VII. *Magnetical Observations in the Britannia and Conway Tubular Iron Bridges.*

By Sir George Biddell Airy, *K.C.B., P.R.S., Astronomer Royal.*

Received October 12,—Read December 19, 1872.

It occurred to me some time since that it would be matter of interest to examine the character of the magnetic action of the iron in the Britannia and Conway Tubular Iron Bridges upon a magnetic needle within the tube. This was suggested to me by consideration, not so much of the mass and extent of the iron structure (although both, in the Britannia Bridge, are very great) as of the peculiar state of tremor to which the iron is continually subjected. After remarking, when within the tube of the Britannia Bridge, the disturbance of the iron produced by a passing train, my hand being firmly pressed against the iron wall, I described to the late Robert Stephenson my impression that the particles of the metal were in a state of "molecular shiver," and he replied that those words exactly represented his own idea on the agitation of the iron. All experiments appear to show that iron, in this state of tremor, is peculiarly subject to the inductive action of external magnetic force. When to this is added the consideration that the tubes have been unmoved in position, and that they have been subjected to this disturbance many times every day since their erection, it seems reasonable to conclude that they will exhibit the greatest amount of induced magnetism which it is possible for malleable iron to receive. I know not how far this susceptibility to magnetic action may depend on the quality of the iron; but I think it proper to state, on the authority of Mr. Edwin Clark, that the iron was made chiefly in Staffordshire and Coalbrookdale, a smaller portion in Derbyshire, and that it was the ordinary "best-best" plates of the day, and intended to be scrap-iron throughout.

My friend Mr. James Carpenter (then Assistant in the Royal Observatory) entered warmly into my views, and at my request undertook the conduct of the requisite observations; and I detached him for a few days (at my own pecuniary expense) from his duties at the Royal Observatory. Captain G. L. Tupman, R.M.A., who was at the time preparing himself in the use of instruments for observation of the Transit of Venus, gave his friendly assistance; and I am confident that the work undertaken by these gentlemen was executed with the greatest care and accuracy throughout.

On my explaining my wishes to S. Reay, Esq., Secretary of the London and North-Western Railway, I was quickly informed that the Directors of the Railway had issued instructions that every assistance should be given by their officers; and I was specially referred to J. O. Binger, Esq., District Superintendent at Chester, and Hedworth Lee, Esq., District Engineer at Holyhead. The observers, on their journey to Bangor, had interviews with these gentlemen, and with Mr. MacGuire and Mr. Macmillan, and explained fully the nature of the assistance which would be most useful to them. It was speedily arranged that the observers should be put in charge of Mr. FLETCHER, foreman of the painters of the iron tube. It appears that it is necessary to give continual attention to the painting of the iron; and the men employed for this purpose acquire a knowledge of the details of the structure and a facility of moving about all parts which are not possessed by any other persons on the railway. The selection of Mr. FLETCHER to communicate immediately with the observers was therefore eminently judicious, and was attended with the best possible effect. Four of his men were in constant attendance on the observers, within the tube; and to their faithful and zealous attention the success of the enterprise is mainly due. Policemen were stationed near the ends of the tube, and signalmen in proper positions, to give timely notice of the approach of trains; and every person connected with the railway was evidently anxious to do his best to aid the party. I cannot too strongly express our obligations to the company and officers of the London and North-Western Railway for their cordial assistance in every part of the experiment.

It was obviously unnecessary to examine the magnetic circumstances in proximity to the iron plates (a condition which may be obtained anywhere), and I therefore determined on making observations solely in the very axis of each tube, as nearly as possible at the centre of its height and the centre of its breadth. The selection of points of observation, as regards the ordinate longitudinal to the tubes, was determined by their structure. The tubes and the land from which they start on both sides of the Menai Strait are more than 100 feet above the level of the sea, and from the brow on each side, from which the tubes start, there is a sloping bank to the water's edge. At the foot of the bank on each side a tower is built; there is also a central tower on the Britannia Rock, in the middle of the strait. Thus each tube consists of four parts having five supports, called respectively The Carnarvon Abutment, The Carnarvon Land Tower, The Britannia Tower, The Anglesey Land Tower, and The Anglesey Abutment. The lengths of the four parts are nearly 90, 170, 170, and 80 yards. The four portions of each tube were built and raised independently, the ends of each being strengthened with iron frames, for sustaining the strains which are incidental to the supporting ends of a tube; but, after they were raised, the abutting ends were connected very strongly by riveted iron plates similar to those in other parts of the tube, and so arranged (by driving the rivets when the distant end of one of the tubes under the uniting process was somewhat raised) that there is a very strong tension in the upper part of the tube, at the place of junction, assisting to support the portions intermediate between two of the towers. The whole bridge consists, therefore, of two tubes, each entire from the Carnarvon Abutment to the Anglesey Abutment, but having greater quantities of iron at the ends and also on each of the three intermediate towers. It appeared to me, therefore, proper that observations should be taken at each of the five points of support (those at the two terminations being carefully taken in the transversal plane of the end of the iron work), and also in the middle of the length of each of the four partial tubes, making in all nine stations for each of the long tubes.

Besides these, it was necessary to select stations, external to the Bridge but in the prolongation of its central line, at which normal observations should be taken, to which those taken within the tubes should be referred. Good stations were found about 700 yards from the Carnarvon Abutment and 600 yards from the Anglesey Abutment.

The circumstances of the Conway Bridge, consisting of only one tube 140 yards long for each line of rails, were much simpler. It was only necessary to make observations at the terminal towers, called the Chester Tower and the Holyhead Tower, and in the middle of the length, for each of the parallel tubes. An external station was found at 700 yards distance from the Chester Tower; but none could be found at a greater distance than 80 yards from the Holyhead Tower. I do not, however, imagine that the action of the iron bridge was in any degree sensible at this distance.

The positions of the tubes of the two bridges with respect to the Magnetic Meridian, and the places of the observing-stations, will be understood from the plans in Plate XVIII.

For support of the instruments in the observations, remarking that the tubes of the Britannia Bridge vary in depth, in their interior, from 22 to 26 feet, I constructed a large wooden step-ladder, 12 feet high, with a flat stage for instruments on the top, supported by two legs striding apart to the breadth of 8 feet (embracing the rails of the railway), which were duly connected with the ladder by cross bars. This structure was found to be very firm. The various parts were so united by screws that they could be easily separated; and the men who attended on the observers were practised in the mounting and dismounting of the ladder-stage, till it was found that they could entirely remove the instruments and stage in one minute of time. This command of the apparatus enabled the observers to make their observations with little disturbance from passing trains. For use in the tubes of the Conway Bridge, which are not so deep as those of the Britannia Bridge, the step-ladder was lowered. It was necessary, in most cases, to use the light of a lamp.

The magnetic observations to be made at all the stations were:—of the direction of total horizontal force, of the magnitude of total horizontal force, and of the magnitude of total vertical force. They were thus conducted:—

The direction of horizontal force was found by observing with a prismatic compass the apparent direction of the tube. From the land stations the direction of the tube's axis was observed without difficulty, and this was taken as the undisturbed or normal azimuth. In the tube stations the disturbed bearing of the end opening (when its centre could be well estimated), or that of a weighted rope hung from the top of the end frame, was observed. Six observations were made at each station. It is to be remarked that, with this instrument, apparent azimuths increase in the direction N.E.S.W., and therefore, in observing a fixed mark, an increase of reading implies that the needle has turned in the direction N.W.S.E.

The magnitude of horizontal force was found by use of a vibrating needle, the same which I used in the fundamental observations in the 'Rainbow' (Phil. Trans. 1839), and which was subsequently lent to Mr. RUNDELL and Staff-Captain EVANS for observations in the 'Great Eastern.' In consequence of the amount of vertical disturbance (to be mentioned hereafter), the needle was sometimes inclined to the horizontal plane so far as to render it necessary to raise the upper part of its case, but not so far as sensibly to change the time of its vibration. Three sets of vibrations, each set consisting of 20 vibrations, were usually observed. It is perhaps proper to remark that the actions of the magnetic bodies surrounding the needle were such that they did not produce a variation of force depending on the variable position of the needle in its arc of vibration, and thus the vibrations give a legitimate measure of the horizontal force.

The magnitude of vertical force was measured by use of a portable dip-instrument, Barrow 24, for the loan of which I am indebted to the courtesy of the Kew Committee. The dip-instrument is furnished with four needles, but only one (marked A 1) was used in these observations, and always with the pole B charged with red magnetism (not always dipping, as will be seen). Usually eight observations were made at each station, four being made by reversing the frame and reversing the needle-pivots on the frame, and four more by repeating that order. The poles were not reversed during the experiments, but they were reversed in some observations of dip at Greenwich. At Greenwich, before and after the experiments, and also at Bangor and Conway, the needle A_1 was compared with A_3. The results were not perfectly accordant, and did not enable me to judge with certainty whether the needle A_1 was sensibly out of balance; and I am inclined to believe that the dips at the experimental stations may be uncertain to the extent of 5′ or more. The dip was always observed in the plane of the apparent or disturbed magnetic meridian.

The first observation of the entire series was taken at Greenwich on 1872, July 31, and the last was taken at Greenwich on August 16.

I now proceed with tabular statements of the observations and their results. In explanation of the azimuths, it is to be remarked that from station 1 to 10 the observers advanced northward along the eastern tube of the Britannia Bridge, observing the apparent azimuth of the northern opening; and then from station 11 to 20 returned southward along the western tube, observing the apparent azimuth of the southern opening; to the latter series 180° will be applied in the following calculations. Similarly in the Conway Bridge, from station 24 to 27 the observers advanced westward along the northern tube; and by stations 28, 21, 22, 23 eastward along the southern tube: 180° will be applied to the latter.

No of Station.	Description of Station.	Apparent Azimuth.	Time of 20 vibrations.	Apparent Dip.
		° ′ ″	s	° ′ ″
1.	External Carnarvonshire Station	343 36 30	97·92	+69 38 49
2.	Carnarvon Abutment (E. tube)	362 4 10	60·43	+ 1 15 15
3.	Middle of Carnarvon Land Tube (E.)	366 41 40	106·20	+ 6 0 15
4.	Carnarvon Land Tower (E.)	361 4 10	115·60	+ 8 14 15
5.	Middle of Carnarvon Water Tube (E.)	361 58 20	108·37	− 2 55 38
6.	Britannia Tower (E.)	355 50 50	128·17	− 5 23 38
7.	Middle of Anglesey Water Tube (E.)	351 0 0	99·87	− 3 12 23
8.	Anglesey Land Tower (E.)	361 3 20	111·57	−15 19 0
9.	Middle of Anglesey Land Tube (E.)	353 36 40	112·23	+16 16 0
10.	Anglesey Abutment (E.)	352 50 0	66·77	+24 51 37
11.	External Anglesey Station	163 16 30	98·80	+69 33 23
12.	Anglesey Abutment (W. tube)	183 3 20	68·93	+27 27 30
13.	Middle of Anglesey Land Tube (W.)	178 58 20	124·30	+16 39 15
14.	Anglesey Land Tower (W.)	178 25 50	117·90	− 3 1 45
15.	Middle of Anglesey Water Tube (W.)	183 54 10	100·37	+ 0 49 15
16.	Britannia Tower (W.)	181 50 50	130·93	+ 3 20 30
17.	Middle of Carnarvon Water Tube (W.)	184 9 10	106·63	+ 1 19 45
18.	Carnarvon Land Tower (W.)	178 12 30	114·10	+ 9 17 45
19.	Middle of Carnarvon Land Tube (W.)	171 5 50	107·97	+15 11 15
20.	Carnarvon Abutment (W.)	171 13 20	62·33	− 4 4 0
21.	Holyhead Tower (S. tube)	169 58 20	126·07	+46 9 30
22.	Middle of Conway Bridge (S.)	31 0 0	173·10	+32 17 0
23.	Chester Tower (S.)	154 47 30	131·30	+35 11 7
24.	External Denbighshire Station	263 34 30	99·13	+69 9 30
25.	Chester Tower (N. tube)	323 10 0	142·60	+44 31 45
26.	Middle of Conway Bridge (N.)	215 47 30	171·17	+18 30 45
27.	Holyhead Tower (N.)	338 40 0	105·93	+38 30 30
28.	External Carnarvonshire Station	85 48 20	98·73	+69 0 38

It appears to me probable that the difference between the corresponding numbers at the two external stations of each bridge is purely accidental; the only difference deserving attention is that at Conway, and there, as appears to me, the action of the iron bridge cannot explain it. I have therefore adopted for each bridge the mean of the two observed numbers for each element at the external stations as the true normal number peculiar to that locality; and, as regards each pair of collateral stations in the two tubes of each bridge, I have thought it best to take the mean. Theoretically, it appears to me that the longitudinal action and the vertical action of each tube increase the longitudinal disturbance and the vertical disturbance in the other tube, but that the transversal horizontal action of one tube is scarcely sensible in the other tube; this view, however, is not borne out by the final results.

Taking the means, then, for the external stations as thus described, the numbers in the 3rd, 4th, and 5th columns of the following Table are obtained. Assuming, in the case of each bridge, the total normal horizontal force=1, the normal horizontal force longitudinal to the bridge will =cosine azimuth of axis of bridge, the normal horizontal force transversal to the bridge, towards the right, =sine azimuth, and the normal vertical force=tangent of dip. Thus the 6th, 7th, and 8th columns are formed.

Normal Local Elements.

Nos. of Stations.	Name of Bridge.	Apparent Azimuth of axis of tube.	Time of 20 vibrations.	Dip.	Longitudinal force.	Transversal force.	Vertical force.
		° ′ ″	s	° ′ ″			
1, 11.	Britannia	−16 33 30	98·36	69 35 41	+0·95850	+0·28500	+2·6882
24, 28.	Conway	−95 18 35	98·93	69 5 4	−0·09254	+0·99570	+2·6166

Proceeding now with the forces in the horizontal plane at each of the tube stations, the total horizontal force at each station is given by the formula

$$\left(\frac{\text{time of 20 vibrations in normal local elements}}{\text{time of 20 vibrations at the station}}\right)^2,$$

of which quantity the logarithm only is used; the longitudinal force at each station = horizontal force at station × cos disturbed azimuth, and the transversal force to the right = horizontal force at station × sine disturbed azimuth. The comparison of these with the longitudinal and transversal forces derived from the normal local elements gives the disturbances of magnetism in both directions at each station. Thus the following Table is formed:—

Forces in the Horizontal Plane at each Tube station.

Nos. of Stations.	Description of Stations.	Disturbed azimuth.	Logarithm of total horizontal force.	Longitudinal horizontal force.	Transversal horizontal force.	Longitudinal disturbance.	Transversal disturbance.
2, 20.	Carnarvon Abutment	− 3° 21′ 15″	0·40958	+2·5635	+0·1502	+1·6050	−0·1348
3, 19.	Middle of Carnarvon Land Tube...	− 1 7 15	9·92620	+0·8436	+0·0165	−0·1149	−0·2685
4, 18.	Carnarvon Land Tower	− 0 21 40	9·86538	+0·7335	+0·0046	−0·2250	−0·2804
5, 17.	Middle of Carnarvon Water Tube..	+ 3 3 45	9·92282	+0·8360	−0·0447	−0·1225	−0·3297
6, 16.	Britannia Tower	− 1 9 10	9·76076	+0·5763	+0·0116	−0·3822	−0·2734
7, 15.	Middle of Anglesey Water Tube...	− 2 32 55	9·98458	+0·9642	+0·0429	+0·0057	−0·2421
8, 14.	Anglesey Land Tower	− 0 15 25	9·86626	+0·7349	+0·0033	−0·2236	−0·2817
9, 13.	Middle of Anglesey Land Tube ...	− 3 42 30	9·84000	+0·6904	+0·0475	−0·2681	−0·2376
10, 12.	Anglesey Abutment	− 2 3 20	0·32254	+2·1002	+0·0754	+1·1417	−0·2096
23, 25.	Chester Tower	− 31 1 15	9·71754	+0·4472	+0·2689	+0·5397	−0·7268
22, 26.	Middle of Conway Bridge	−146 36 15	9·51892	−0·2758	+0·1818	−0·1832	−0·8139
21, 27.	Holyhead Tower	− 15 40 50	9·86174	+0·7003	+0·1966	+0·7928	−0·7991

The principles of the treatment of the vertical forces are similar. The vertical force at each station is found by the formula, total horizontal force at station × tan disturbed dip; and the vertical disturbance is the difference between this number and the vertical force in the first Table. Thus the following Table is formed:—

Vertical Force at each of the Tube stations.

Nos. of Stations.	Description of Stations.	Disturbed dip.	Vertical force.	Vertical disturbance.
2, 20.	Carnarvon Abutment	− 1° 24′ 22″	−0·0630	−2·7452
3, 19.	Middle of Carnarvon Land Tube ...	+10 35 45	+0·1578	−2·5244
4, 18.	Carnarvon Land Tower	+ 8 46 0	+0·1131	−2·5691
5, 17.	Middle of Carnarvon Water Tube ...	− 0 47 57	−0·0117	−2·6999
6, 16.	Britannia Tower	− 1 1 34	−0·0103	−2·6985
7, 15.	Middle of Anglesey Water Tube......	− 1 11 35	−0·0201	−2·7083
8, 14.	Anglesey Land Tower	− 9 10 22	−0·1187	−2·8069
9, 13.	Middle of Anglesey Land Tower......	+16 27 37	+0·2044	−2·4838
10, 12.	Anglesey Abutment	+26 9 34	+1·0322	−1·6560
23, 25.	Chester Tower	+39 51 26	+0·4357	−2·1809
22, 26.	Middle of Conway Bridge	+25 23 52	+0·1568	−2·4598
21, 27.	Holyhead Tower	+42 20 0	+0·6626	−1·9540

Finally, in order to obtain results which appear to possess more of a physical character, we shall assume that each of the disturbances (longitudinal, transversal, vertical) is produced simply by each of the normal forces (longitudinal, transversal, vertical); and we shall exhibit the proportion of the disturbance produced to the force which produces it.

$$\text{Values of the fraction } \frac{\text{Disturbance of magnetic force}}{\text{Normal force which produces it}}.$$

Description of Stations.	Fraction for longitudinal force.	Fraction for transversal force.	Fraction for vertical force.
Carnarvon Abutment	+1·6745	−0·4729	−1·0212
Middle of Carnarvon Land Tube	−0·1199	−0·9421	−0·9391
Carnarvon Land Tower	−0·2348	−0·9838	−0·9556
Middle of Carnarvon Water Tube	−0·1278	−1·1570	−1·0044
Britannia Tower	−0·3987	−0·9593	−1·0038
Middle of Anglesey Water Tube	+0·0059	−0·8494	−1·0075
Anglesey Land Tower	−0·2332	−0·9885	−1·0442
Middle of Anglesey Land Tube	−0·2797	−0·8335	−0·9240
Anglesey Abutment	+1·1911	−0·7355	−0·6160
Chester Tower	−5·8326	−0·7299	−0·8335
Middle of Conway Bridge	+1·9801	−0·8174	−0·9400
Holyhead Tower	−8·5674	−0·8026	−0·7468

The numbers in the third and fourth columns of this Table, including the Conway as well as the Britannia Bridge, present a good agreement. Their general result is this: that in the axis of a rectangular tube, at all parts except very near the ends, the action of external magnetic forces in planes normal to the axis is absolutely destroyed. In the second column for the Britannia Bridge there is one anomaly at Middle of Anglesey Water Tube of which I can give no explanation. It is a certain fact of observation; it may arise from some peculiar steely character of the iron in its neighbourhood. Putting this aside, the other numbers for the Britannia Bridge are exactly what we should have expected from a structure so closely resembling a bar magnet; the longitudinal force is greatly increased at the ends, but is diminished in all other points; not, however, as in the transversal forces, to its complete annihilation, but diminished by about one fourth part. For all these cases the circumstances of position of the bridge with respect to the magnetic meridian are favourable.

For the second column, as applying to the Conway Bridge, the position is unfavourable, the axis of the bridge being very nearly transversal to the magnetic meridian, and the denominator of the fraction consequently very small. Still, referring to the last Table but two, there can be no doubt that the character of the forces is such as we should have expected in a tube whose length is directed in the N.W. quadrant, instead of the S.W. I can give no accurate explanation of this phenomenon. It would almost seem that, even in a structure so simple and so rigorously rectangular as the bridge-tube, we cannot treat the effect of one of the rectangular forces as being strictly confined to that rectangular direction; yet I do not see how the transversal actions can explain longitudinal force in one direction rather than in the other.

It may be worth adding that, in the course of this discussion, I have conceived that possibly some difference of effects may have arisen from the difference in the direction of the iron planks of which different parts of the bridges are built; and to test this, I have had square plates constructed of narrow planks, riveted together like those of the bridges, the trials of which were thus conducted:—First, the square plate was placed on the equatoreal plane of a "Magnetic Anvil" and carefully hammered, and was then placed under a prismatic compass with which a distant object was viewed, with its planks directed at one time N.E. or S.W., and at another time N.W. or S.E.; it gave no sign of quadrantal deviation. Second, the plate was placed on the dip-plane and hammered with the same violence (as well as I could judge), with each of its four edges downwards in four different examinations, and after each hammering was placed under the compass, with the edge that had been lowest placed alternately E. and W.; the deviations produced were sensibly the same (at least I could not certainly answer for any difference), whether the sides of the planks had been horizontal or vertical during the hammering upon the dip-surface. Both experiments appear to show that none of the magnetic results in the bridge-experiments can depend on the direction of the iron planks.

I may, however, mention that in the horizontal structures forming the roof and floor of the bridge the planks are longitudinal, and that in the vertical side walls the planks are vertical.

Postscript.

Received October 22, 1872.

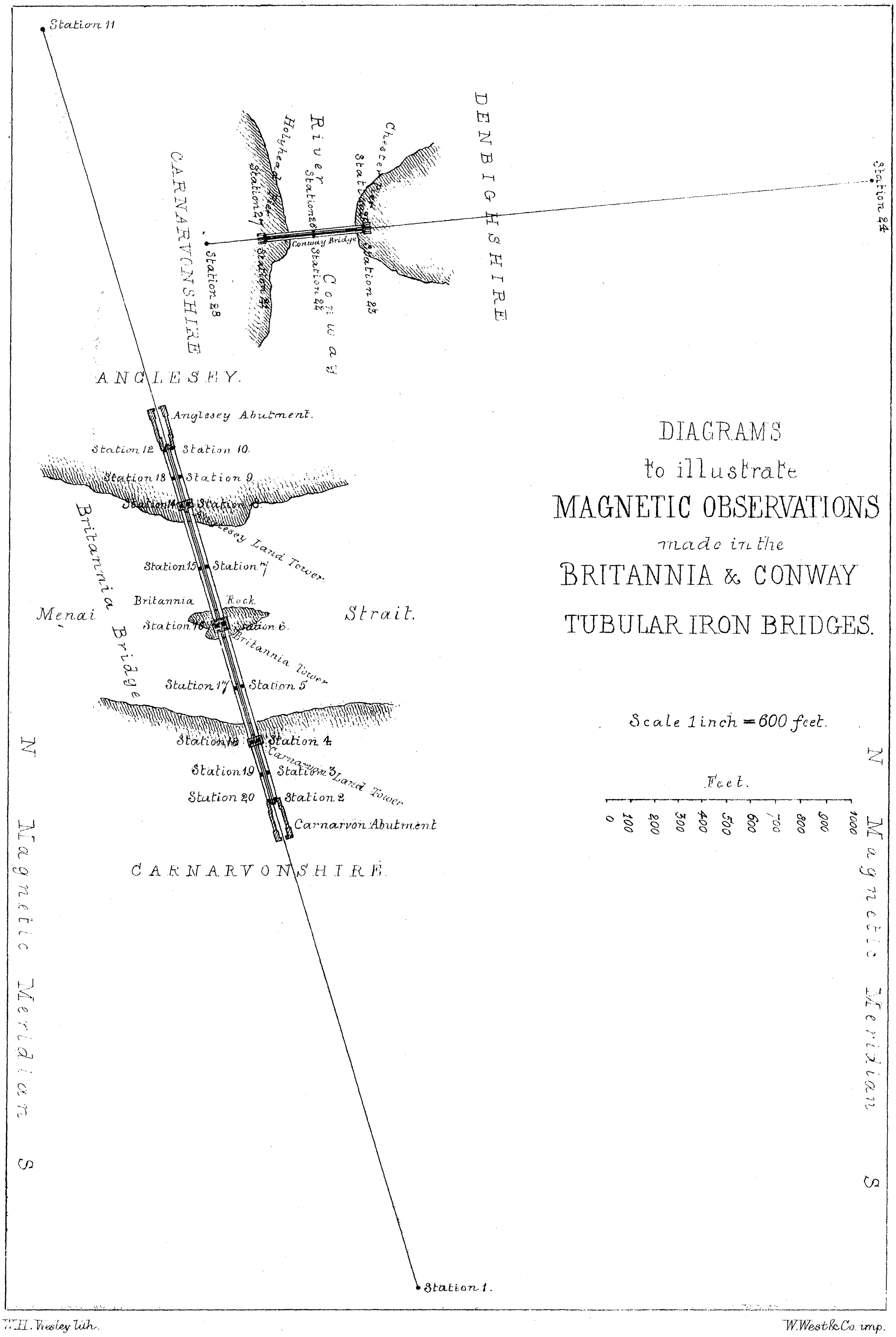
With the hope of obtaining some information which might explain the anomaly in the amount of longitudinal disturbance in the Anglesey Water Tubes, I inquired of Edwin Clark, Esq. (under whose immediate superintendence the Britannia and Conway Bridges were constructed) whether there was any thing peculiar in the iron material of those tubes. Mr. Clark informed me that there was no known difference in the iron; but he reminded me that the Eastern Anglesey Water Tube was the tube first raised, and that it was this tube which, in consequence of the bursting or rather longitudinal disruption of one of the cylinders of the hydrostatic press by which it was raised, suffered at one end a fall of 8 or 9 inches. The details of this accident are given in the work 'On the Britannia and Conway Tubular Bridges,' pages 690 &c. There is no doubt that the strain then sustained by the tube greatly exceeded any other strain to which it has been exposed. On referring to the first Table, it will be seen that the times of vibration are disturbed in both the Anglesey Water Tubes, slightly more so in the eastern than in the western tube. If, therefore, the magnetic longitudinal influence exhibited within the western tube was really affected by this accident, and to the supposed amount (a thing on which I have no doubt), it would seem that the longitudinal effect of the eastern tube is nearly as great at an external point (at a distance equal to that of the collateral tubes in this bridge, 27 feet centre to centre) as in the centre of that eastern tube—a law which it is impracticable to verify in this instance, but which I think is very probably correct.

Mr. Clark remarks, "It would indeed be extremely interesting if you discovered the effects of a fall that took place a quarter of a century ago by a magnetic experiment made now." I believe that this point has really been gained.

The tubes of the Britannia Bridge were built and riveted with their lengths very nearly in the magnetic E.–W. direction, in which state the terrestrial magnetism would have very little influence on them. It seems probable, therefore, that the magnetism which they now possess has been received entirely since their establishment on their piers.

With regard to the anomaly of the longitudinal forces in the Conway Bridge, I find that the tubes were built and riveted with the Holyhead end about 48° 50′ west of the magnetic N.; in this state the tubes would receive much longitudinal magnetism with the sign that is shown in our observations. Each tube was then mounted with its axis nearly magnetic E.–W.; and it appears that the forces subsequently acting upon it have not sensibly altered the longitudinal magnetism impressed on it during its construction.

1872, *October* 21.



W.H. Wesley lith. W. West & Co. imp.