Zeitschrift: IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht

Band: 2 (1936)

Artikel: The constructioin of the Kincardine-on-Forth bridge

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DOI: https://doi.org/10.5169/seals-3221

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The Construction of the Kincardine-on-Forth Bridge.

Der Bau der Kincardine-on-Forth Brücke.

La construction du pont Kincardine-on-Forth.

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Special Note on the Mechanical Part of the Swing Bridge Span.
Bemerkungen über den mechanischen Teil der Drehbrücke.
Remarques sur la partie mécanique du pont tournant.

J. G. Brown,
M. Inst. C. E.

Introduction.

The Kincardine-on-Forth Bridge has been constructed with the dual purpose of improving road transport facilities in Scotland and of relieving unemployment in the districts near the site of the bridge.

The initial promotion of the scheme was carried through in 1931 by a Joint Bridge Committee formed by the County Councils of Fife, Clackmannan and Stirling, and the Borough Counsils of the towns of Dunfermline and Falkirk.

The Joint Bridge Committee appointed Sir Alexander Gibb & Partners as their Technical Advisers and Consulting Engineers.

The Bridge was designed and tenders were called for and a firm of Contractors were selected. This firm, The Cleveland Bridge & Engineering Company, Limited, of Darlington, commenced work at the beginning of January 1934.

A grant of financial assistance was obtained from the Ministry of Transport, from the Road Fund, to the extent of 75 % of the total cost of the scheme, the remainder being contributed by the above Local Authorities.

Selection of Site.

The choice of Kincardine as a site for a crossing of the Firth of Forth is a natural one. The banks of the river draw together at this point to form the second narrows in the river above the famous Forth Railway Bridge, which lies 13 miles to the East at Queensferry, the site of what may be called the first narrows.

Kincardine lies 10 miles downstream and East of Stirling, whose castle has guarded the route to the towns of the North East, Perth, Dundee, Aberdeen and

Inverness, from historical times and whose bridge is the most Easterly road crossing of the Forth at present.

The new bridge will, therefore, provide a shorter alternative route to these towns, will correct the present tendency to congestion of traffic through the town of Stirling and, in addition, will provide a much shorter direct road access between the industrial area of Glasgow and the comparatively isolated peninsular of East Fife, which lies between the encircling pincer-like arms of the sea formed by the Firth of Forth on the South and the Firth of Tay on the North.

It will also compete to a considerable degree with the half-hourly vehicle ferry at Queensferry, by affording an alternative crossing 20 miles nearer to Edinburgh than the existing alternative route through Stirling.

This ferry is the vital link connecting Edinburgh with the main highways leading to the North of Scotland.

To complete the case for a bridge at Kincardine, it is only necessary to add that it will cost almost exactly one tenth of the estimated cost of a recently proposed road bridge at the first narrows site near the great railway bridge at Queensferry.

Conditions affecting the Design.

The passage of sea-going ships to and from the port of Alloa, which lies 4 miles above the bridge, has necessitated the provision of a very large opening span, and the interests of less important river traffic have demanded a head room in the centre of the bridge of 30 feet above high water.

Consequently, the roadway to the bridge rises from the comparatively low lying ground on either bank in a vertical curve which has its highest point at the centre of the Swing Span.

On the South shore the ground is so low the river bank is not very clearly defined.

The river, which is tidal with a range of 18 feet, is 3,000 fest wide at periods of extreme high water, when the flats on the South shore are covered to a depth of one or two feet, but at ordinary high water periods the flats or "saltings" which are covered with coarse grass, are dry and the width of the river is then about 1,800 feet.

This additional 1,200 feet width of "saltings" is in fact a bank of silt some 50 feet deep which has been deposited on the gravels and clays of the river bed and its existence has meant that a considerable length of approach structure has had to be provided.

An approach embankment covers a little more than 500 feet of the "saltings" but owing to the rising curve of the bridge profile, and the impossibility of placing a high embankment on such soft ground, foundations for a crossing of the remainder of the "saltings" have had to be sought at a greater depth and the bridge structure proper commences here, about 700 feet from normal high water mark.

On the North shore the bridge is extended beyond the high water line in order to cross the London & North Eastern Railway which runs close beside the shore.

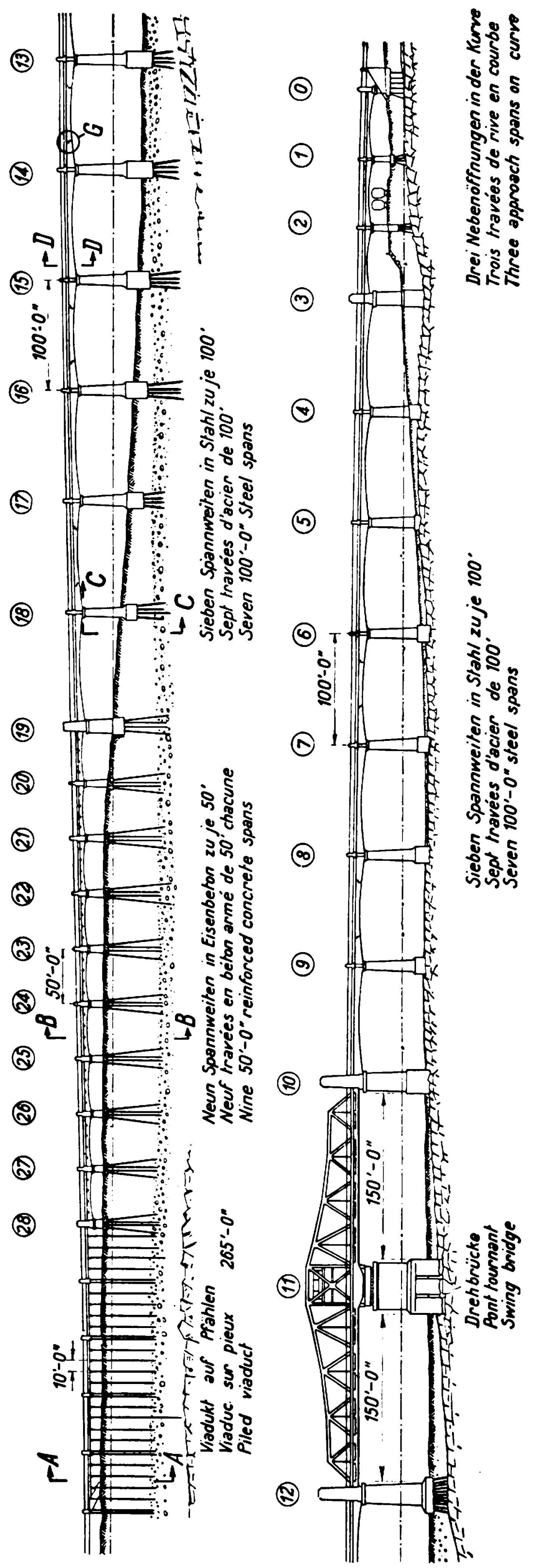


Fig. 1.

These additional lengths of bridge at either bank make the complete distance between abutments 2,692 feet.

The geology of the site is interesting. It provides excellent foundations on the sandstone rock of the Carboniferous period at no great depth. But this is only the case over half the width of the river from the North bank, until the pier of the Swing Span is reached. From there Southwards, the level of the sandstone drops away to increasing depths and one of the original trial borings, made at about the middle of the "saltings", failed to find rock at a depth of 45 feet below the average level at which it is found on the North side of the river.

There are evidences of an important geological fault on the centre line of the river and also of the existence of the old preglacial river valley, supposed by some to be of great depth. Either or both of these suppositions may explain the change in the rock level.

Whatever the cause of this sudden dip of rock, its result is that the Southern half of the bridge has had to find foundations above the rock level.

This problem was greatly simplified by the presence of a bed of hard bound gravel, which was disclosed by the trial borings during the initial survey and which by its extent and its level suggests that it formed the river bed at some comparatively recent period — (geologically speaking) — and has been buried in silt since then. Below this gravel and above the rock are clays containing boulders and stones.

General description of the bridge and approaches.

The bridge, as can be seen from the accompanying illustrations, is a multiple span structure employing a large variety of types of construction.

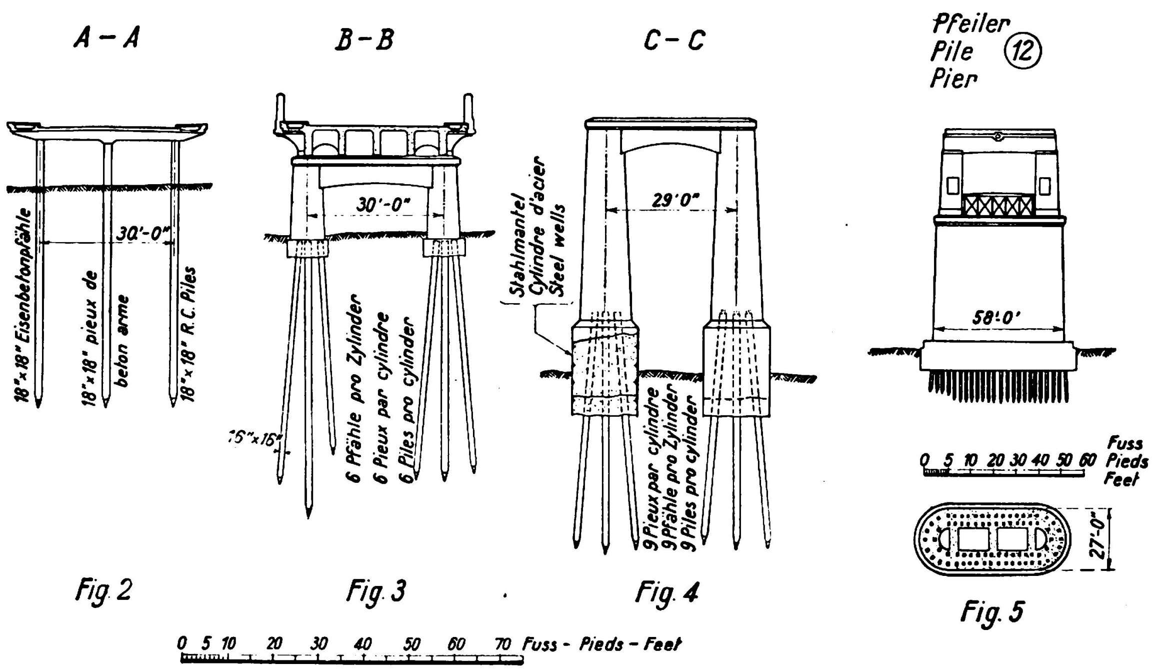


Fig. 2 Fig. 3 Fig. 4 Fig. 5

It carries a 30 feet wide carriageway and two 5 feet wide footpaths.

At its centre is the large Swing Span which constitutes its most interesting feature and this is flanked on either side by a symmetrical arrangement of 14 steel spans of 100 feet, seven on each side. These spans may be described as the main steel bridge which covers the normal width of the river.

On the South side a considerable length of reinforced concrete approach structure is made necessary by the presence of the "saltings" described above.

This approach structure consists of 9 spans of 50 feet each, and 260 feet of viaduct carried on bents of piles at 10 feet centres.

On the North side 3 approach spans are necessary to cross the railway and these are steel spans of 62'6" each and are placed on a curve in plan in order to allow the approach road and embankment to take the most economical line through the town of Kincardine.

Foundations and piers.

In describing the structure of the bridge in detail the Swing Span and its three piers will be treated separately as they form the most important and interesting features of the bridge. The remainder of the structure divides itself into five parts, namely: —

1) The Approach Spans and Piers on the North Side.
2) The 100 feet steel Spans and their Supporting Piers on the North Side.
3) The corresponding section of 100 feet Steel Spans on the South Side.
4) The Reinforced Concrete 50 feet Spans on the South Side.
5) The Reinforced Concrete Approach Viaduct on the South Side.

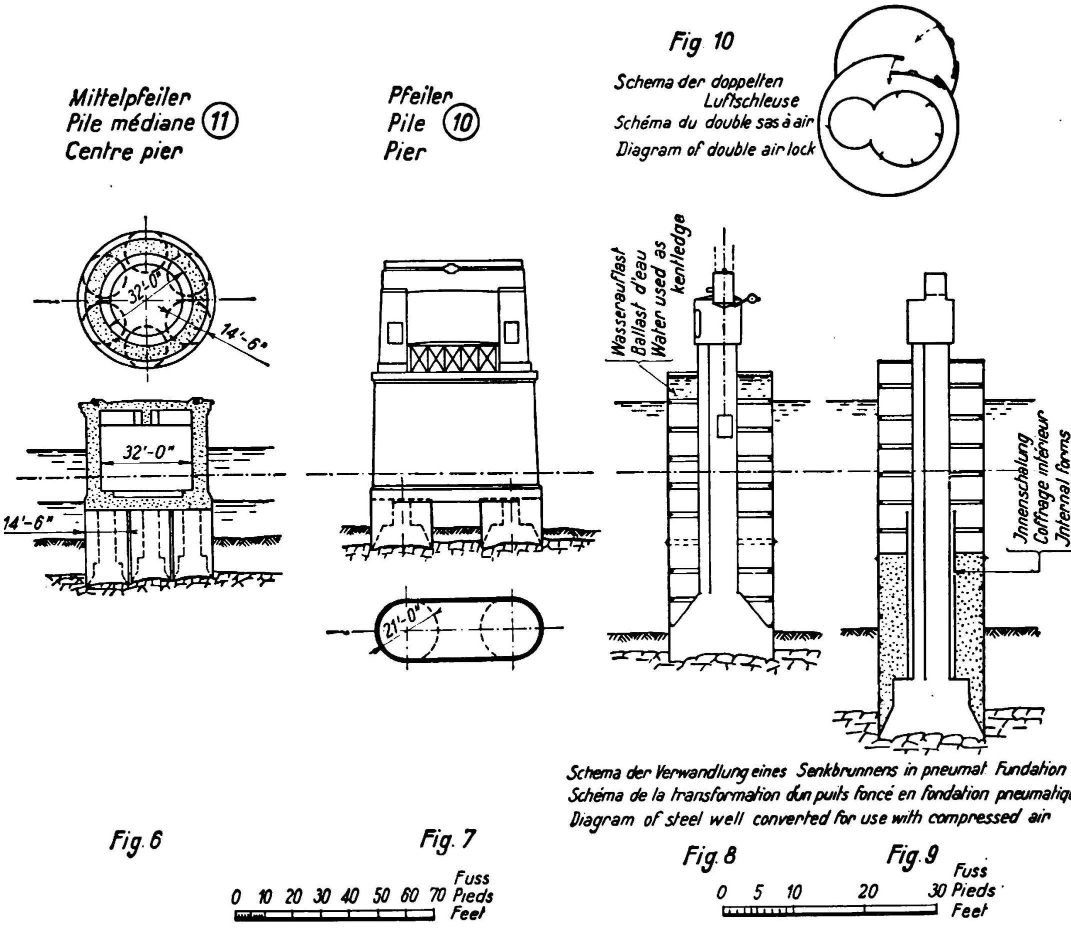
The section will be descrribed in numerical order and the methods of construction will be described at the same time in order to avoid repetition.

1) The three steel approach spans at the North end of the bridge rest upon the Abutment, Piers Nos. 1 and 2, and Pier No. 3. The Abutment and its wing walls is a mass concrete structure supported upon a piled foundation, consisting of 36 reinforced concrete piles 16"×16" in section and 20 feet long, which were driven down on to the rock. Piers Nos. 1 and 2 are similar mass concrete piers, rectangular in plan and supported on 20 piles each, similar to the Abutment. The methods of construction are without special interest. The piles were driven to refusal and, therefore, no special final set per blow was required.

2) The seven 100 feet steel spans are supported by Piers Nos. 3 to 10. Pier No. 3 is a special pier with dimensions made larger than the normal pier in order to accommodate an architectural feature in the form of a pylon on either side oft the bridge, marking the commencement of the bridge proper. It consists of two very wide tapered columns, circular in plan and joined at their heads by a heavy reinforced concrete cross beam. It was founded in the open in the same way as the other piers on solid rock.

Piers Nos. 4 to 9 are all similar piers which stand on twin cylindrical bases 14'6" in diameter (Fig. 4). The bases end just below low water and the piers rise from that level in the form of two tapered columns, having a diameter of 8 feet at their heads where they are tied together by a reinforced concrete beam 4'6" wide and heavily reinforced to form a monolithic portal with the columns. The columns themselves have an external skin 9" thick of rich concrete of 1:1:2 proportions in which is embedded a moderate amount of vertical and circumferential steel reinforcement, the vertical steel being carried down into the base. Within the 9" skin is a core of 1:3:6 concrete (Fig. 4).

Piers Nos. 3, 4 and 5 were founded on rock within open wells. These wells were built up of cylinders 14'6" in diameter and about 4' high, made of 5/16" steel plate stiffened with angle rings and were lowered on to the river bed and reached above high water level. Enough of these cylinders were supplied to allow work to be done at two piers simultaneously. They were sunk until the cutting edge, formed by a heavy doubling plate, reached rock by excavating inside the wells with a grab. The water inside the wells was pumped out and the rock surface excavated by labourers working inside the wells until a firm level bed of sound rock was obtained. The wells were then filled solid with concrete up to low water level to form the two base cylinders. Steel forms were placed on the base concrete and the construction of the tapered columns continued until the work was brought up above high water level. The upper portion of the wells above the section filled with solid concrete were then removed by breaking a bolted joint and used again on another pier. The removal of the bolts had to be done by a diver working at slack water periods.



This method worked well on Piers Nos. 3, 4 and 5, but as the work got further out into the river the depth of the soft material overlying rock decreased until it reached a minimum of only 2 feet. At Pier No. 6 where it is about 5 feet deep, it was found that the material was not sufficiently stable and impervious to prevent the hydrostatic pressure outside the well, when it was pumped dry, from forcing the water through the ground and under the cutting edge and so flooding the well. Accordingly the necessary plant was brought to the site to enable the remainder of the piers to be completed by the method of compressed air caisson.

This method resulted in rapid and consistent progress being made and enabled careful inspection and perfection of the foundations to be carried out before concrete was placed.

The wells already described were adapted to take an access shaft carrying a double air lock at its top, by the provision of a substantial cone-shaped plate which formed the roof of the working chamber and reduced in diameter from that of the well at its bottom to that of the access shaft at its top. The double lock consisted of a vertical lock for materials and a horizontal lock for men (Fig. 8 and 10).

The portion of the well above the cone plate was filled with water to a level above that of the river outside in order to provide sufficient kentledge to prevent the well floating.

For purposes of economy the cone shaped adaptor plate was removed from each well and transferred to another, only two such plates being provided. In order to do this it was necessary to remove the water kentledge and supply about 200 tons of solid kentledge in its place, until the concrete filling inside was heavy enough to overcome any possible uplift on the well.

The first layer of concrete was, of course, placed on the rock while the well was still under compressed air, 3 or 4 bent pipes were passed under the cutting edge and brought up inside to a height above the top surface of the first lift of concrete. This prevented any possibility of the air blowing through the concrete during deposition and causing porous channels and leaks. After the concrete hat set, these pipes were closed with screwed caps, the pressure was taken off the well, the cone plate, access shaft and air lock were removed and the construction of the columns proceeded with as in an "open" well.

3) Piers Nos. 10, 11 and 12 are the large piers specially provided for the Swing Span and will be described later. Piers Nos. 13 to 18 are the same as Piers Nos. 4 to 9, described above, but they are not founded on rock as are the latter. They are founded on the gravel bed which stretches under the bank of silt which forms the South shore of the river. The foundation consists of 18 piles, 9 in each cylinder, 4 of which are driven vertical and 5 of which are driven to a slight batter of 1 in 12, 3 at right angles to the centre line of the bridge and 2 in line with it. Pier No. 19 is the same as Pier No. 3, except for its foundations which are similar to those of Piers Nos. 13 to 18.

These piles are 18" $\times$ 18" square in section and vary from 45' to 65' in length, but the great majority of them were made 55' long. They have cast iron points and are reinforced with four $1^1/_2$" diameter rods in one continuous length bound by 3/16" stirrups at 9" spacing. This spacing is reduced at the head and the point to strengthen the pile against bursting.

The sequence of operations with these piers was to sink the wells, which were the same as those described above, to a depth of 10 feet below the surface of the river bed by excavating with a grab and then to drive the piles inside the well.

Excavation in some of these cylinders was delayed by the difficulty experienced in penetrating the gravel owing to the pressure of large boulders and stones. The driving of the piles was done from a travelling frame which could both turn and travel on a steel gantry over the wells. A single acting steam hammer, the moving part of which weighed 5 tons, was used.

The piles were driven until the penetration under six blows of the hammer was less than 1". The fall of the hammer was altered to suit the length of the pile. For a 65" pile it was 4'3" and for a 55' pile it was 3'9".

As a general rule the piles began to drive easily and came against the hard stratum fairly suddenly and then could be driven very little further. At the few places where the piles penetrated the hard stratum a period of steady driving followed, gradually becoming more difficult until the required resistance was reached.

The heads of the piles were protected during driving by a helmet of cast steel which was packed with paper or sacking. The hammer struck on a hard timber dolly about 24" high, fitted into the top of the helmet.

During the driving of piles within the wells near the middle of the river it was necessary to lower the level of the water inside the cylinder below that outside, by pumping and to rely on the seal, provided by the 10 feet of material into which the well was sunk, to resist the resulting external hydrostatic pressure.

By the provision of a sluice valve in the cylinder below low water level it was possible to limit the time that the cylinder was under pressure to the minimum necessary to allow the piles to be driven and disconnected from the guides of the pile frame. This latter operation could only be performed when the water was 5 feet below the head of the pile.

The greatest pressure to which these wells were subjected during the course of the work was that due to a head of 15 feet.

When pile driving was completed a plug of concrete about 3 to 4 feet in height was deposited in the bottom of the well, through water, using special buckets with hinged bottoms which opened to discharge the concrete as soon as they were hoisted after being lowered on to the bottom, according to the Panchard system.

When this plug had been given time to set the well was pumped dry and men went down and cleaned off the slurry of cement and mud which covered the top surface of the plug to the depth of about 12", until firm material was uncovered. Concrete was then deposited as for the other piers, the piles being roughened to give the concrete a strong grip and finally cut off at a level which allowed them to protrude 3 feet into the tapered columns (Fig. 4).

A description of these piers would not be complete without mention being made of the riveted steel forms used in their construction. These forms consisted solely of a steel skin fitting the surface of the concrete of the tapered columns and the arched cross beams, which was sufficiently stiffened by angle sections to support the weight of the wet concrete without outside support. They were comparatively light and rigid and the various pieces were bolted together by means of flanged joints and they could be erected and dismantled easily and quickly without the necessity of employing tradesmen.

On the other parts of the work welding was used instead of rivets which had the advantage of still lighter construction and left no marks of counter-sunk rivet heads in the concrete (Fig. 21).

4) The nine 50 feet spans of reinforced concrete are carried on piers similar in every way to those above described, but of smaller dimensions (Fig. 3). The diameter of the tapered columns being 6 feet instead of 8 feet. They are supported on 6 piles per column instead of 9, and the piles were 16" × 16" in section instead of 18" × 18". The penetration obtained was greater, but this was due merely to the increasing depth of the overlying silt as the bank of the river rises.

All the foundations were above high water so that no problem was presented in their construction, except that of access of which more will be said later.

Steel forms similar to those used for the 100 feet span piers were used for these piers also.

5) The remainder of the bridge on the South side is carried on a reinforced concrete viaduct consisting of a 10" reinforced concrete slab, which forms the carriageway, reduced to 6" on either side to carry the footpaths.

This slab is supported on transverse beams set at 10 feet centres which are supported on 3 piles, 1 in the middle and 1 at the line of the kerb on each side. The portions of the beams supporting the footpath slab are cantilevers (Fig. 2).

The piles used are 18" × 18" reinforced concrete piles 65 feet long. These piles have the greatest penetration of any on the bridge, they are founded at a depth of 50 feet below ground level.

The part of the viaduct abutting on the approach bank is braced by diagonal and horizontal members of reinforced concrete, which are built monolithic with the piles in five bents.

Stagings for Construction.

Mention was made above of the problem of gaining access to the line of the bridge. This was a question of the greatest importance to the Contractors and particularly affected the work on the South side.

During the initial consideration of the general scheme of construction it was, of course, necessary to make a choice between the use of floating plant or the provision of a temporary staging upon which cranes and other plant could stand and travel. The Contractors very wisely, in view of the strong fluctuating tidal currents in the river, decided to provide a staging over the whole length of the bridge, except for a gap at the Swing Span to allow the passage of ships during the construction of the bridge. But whatever decision had been made elsewhere, on the South side it was necessary to provide a staging both across the "saltings" as a means of access and along the line of the bridge as a working platform. After several trials it was decided to abandon the use of piles which it was found would have to be very long to support the load of a crane track and a crane and, consequently, most uneconomical, but instead to rely on a mattress of close set sleepers with a superstructure of timber cribwork to distribute the load over the grass grown crust of the "saltings" sufficiently to keep it within its bearing capacity. This proved quite successful and was used also for the double track on either side of the line of the bridge, which supported the travelling gantry used for driving piles.

In the river, timber piles were used to support the staging, which was heavily braced with steel angle sections. The crane track was carried on 18" joists (Fig. 21).

Steel and reinforced concrete spans.

Recommencing at the North side, the design and construction of the steel and concrete spans of the bridge will be described.

The approach spans on the North side of the river, crossing the railway, are

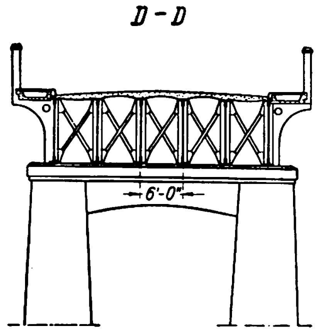
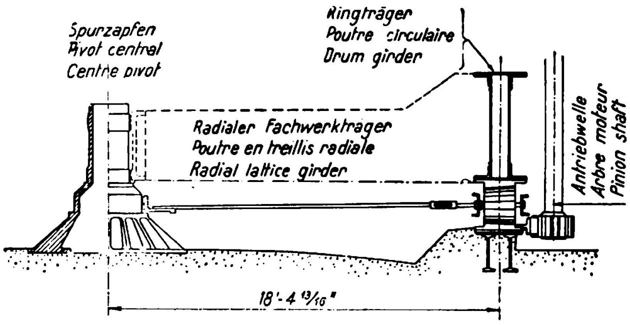


Fig. 11

0 10 20 30



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12 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

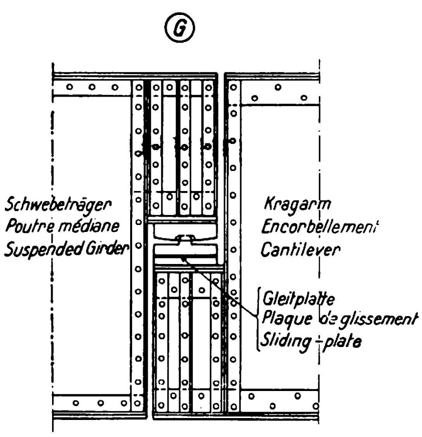
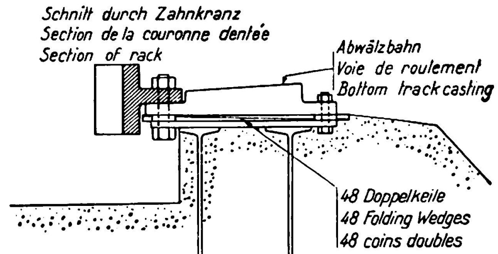


Fig. 12

12 0 1 2 3



Einzelheit der Abwälzbahn
Détail de la voie de roulement
Detail of lower roller track

Fig. 14

12 6 0 1 2

continuous steel spans on a curve. The continuity of the spans was retained in order to allow an arched form of girder to be used which would conform with the design of the main bridge.

Their detail design is similar to that of the 100 feet spans which will be described later, but they are reduced in size in proportion to their span.

The chief point in which they differ is that on account of the curve of the bridge the carriageway has been given a moderate degree of super-elevation and has been widened over the curved portion. In order to reduce the dead load which would be imposed by merely thickening the concrete, which forms the carriageway, on one side so that the required slope could be obtained, the girders themselves have been raised on their bearings from the inside of the curve, outwards, so as to reduce the required thickening of the concrete to a minimum. This has resulted in a rather complicated piece of steelwork, particularly in the case of the cross bracing and footpath brackets.

2) and 3) The 100 feet steel spans are deck spans designed on the principle of alternate spans continuous with two cantilevers at each support alternating with short suspended spans resting on the ends of the two cantilevers (Fig. 1 and 12).

This arrangement has the advantage of bringing the maximum bending moment over the supports where the greatest depth of girder occurs and simplifies the provision of expansion joints. The arched form of girder resulting from this arrangement gives the bridge a pleasing appearance.

Each span consists of six girders spaced at 6 feet centres, built up of web plate with angle stiffeners and flanges of double angles and plates. They are 9'1" deep at the supports and 5'2" deep at the centre. The girders are tied together with angle cross bracing and by the deck of buckled plates. The plates are concave upwards at the sides of the carriageway and concave downwards in the centre in order to suit the camber of the concrete filling which forms the road foundation.

The footpaths consisting of steel plates covered with concrete are carried on brackets springing from the webs of the outside girders.

Fig. 15.

General view of bridge. Looking up-stream and west. From north tower of electricity power crossing. Conductors cross the picture in the left hand corner.

The bearings of the girders on the piers are alternately fixed and sliding bearings. The sliding bearings consist of steel plates fixed to the girders sliding on phosphor-bronze plates, fixed in cast iron seatings bolted to the piers. Slotted holes are provided for the holding down bolts.

The bearings of the short suspended spans rest on stiffened brackets at the ends of the cantilevers (Fig. 12). One end is sliding and the other end is fixed in position by a knuckle working in a shallow trough, which allows a rocking motion at the point of contact.

The design of these spans greatly simplified the problem of erection. The steelwork was delivered by rail in three standard fabricated units: —

I) Pieces formed of a cantilever and a similar portion of the girder continuous with it, which took the form of a double cantilever on either side of the support.

II) The centre sections of the continuous girders.

III) The short suspended girders complete.

Two 5 ton Locomotive Cranes picked up the double cantilever pieces i), at each end and travelled with them out on to the construction staging on the

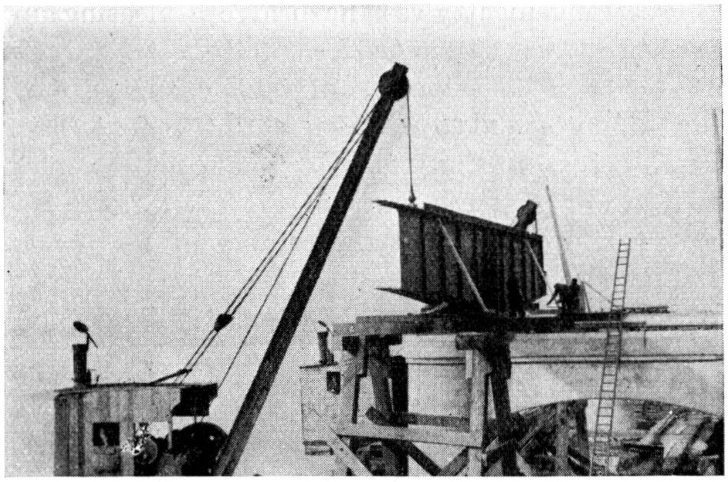


Fig. 16.

Steel erection 100 feet steel spans. 5 ton locomotive cranes lifting double cantilever section onto top of pier.

downstream side of the bridge and placed them on the piers (Fig. 16). A second double cantilever piece was erected on the adjacent piers and then the centre section II) of the continuous girder was joined to the two double cantilever sections, the projecting ends of which were steadied by temporary timber staging.

This completed one continuous girder and two projecting cantilevers, a second girder was similarly erected, the two were braced together and then pushed over on a roller track to the upstream side of the piers. The weight of these two girders together was about 55 tons.

The other pairs of girders were erected in the same way and pushed into position by the use of jacks. This completed the erection of six girders on one pair of piers. Work then passed on to the next pair and when the six girders were erected on these there remained only the gaps for the suspended girders iii) to be filled. These girders were also erected on the downstream side and were pulled over, one by one, on a temporary skid rail placed on the tops of the ends of the cantilevers.

The site riveting consisted only of riveting the joints between the centre sections and the cantilever portions of the continuous girders, the cross bracing and the buckled plate deck.

The whole of the steel for the South side was delivered by rail to the North side and floated across the river on pontoons.

Three full spans, two girders wide, were erected at the Contractors' works at Darlington, to test the workmanship of the steelwork before despatch to the site and this was clearly shown later when the whole of the 14 spans were erected and fitted together without any difficulty.

4) The reinforced concrete approach spans on the South side (Fig. 3) consist of 5 reinforced concrete beams spaced at 7'6" centres continuous over two supports with an expansion joint every 150 feet for which steel bearing plates sliding on phosphor-bronze seatings are provided.

The two intermediate bearings are merely arranged to be non-monolithic, by interposing a layer of bitumen between the top of the piers and the underside of the beams. The beams have a similar arched form to the steel spans and are 5'8" deep at the supports. The beams are monolithic with the deck slab which is 10" deep and the footpaths are cantilevered out and are supported on brackets in order to imitate the design of the steel spans. The footpath brackets which, naturally, project from the side of the outside beam are reinforced by jack arches in line with the brackets between the outside beam and its neighbour.

These brackets and jack arches complicated the design of the form work, which had necessarily to be self-supporting between the piers. Any intermediate supports of a temporary nature placed on the "saltings" would have been so unreliable, due to the yielding nature of the ground, as to have been dangerous.

Steel forms were used, the sides of the beam forms being sufficiently strong to support the whole of the concrete of the span including the deck. It can be easily imagined that the large gaps in the side forms of the outside girders, necessary for the formation of the brackets and jack arches, weakened the beam strength of the forms seriously.

In practice, the beams were poured separately up to the underside of the deck. Closing spaces were left over the supports to guard against shrinkage cracks and to allow the beams free action initially as simply supported spans, because the tensile steel necessary over the supports for continuity, was at this stage above the level of the concrete.

The forms were removed after 7 days and the deck shuttering was erected on the beams themselves, being supported by the bolts left in the concrete for the purpose.

This method also had the effect of facilitating the stripping of the beam forms.

The closing spaces were filled when the deck slab concrete was poured.

5) The piled viaduct structure has been described earlier. It is only necessary to add that the form work for this section was entirely of timber and that the expansion joints are provided at every 50 feet. These are arranged for by widening every fifth cross beam and supporting it on 5 piles instead of 3. The free end of the deck slab rested on half the width of this widened beam, discontinuity being ensured by painting the bearing surface of the concrete with bitumen. These joints work easily.

Swing Span piers.

The three piers of the large Swing Span are the most important units in the foundations of the bridge and, consequently, occupied the most time.

They will be described in the order in which they were constructed.

Centre Pier.

The centre pivot pier was designed as a hollow cylindrical pier, 42 feet in diameter, founded on rock inside an open sheet pile cofferdam. The cofferdam was driven, using Larssen No. 2 steel sheet piles, and attempts were made to dewater it which failed several times. This was due partly to the presence of boulders in the 8 feet of gravel and clay overlying the rock, and partly to the buckling and twisting of the lower ends of the piles causing the grips to open. Finally, when the last attempt to dewater was made and the bottom was actually uncovered in places, a very violent blow in, under the feet of the piles, occurred at high water, which scoured out the internal material holding the feet of the piles and forced in a length of some 15 feet of the sheeting up to the point where it was held by the lowest waling. After this the attempt to work in the open was abandoned and the foundation of the pier was re-designed.

This arrangement consisted of six wells of 14'—6" diameter to be sunk under compressed air to rock, arranged with their centres on a circle of 32'—0" diameter (Fig. 6).

Just below water level these wells, which were filled solid with concrete, are tied together by a heavy circular slab of concrete 4'—0" in depth and heavily reinforced with steel. On this slab the walls of the cylindrical pier, which are 5'—0" thick, are built according to the original design. In order to overcome the difficulty of kentledge, which was described in connection with the compressed air wells used for the 100-feet span piers, the six wells for the centre pier were built of concrete inside the steel shells. The cutting edges were suspended from three pairs of jacks by perforated straps and as the concrete was filled into the cylinders and the load on the temporary staging supporting the jacks was increased the wells were lowered down on the straps in order to obtain partial support by floatation (Fig. 23). The wells were finally lowered on to the bottom and excavation began under compressed air, until a sufficiently stable bearing had been obtained to allow the support of the jacks to be dispensed with.

Centre Pier.

All these wells were sunk without any serious delay and excellent foundations about 4'—0" into hard sandstone were obtained. The working chambers and the access shaft space were then filled with concrete and work commenced on the concrete slab.

This slab, as mentioned above, was below low water level, but the cofferdam was sufficiently watertight to allow a moderate difference of level between the inside and outside water levels to be maintained.

Work, thereafter, proceeded without special difficulty and the pier was raised above high water.

At the top this hollow pier carries 4 steel lattice girders 6'—6" deep, arranged radially in the form of a cross and embedded in concrete. These girders support the central pivot of the swing bridge, the weight of the bridge, however, is carried by the walls of the pier on a roller path.

The reinforced concrete roof of this pier is supported on the radial girders. All the concrete in this pier was of $1^1/_2$: 2: 4 proportions.

As a protection to the Swing Span at this pier a timber jetty has been constructed, which is slightly wider than the steelwork of the Swing Span and is 420 feet long from end to end. Stretching up and downstream this jetty is provided to assist any vessel passing through the bridge which is not entirely under control, and protect the steelwork of the bridge when it is open, from any error of judgment on the part of the pilot. The timber used for this jetty, which contains 212, 14"$\times$14" piles 50 to 60 feet long, is of British Columbian Pine and for protection against deterioration the timber was creosoted under a pressure of 180 Lbs per sq. in. In order to obtain as reliable a protection as possible, the surface of the large timbers was incised before being creosoted.

The pitch of the incisions, which are $^1/_4$" deep, is 8" and the lines of incision are 1" apart, the incisions being staggered so that the incision on one line comes opposite a space between two incisions on the adjacent line.

The average results obtained were 4 Lbs. of creosote per cubic foot and the gain in penetration due to incising with this timber was 0.72 Lbs per sq. ft. of exposed surface.

The upstream and downstream ends of the jetty are strongly braced radially to resist collision and the remainder of the jetty is braced in the vertical plane.

Galvanised iron bolts, washers, plates and dogs are used for the fastenings. The jetty also formed a very convenient staging for the erection of the Swing Span steelwork (Fig. 22).

North End Rest Pier.

After the experience gained with the central pier it was decided not to attempt the foundation of the North end rest pier of the Swing Span inside an open cofferdam. The pier, which was originally designed with a mass concrete foundation similar to the centre pier, was re-designed on similar principles (Fig. 7).

Two large cylinders of 21 feet diameter were used in this case and were sunk under compressed air in a manner similar to that used elsewhere. The two wells being built of concrete inside steel shells, but owing to their greater size were supported on 4 pairs of jacks instead of 3.

As in the case of the centre pier a heavy slab joins the heads of the two cylinders just below low water and use was made of the cofferdam to maintain a moderate difference between external and internal water levels. The pier above the foundation cylinders and slab consists of a hollow rectangular pier with semi-circular ends. The walls are 5'—0" thick at the base, tapering to 3'—6" at the top, and the internal space is divided into two rectangular and two semicircular compartments, by cross walls 3'—6" thick.

The top of the pier has a reinforced concrete roof and carries, in addition to the ends of the 100-feet span girders, the bases for the rollers upon which ride the two wedges which lift the nose of the Swing Span into position at each end; a socket for the locking bolt of the Swing Span and electrical devices for bringing the bridge to rest and centering it over on the carriageway.

Above the level of the carriageway this pier carries a large portal structure which is partly of agricultural and ornamental significance and partly necessary to house the safety gates which are lowered horizontally across the road and footpath when the bridge is opened to allow the passage of a ship. When the road is open the gates are hoisted and hidden inside the portal beam.

South end Rest Pier.

The third pier for the Swing Span was also designed to be constructed inside an open cofferdam, but in view of the uncertainty of the level of sound material, which was not shown very clearly by the survey borings, and the excessive depth before rock could be obtained, it was decided to drive piles in this foundation.

Seventy six piles were driven around the circumference of the pier, under the walls, in two rows. The outer row of forty two piles were driven to a batter of 1 in 10, the remainder being vertical. These piles were 18" by 18" in section and 40 feet long and were driven to refusal with an average penetration of 20 feet below the river bed.

This foundation was treated in much the same way as the small foundations for the 100-feet span piers.

The cofferdam was driven to a penetration of about 15 feet and the ground was excavated inside by grabbing to a depth of 10 feet below the river bed level.

The piles were then driven and 3 feet of concrete was placed on the bottom, through water. When this had set the cofferdam was pumped dry and construction continued inside (Fig. 5).

The base of the pier consists of 6 feet of concrete and above this level the structure is the same as the North end rest pier.

The piles were roughened or broken down and the steel reinforcing rods incorporated in the concrete of the walls of the pier.

For all three of these piers the outer face shuttering was of welded steel construction and was of particular advantage at the curved corbels at the tops of the piers (Fig. 21).

The Swing Bridge.

The steelwork of the Swing Bridge is 364 feet long from end to end and, when closed, spans two openings of 150 feet clear width.

The 30 feet carriageway passes between the two warren type girders of the span, at a level slightly above the bottom boom, and the footpaths are cantilevered out on brackets springing from the vertical members of the truss. The weight of the bridge which is 1600 tons, rests upon 60 cast steel rollers which run on a cast steel track supported over the centre of the wall of the central pier.

To commence then at the bottom, the roller track will be described first. The foundation for this track consists of a circular box girder built of two joints 20" deep with $^7/_8$" cover plate. On this bed the cast steel sections of the roller track were laid. For purposes of level adjustment 48 pairs of machined steel folding wedges were interposed between the foundation plate and the track castings, and the beds for these wedges were ground plane. The track castings were placed and adjusted for radial inclination and circumferential level to limits of $^1/_{64}$" on temporary wedges. The pairs of wedges were then checked for

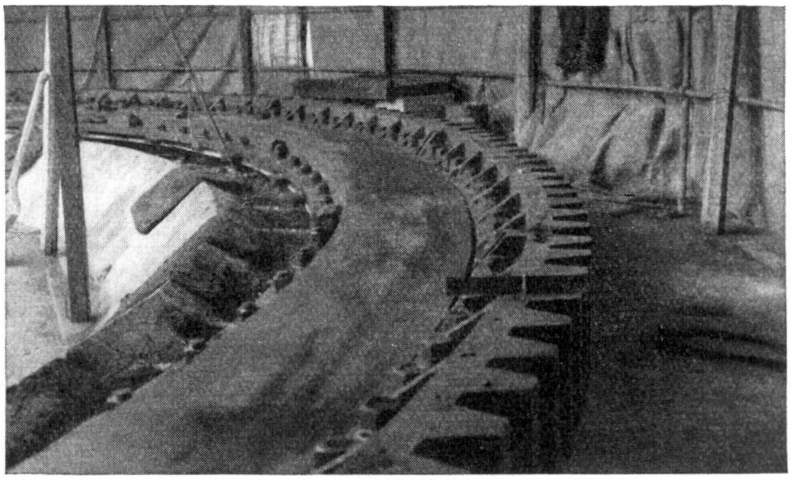


Fig. 17.

Swing bridge. Lower roller track castings bolted down with rack sections bolted on.

correct taper to give the right inclination to the track, by using a $^4/_{1000}$" feeler between them and their top and bottom bearing surfaces. Any errors of taper were rectified and the wedges replaced.

The circumferential level was finally adjusted and when correct within the

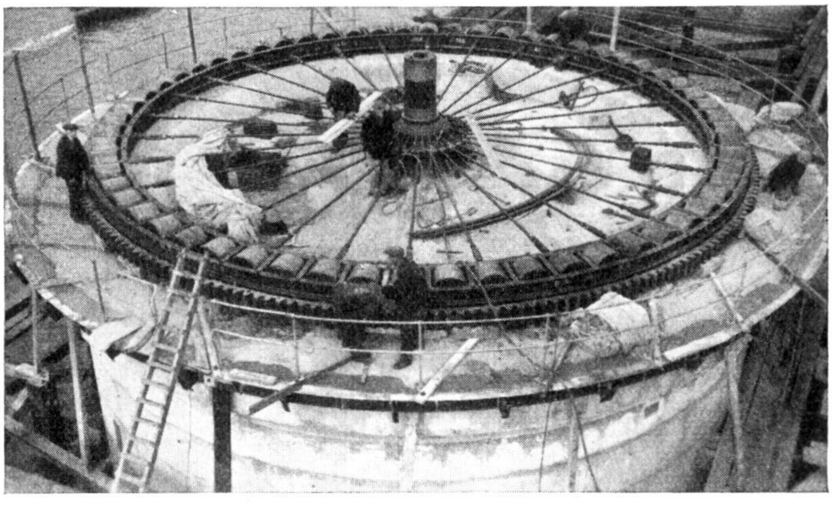


Fig. 18.

Swing bridge. Centre pivot. Radius rods and cast steel rollers on centre pier (Nr. 11). Shows rack bolted on.

limits of accuracy obtainable, the track castings, wedges and foundation plate were drilled simultaneously and bolted together with turned bolts (Fig. 14).

The spaces between the wedges were then filled with a dry hard rammed mortar of cement and sand of I: I proportions.

A toothed cast steel rack section was bolted to the track castings and the cast steel rollers were assembled. These were fabricated in cages of channel sections holding 5 rollers and each alternate roller has a radius rod which is connected to the centre bearing, which turns on a machined journal on the centre pivot.

The upper roller track castings, which are identical with the lower track, were placed on the rollers and a very stiff drum girder, 5 feet deep, of box section was lowered thereon (Fig. 19, see also Fig. 17 and 18).

This drum girder performs the function of distributing the weight of the bridge as evenly as possible upon the rollers, and the upper track casting was adjusted from its lower flange plate by inserting thin packings (Fig. 19) until

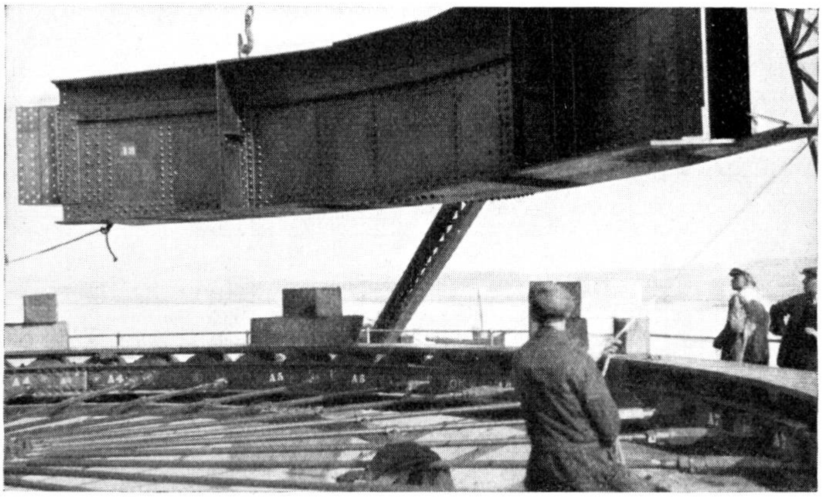


Fig. 19.

Swing bridge. Drum girder being lowered into position on top of upper roller track castings which are resting on top of the rollers.

a $^4/_{1000}$" feeler could not be inserted at any point between a roller and the upper track.

The drum girder and superstructure were rotated into different positions for the purpose of this test.

The drum girder is radially braced to the centre pivot of the bridge by lattice girders bolted to the castings turning on two machined journals on the pivot at the top and bottom (Fig. 13). These lattice girders support the floor of the machinery room and its machines.

The drum girder receives the weight of the bridge at 8 points. These 8 points are the bearings of 4 very deep girders, 2 to each girder. These are the main distribution girders, which are built integral with the centre section of the bottom boom, and are box girders 8'—4" deep, and two main cross girders, which are stiffened web plate girders, across the line of the bridge, 11'—0" deep.

The space between the four walls formed by these four girders is used as the machinery room.

The main girders of the bridge are of normal construction, the top and bottom booms are of box section, one side at least being formed of open lattice bracing. The diagonals are deep H sections formed of a web plate and four unequal bulb angle sections. The verticals are I girder section. All sections are 22″ deep. The deck bearers are 20" joists placed longitudinally at 5 feet centres on cross girders at 20'—3" centres, which are 5 feet deep.

The decking is of buckled plates similar to the 100-feet spans and, like them, is covered with concrete.

In the case of the swing bridge the concrete has articulated joints at intervals, filled with bitumen and sealed with a corrugated copper strip. A system of triangular sway bracing of light lattice members, joins the two top booms and between them, in the centre of the bridge, is placed the operator's cabin from which the swinging of the bridge is controlled.

Machinery.

The operation and control of the bridge is electrical.

The bridge is swung by a dual pinion and rack system, the rack being fixed to the pier is, consequently, stationary. The two pinions turn in bearings fixed to the bridge and, consequently turn with it. The pinions are driven by $9^1/_2$"

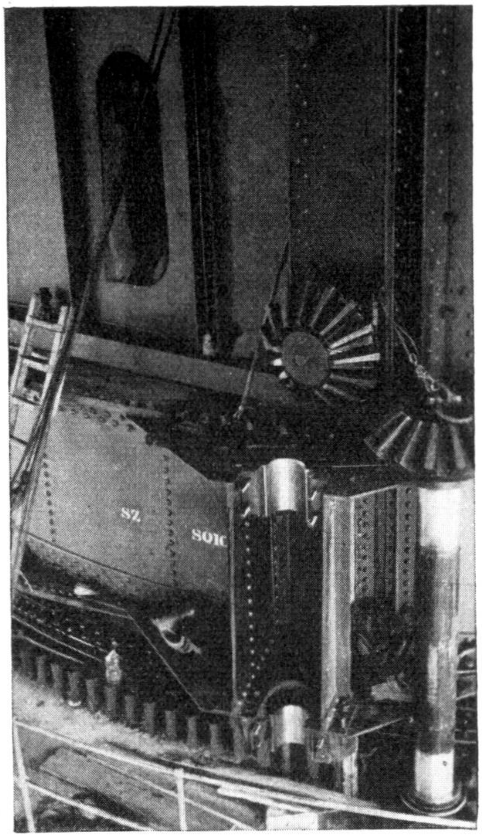


Fig. 20.

Swing bridge. Pinion shaft and bevel gears, Pinion shaft bearings. Toothed circular rack. Door of machinery room.

diameter vertical shafts connected by bevel gears to horizontal main shafts passing through the walls of the machinery room, that is to say, the webs of the main cross girders. These main horizontal shafts are driven through a train of reduction gearing by two 50 H. P. Direct Current Motors. The two drives are entirely independent.

The supply of power to the bridge is Alternating Current obtained from the Local Electrical Company and is conveyed by a cable running along the bridge, descending below the river in order to cross to the central pier which it enters by means of a duct through the wall placed above high water level, and thence, after subdivision into small cables, reaches the machinery room through the hollow shaft of the centre pivot to a vertical series of collector rings and brush

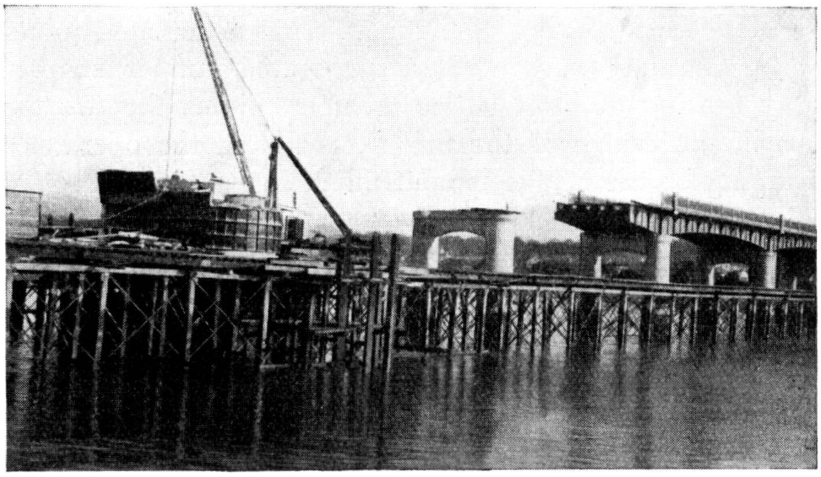


Fig. 21.

Pier Nr. 10 under construction. Shows welded steel form work. Projecting cantilevers of steel spans with brackets for suspended girders. Temporary timber staging on piles.

contacts. The A. C. supply is converted for use in the D. C. Motors by a Ward Leonard Motor Generator Set, and a standby set, in case of a failure in the normal supply, is also provided. This consists of a 150 H. P. 4 cylinder, horizontally opposed, solid injection Diesel Engine, which drives a 40 K. W.

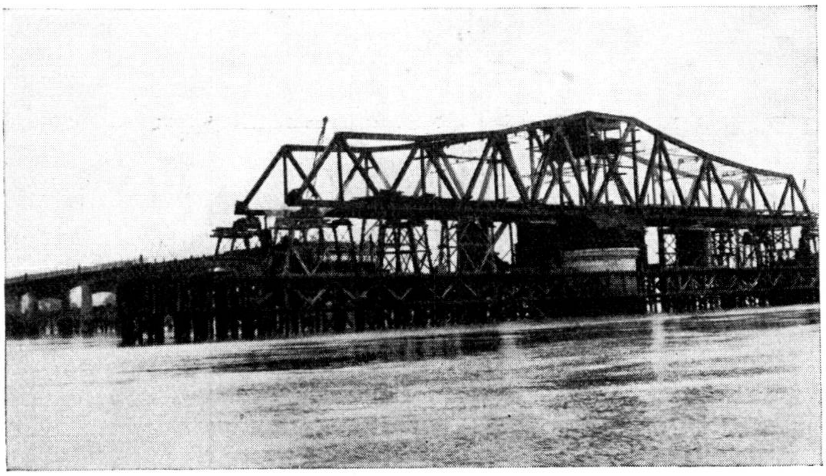


Fig. 22.

Swing bridge nearing completion. Shows permanent timber jetty and temporary trestles for erection.

Direct Current Generator and a 36 K. W. Alternator for lighting the bridge. For the hydraulic power by which the wedges and locking bolts are operated, a 25 H. P. Direct Current Motor is provided, coupled to a six ram oil pump which has four rams working at 3000 lbs. per sq. inch, and two rams working at

1000 lbs. per sq. inch, the former are for the wedges and the latter for the locking bolts. All this machinery, including the usual compressed air starting system for the Diesel Engine, is remotely controlled from the control cabin.

In view of the exceptional size of the swing span every care has been taken to ensure that the various operations in opening and closing the span are automatically carried out in proper and regular sequence by electrical control to eliminate the risk of accident due to an error on the part of the operator. In addition, duplication of essential plant and controls has been kept in view wherever possible to prevent the complete breakdown of the operations in the event of a fault occurring in any of these.

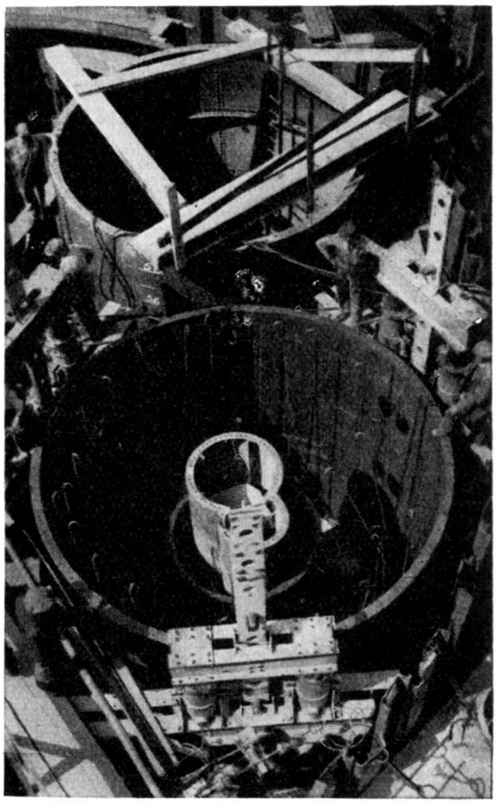


Fig. 23.

Centre pier No. 11. Compressed air wells at pier No. 11. Showing access shaft. Internal shuttering. Reinforcing rods and steel well suspended from perforated straps on hydraulic jacks. Compare with fig.8, 9 and 10.

The operator stands at a control desk in the cabin, where a hand wheel as it is turned round carries out the proper sequence of operations, the completion of each operation being indicated by coloured signal lamps on the desk.

The operation of closing the roadway to traffic and opening the Bridge to river traffic is as follows: —

1) Power supply switched on for Ward Leonhard set and hydraulic pumps.
2) Road traffic signals at both ends of the Bridge turn from green to red and warning bell rings. Interval until assistant in roadway indicates to operator in cabin by gong that roadway is clear of vehicular and pedestrian traffic.
3) Gates lowered across roadway and footpath at both ends of Bridge. Red light at end of jetty changes to amber, semaphore arm drops and syren sounds to indicate to vessel that Bridge is about to be opened.

4) Wedges holding up ends of Bridge withdrawn by hydraulic power.
5) Locking bolt withdrawn by hydraulic power.
6) Bridge swung through 90^0 to open position. The acceleration to maximum uniform speed and deceleration at the end of the travel is controlled automatically by limit switches.
7) Second red light at end of jetty turns to amber and another semaphore arm drops to indicate that passage is clear for shipping. A syren is also sounded.

For the closing of the Bridge the operations are reversed. It is possible by manipulating the handwheel in the cabin to make the Bridge open or close clockwise or counter-clockwise, or end for end, as desired.

For ensuring the exact centering of the Bridge a photo-electric device is incorporated. This consists of three coloured lights on the control desk, the lighting of the lamp at either end indicates that the Bridge is nearly centred, whilst the centre lamp when alight shows that the Bridge is centred within $1^1/_2$" or sufficiently near the dead centre for the locking bolts to be driven home. The two locking bolts and the four wedges under the ends of the Bridge each travel 27 inches, and their relative movement is indicated by dials on the control desk. In the event of a breakdown of one of them this is instantly shown on the desk by a warning light, and the operation stops. A hand pump is installed in the machinery room to allow for the defective wedge or bolt being operated by this means.

In the event of a failure of any of the essential traffic control lights, this is indicated by a warning lamp in the cabin.

The whole operation of opening or closing the Bridge occupies four minutes as follows: —

Withdrawing wedges	$1^1/_2$ minutes
Withdrawing locking bolts	$^1/_2$ minutes
Swinging Bridge through 90^0	2 minutes
Total =	4 minutes

The shipping using the river will pass the site of the Bridge within one or two hours on either side of High Water. It will be necessary, however, to have the Bridge Staff constantly in attendance for maintenance etc., and the intention is to have three groups of Bridge operators and assistants, each group working an eight hour shift.

Summary.

The bridge, which crosses the river Forth, was promoted by a Joint Committee of the interested Local Authorities and the Ministry of Transport contributed largely to the cost.

The site of the bridge is the most Easterly site consistent with moderate cost, and the bridge will improve road communication between Glasgow and Edinburgh and the Nort East of Scotland.

River traffic has necessitated the provision of a large opening span and the site conditions have resulted in a bridge $^1/_2$ a mile in length employing many different types of construction.

The foundations of the Northerly half are all on rock at easy depths and compressed air caissons adapted in a simple manner from open steel wells were largely used for these foundations. On the Southern half of the bridge use was made of reinforced concrete piles up to 65 feet in length and 18"×18" in cross section.

The 14 deck spans of 100 feet are constructed of steel girders 6 to a span, employing the cantilever and suspended girder priciple.

The road, which is 30 feet wide, is formed of steel buckled plates covered with concrete and a bituminous surface.

The two footpaths throughout the bridge, each 5 feet wide, are carried on cantilever brackets on either side of the main structure.

The approach spans on the North side are constructed on a curve and are of steel with super-elevation built in.

The approach on the South side consists of 9 reinforced concrete spans of 50 feet, having 5 girders each and 260 feet length of viaduct supported on piles. The 50 ft. spans involved some difficult form work. The forms for concrete throughout the bridge were of steel.

There are 3 large piers supporting the Swing Bridge, 2 of these were founded on rock by use of compressed air caissons and the Southern pier was founded on piles.

The Swing Span, 364 feet long, is a rim bearing Swing Bridge of the largest type with a moving weight of 1600 tons.

The roller track supporting the bridge involved some accurate workmanship.

The bridge itself is a through span of the Warren girder type, with a steel plate deck covered with concrete for the carriageway.

The turning machinery, which is electrically operated, is located beneath the roadway and is remotely controlled from a cabin suspended between the girders above the road. Wedges and centering bolts are hydraulically operated and photo electric equipment is used for centering the bridge accurately.

A standby generating set driven by a Diesel Engine is provided.

The bridge can be swung open in four minutes.

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