THE FORTH BRIDGE.

By ARTHUR J. KNOWLES.

THERE are two rival railway routes to Scotland, both finally arriving at Perth. The London and North Western and Caledonian—owning what is known as the West Coast Route—run *viâ* Coatbridge, near Glasgow, while the Great Northern, North Eastern and North British—owning the East Coast Route—run *viâ* Edinburgh. The distance from London to Coatbridge or from London to Edinburgh is about the same by the two routes, and the East Coast possesses the better, because more level line. But, in consequence of the barrier of the Forth, the East Coast Route has to make a long *détour* to the west after passing Edinburgh, while the West Coast can run fairly straight from Coatbridge to Perth. In addition to this the East Coast run from Larbert to Perth over the West Coast line, and have to pay a heavy toll for the privilege of doing so. It will therefore be evident that it was a great object to the East Coast companies to get across the Forth as low down as possible, and since 1865 various schemes have been brought forward for doing this. The first Act for the construction of a bridge at Queensferry—the site of the present bridge—was obtained in 1873, but it was not till 1880 that any work was actually begun. In that year the construction of a suspension bridge designed by the late Sir Thomas Bouch was commenced, but the disastrous failure of the Tay Bridge, which had been designed by the same engineer, prevented this being proceeded with. Nothing daunted however, the East Coast companies instructed their engineers, Mr. (now Sir John) Fowler, Mr. Harrison and Mr. Barlow, to report on the practicability of crossing the Forth by a bridge or otherwise. The result of their deliberations was the recommendation of the present bridge, designed by Sir John Fowler and Mr. B. Baker, and in 1882 an Act of Parliament was obtained authorizing its construction. It was accordingly begun in January, 1883, and has thus taken just seven years to complete, a by no means extravagant time considering the size and novelty of the undertaking.

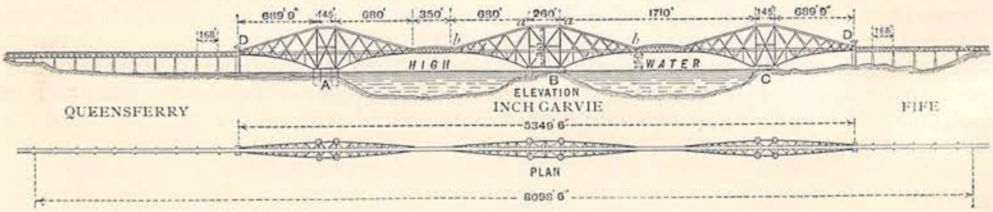
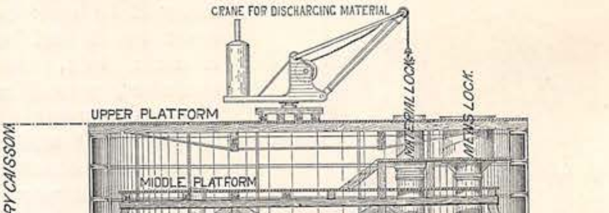


DIAGRAM OF PRINCIPAL DIMENSIONS.

The bridge consists of three main piers, A, B and C, formed of steel tubes well braced together, each main pier resting upon four masonry piers rising from the bed of the Forth. From each side of these three main piers there projects a "cantilever" or bracket, *a b*, jutting out over the water for a distance of 680 feet. A cantilever may be popularly defined as anything overhanging or projecting from its support, and a good illustration of one of the cantilevers of the bridge is furnished by an ordinary five-barred gate hanging by two hinges to the gate-post, and not resting on the ground anywhere, being held up only by the hinges. Imagine a gate 680 feet long, 340 feet deep at the end by the gate-post, and forty feet deep at the other end, fastened to a gate-post 360 feet high by two hinges, one at the top, and one at the bottom of the gate. The network of bracings crossing each other all along the cantilever would be represented by the bars of the gate, their object being to stiffen the frame so that it shall not drop down at the end away from the hinges. The bottom members of the cantilevers are steel tubes, twelve feet in diameter where they spring from the main piers, and gradually tapering, till at the outer ends they are only three feet square. The top members are box lattice girders tapering from twelve feet deep by seven feet wide, to five feet deep by three feet wide. All the intermediate bracings are composed of tubes or lattice girders according to their having to resist a pushing or a pulling force, so that one can see at a glance which parts are in compression and which in tension.

The cantilever on one side of the pier balances the one on the other side, and the ends, D D, of the Queensferry and Fife cantilevers nearest the shores, are held down to a massive masonry pier by a weight of about 1,000 tons, so that when a train is in the middle of the big span these shore cantilevers may be kept from lifting.

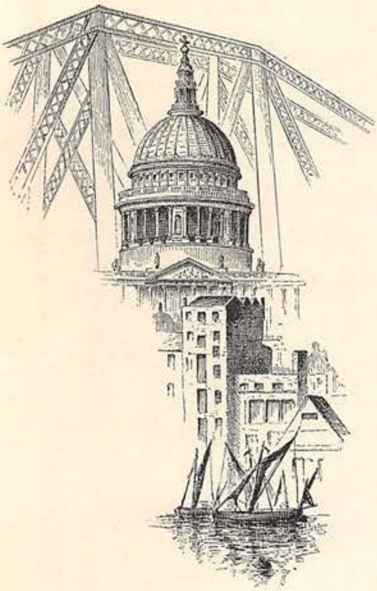
The distance between the main piers is 1,710 feet, but the cantilevers jutting out towards each other only cover 680 feet each—1,360 feet together, leaving a space of 350 feet between their ends. This is bridged across by an ordinary girder resting upon the ends of the cantilevers. It is called the central girder, and it may be as well to state that it fulfils no other purpose than to bridge across the gap between the cantilevers. Many people imagine that the bridge as it stood in September, 1889, was in a very insecure state, and that the insertion of the central girders bound it together like the keystone of an arch. This is not so, they are simply so much additional weight on the ends of the cantilevers, and the bridge was as secure then while being built as it is now when completed. This security while building is one great advantage of the cantilever type of bridge, especially in a stormy place like the Firth of Forth.



METHOD OF SINKING CAISSON.

The masonry piers on which the main steel piers rest are many of them situated in deep water, and had to be constructed by the pneumatic or compressed air process. A large iron cylinder—called a caisson—was built on shore, deep enough to reach from the bottom of the foundations to above high water level. This cylinder was seventy feet in diameter, and the lower edge was made sharp, so that when it rested on the bottom of the river it cut into the ground. Seven feet above the cutting edge there was an air-tight roof, forming a chamber at the bottom of the cylinder seventy feet in diameter and seven feet high, with no bottom to it. The cylinder was launched like a ship and towed out till it was exactly over the place on the bed of the river where it was to rest. It was then loaded with concrete so as to make it sink till the cutting edge rested on the ground. Air was now pumped into the chamber, with the effect of driving out the water. In order that this air might drive out the water from the chamber, it had necessarily to be able to overcome the force which was causing the water to come in. This force varied according to the depth of the chamber below the surface of the water and was due to the weight of a column of water of that depth, and the same diameter as the chamber, namely seventy feet. To overcome this force the pressure of the air had to be raised till it was equal to the pressure produced by this column of water, and so long as this pressure was kept up no water could get into the chamber. In sinking through clay, the water was kept out to a great extent by the clay pressing against the side of the caisson as it sank, none coming through the clay itself, and consequently less pressure was necessary than the depth of water would theoretically require. The greatest pressure used was thirty-three pounds on the square inch above the ordinary pressure of the atmosphere, equivalent to that produced by a column of water about seventy feet high. The mercury of a barometer placed in the chamber would then stand at about ninety inches. A curious illustration of the reality of this pressure was furnished unintentionally by a visitor who descended into the chamber. Having a flask in his pocket, he refreshed himself with a drink when in the chamber, corked his flask, and put it back into his pocket. On coming out of the chamber the flask suddenly exploded. It had been filled with air at a pressure of thirty pounds to the square inch, and when that pressure was removed from the outside of it by bringing it into the open air, and still remained within, the flask was not strong enough to stand it, and gave way.

The water having all been expelled, the workmen descended into the chamber and dug out the earth, or blasted the rock from under the edges of the caisson, so as to allow it to sink below the bed of the river. As soon as it had been sunk deep enough to give it a firm bed, the whole caisson, including the chamber, was filled up with concrete. This consists of cement and gravel mixed with water and is quite soft and fluid when put in, but soon turns as hard as stone, transforming the hollow cylinder into a solid mass of rock resting securely in the bottom of the river. On the top of this the granite pier was built to a height of eighteen feet above high water. The total weight resting on the ground below one of these piers is about 24,000 tons when most heavily loaded in a gale of wind. The area of the bottom of the caisson being about 3,850 square feet, the maximum pressure is only about six tons on a square foot.

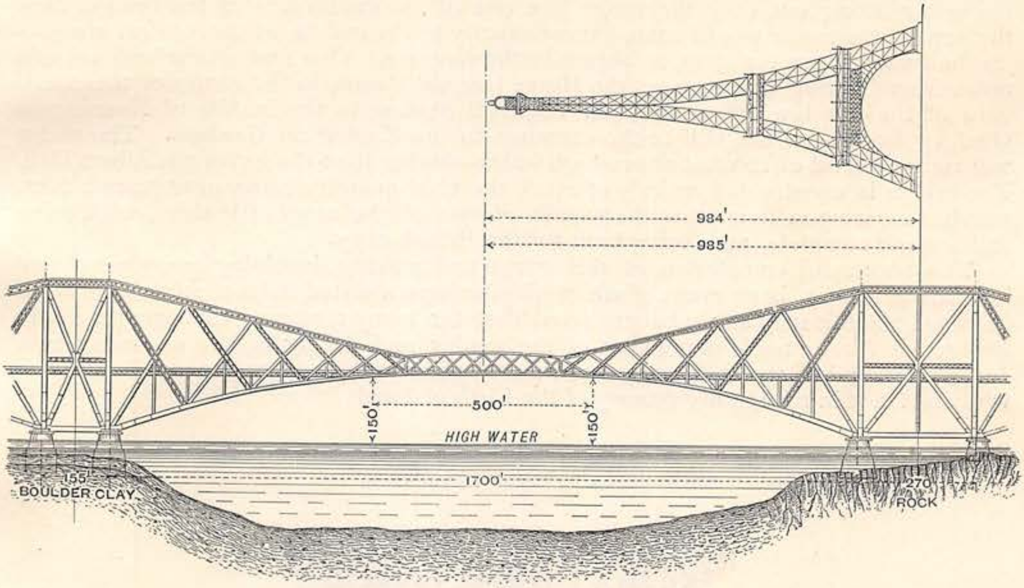


The foundations having been got in, the next proceeding was the erection of the three main piers. They were all three built in the same way, but the centre one—on the island of Inch Garvie—is the one described here. It is 260 feet long, and 360 feet high. Measured across it is very much wider at the bottom than at the top, the dimensions being 120 feet and thirty-three feet respectively. This broad base gives it great stability to resist the pressure of the wind. A good idea of the great height of these main piers is given by the accompanying sketch, showing one of them towering up behind St. Paul's Cathedral, the level of the ground corresponding to the level of high water at the bridge.

The lower part was erected in the ordinary way with cranes resting on the staging, but the work soon got beyond the reach of these. Then immense platforms were constructed, embracing the whole of the pier, and resting upon parts of the permanent work already built. A strong railing surrounded the platform, and upon it were placed cranes and other appliances for building and riveting, as well as hoists to raise men and material from the staging below. Then the erection went on above the platform as far as the cranes could reach. When this was done the whole platform was lifted by hydraulic rams and secured to the parts of the pier which had just been built, and then the cranes set to work again until they had done as much as they could reach, when another lift took place and so on till the platform reached the top of the pier. Just below the platform and surrounding each vertical column were large cages covered with wire netting. They contained riveting machines, and riveted the columns as they were built.

The main piers being completed, the next step was the building of the great cantilevers jutting out on each side of them. The method adopted for doing this was very striking on account of its simplicity and daring. Three movable steam cranes were used, one placed on the sloping top member of each cantilever, and two on the internal viaduct or railway. By means of these the material was lifted up from barges in the river below, and immediately put in place and bolted up. The cranes were then moved forward so as to rest on what they had just been building, and in this way the cantilevers were extended out over the water without any support from the ground beneath. This system of building out by "overhang" as it is called, had to be adopted on account of the great depth of water—about 200 feet—between the main piers, which rendered any kind of scaffolding out of the question. Platforms for the workmen to stand upon were hung from the various members of the cantilever as they were built out and moved forward with them.

The central girders are built in exactly the same way. They were temporarily tied back to the ends of the cantilevers and built simply as an extension of them till they met in the middle of the span. The two halves were then connected, and as soon as this was done the temporary connections with the cantilevers were severed, and the central girders left free to expand and contract. In all metal structures an allowance has to be made for their change of length under the influence of heat or cold. For instance, the rails between London and Edinburgh are at least 200 yards longer in summer than in winter, and to provide for this a small space is always left between the ends of the rails when they are laid down. In the large spans of the bridge allowance is made for an extreme movement of twenty-four inches, which is all to take place at one end of the central girder. At this end the girder hangs from a rocking pillar, to the top of which it is fastened. The effect of any change in the length of the central girder or the cantilevers is thus simply to push or pull the top of this pillar backwards or forwards, the bottom end resting in a ball-and-socket joint at the end of the cantilever. The connection also allows of movement sideways. This takes place when the sun is shining on one side of the cantilever. The side in the sun expands, while that in the shade does not, the result being that the cantilever bends away from the sun. A movement of over five inches from west to east was observed one sunny day last summer between the morning and the afternoon.



THE BRIDGE AND THE EIFFEL TOWER.

Another cause of sideway movement is wind, which is calculated to cause a deflection of rather under nine inches when blowing with a force of thirty pounds on the square foot.

The bridge is designed to carry trains of unlimited length on each line of rails weighing one ton per foot run, or trains on each line made up of two engines and tenders weighing in all 142 tons, at the head of a train of sixty short coal trucks weighing fifteen tons each. Also to resist a wind pressure of fifty-six pounds on the square foot over the whole surface, equivalent to about 8,000 tons.

It must not be supposed however that the imposition of loads a little greater than these would be sufficient to destroy the bridge, or that a wind blowing with a force of sixty pounds to the foot would blow it over. All engineering works are designed with a certain "factor of safety," or in other words are always made much stronger than is theoretically necessary. The factor of safety for the bridge is over four, that is to say, it is four times as strong as is necessary to carry the loads just mentioned, while to overturn it would require a wind pressure of four hundred-weight or 448 pounds to the square foot, which is eight times the maximum pressure for which the Board of Trade require allowance to be made.

Although it is quite impossible to convey by words or drawings any adequate idea of the size of the bridge, yet a comparison with some well known works and places may be of interest. The Eiffel Tower caused a good deal of interest last year and was ascended by a very large number of people. Suppose it placed in a horizontal instead of a vertical position, with its base in the centre of Inch Garvie main pier, and the tower jutting out over the water like one of the cantilevers of the bridge, then the top of the tower would come almost exactly to the middle of the central girder—just half-way across the span, as shown in the diagram. One span of the bridge would reach from Charing Cross across the Horse Guards' Parade to the centre of the courtyard of the Foreign Office, or from Vauxhall Station to the middle of Kennington Oval, or from Primrose Hill to the entrance to the Zoological Gardens. The trains will run at a level of 160 feet above high water—higher than the top of the Albert Hall. The bridge is constructed entirely of steel, the total quantity being over 50,000 tons, which is close upon four times the weight of one of the new battle ships, with guns and armour complete, now being built for the British navy.

The successful completion of this great undertaking, involving many novel and intricate problems, is an event of which all who have assisted in its execution may well be proud; and it may safely be predicted that for many centuries to come the Forth Bridge will form a noble monument of the genius and daring of the engineers who designed it, and of the skill, perseverance and pluck of the contractors and workmen who erected it in the stormy estuary of the Firth of Forth.