid vertical axis fixed to the end of the strut and resting against bearings so as to keep the strut horizontal.

Magazine for September, 1881. This instrument consists of a horizontal lever carrying near one end a heavy mass, and provided at the other end with knife-edges in a line at right angles to the length of the lever. The lever is supported by two flat springs, acting, through a link, on a knife-edge attached to it at a point between the mass and the knife-edges before mentioned, which are by this means held up against the apex of inverted V-grooves rigidly fixed to the framework. In the form of this instrument previously described in this *Philosophical Magazine*, the supporting springs were of the ordinary spiral type; but in subsequent instruments two flat springs have been adopted, because for the same period of oscillation of the lever without compensation they give a more compact arrangement. These springs are now made of such variable breadth between the fixed and the free ends that, as they are supporting the lever, each part is equally bent. They may either be initially straight, and bent into a circular form when in use, or they may be initially set to a circular form and straight when in use. When the lever is supported in this way it has a fairly long period of free vibration; and this may be increased to any desired extent by means of a second pair of springs, which pull downwards on a light bar fixed vertically above the axis of motion of the lever. This second pair of springs, besides providing the necessary compensation for the positive stability of the lever and supporting-spring system, gives a ready means of obtaining a fine adjustment for bringing the lever to the horizontal position. This is accomplished either by giving to the points of attachment of the compensating springs a screw-adjustment so that they can be moved a short distance backward or forward, or by making the point of attachment of one spring a little in front of, and of the other a little behind, the vertical plane through the knife-edge. The lever can then be raised or lowered by increasing the pull on one spring and diminishing that on the other. Sir William Thomson has recently suggested to the writer that a

flat spring, which in its normal state is bent to such a curvature that it is brought straight by supporting a weight on its end, might be found a good arrangement for a vertical motion seismometer. This would certainly have considerable advantage in the way of simplicity, and with proper compensation applied, say to the index-lever, so as to lengthen the period, may be found very suitable. The only doubtful point seems to be whether the want of rigidity in the spring may not lead to false indications in the record due to the horizontal motions.

The application of a rigid horizontal lever, pivoted on knife-edges and supported by springs as a vertical-motion seismometer, was first described in the earlier of the two papers to the Seismological Society of Japan, quoted above. The advantage of this arrangement, as rendering it possible to obtain a long period of free vibration by placing the intermediate point of support below the line joining the other two, was also pointed out. The advantage obtained by the lever itself, without compensation, over an ordinary stretched string was more specifically pointed out in the other papers referred to; and a method of obtaining very perfect compensation, either for a lever or an ordinary spring arrangement, by means of a liquid was then given. The idea of increasing the period of a vibrating system by the addition, as it were, of negative stability, which was first brought forward in these papers, has been worked out in various ways; but the method described in this paper is the most perfect yet adopted. Its application to the ordinary pendulum was also brought forward and discussed at a subsequent meeting of the Seismological Society of Japan.*

The apparatus above referred to for recording the horizontal components of the motion during an earthquake may, when properly adjusted, be used for registering minute tremors and slow changes of level of the earth's surface. It is, however,

* "On a Method of Compensating a Pendulum so as to make it Astatic," by Thomas Gray, *Trans. Seis. Soc. Japan*, vol. iii. p. 145.

absolutely necessary for such a purpose that friction of the different parts should be reduced to a minimum ; and hence the siphons, or the marking-points when a smoked surface is used, are only brought for a few seconds at a time into contact with the paper, thus recording a series of dots close enough together to form practically a continuous line. Another method, which gives excellent results and is simple, has been much used by Professor Milne in Japan. It consists in passing from the point of the index, through the paper, to the drum, a series of sparks from an electric induction-coil. The sparks can be made to pass at regular intervals by a clockwork circuit-closing arrangement ; and, by the perforations they leave, a record both of their position and the corresponding time is obtained.* This method is absolutely frictionless so far as the recording-point is concerned, and has the advantage that the sheet can afterwards be used as a stencil-plate for printing copies of the record. An ordinary simple pendulum, furnished with a very light vertical index of thin aluminum tube giving a multiplication of 200, has been for some time in use. The record of the position of the end of the index is taken on two strips of paper which are being slowly pulled along, in directions at right angles to each other, under it. The sparks perforate both sheets simultaneously, thus automatically breaking up the motion into two rectangular components. The details of some forms of apparatus for this purpose will form the subject of a separate communication.

MECHANICAL DETAILS.

The record-receiver consists of a long ribbon of thin paper, about five inches broad, which is slowly wound from the drum *A*, situated behind the drum *C* (Plate fig. 1), on to the drum, *B*, by means of a train of clockwork driven by a spring or a weight of sufficient power to keep the

* This method of recording the motions of an index was used by Sir William Thomson in his "Spark Recorder." "Mathematical and Physical Papers," vol. ii. p. 168.

ribbon taut. The rate at which the paper is fed forward is governed by a second train of clockwork, driven by a separate weight and governed by means of two Thomson spring-governors. In gear with this train of wheelwork there is a third drum, *C*, round which the paper is taken as it passes from the drum *A* to the drum *B*. This drum is kept moving at a uniform rate, and serves to regulate the motion of the paper. The object of the double set of clockwork mechanism is to render the rate at which the paper is fed forward independent of the size of the coil on the drums *A* and *B*. The surface of the drum *C* is covered with several thicknesses of blotting-paper for the purpose of giving a soft surface for the siphons to write upon, and of preventing the ribbon blotting or adhering to the drum in consequence of ink passing through the paper. This blotting-pad is of some importance, because a cheap kind of thin paper is found to answer perfectly for the siphons to write upon. They move with less friction on a moderately rough surface and on paper which rapidly absorbs the ink. Under ordinary circumstances the paper is fed forward from a quarter of an inch to an inch per minute, this being kept up continuously for the purpose of allowing the magnitude and the time of occurrence of any disturbance, which is of sufficient amplitude to leave a record, to be accurately obtained. This obviates the unavoidable uncertainty which exists as to the action of any automatic contrivance designed to come into action at the time of the disturbance. The time of occurrence is obtained by causing the siphon, *D* (figs. 1 and 3), to mark equal intervals of time on the paper ribbon. The siphon is fixed to a light index-lever which is pivotted on the end of the lever, *E*, and the link, *F*. The lever *E* turns round an axis at *G*, and rests with its end in contact with the wheel, *H*, which is fixed to the end of the hour-spindle of the clock, *K* (fig. 1). As each tooth of the wheel *H* passes the end of the lever *E* a mark is made on the paper, and the end of the hour is distinguished by putting a larger or a double tooth at that part of the wheel.

The time at which an earthquake has occurred can thus be found by measuring the distance of the record of the disturbance from the last time-mark, then counting the number of intervals from the last hour-mark, and then the number of hours to a known point. It is convenient to mark the hour once or twice a day on the paper, so as to save trouble in the reckoning should an earthquake occur.

The ordinary rate of motion is much too slow for the record to show the motions of the earth in detail; and, as has been already stated, this is obtained by automatically increasing the speed at the commencement of the shock. The arrangement for doing this is shown at *Q* (fig. 1), and is also illustrated diagrammatically in fig. 2. Referring to the diagram, *a* and *b* represent two levers, which are pivoted at *c* and *d* respectively. On the right-hand end of the lever, *b*, a ball, *e*, is fixed, and the weight of this is counterpoised by another ball, *f*, which rests on a rocking platform, *g*, pivotted on the other end of the lever. Opposite the end of the rocking platform, *g*, and fixed to the end of the lever, *a*, there is another platform, *h*, which receives the ball, *f*, when it rolls off the platform, *g*. The ball is prevented from rolling sideways by a light spring, *i i*, fixed to the sides of the platforms. On the end of the lever, *a*, or on another lever connected with it, the end of the spindle of the wheel, *j*, is supported. This wheel is in gear with the pinion, *k*, which is on the shaft of the most distant of the two governors from the driving-power. The ball, *f*, is so adjusted over the pivot of the rocking platform, *g*, that an exceedingly slight disturbance causes it to roll forward on to *h*, tilting *g* over, and at the same time pushing down the end of *a* and raising the wheel *j* out of gear with the pinion *k*, thus allowing the clockwork to run on without the governor which regulates the slow speed. The rate of motion then rapidly increases until the second governor acquires sufficient velocity to control the speed, after which the paper moves forward at a rapid but uniform rate. In order to again reduce the speed after a sufficient interval has elapsed, the rolling forward of the ball

f , allows the unbalanced weight of e to bring a wheel, l , on the spindle of which a "snail," m , is fixed into gear with the pinion, n , which forms part of the clockwork mechanism. The spindle of l rests on a spring, o , which is adjusted so as to push the lower part of the "snail" just into contact with a pin, p , fixed in the lever b . The weight of e , acting through the pin p on the "snail," deflects the spring, o , and brings the wheel, l , into gear with the pinion n . The "snail" is then gradually moved round and raises the ball, e , and the end of the lever, b , at the same time lowering the rocking platform, g . After this has proceeded so far as to cause the platform g to come below the lever of h the ball rolls back to its original position; and, as the "snail" moves round, the platforms are gradually raised to their original positions, the wheel j again comes into gear with the pinion k , and the speed is reduced. The wheel, l , remains in gear with the pinion n for a short time after the speed is reduced, so as to allow the final adjustment in position of the platform g and the ball f to be made gently. After this is accomplished a hollow in m allows the spring o to push the wheel l out of gear, and everything is left in readiness for the next disturbance.

In order to obtain the rate at which the paper is moving at any instant during the transition period between the slow and the quick speed, the movement of the lever a allows a wire forming the tail piece of D (Fig. 3) to fall until a pin on a forked lever touches the seconds wheel S . The siphon therefore records both the long and short time intervals.

One of the "conical pendulums" used for actuating the siphons which record the two horizontal components of the motion is illustrated in plan in fig. 4, and in elevation in fig. 5. It consists of a thin brass cylinder r , filled with lead, and held deflected by a light tubular strut, s , furnished with a knife-edge at t , which rests against the bottom of a vertical V-groove fixed to the support u . The weight of the pendulum-bob and strut is supported by a thin wire, v , attached in

the lower end to a stirrup, w , pivoted at x a little below and in front of the centre of gravity of r , and taken at the upper end over a small wheel, y , to a drum, z , round which the wire may be wound so as to adjust the level of the strut, s . The position of the pivot, x , is so arranged that the knife-edge at t has little or no tendency to rise or fall, no matter at what part of the strut the cylinder r may be clamped. The wheel y is provided with adjusting screws, a_1 and b_1 , by means of which the top of the wire can be placed vertically above the knife-edge, or as much in front of or behind that point as may be necessary to make the period of free vibration of the pendulum have any desired length. A light aluminium lever, c_1 , is hinged to the strut s at d_1 , and is provided at its outer end with a small hollow steel cone, e_1 , which may be placed over one or other of a series of sharp points, f_1 , fixed to the vertical arm of the cranked lever, g_1 . The lever g_1 turns round a horizontal axis at h_1 in bearings fixed to the ink-well, i_1 , and the vertical arm is hinged at j_1 , so as to be free to turn in a direction at right angles to the plane of the crank. A siphon, k_1 , is fixed to the horizontal arm of the lever g_1 , and, drawing ink from the well, i_1 , writes a continuous line on the paper ribbon. The horizontal arm of the lever g_1 is made very flexible in a horizontal direction, and besides can be turned round a vertical axis to such an extent as allow the pressure of the point of the siphon on the paper to be adjusted until it is only sufficient to give a record.

The horizontal-lever pendulum used for actuating the siphon which writes the vertical motion is illustrated diagrammatically in fig. 6. It consists of a horizontal lever, l_1 , carrying at one end a cylindrical weight m_1 , and free to turn round knife-edges, n_1 , fixed to the other end of the lever. The lever is supported in a horizontal position by two flat springs, clearly shown in fig. 1, and indicated at o_1 , fig. 6. A light aluminium index, p_1 , pivotted at q_1 , and connected by a thin wire or thread to the end of the lever l_1 , carries a fine siphon, r_1 , which rests with one end in the ink-well, s_1 , and

the other end touching the surface of the paper. The end of the index is weighted sufficiently to cause it to follow the motions of the lever. This arrangement gives a period of free vibration of about two seconds in the actual instrument; and in order to increase this period a second set of springs, indicated at t_1 , are made to act on knife-edges, u_1 , fixed vertically above n_1 , so as to add negative stability to the arrangement. When the lever is deflected downwards the pull on the supporting spring is increased, but at the same time the knife-edge u_1 comes in front of the vertical plane through n_1 ; and, since the lower point of attachment of the compensating spring t_1 is far below n_1 , a couple is introduced which compensates for the greater upward force. The same is the case in the reverse order, when the lever is deflected upwards. Hence, if the pull exerted by t , and the other conditions mentioned below be properly adjusted, the horizontal lever may be made to have any desired period of free oscillation. In actual practice some positive stability must be given to the lever in order that its position of equilibrium may be definite; but its period may be made so great that, even if oscillations of considerable amplitude in its own period are set up, they will be so slow compared with those of the earthquake, that the undulating line so drawn will still be practically straight, so far as the earthquake record is concerned. In order to insure good compensation, the condition must be fulfilled that the rate of variation of the compensating couple is always the same as that of the supporting couple. If this be not the case, the pendulum must either be left with excessive positive stability for small deflections, or it will be continually liable to become unstable by the compensating couple becoming too great when the deflection exceeds a certain limit. In the present instance, let the modulus of the supporting spring be M , the arm at which it acts a ; let the modulus of the compensating spring be M_1 , and the distance between n_1 and u_1 be a_1 . Then for a deflection of the lever equal to θ we have, on the supposition that the length of the

supporting spring and link is great compared with a_1 , for the return couple $Ma^2 \cos \theta \sin \theta - M_1 a_1^2 \cos \theta \sin \theta - M_1 \beta \sin \theta$, where $\beta + a_1$ is the total elongation of the spring for the horizontal position of the lever. Now our condition necessitates β being either zero or negative; and in order to keep within this condition the length of the unstretched spring and link are made to reach a little above n_1 , and the height of n_1 is made adjustable, so that $M_1 a_1^2$ can be adjusted to be as near Ma^2 as may be desired.

NOTES.—In making siphons glass fibres ought to be selected which have been broken at right angles to their length. These broken ends may be made smooth by taking a bundle of fibres between the finger and thumb and gently rubbing them on a brass plate covered with a little fine emery and water. Another plan which suggests itself is to bed the end of the fibres in Canada balsam, from which the turpentine has been driven off by heat, and allow the same to harden. After grinding on the brass plate the Canada balsam may be removed by alcohol. The fibres are bent by holding them over the glowing end of a pencil-like stick made of charcoal powder and rice paste. The short writing end of the siphon is formed first, and it ought to be slightly inclined in the direction of motion of the paper. They are fixed on the aluminium stems with parafine, the holders or stems being heated with a hot wire. The ink, which may be fed to the ink holders by a pipette, is made from water and a blue anyline dye. It ought to be filtered.

The paper may be readily wound back upon the roll from which it was fed by turning the same by hand, first having removed nearly all the weights from the cord on the right hand side and turned the pointers back from the paper. All the weights on the right side must be removed before taking out the cylinder on which the paper is wound.

A form of multiplying pointer which works satisfactorily is shown in fig. 7. In this figure s is a cross section of the

strut s shown in fig. 5 near to the weight r . The lower end of a light bell crank lever l , pivotted at o , rests against this. The end of this is connected by the thread t with the writing pointer k , which is pivotted at m . In one direction the writing pointer moves by the influence of gravity. As the greatest acceleration of earthquake motion which we are likely to experience is less than g , the arrangement promises to continue to yield satisfactory results.

When adjusted for working see that all pivots connected with the writing levers turn easily, but they must not have the slightest lateral looseness. The left hand double cord requires 28 lbs. and the right hand cord from 8 to 14 lbs. as driving weights. They require a fall of about 4 ft. 6 in.

AUTOMATIC TREMOR RECORDER.

This instrument, since it was described in Vol. XI. of the Society's Transactions, has been slightly modified. It now consists of a simple pendulum furnished with an aluminium pointer giving a multiplication of 200. At intervals of five minutes, sparks from an induction coil pass from the point of the index and perforate two bands of paper moving at right angles. As shown in the above-mentioned volume the movements of this instrument appear still to accompany the following conditions:—

1. It almost always records tremors when heavy winds are blowing in Tokio.

2. It almost always records tremors when heavy winds are blowing behind the mountains at a distance of 60 to 150 miles, although in Tokio and on the surrounding plain it may be absolutely calm.

The writer regards the instrument as having greater interest for the Meteorologist than for the Seismologist.

MILNE'S DUPLEX PENDULUM SEISMOGRAPH.

The instrument exhibited only differed from the instrument described in Vol. XII., by embodying the improvement

suggested by Dr. C. G. Knott, and more refinements in workmanship and construction.

Thus far it has worked with more satisfaction than any other instrument giving statical records.

An example of one of the diagrams given by this instrument is here reproduced. It represents a tolerably severe shock, which occurred on September 5th. The object in reproduction is partly to show the clearness in definition of the diagram and partly on account of the peculiarity of some of the movements which it will be seen are nearly circular.

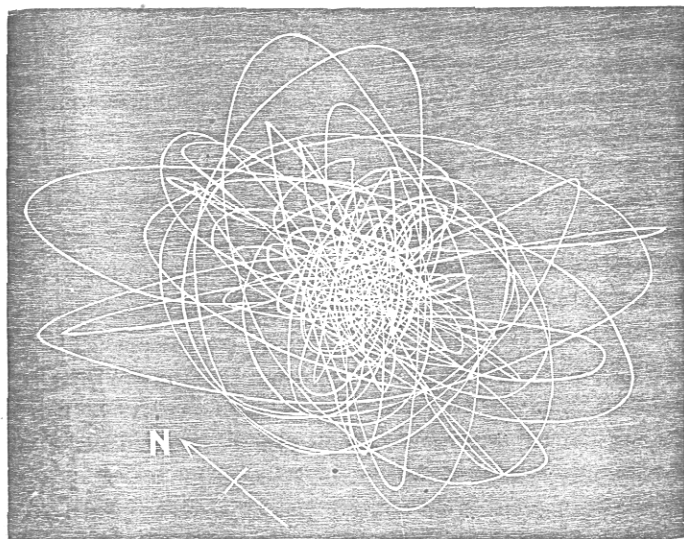
In order to separate some of these vibrations most of which in all instruments giving statical records are confusedly superimposed upon each other, a record receiving apparatus carrying a long plate of smoked glass is being arranged, so that the plate of smoked glass, after having received two or three vibrations drops out of contact with the recording index. After this it is moved a short distance horizontally and then moved vertically upwards to again touch the pointer and then receive two or three of the succeeding vibrations. This operation is repeated about 12 times, so that the total motion of the ground will be recorded in twelve parts and the confusion resulting from superposition be in this way avoided.

A SEISMOGRAPH FOR LARGE MOTIONS.

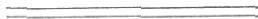
For recording large motions any ordinary seismograph recording without multiplication may be used. The one at present employed by the author consists of a plate and ball seismograph recording by means of a pencil sliding in a tube upon a sheet of paper. The position of the pencil is at the centre of inertia of the upper movable plate. (See *Phil. Mag.* Nov. 1881.)

To complete these instruments a seismograph for vertical motion writing on a stationary plate and seismographs for horizontal and vertical motion writing on moving surfaces are required.

THE EARTHQUAKE OF SEPTEMBER 3RD, 1887, AS RECORDED BY
MILNE'S PENDULUM SEISMOGRAPH.



MULTIPLICATION = 6.



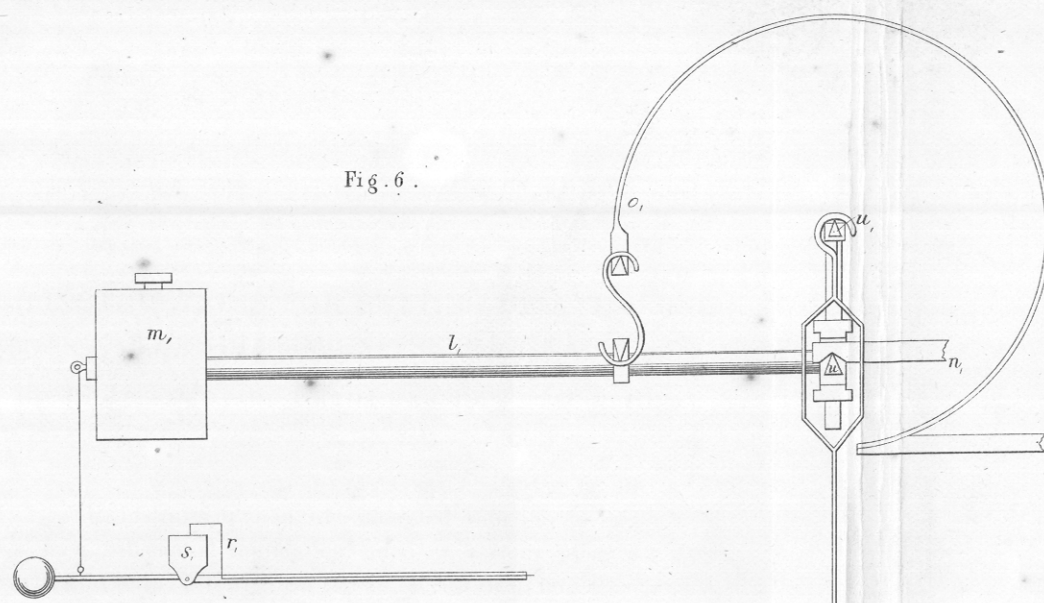


Fig. 6.

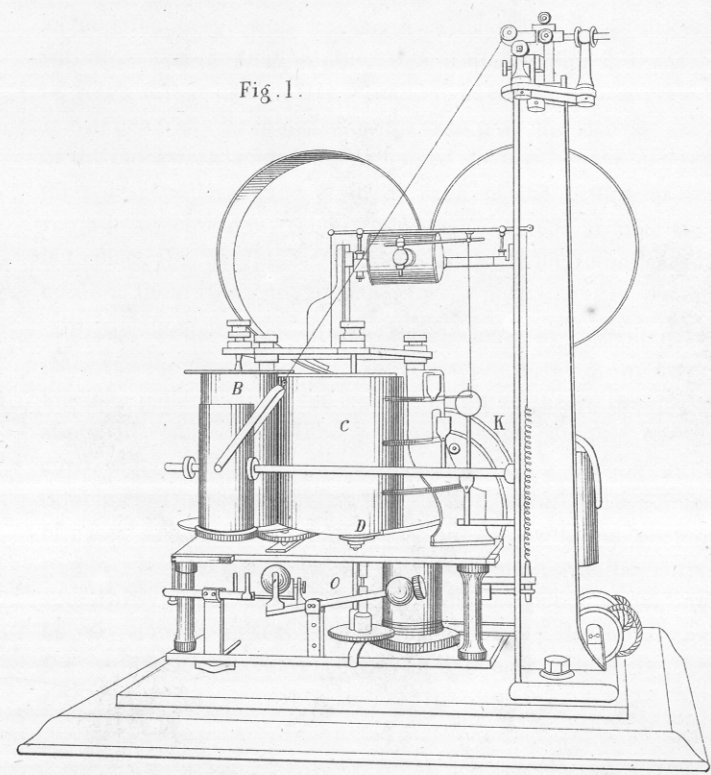


Fig. 1.

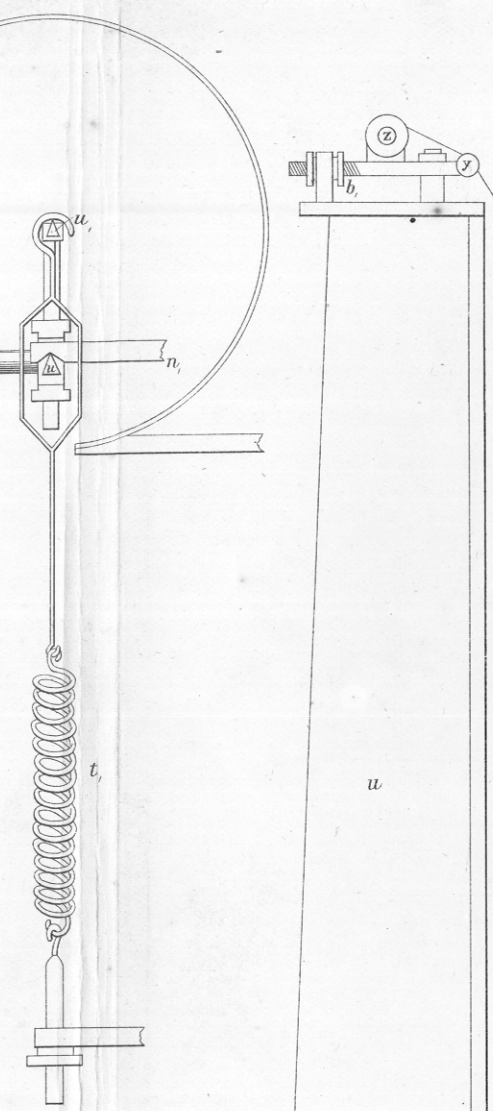


Fig. 5.

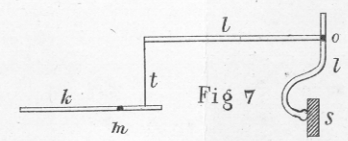


Fig. 7.

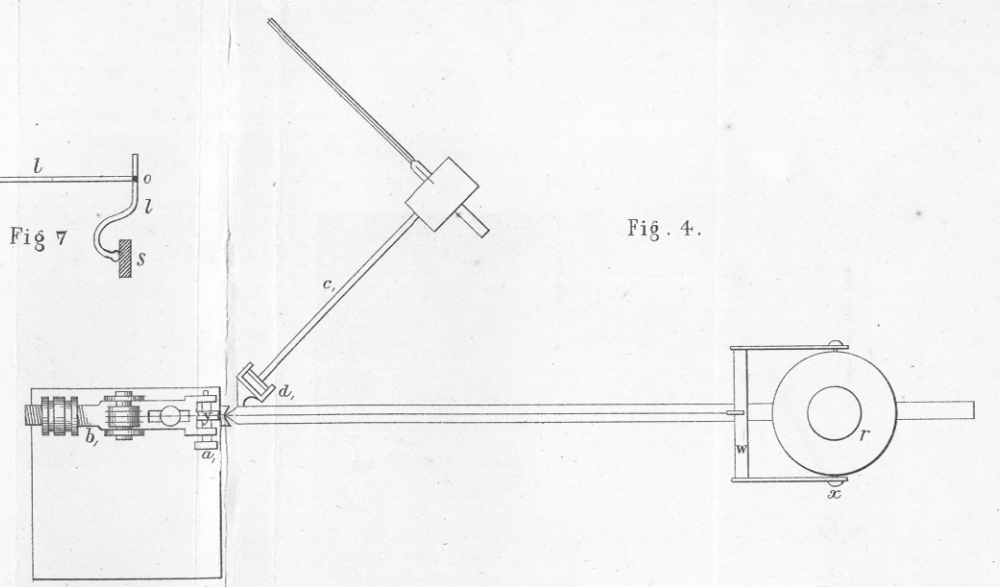


Fig. 4.

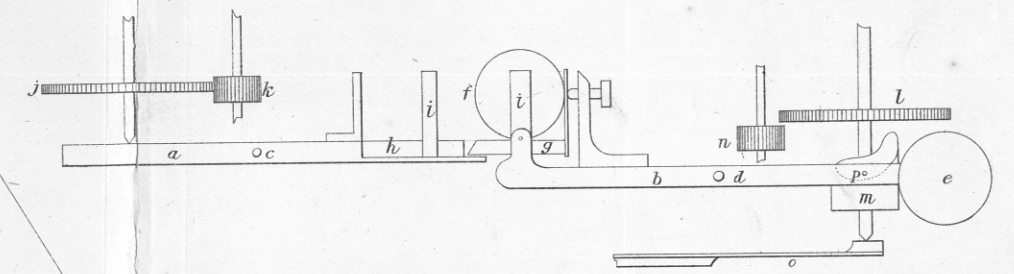


Fig. 2.

