"On the Small Vertical Movements of a Stone laid on the Surface of the Ground." By Horace Darwin. Communicated by Clement Reid, F.R.S. Received April 17,—Read May 2, 1901.

In my father's book on Vegetable Mould and Earthworms an estimate is given of the rate at which stones placed on the surface of the soil are buried by the action of earthworms. The estimate is rough, and as far as I know no attempt has been made to detect such movements when small, or to determine them accurately when they are large.

The experiments described in this paper were undertaken originally to measure accurately the downward movement of a stone caused by earthworms. The upward and downward movements due to varying moisture of the soil and to frost were found to be much larger than was expected. These movements, interesting in themselves, increase the difficulty of accurately determining the movement due to the action of earthworms.*

The experiment was begun on September 5, 1877, and the position selected is in a nearly level field which had probably been pasture for considerably more than fifty years. It is to the south of my father's house at Down, close to some railings separating the field from the lawn and under a large Spanish chestnut tree. He approved at the time of the selection of this position; at a later date he considered a mistake had been made, as he thought there were fewer worms under trees.†

It was necessary to have a fixed point from which the displacement might be measured; this was managed in the following way:—An iron rod was driven into the ground by means of a heavy hammer; it was then removed, and a copper rod, slightly larger (22 mm. in diameter), was driven into the hole; the bottom of the rod was about 2·63 metres from the surface. The top of this rod is the point from which all measurements were taken.

A circular stone about 460 mm. in diameter and about 57 mm. thick, weighing about 23 kilos., was placed on the ground with the rod projecting through a hole in its centre. A brass cylinder, slightly smaller than the hole in the stone, had previously been firmly fixed in the hole by running in melted lead. The brass cylinder had three projecting pieces at its top; three symmetrical radial right-angle grooves were cut, one in each of these projecting pieces. This gave the usual

* See 'Vegetable Mould and Earthworms,' by C. Darwin, 1883, p. 121, where a short preliminary account of the experiment is given.

† *Ibid.*, p. 146. In Knowle Park, under beech trees, worm eastings were almost wholly absent.

form of geometrical bearings for the three rounded feet of the stand which carried the micrometer used for measuring the relative positions of the stone and the top of rod.

The action of the earthworms would cause the stone to sink relatively to the top of the rod, but the following other causes should also be considered :—

1. *The Growth of the Roots of the Tree.*—The copper rod passed through about 2·63 metres of slightly sandy red clay which overlies the chalk, and contains many flints; some of these were broken or displaced by the passage of the iron rod. Great force was required to draw the rod out of the ground, and in doing so its sides became scored by the flints. It is, therefore, safe to assume that the flints were pressed with considerable force against the rod, and that their sharp edges gripped it tightly. The point where the rod was gripped, and where there was no relative movement between it and the clay, was unknown ; probably, however, it was well below the level of the roots of the tree. The roots growing larger in diameter would raise the stone relatively to the top of the rod. The amount of this movement is quite uncertain.

2. *Dampness of the Ground.*—The clay and the surface soil both, no doubt, swell with increase of moisture. The swelling of the clay above the unknown point at which the rod is gripped will raise the stone, and the swelling of the surface soil will have the same effect.

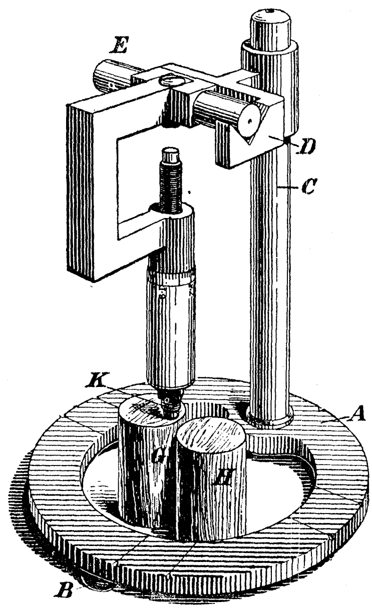
3. *Expansion of the Rod from Change of Temperature.*—The effect of this is very small and is quite negligible when measurements, taken at the same time of year, are compared. If we take a high estimate and assume that the summer and winter temperature of the rod differed by 10° C., the relative movement of the stone and the top of the rod would be about 0·4 mm.; this is on the assumption that the rod is only gripped close to its lower end, and that the expansion practically of its whole length is taken into account. An attempt was made to eliminate this error by sinking two rods alongside of each other, one being of iron and one of copper, and by taking measurements from both rods. This attempt failed, and the results now given are the measurements from the copper rod only.*

The measuring apparatus is shown in fig. 1. It consists of a brass ring A, with three short rounded feet B, which rest in the radial grooves before mentioned. This annular base carries a vertical brass rod C, to which is soldered an arm with V-bearings D. Trunnions E were fixed to the usual form of micrometer screw gauge as shown in the figure, the trunnions were supported by the V-bearings in the arm,

* Professor Judd pointed out that the clay with flints through which the rod passed probably contained small quantities of calcium carbonate which would be slowly dissolved by rain, and that this would produce a small error.—May 2, 1901. H. D.

and the micrometer screw was used for the measurement. G and H are the tops of the iron and copper rods; the micrometer screw is turned till its lower end K just touches one of the rods; the upper end of the screw is not used at all. The stand and micrometer were kept indoors till wanted.

FIG. 1.



The method of reading was as follows :—

The grooves for the feet of the stand were cleaned, and the stand placed with its feet resting in them. The trunnions of the micrometer gauge were placed in the V-bearings; the screw was then adjusted till the lower end just touched the top of one rod; by swinging the gauge, which hangs by its trunnions in the bearings, this adjustment could be done with great delicacy.

The gauge was moved sideways by sliding the trunnions along the bearings; this horizontal movement brought the screw over the centre of the second rod, and a second measurement was taken. This second measurement, however, was not used.

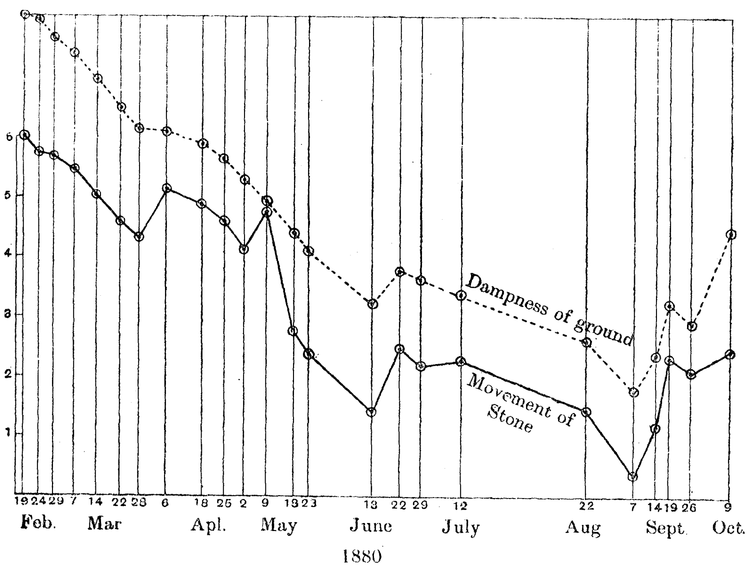
The tops of both rods were smooth, and a piece of copper was attached to the iron rod in order to give a surface which would not corrode. The micrometer screw was graduated to 0·01 mm., but as we had not realised the importance of making sure that there was not a small lateral displacement of the trunnions along the bearings, the last place

of the decimals was not reliable. This error existed because the horizontal movement of the trunnions along its bearings was not strictly parallel to the surface of the top of the rods from which the measurement was taken. As the readings from one rod only were used, it would have been better if this lateral displacement had been impossible. With care, however, consecutive measurements agreed within 0·01 mm., showing that the method was capable of far greater accuracy than was required.

During the experiment the stone sank more than the range of the micrometer screw. The arm was unsoldered, moved upwards sufficiently far to allow the screw to be used again, and was then re-soldered. This operation, no doubt, introduced a small error.

The curve marked "Movement of Stone" in fig. 2 represents the up

FIG. 2.



and down movements of the stone from February 19 to October 9, 1880, due to the varying dampness of the ground.

The points corresponding to each observation are surrounded by a small circle; their vertical distance apart is the movement of the stone magnified 8 times, each division of the scale representing 1 mm.; the horizontal distance apart is proportional time.

The following are the observations from which the curve is constructed. The numbers in the second column give the distance moved downward by the stone from its position on February 19, 1880:—

		mm.			mm.
Feb. 19	....	0·00	May 18	....	3·23
„ 24	....	0·28	„ 23	....	3·62
„ 29	....	0·43	June 13	....	4·59
Mar. 7	....	0·54	„ 22	....	3·53
„ 14	....	0·97	„ 29	....	3·81
„ 22	....	1·43	July 12	....	3·72
„ 28	....	1·69	Aug. 22	....	4·56
Apr. 6	....	0·89	Sept. 7	....	5·62
„ 18	....	1·11	„ 14	....	4·84
„ 25	....	1·43	„ 19	....	3·69
May 2	....	1·89	„ 26	....	3·91
„ 9	....	1·27	Oct. 9	....	3·58

The curve shown by the dotted line roughly represents the dampness of the soil. Mr. Baldwin Latham has most kindly supplied me with the rainfall during this period at Leaves Green, about 1 mile distant, and nearly at the same level as Down. I have assumed that the soil dries at a uniform rate; this assumption cannot be correct, but no other is possible. The varying rate of drying will, no doubt, depend on temperature, wind, and dryness of the air, as well as on the rate at which the water drains away.

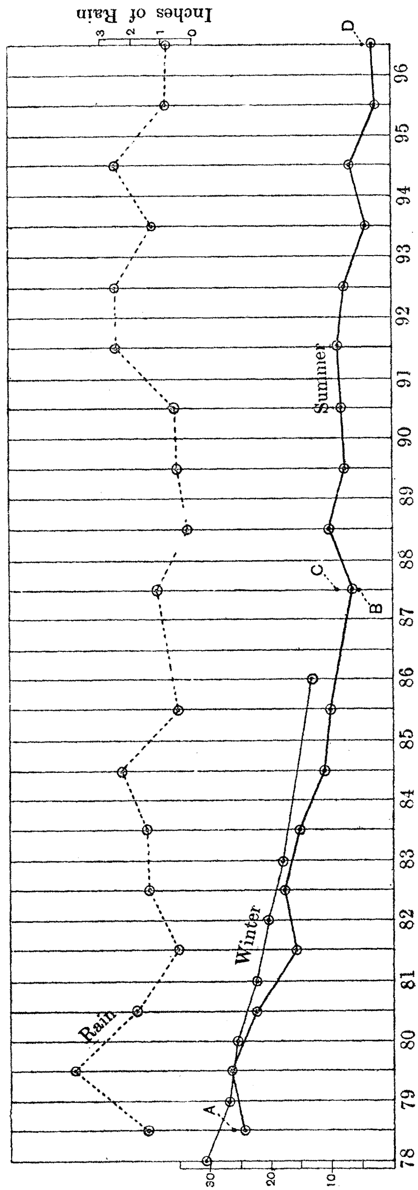
The ordinates are proportional to the amount of the rainfall, less the assumed amount which has evaporated or drained away; both quantities are calculated from February 19, the date of the beginning of the curve. The curves representing the dampness of the soil and the movement of the stone are 16 mm. apart on February 19, the beginning of the experiment, and the rate of drying has been assumed to be great enough to bring them again 16 mm. apart on October 9, at the end of the experiment.

The curves follow each other in a striking manner after May 18. On May 9 the stone-curve rises to a sharp peak when there was no corresponding rainfall, suggesting an error in reading the micrometer on that date; this is the most probable explanation. Mr. W. N. Shaw tells me that there was a thunderstorm on May 4 in the South and West of England with variation in the local rainfall; but this is unlikely to be the explanation, as the rainfall between May 1 and May 9 at Greenwich, 10½ miles distant, is the same as the Leaves Green, 1 mile distant. On April 6 there is again a discrepancy; the form of the curve does not on this date suggest an error in the micrometer reading, and no explanation is suggested.

The direct effect of artifically wetting the ground was tried on July 9, 1878. The ground was not dry, as there had been rain in the previous night. About one hour after the water had been poured on the ground near the stone it had risen 0·4 mm.; six hours later it had risen 0·1 mm. more.

Fig. 3 shows the permanent downward movement of the stone from

FIG. 3.



1878 to 1896. The curve is constructed from readings taken near the middle of January when the ground was free from frost. The points which correspond to these readings are surrounded by small circles and are joined by straight lines. The points are at equal distances apart

in a horizontal direction, and their vertical distance apart is 4/5 of the actual displacement of the stone, the numbers on the scale representing mms. This curve is marked "Winter." There were no winter readings after 1886. The Summer curve is made in a similar manner; the dates of the observations are more irregular: the corresponding points, however, are equally spaced in a horizontal direction.

The measurements from which the curve is constructed are as follows; the second column gives the position of the stone measured in mm. :—

	mm.		mm.		mm.
1878, Jan. 26	30·91...	July 7	24·50	1887, Aug. 21	6·50
1879, „ 3	26·92...	„ 10	26·34	1888, Sept. 20	10·34
1880, „ 11	25·59...	„ 12	22·24	1889, „ 17	7·53
1881, „ 9	22·28...	„ 29	15·84	1890, „ 24	8·16
1882, „ 9	20·42...	„ 10	17·61	1891, Aug. 6	8·90
1883, Apr. 3	17·82...	Aug. 1	15·27	1892, Sept. 6	7·72
1884, no winter reading.	...	Sept. 14	11·38	1893, Aug. 2	4·03
1885, „ „	...	July 19	11·02	1894, Aug. 24	6·86
1886, Mar. 1	13·13...	No summer reading.		1895, Sept. 17	2·50
				1896, Aug. 2	3·14

The stone was accidentally removed and no readings were taken after 1896.

If we take the winter readings, we find that the stone sank 17·8 mm. in the eight years from January 1878 to March 1886, or at the average rate of 2·22 mm. per year, rather less than 1 inch in ten years. My father found* that small objects left on the surface of a field were buried 2·2 inches in ten years. This result is obtained from observations in a field near the stone. The large stone sank more slowly, a result we should expect.

The curve shows that the rate of sinking was greater at the beginning than at the end; this is probably due to the decaying of the grass; the turf was not removed, the stone resting directly on it.

The third curve, marked "Rain" on this diagram, roughly indicates the dampness of the ground. The ordinates of the curve are proportional to the rainfall at Greenwich Observatory during the twenty days before the date of the summer reading. The curve is only a very rough indication of the dampness of the soil, as no account is taken of the rainfall for a longer period than twenty days before the observation, and neither is the evaporation during this period allowed for. The rainfall at Down also is assumed to be the same as at Greenwich, although they are $10\frac{1}{2}$ miles apart, and Down is 569 ft. above Ordnance datum, and Greenwich is 155.

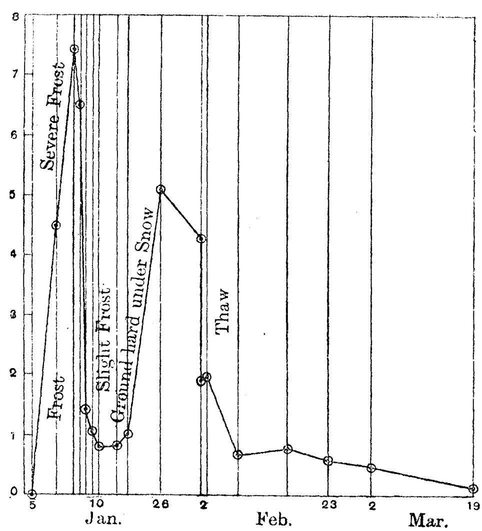
The summer curve is far more irregular than the winter curve; this

* 'Vegetable Mould,' 1883, p. 142.

no doubt is due to the greater variation in the dampness of the soil in summer than in winter. The rain-curve and stone-curve roughly follow each other. In 1888, however, the stone rises and the rain-curve shows very little rain for the twenty days before September 20, the date of this observation. During June, July, and August a great amount of rain fell; and although there was very little rain from September 1 to 20, the ground was probably damper than the rain-curve indicates. At Hayes, $3\frac{1}{2}$ miles from Down, the rainfall on these days was greater than at Greenwich, but still very small.

If the points marked A and B are joined by a straight line, it will roughly represent the mean movement during the first nine years of the experiment. These points were selected so that the line joining them appeared to represent the mean movement to the best of my judgment. In the same manner the points C and D were selected, so that the line joining them represented the mean movement of the last nine years of the experiment. The movements deduced by this method are 2·3 mm. per year for the first nine years, and 0·36 mm. the last nine years. The slow movements for the latter period are surprising. The movement given above and obtained from the winter curve is 2·22 mm. per year.

FIG. 4.



During the last five years the rainfall on the twenty days before each observation was distinctly above the average; it was 2·09 inches, and the average for these twenty days during the whole experiment is

1·54 inches. This will perhaps partially explain the slow movement at the end of the experiment.

The curve, Fig. 4, shows the movement due to frost. It is constructed as before, and the ordinates represent the position of the stone magnified 8 times. On February 2, at 12.45 P.M., the thaw was beginning, but the ground was still hard; readings were also taken at 3.25 P.M. and 5.25 P.M. The stone fell 2·37 mm. in 4 hours 40 minutes.

May 9, 1901.

Meeting for Discussion.

Sir WILLIAM HUGGINS, K.C.B., D.C.L., President, in the Chair.

A List of the Presents received was laid on the table, and thanks ordered for them.

Professor Franz von Leydig was balloted for and elected a Foreign Member of the Society.

The President stated from the Chair that the meeting was convened in pursuance of the following resolution of the Council, passed at their meeting on February 21, viz.:—"That a special meeting of the Fellows be called in order that the President and Council may have an opportunity of hearing the views of the Fellows on the questions raised in the Report of the British Academy Committee, it being understood that no vote will be taken."

The Report under reference was laid before the meeting, and a discussion ensued, in which the following Fellows took part:—Sir Norman Lockyer, Dr. Johnstone Stoney, Professor A. R. Forsyth, Professor S. P. Thompson, Professor E. Ray Lankester, Sir John Evans, Professor A. Schuster, the Right Hon. J. Bryce, Professor J. D. Everett, Sir Henry Howorth, Sir A. Geikie, Dr. J. H. Gladstone, and Mr. G. J. Burch.

FIG. 1.