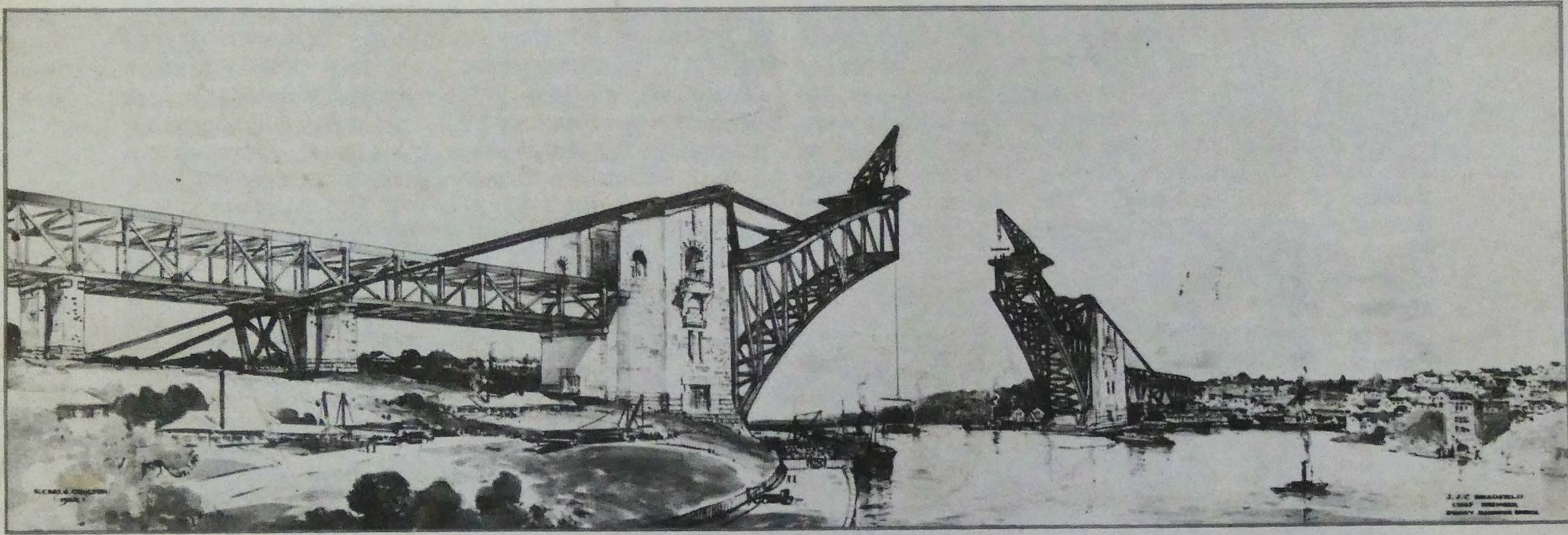
SYDNEY HARBOUR BRIDGE



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SYDNEY HARBOUR BRIDGE

AND

METROPOLITAN RAILWAY CONSTRUCTION

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Sydney Harbor Bridge

By J. J. C. Bradfield, D.Sc., M.E.*

Historical

The first definite proposal for the bridging of Sydney harbor was made in 1815 by Francis H. Greenway, government architect, who proposed to build a fort on Observatory hill, with an advanced redoubt on Dawes point, and to construct a bridge thence to the northern shore of the harbor. Little is known, however, of the details of this proposal. The earliest recorded drawing of a bridge to connect Sydney with North Sydney was made in 1857 by a Sydney engineer, Peter Henderson, who had served his apprenticeship in the English workshops of George Stephenson, and had been associated with Brunel. For over 20 years there was no further definite proposition, but in 1878 Mr. W. C. Bennett, commissioner for roads and bridges, suggested a floating bridge. A year later, Mr. J. E. Garbett offered to build a high-level bridge on behalf of a company at a cost of £850,000. This offer was accepted in 1881, and Mr. Garbett deposited £5,000 as security. Owing to a change of government, however, the matter was not proceeded with, and the deposit was returned in the following year. Later, Sir John Fowler planned a suspension bridge at an estimated cost of £400,000. In 1885 the idea of tunnels, in contradistinction to a bridge, was brought forward by Mr. C. O'Neill, in association with Mr. Gipps.

Public interest in the matter was now growing, and in 1888 Sir Henry Parkes was urged to build a bridge to commemorate the centenary of the colony. Nothing was done, but the agitation continued, and in 1890 a royal commission of inquiry was appointed. Eight schemes, including proposals for connection by tunnel, were examined. Although it was deemed inexpedient, for the time being, to connect the northern and southern shores by either bridge or tunnel, the commission arrived at the important conclusion that, in the event of it being found necessary to make the connection, "it should be by means of a high-level bridge, and that, if it were possible to throw a bridge across in one span, such plan should be adopted." A period of inaction followed until 1896, when fresh proposals emanated from private enterprise, and between that year and 1899 four private bills to cover the construction of either bridges or tunnels were brought before parliament. Sir John Sulman was responsible for the presentation of plans for tunnel construction, and Messrs. B. O. Simpson and W. Kenwood designed bridges.

The first definite action towards building a bridge was taken by the late Mr. E. W. O'Sullivan, when minister for works, in 1900. He called for competitive designs and tenders, and in response 24 schemes were submitted. These were given mature consideration, but were all rejected. In the year following, an advisory

Fig. 1. The Main Arch of the Sydney Harbor Bridge

The span is 1,650 ft.; the width, 160 ft.; and the clearance above high water, 170 ft.

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board was appointed which called for new designs and tenders. Twelve were received, and in November, 1903, the board recommended the acceptance of a tender by J. Stewart and Co. for a cantilever bridge from Dawes point to McMahon's point, estimated to cost, with approaches, £1,940,050. A change of government, however, caused the matter to be dropped, which was perhaps just as well, for subsequent investigations have disclosed that the location would not have been satisfactory, and that the proposal would have been a menace to navigation.

ing navigation. He submitted designs and estimates for three types, cantilever, suspension and cantilever arch, and recommended the adoption of the first. The report of the public works committee recommending construction of a cantilever bridge from Dawes point to Milson's point was submitted in July, 1913, but it was not until 1916 that an enabling bill was brought down in parliament. This was twice passed by the legislative assembly, and on both occasions rejected by the legislative council. In September, 1922, however, a comprehensive measure passed both houses.

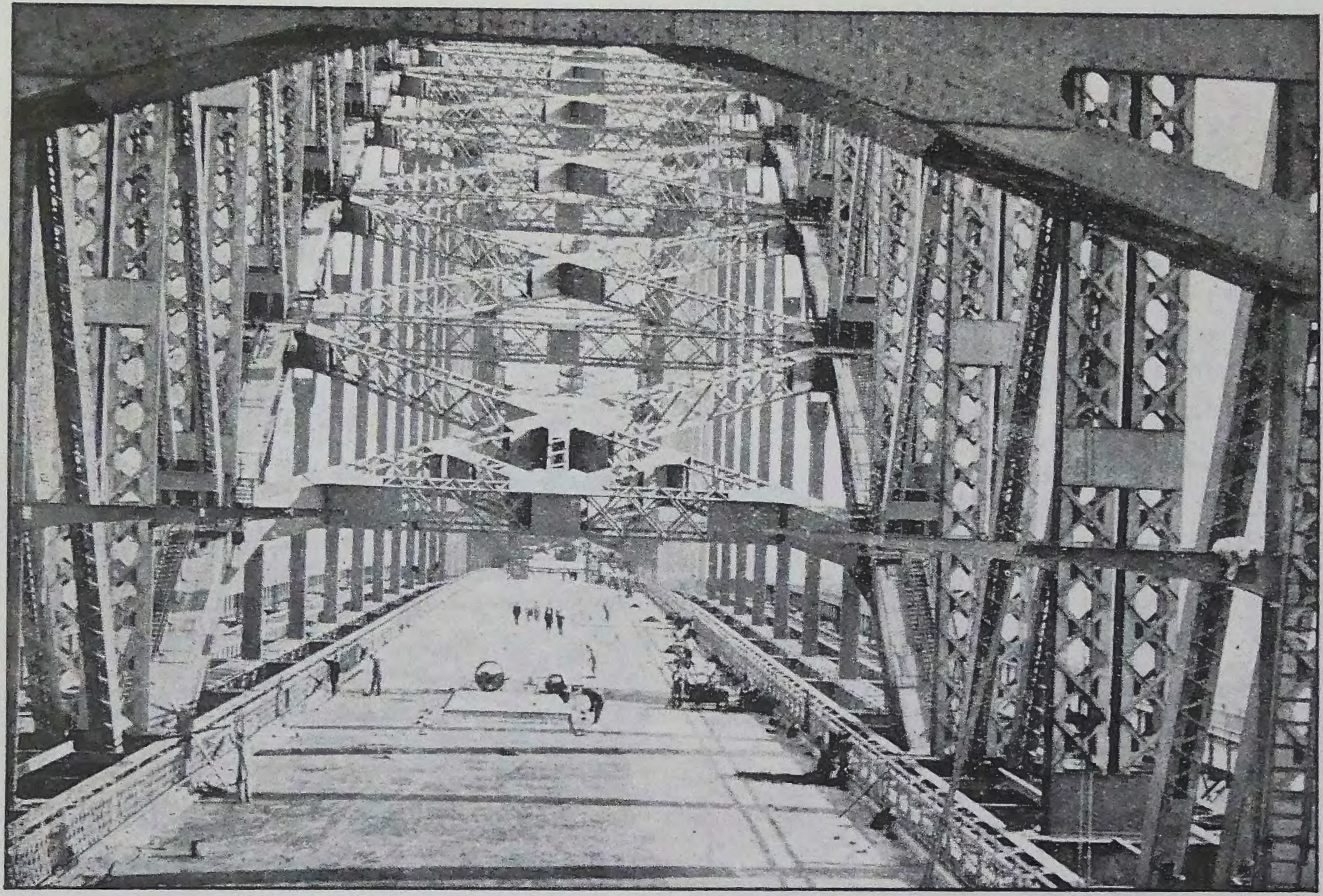

Fig. 2. The Central Roadway of the Bridge
The roadway, 57 ft. wide, provides for six lines of vehicles; it is bounded on each side by two lines of electric railway, and a 10-ft. footway.

In May, 1908, the Wade ministry appointed another commission of inquiry. This commission recommended railway and road tunnels instead of a bridge, but another change of government interrupted the investigations. In July, 1911, however, Mr. W. A. Holman, who was then acting premier, announced that the cabinet had decided on a bridge for tramway, vehicular and pedestrian traffic, and on a subway for railway communication. Both proposals were referred to the public works committee for inquiry, but the minister was advised that the bridge and subway would not be suitable and would menace navigation. The writer, who had submitted this advice as principal designing engineer, was then given permission to prepare counter proposals for a bridge to span the harbor without obstruct-

Preparations for building the bridge now began in earnest. While the measures had been before parliament, the writer had been investigating bridge construction abroad, and had come to the conclusion that there were no insuperable difficulties to the erection of an arch bridge of the span required, and that an arch bridge would cost £350,000 less than a cantilever. Accordingly, world-wide alternative tenders were called in 1923, on plans and specifications prepared by the writer, for the construction of a cantilever bridge or of an arch type with abutment towers and pylons. The tender of Dorman Long and Co. Ltd. for a two-hinged arch bridge in conformity with the specification was accepted by the government on March 24, 1924. The contract price was £4,217,721, and the period for completion was six years from date of acceptance. A great deal of the material was to be obtained, and most of the fabrication performed, locally.

The first sod for the construction was turned on July 28, 1923; the official opening will take place on March 19, 1932. The actual cost of construction was £6,250,000, and the total cost of the enterprise, including construction, resumptions, etc., is about £10,000,000. The principal materials of construction are steel, concrete and granite. The steel was fabricated in workshops established by Messrs. Dorman Long and Co. Ltd. near the north abutment, and the granite was quarried at Moruya, on the south coast of N.S.W.

The Design

The bridge, as now completed, consists of a two-hinged arch with five steel approach spans at each end. The main arch, Fig. 1, has a clear span of 1,650 ft., a width of 160 ft., and a clearance above high water of 170 ft. It contains 37,000 tons of steel, and is the largest arch bridge in the world. The total length of the bridge and all approaches is $2\frac{3}{4}$ miles, and the total weight of steelwork is 52,300 tons. In addition to being the largest and heaviest arch bridge, it is the widest bridge of any kind in the world. Its provision for traffic comprises four lines of electric railway, a roadway for six lines of vehicles, Fig. 2, and two 10-ft. footways, all on one deck. The maximum hourly traffic capacity is 128 electric trains, 6,000 vehicles in each direction and 40,000 pedestrians. In building this great structure members have been fabricated and erected of a size and weight never before attempted for any bridge in any part of the world.

The main span comprises two silicon steel arches spaced 98 ft. 6 in. apart, centre to centre, set in vertical planes with a span of 1,650 ft., and a rise of 350 ft. at the centre of the lower chord at the crown. The depth of the truss at the crown is 60 ft., and at the end posts 187 ft. 9 in., while the highest point of the steelwork at the centre of the top chord is 440 ft. above standard datum.

Each arch truss is divided into 28 panels with a single system of bracing, the two trusses being braced together by systems of laterals in the planes of the top and lower chords. The lower chord varies in depth from 48 in. at the crown to 99 in. at the hinges, the width 11 ft. overall being uniform throughout. The cross sectional area at the crown is 1,060 sq. in., and at the main bearing 2,700 sq. in. or about 19 sq. ft. of solid steel. The top chord is 40 in. deep and 11 ft. wide throughout. All main members are of silicon steel. The heaviest angle used is 12 x 12 x $1\frac{1}{4}$ in.; the thickest plate 2 in., and the largest rivet $1\frac{9}{32}$ in. in diameter, with a grip of $9\frac{7}{8}$ in., all of which are larger than hitherto required for bridge or other steel construction.

The thrust of 44,000,000 lb. (approximately 20,000 tons) from each arch truss is transferred from the lower chord to the concrete skewbacks through the steel pedestals described below, which reduce the thrust on the concrete immediately under the pedestals to 800 lb. per sq. in. The upper steel saddle is fixed to the bottom chord and transmits the thrust through a $14\frac{1}{2}$-in. diameter pin, 13 ft. 8 in. long, to the lower saddle, which is attached to the two main webs; these are inclined at an angle of 54 deg. to one another and secured together by 10 cast steel diaphragms. These webs are of forged steel $9\frac{1}{2}$ in. thick and weigh 33 tons. They transfer the arch thrust to the six steel castings which,

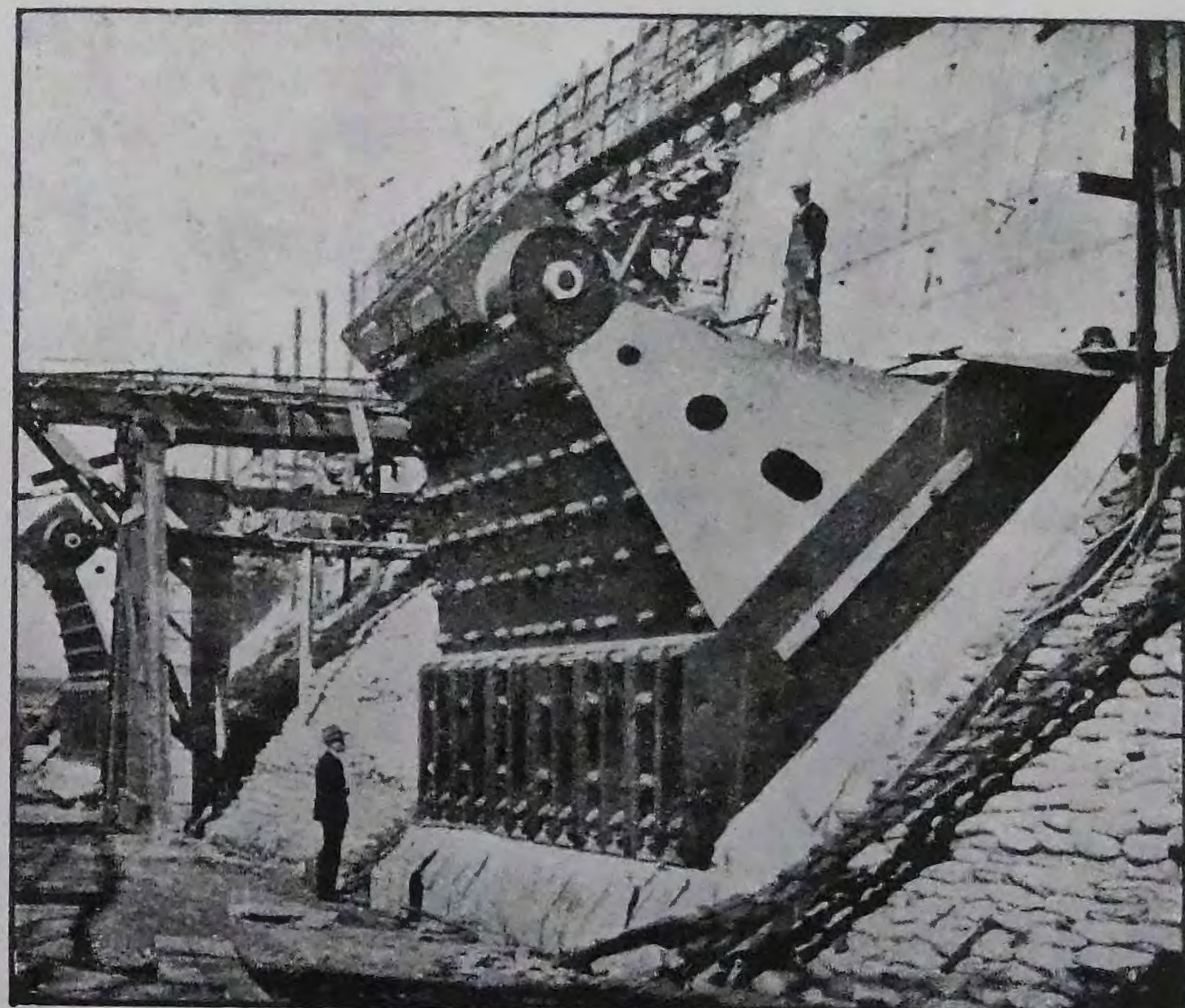

Fig. 3. Main Bearing for Southern Half-arch

bolted together, form a base 24 ft. by 21 ft., that is, an area of 504 sq. ft., resting on the inclined face of the skewback. The height from base to centre of pin is 13 ft. $11\frac{1}{4}$ in., and the weight of the bearing is 296 tons.

The main bearings transmit the whole pressure through the skewbacks to the solid sandstone of the foundations (Fig. 3). The pressure on the inclined face of the reinforced concrete is 800 lb. per sq. in., but, when this thrust reaches the sandstone foundation through the concrete, it will not exceed 200 lb. per sq. in., or about 14 tons per sq. ft. Each skewback is 40 ft. wide and 90 ft. long, and is founded at least 30 ft. below ground surface into solid rock.

The granite faced towers and pylons, simple and elegant, are the architectural features of the bridge and harmonise with the lines of the arch. They give the touch of distinction to the bridge, which would otherwise be an immense utilitarian steel structure. The top of the tower of the post office, the top of the flagstaff on the Sydney Church of England grammar school at North Sydney and the tops of the bridge towers are all at approximately the same level. These pylons, the tops of which are 285 ft. above mean sea level, by their weight, steepen the resultant arch thrust, and so minimise the size of the skewback foundations. From ground to deck level the abutment towers are hollow rectangular concrete chambers 223 ft. face width, and 162 ft. long, stiffened by interior concrete walls. The pylons above deck level measure 81 ft. by 47 ft., and

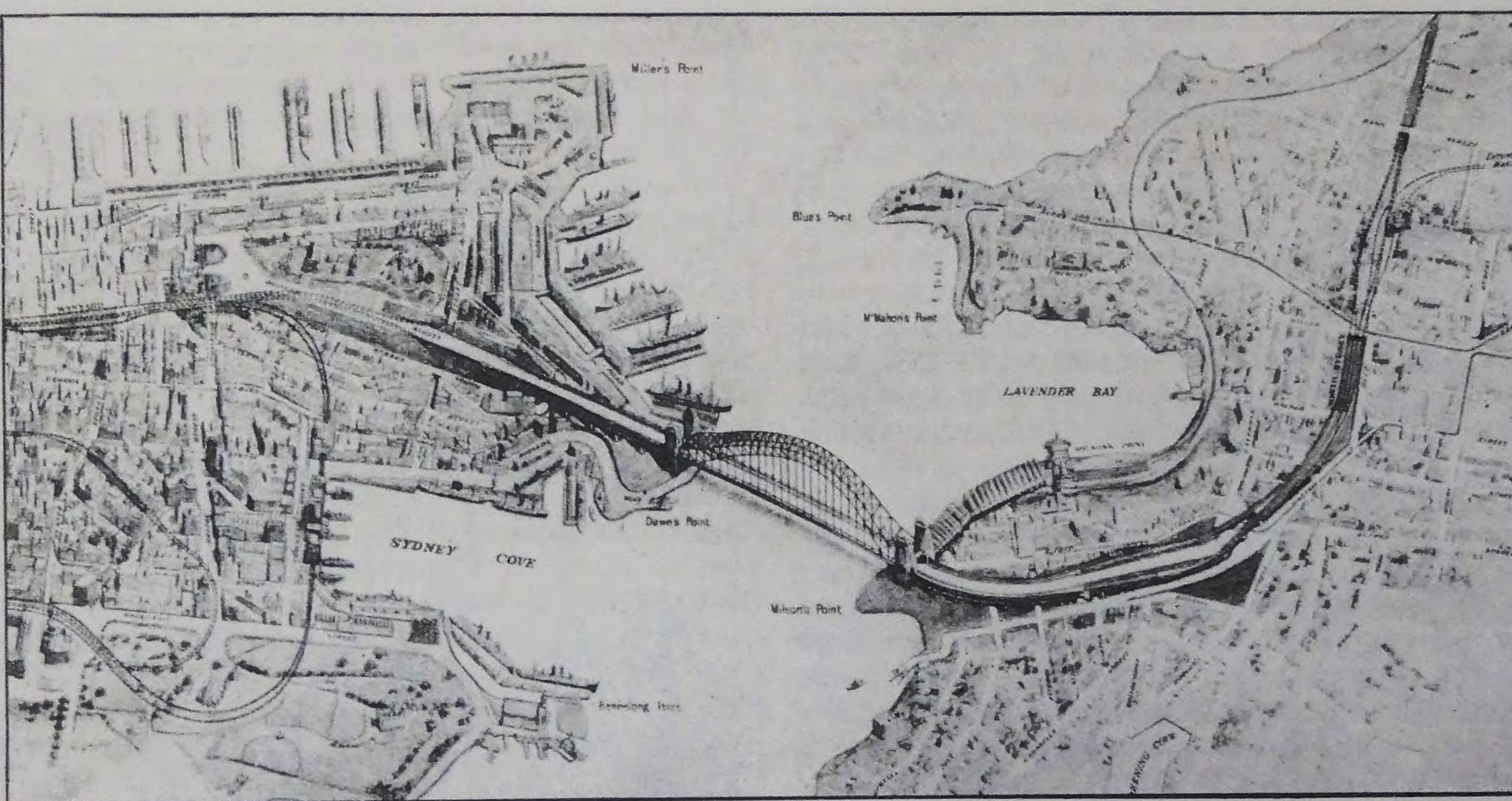

Fig. 4. Location of Bridge and Approaches

are also of hollow reinforced concrete construction. Each is pierced by an arch opening through which the outer railway track and a footway pass.

The general location of the bridge and approaches is shown in Fig. 4. The four bridge rail tracks connect with the Milson's point line about 200 ft. on the Milson's point side of Waverton station. The railway tracks are carried over Eureka street by a reinforced concrete arch bridge, and Bank street is taken over the railway by a reinforced-concrete girder bridge. Soon after leaving Bank street they enter two double line tunnels, and, passing under Graythwaite, the Church of England grammar school grounds and Blues Point road, they emerge at the first station—North Sydney—situated in open cut between Miller and Walker streets, as four single line tunnels. The next station—Kirribilli—is situated in front of the old North Sydney town hall. The four tracks then traverse the bridge, run underground in pairs on either side of the bridge highway near Argyle Cut and junction with the city railway at Wynyard Square, a total length of 2 miles 33 chains from the offtake near Bay Road station. At the outset the eastern pair of tracks will be used to take the trams across the bridge to Wynyard station. The tramways from Miller street and Lane Cove road will be deviated to Blue street, and thence the trams will traverse the eastern pair of tracks into the city.

The roadway approaches on the city side commence at Wynyard street; York street has been widened to 81 ft. northward from Wynyard street; Kent street widened to 81 ft. northward from Napoleon street to Gas lane, whilst York, Clarence and Kent streets are connected near Grosvenor street by a crescent to the bridge highway, constructed as an 80-ft. roadway, and two 16-ft. footpaths along the line of Princes street to the arched viaduct in approach to the main bridge. Between York street, Kent street and the crescent will be two parklets. This necessitates the remodelling of Princes street and Upper Fort street. A connection to the bridge highway will be made from Watson road, thus affording direct access to the bridge for vehicular and pedestrian traffic from the low levels at Miller's point. From the end of the steelwork there are three concrete arch spans, a length of retaining wall, then a concrete arch bridge across Argyle Cut, after crossing which the four tracks are tucked under the roadway avenue.

After traversing the bridge to North Sydney, the roadway approaches reach the existing surface at the intersection of Alfred and Junction streets, and are continued along Junction street to the intersection of Blue street with Walker street, and thence to the Lane Cove road. From Alfred street, North Sydney, via the North Coast to Brisbane the roadway is named the Pacific Highway. As on the southern side, extensive remodelling is taking place and the character of the district will change from a residential to a business area.

The building of the northern approaches necessitated the closing of some streets, the deviation of others and the formation of new avenues which will greatly improve the existing traffic facilities. Junction street, between Alfred and Walker streets, has been widened to 100 ft., the north-eastern building line remaining as at present; Willoughby street is closed between Brisbane and Alfred streets, whilst Alfred street is deviated between Junction and Willoughby streets. From the intersection of Alfred and McDougall streets to the intersection of Burton and Broughton streets a new roadway has been constructed which will be of great convenience to the residents of Kirribilli.

At Kirribilli station the bridge roadway is 57 ft. wide, located between the two pairs of railway tracks. Kirribilli station has one island platform on each side of the roadway, the platforms being connected by a concourse underneath the roadway. The roadway is graded more steeply than the railway, and just before reaching the existing surface near Junction street it passes under the two easternmost tracks.

The crossings of the tracks over the roadway and over Alfred street are made by a steel bridge of 220-ft. span and a reinforced concrete arch, 120-ft. span. Between Arthur and Alfred streets, the tracks and goods' siding are carried on a viaduct, which, supported on piers, consists of steel girders encased with concrete; the whole is waterproofed, enabling a ballasted track to be used and space below formed into shops. Access to the footways on the bridge, which are each 10 ft. wide, is made at Burton street.

The wearing surface of the bridge roadway is Neuchatel asphalt laid on coke concrete, and of the footways mastic asphalt carried by the rough decking.

Fabrication of Bridge

Dorman, Long and Co.'s tender provided for the fabrication of the bridge in Sydney, and, in accordance with the terms of the specification, the abandoned passenger station and an area of land at Milson's point were made available for the erection of the workshops. After the contract had been signed, the company excavated the cliff face, levelled the site, reclaimed a portion of the foreshores by straightening the shore line, constructed a wharf and erected the workshops. The entire fabrication of the steelwork for the bridge has been carried out in these shops, which, with the machinery and equipment, are the finest bridge construction shops in the world. The light shop, in which the material is straightened, cut to length, planed and drilled, and the lighter members assembled and riveted, is 600 ft. long and 130 ft. wide, and is divided into two bays each 65 ft. wide. Above portion of the shop is the template shop, 200 ft. by 130 ft., where the members of the bridge have all been marked out full size upon the floor and templates made of each member. The heavy shop containing the plant to assemble and finish off the heaviest members is 500 ft. long and 147 ft. wide.

The steel was brought to the site by steamer, unloaded by the travelling wharf cranes, each of 10 tons capacity, and placed on skids in the stockyard adjacent to the wharf. The material, from the B.H.P. Co.'s steel works at Newcastle, was sorted and stacked by the five-ton semi-Goliath travelling cranes, and, as required, was transferred to the light shop by a double five-ton travelling crane. If necessary, the plates were passed through the plate mangle, which will straighten plates 12 ft. wide and 2¼ in. thick; a press machine straightened the rolled sections, inserted tooth blades, and cut sections up to 24 in. by 7½ in. Cutting the plates to length was done with the plate shears, which will shear plates 9 ft. wide and 2¼ in. thick. The edges of the steel plates were planed in two edge-planing machines; the smaller is 28 ft. long and the larger 66 ft. long with rack and pinion drive.

The material thus cut to length and width and edge-planed was marked out for drilling from the drawings and from templates made in the template shop, thence passed on to the drilling machines, which ensures that all similar members are uniform. This equipment consists of 18 7-ft. 6-in. arm radial drilling machines and eight gantry-type travelling drilling machines, each mounting two 6-ft. arm radial machines, each with individual drive through a four-speed gear box.

After being drilled, the various parts of the members were assembled and held together by pins and bolts, then riveted by hydraulic riveters weighing 4 to 12 tons each, and carried by electrically-operated travelling gantries. The power of these riveters is supplied by an accumulator working under a pressure of 1,500 lb. per sq. in., so that the rivets, heated in oil furnaces, are pressed into the holes and completely fill them. The pressure on each rivet was 80 tons, with the 12-ton gantry, and 45 tons with the other riveting gantries. Air-driven riveters were also used.

The ends of the members thus assembled were next planed to a true surface by the end-planing machine in the heavy shop. The ordinary difficulties of fabrication were greatly increased owing to the type and unprecedented size of most of the bridge members, but even more so on account of the accuracy required.

Construction

The erection of the approach spans presented no problems of undue magnitude. Commencing from the extreme end of the approach on either side, and working inwards towards the harbor, the necessary excavation was performed for the

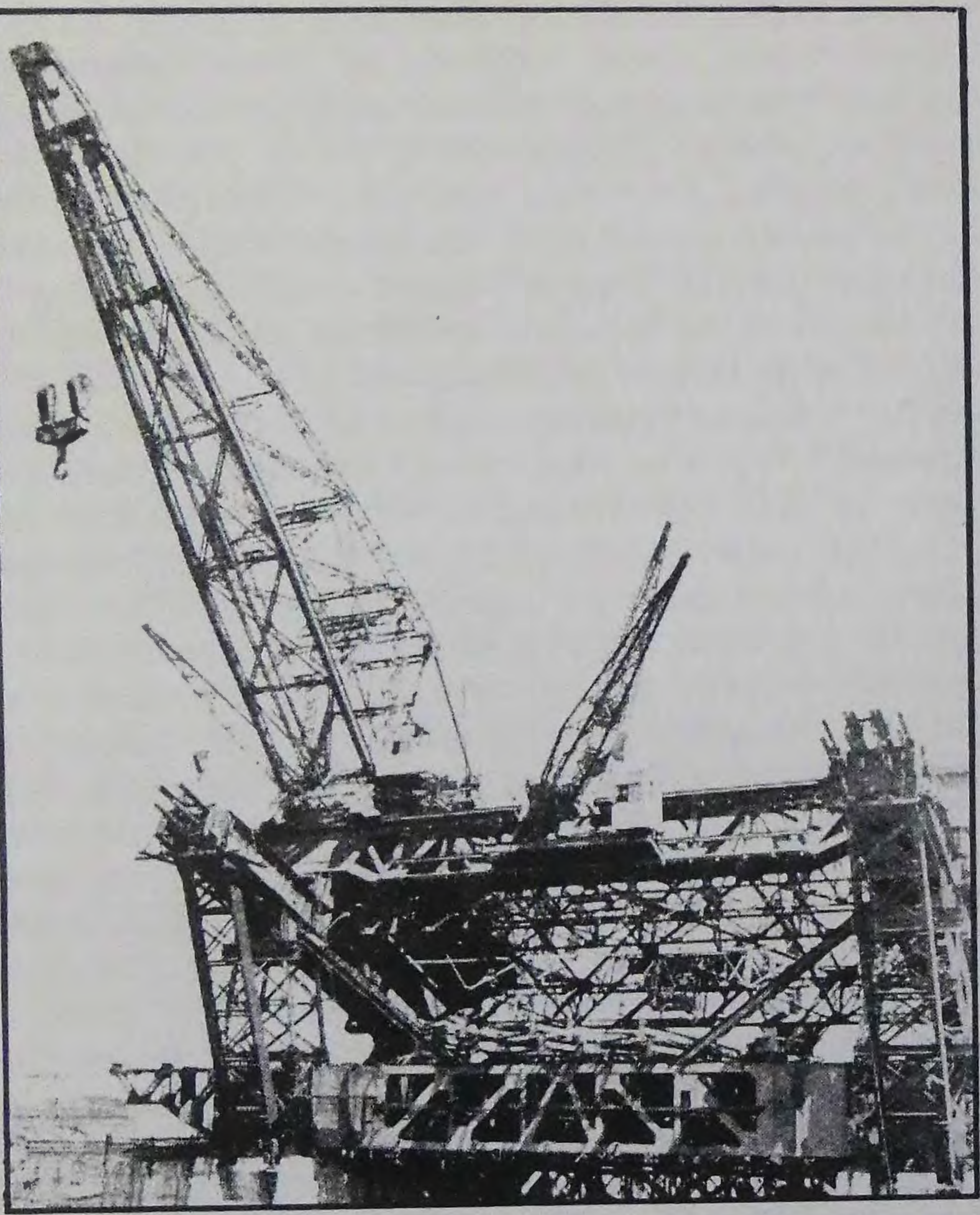

Fig. 5. A Creeper Crane on the Steel Ramp

approach piers and the two abutment towers. Concurrently with this work on the southern side, a retaining wall some 40 ft. high was constructed on the eastern side of Dawes Point park along Hickson road. The wall embodies as part of its structure the concrete bases of approach piers Nos. 2 and 4.

The approach spans were supported on timber falsework erected by means of five-ton steam locomotive cranes, which moved forward on the falsework so erected. At the extreme end of the approach, meanwhile, a 25-ton electric crane was erected on timber trestling. This crane erected the steelwork of the approach spans on the falsework in front of it, working down towards the harbor, and was so arranged to travel out on the deck of the span which was being erected in front.

On each side, the approach spans were built successively towards the harbor, and in the meantime the abutment towers on each shore were constructed, so that the fifth approach span on either shore was completed, resting on the back wall of the abutment tower.

The 25-ton crane, having completed the steelwork of the approach spans, then constructed the steel deck above the abutment towers, and erected the steel ramps for supporting the creeper cranes, Fig. 5, the top surface of the ramps corresponding to the level and plans of the top chord of the arch. The 25-ton cranes were required to dismantle the creeper cranes, and for constructing the pylons and removing the erection cables.

Each creeper crane weighs 605 tons, of which the undercarriage weighs 330 tons. The main hoist will lift 122 tons through a height of 480 ft., being operated by two 120-h.p. motors. At the rear of the traversing carriage are two $2\frac{1}{8}$-ton derrick cranes for handling material, stagings, etc. The five-ton "walking crane" on the front of the undercarriage is independent of the main crane, and is fitted with hoisting, traversing, and slowing motions.

The main span was erected by cantilevering out from each shore, the half-arches on each side being held back by means of a cable anchorage of 128 cables, attached at the tops of the end posts, passing over steel saddles supported rigidly on the floor of the abutment tower in eight rows of 16 cables, thence (to ensure that the cables did not touch other) through individual wrought iron pipes in the concrete tunnel saddles at the mouths of the cable tunnel in 32 rows of four cables each. The cable tunnel, 120 ft. long on the slope, is inclined at 45 deg. to the vertical, and meets to form a loop enclosing a mass of solid sandstone, the weight of which resists the upward pull of the cables.

The abutment towers are required for the erection of the arch. The reinforced concrete slabs forming the floor of the abutment towers at R.L. 155.50 supported the tower saddles, through which the 128 cables were rooved in eight rows of 16 cables each, and formed immovable supports for the cables, as the abutment towers are unaffected by wind and temperature, which were important factors in the erection of the arch. The floor of each abutment tower was also utilised as a working platform.

The scheme of erection in the early cantilever stages consisted of attaching numbers of cables to the tops of the end posts to balance the arch, the number of cables being increased as the load on the arch increased. The solid mass of the abutment tower formed a support for a temporary raking strut between the top of the end post and the top of the abutment tower, against which the cables strained back. The cables and struts are clearly seen in Fig. 6. This "temporary raking strut," rigidly supported at its base, formed a steady support for the arch, and enabled the stress per cable to be increased considerably in excess of the amount necessary to balance the arch; the frictional resistance of the cables round the tunnel face was thereby increased, and the possibility of the cables slipping in the tunnels under the action of wind and temperature on the structure became negligible.

Fig. 6. Commencement of Arch Erection, showing Straining Cables and Raking Struts

For the first few panels of the arch it was impracticable to use temporary sway frames at each vertical, as was done later, and if the arch had only been hanging from cables without the raking struts, the relative deformation of one arch truss in regard to the other when the jib of the creeper crane was traversed and a heavy member lifted directly over one truss would have been sufficient to produce heavy bending stresses in the top and bottom lateral bracing, sufficient to bring about collapse of the structure. Many of the members lifted in the first few panels of the arch weighed about 100 tons; the main jib and its carriage, with the member lifted, weighed about 400 tons—a heavy eccentric load. By means of the rigid support formed by the raking struts, the deformations were reduced to a minimum, and the lateral members were not overstressed in bending. The raking strut with its rigid base was vital in the early stages of the erection scheme, and without the rigid support formed by the abutment tower its use would have been impracticable.

The cables required for the anchorage were threaded into position round the cable tunnel, through the tunnel saddle and pylon saddle, and the free ends were laid over the front wall of the abutment tower. Each cable is 2.76 in. in diameter, approximately 1,200 ft. long from end to end, and is made up of 217 wires, one centre wire 0.20 in. diameter, and 216 wires each 0.16 in. diameter. The ultimate strength of a cable is 360 tons as a minimum; the final load carried per cable was 125 tons. Each cable was cut to the correct length and fitted with a cast steel socket. To connect the cable to the socket, the cable was passed through the socket; the wires were opened up and cleaned, some wires being bent over at the ends, and the socket forced upwards on the cable until the opened wires filled the bell-shaped mouth of the socket. The whole of the socket, with its contained wires, was heated by blow-lamps, and molten white metal of composition-lead 86 per cent, antimony 11 per cent, tin 3 per cent was then poured into the socket. When solidified, the socket connection developed the ultimate strength of the cable itself. All socketing of cables was performed in sheds erected on the end of the pylon cross-girder.

The final anchorage consisted of 128 cables, arranged at the end post in eight horizontal rows of 16 cables each. The cables had two 3-in. bolts per cable fitted with special thread, nuts, and spherical-seated washers; the bolts passed through the socket flange and on either side of a pin 11 in. in diameter, which was grooved to allow the passage of the bolts. At the back end of the pin, the bolts passed through a rectangular forged steel saddle, and projected beyond the saddle a sufficient distance to allow the nuts to be slackened off when the cables had to be removed after the arch had met at the centre. The 11-in. diameter pins bore on large fan-shaped built-up steel link plates; five links to each anchorage were connected to the top chord by means of two pins 27 in. in diameter, each 6 ft. 1 in. long. The pins passed through holes 27 in. diameter in the webs of the top chord, suitably reinforced by pin plates. The weight of the link plates is taken by the joist on the end of the end post bracket.

As the erection proceeded, panel by panel, only sufficient cables were attached and tensioned up to balance the arch and to ensure that the permissible load on the raking strut would not be exceeded under changes of temperature. Eventually, at the seventh panel, the whole of the 128 cables were in action, and the raking strut was no longer required.

When attaching cables, first the anchor bolts and saddles were put in position, and the cable socket was threaded on to the ends of the bolts to a calculated distance, so that the stress in each cable was about 10,000 lb. In order to tension up the cables, hydraulic jacks were used, operating on the back ends of the bolts behind the saddles, the jacks thrust against a cross-head bolted on the ends of the bolts and pushed back against the saddle, so that the nuts on the saddle were relieved of stress. When tensioning, the whole cable was jacked up in this way, the bolts moving through the saddle, and the nuts were turned by hand following the movement of the jacks, until the desired load was in the cable, as measured by the pressure gauge on the jack. The tension was checked from time to time by vibrating the cables over the length of 133 ft. between the end post and pylon saddle. According to the properties of the cables, its span, weight per ft., etc., the stress in the cable is related to its rate of vibration per minute. This formed a check on the equal distribution of load in the cables.

The heavy members of the first panel on the Dawes' point side were landed within reach of the creeper crane by the "Titan" floating crane. The first member lifted into place was the section of the first panel of the lower chord adjacent to the western bearing at Dawes point. This member was put in place on October 26, 1928. It weighed 88 tons. The arch trusses were completed on September 10, 1930. The corresponding member of the eastern truss at Dawes point, was placed in position on November 7, 1928.

The arch was cantilevered out panel by panel, the cables supporting the steelwork as it was built out. When 13½ panels had been erected on each side, the weight of steelwork in each half-arch was 13,670 tons, supported by 128 cables, the tension on each cable 107.2 tons, the total pull on each system of cables being 27,440 tons, and the thrust on each of the four main bearings being 17,660 tons.

To offset the stretch of the cables and the deformation of the structure as erection proceeded, and to allow a sufficiency between the lower chords for the meeting on the centre pins, the end posts of the arch were set back at the top with a rake off 30 in. from the vertical. At the completion of the cantilever stage of the two half-arches of 13½ panels each, this backward rake was reduced by the stretch of the cables and the deformation of the structure to 18 in. on the south side and 14⅜ in. on the north side; the gap between the ends of the lower chords at the centre to allow for the meeting of these chords on the centre pins was 31½ in. on the east, and 31⅜ in. on the west side. These gaps were affected by temperature and could have been 4 ft. 3 in. at minimum temperature, due to contractions of the cables and steelwork, and 1 ft. 9 in. under maximum conditions, due to elongation of the cables and steelwork.

Both half-arches were finished off identically at the centre joint, and the lower chord on each side was fitted with a heavy forged steel saddle to enclose a pin 8 in. in diameter. Before closure was commenced the 8-in. pins were set-screwed into the saddles on the southern side, and to provide for the half-arches being out of alignment horizontally and vertically, lateral adjustment was provided by means of 10-in. square locking bolts. The pin, saddles and locking bolt for one half-arch are shown in Fig. 7.

The fabricated steelwork of each lower chord at the centre joint was machined to receive the steel forgings which enclosed the centre pins 8 in. in diameter. On the northern half-arches, each steel forging was carried by two of the four web plates, and between each forging a heavy steel diaphragm was built, having an opening 10 in. square, into which the locking bolt from the truss opposite could engage. On the southern half-arches the 8-in. pins in two lengths were set-screwed into the steel forgings, and the locking bolt, 10 in. square with tapered point, was placed in the centre between the two 8-in. horizontal pins, and could be thrust forward by an hydraulic jack into the opening of the diaphragm, which would bring the opposite half-arches into line and level.

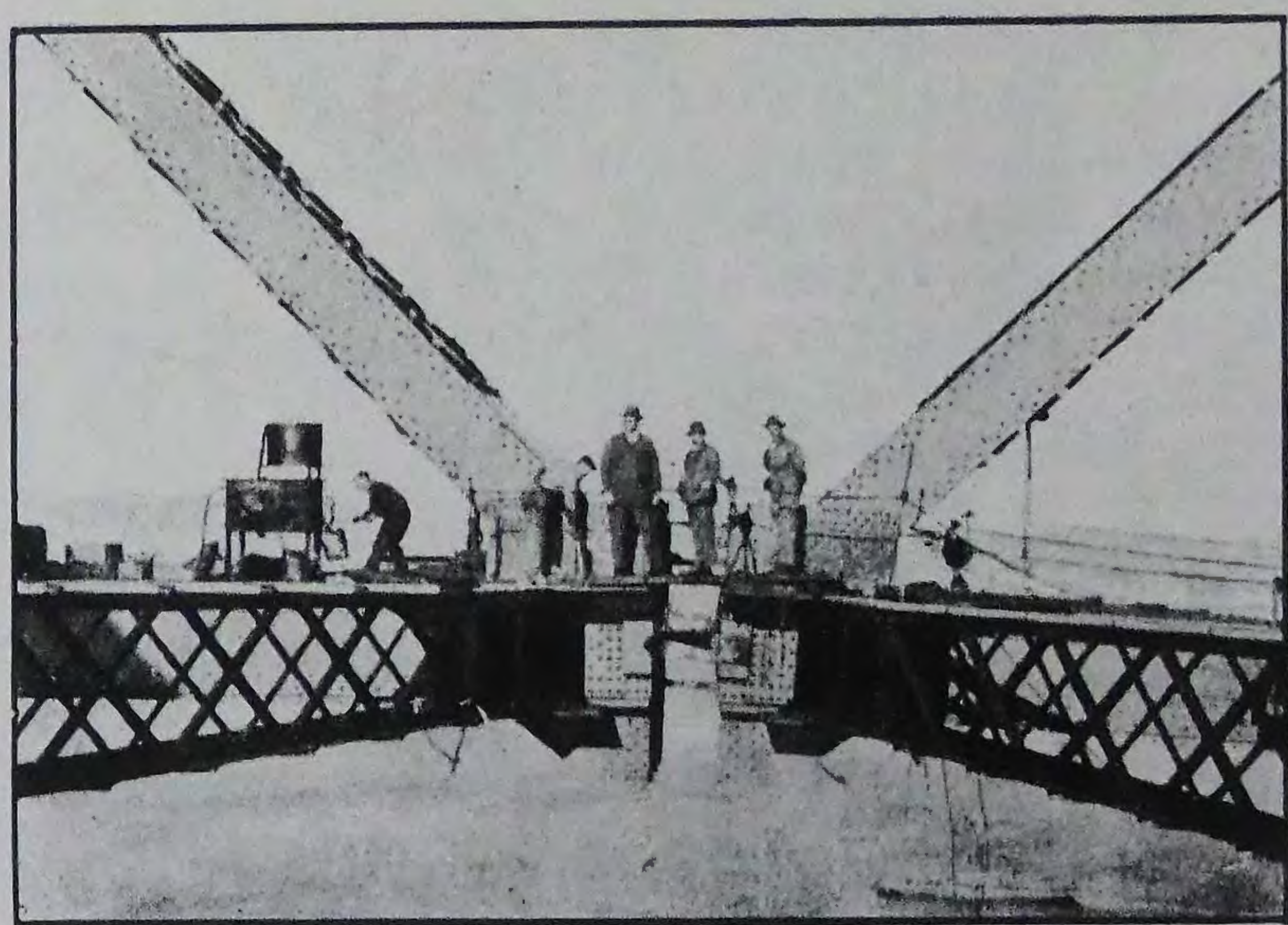

Fig. 7. Closing of One Half-arch showing the Pin, Saddles and Locking Bolt

To close the gap of about 31½ in. between the half-arches the nuts on each pair of link bolts connected with a cable were run forward one by one in successive fleets of 3 in., 4 in., 5 in., and 6 in. respectively. A fleet forward of 3 in. at each end of the arch closed the centre gap by nearly 12 in. Each cable was adjusted independently by means of a high-pressure jacking equipment working up to a pressure of four tons per sq. in.; and to ensure that each cable was let out the exact amount determined on for each fleet, special gauges were used to measure the distance the nuts had to be moved back on the 3-in. link bolts. For the first three fleets the hydraulic jacks operated against the back face of the saddle and pushed the 3-in. bolts upwards by thrusting against a cross-head attached to the ends of the bolts. For the later fleets extension bolts were fitted over the ends of the 3-in. bolts when the outstanding length of these was too short for the jack.

The work was carried out in two 12-hour shifts until contact was made on the centre pins, which took place after the first and the second fleet of 3 in. and 4 in. respectively had been completed on all the 128 cables at each end of the bridge, and the third fleet of 5 in. was in progress, 37 cables being let out on the north side and 53 on the south side. At 11 a.m. on August 19, when the gap was 4½ in. between the eastern and 4¾ in. between the western lower chords, the locking bolts were forced home by the hydraulic jacks to bring the half-arches into correct line and level. Immediately prior to the jacking, the half-arches—mostly caused by temperature—were about 3¼ in. out of line horizontally and 2 in. vertically, the sun influencing the half-arch and cables on the northern side more than on the southern and the eastern truss very slightly more than the western truss.

The fleeting forward of the nuts was continued until, at 10 o'clock p.m., August 19, at a mean temperature of 62 deg. F., full contact was made on the pins. The circumstances proved ideal, as the temperature continued constant throughout the night, until it began to increase with the sunrise, which ensured that the half-arches did not draw apart, as would have happened had a fall in temperature caused the cables to contract. Once full contact was made, as the slacking of the cables continued, the half-arches bore on the centre pins with an ever-increasing intensity.

The arch was now in a three-hinged condition except for the residual tension still in the anchorage cables. The rake-back of the end posts at this stage had been reduced to 5⅜ in. on the south and 5⅜ in. on the north side; the half-arches had dropped 4 ft. 1¼ in. at the centre, due to the fleeting forward; and immediately prior to meeting, the centre pins were 348 ft. 6 in. above the level of the centre of the pins in the main bearings at the abutments.

The third, fourth and fifth fleets of the nuts were completed when the tension in the cables was reduced sufficiently to admit of their being detached from the link plates at the ends of the top chords. This was carried out by means of a special frictional gripping device attached to the cables some 20 ft. behind the arch, and then by pulling on this grip with the 25-ton crane through a heavy block-and-tackle purchase, and working in conjunction with the hydraulic jacks, the cable bolts being released from the link pins, and the cables were allowed to slide back until the socketed ends rested against the pylon saddles. When the operation was completed at one set of link plates, there was practically no tension at the other end of each cable, which was removed from the link plates and run down to the pylon saddle by means of a light electrically-driven winch. Whilst the cables were being disconnected from the link plates, the erection of the centre posts, top chords, and top lateral bracing of the 14th panels was undertaken.

During the erection of the half-arches the structure consisted of two cantilevers, in which the top chords were in tension. In order to withstand the high-tension erection stresses, the four vertical webs of the top chords of the first five panels were strengthened by means of additional plates attached thereto by specially-fitted pins and bolts. The weight of this additional erection material was 798 tons.

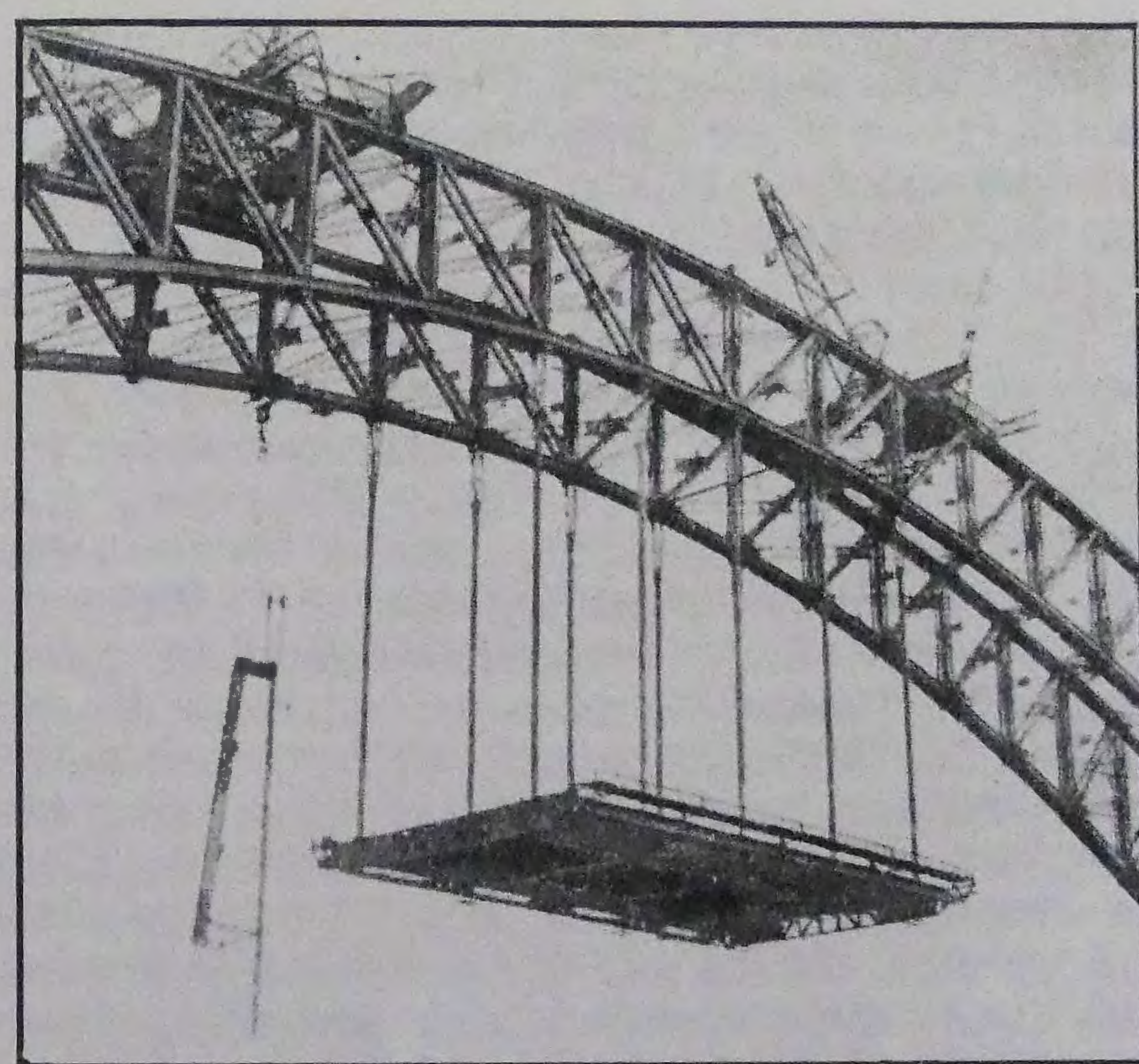

Fig. 8. Lifting of Vertical Hanger by Steel Cradle

Before the final jacking operations were undertaken to change the arch from the three-hinged to the two-hinged condition, it was necessary for each member of the arch to have its final effective section, so that, while the cables were being disconnected, the pins and bolts connecting the temporary tension plates in the five end panels were driven out, so that the temporary erection material would not take any of the jacking stress. The arch was converted into the two-hinged condition by jacking the top chords apart at the centre top chord joint.

The permanent joint at the centre of each top chord consists essentially of four forged steel saddles enclosing two pins, each 10 in. in diameter. The saddles and pins were hung in the gap between the chords in a special frame before the four hydraulic and eight screw-jacks were assembled. As the force was applied by the hydraulic jacks, the screw-jacks were made to follow up the motion, as the gap between end plates of the chords opened out. The difference between the overall width of the permanent saddles and pins, and the distance between end plates of the two chords after jacking, was to be made up by parallel fitted filler packs measured off and machined out of forgings provided for the purpose.

The calculated thrust depended upon the elasticity of the structure, the loads upon it, and the temperature of the structure. The members of the arch had to be brought into their proper elastic condition, and to effect this the temporary reinforcing plates in the first five panels of the top chords on each side were disconnected; as the cables were being removed, the tension in the chords was relieved sufficiently to allow this to be done.

The cables were removed as rapidly as possible, careful note was made of the load imposed on the structure by the erection equipment, and thermometer stations had been established at 24 points throughout the structure. Meanwhile the jacking equipment was assembled in the space between the ends of the top chords at the centre. This consisted of four hydraulic jacks, each 950 tons capacity, two operating near the top and two near the bottom flange of each top chord. Each jack was made of 3 per cent nickel steel, $2\frac{1}{2}$ in. thick, and worked at a pressure up to 4 tons per sq. in. Two screw-jacks were placed alongside each hydraulic jack to follow up the movements of the latter, eight hydraulic and 16 screw-jacks being employed in all for the jacking. The screw-jack consisted of a central cylinder into which left- and right-hand buttress-threaded rams were screwed. By rotating the central cylinder with capstan bars, the required movements were obtained. The hydraulic pressure on each truss was supplied from two hand-operated pumps with the necessary gauges. Each jack and gauge had been calibrated under the specification in the 1,250-ton testing machine provided by the contractors under the specification for testing model members for the bridge.

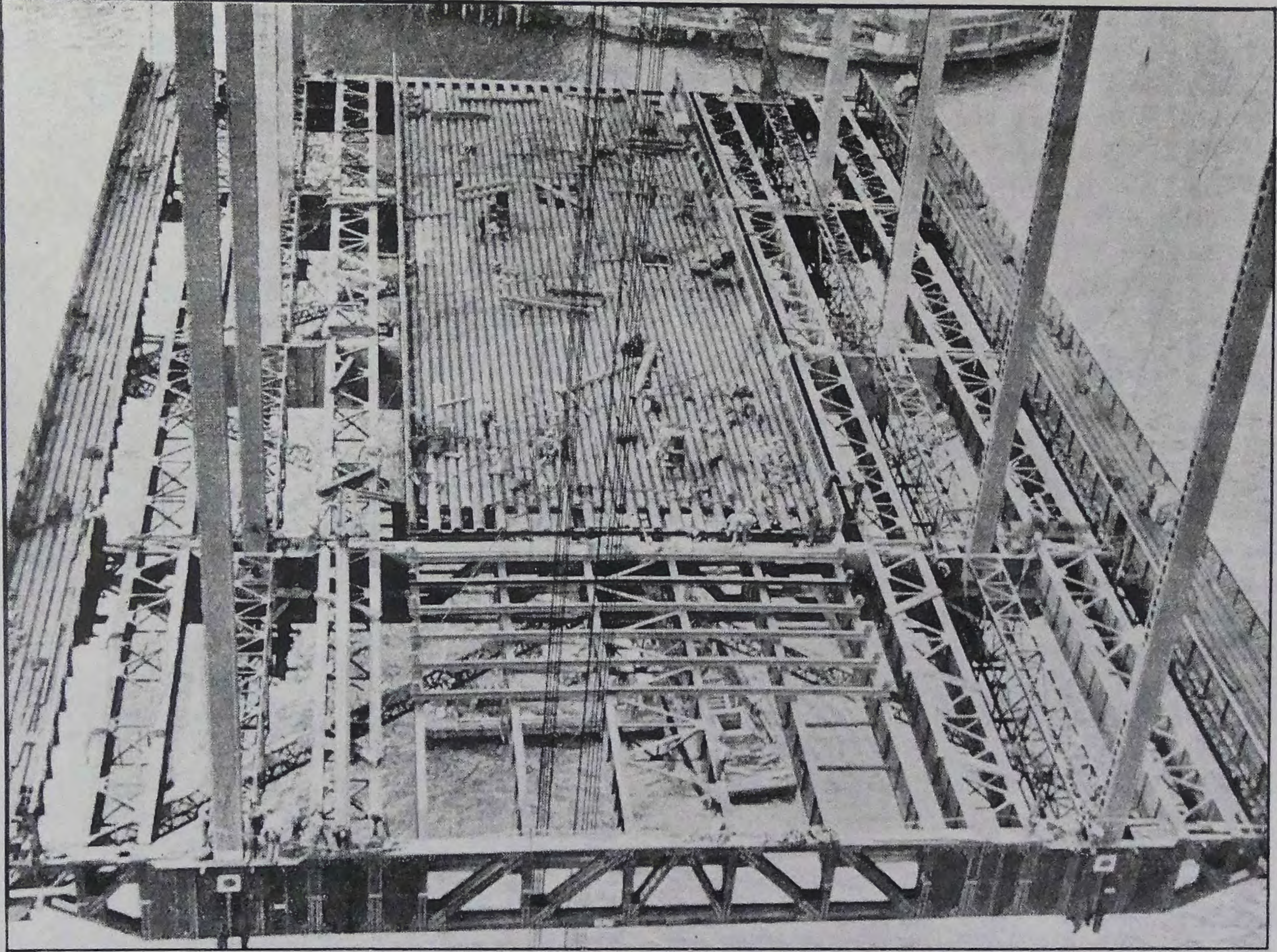

Fig. 9 The Decking of the Bridge showing the Position of the Roadway, Electric Railway Lines and the Footways

On Monday, September 8, 1930, the cables had been all removed except 37 on the southern side and 15 on the northern side, and some of these were hanging slack. The day was cloudy and extraordinarily well suited for the performance of the final jacking operation, on account of the equable temperature and the extremely small variations in the temperature of the various members of the structure as indicated by the 24 thermometers. It was accordingly decided to perform the jacking before the remaining cables were released, as the possible error involved in the calculation of the effect of the weight of the cables was less than that which would have been caused in determining the mean temperature and its effect had not such perfect temperature conditions prevailed. The jacking force, as calculated for a temperature of 60.5 deg. F. was 3,272 tons per truss, corrected by —22 tons for the cable effect, and so at 5.15 p.m. the 3,250 tons force was applied by the jacks to each arch truss.

During the operation the chords were forced apart a total distance of about $5\frac{1}{4}$ in. The total gap on completion of the jacking was 20 9/16 in. on the eastern truss, 20 25/32 in. on the western truss. The space occupied by the saddles and pins was 24 in. The remaining space was filled with fitted packs in pairs. Three were machined to size, and on the morning of September 10 the packs were fitted in position, the load on the jacks released, and the jacks removed.

From the time the lower chords met on the 8-in. pins until the top chords were jacked up and all cables removed, the centre of the lower chord rose upwards a distance of 1 ft. $1\frac{1}{2}$ in., the elevation of the centre pins at a temperature of 65 deg. F. being 349 ft. $7\frac{1}{2}$ in. above the level of main bearing pins. With total dead load the structure assumed its geometrical form; with the elevation of the lower chord centre joint 350 ft. above the level of the main pins at a temperature of 72 deg. F.

As soon as the arch was completed the erection of the deck was undertaken. The hangers, 42 in number, vary in length from 192 ft. at the crown to 21 ft. at the fourth panel point from either end. The hangers are of box section, 3 ft. $\frac{1}{2}$ in. x 2 ft., and bored for the 14-in. pin which connects the cross girder to the hanger.

The long, slender hangers had to be lifted from the horizontal to the vertical position by a specially-designed steel cradle 110 ft. long, as shown in Fig. 8. The hanger was secured to the cradle by means of a pin 6 in. in diameter. The creeper crane lifted the cradle which supported the hanger, and the cradle was tilted from the horizontal into the vertical position by the jigger hoist of the creeper crane as the cradle was lifted by the main hoist.

In the shops the cradle and hanger were handled by the 125-ton overhead crane attached to V-links near the centre of gravity of the hanger. The hoisting arrangements in the field consisted of a special link attached to the main 122-ton hoist of the creeper crane. From this link a bridle made of sections of the arch anchorage cables and U-bolts was connected to $7\frac{1}{2}$-in. diameter pins in the head end of the cradle $10\frac{7}{8}$ in. above the top flange of the cradle girder. For tilting into a vertical position, the 20-ton jigger hoist was connected to a bridle with a double purchase between the main hoist link and the pulley wheels on the top of the horn bracket. The main hoist and jigger hoist travelling at the same speed ($12\frac{1}{2}$ ft. per min.) lifted the top end twice as fast as the bottom end, until the hanger became vertical.

When the hanger was vertical, the jigger hoist was slackened off, and the cradle took up a position such that the hanger was balanced vertically but offset about 9 ft. 6 in. from the line of the main hoist. The whole was then swivelled round at right angles so that the hanger was in position immediately under the lower chord. From this position the top end of the hanger was entered into the gussets.

When the first pair of hangers were in place, the centre cross-girder was hoisted from the pontoon by both cranes, each crane hoisting one end of the girder. The weight of the main cross-girder was 95 tons. For subsequent cross-girders, one crane only could be employed, lifting from the centre of the girder.

As three sets of hangers and cross-girders were completely erected, forming the two central panels of the deck, all the steel stringers, joists, handrails and trough plates were hoisted by the creeper cranes and fixed in position complete. The deck was erected in this way, panel by panel on both sides of the centre, until the creeper cranes regained their original situation on the first panels of the arch.

The 25-ton cranes which had originally erected the approach spans were set up on timber gantries to dismantle the creeper cranes, and then were themselves taken down by seven-ton cranes erected on timber trestles for the completion of the pylons.

Deck details now remained to be finished. The pipe handrails on the parapets were fitted into place throughout the length of the bridge, and overhead wiring structures were erected on approach spans, pylons, and main span.

Coke concrete was poured in the steel troughs of the roadway deck, and for a thickness of 4 in. above the troughs. The concrete was poured in three strips, commencing on the northern approach spans, then the southern approach spans, and the main span working from the centre.

The coke concrete was of a type specially developed for the bridge, using metallurgical coke from the south coast and high-strength cement. On account of the large span of the arch, every lb. per ft. run of bridge requires half a ton of steel in the bridge to carry it, so that lightness was an essential feature of the concrete.

After an exhaustive series of tests, the composition and grading of the coke concrete was finally determined. The concrete consists of four parts of metallurgical coke, $1\frac{1}{8}$ in. in size down to $\frac{3}{8}$ in., $2\frac{1}{2}$ parts of fine coke, from $\frac{1}{4}$ in. size down to dust, and one part of special cement, giving 7,000 lb. per sq. in. crushing strength when mixed with standard sand in a

3 : 1 mortar at 28 days. The laboratory tests of the concrete gave results of 3,000 lb. per sq. in. crushing strength at 28 days. Some field tests actually cut out of the pavement gave 4,000 lb. strength.

A pavement of natural rock asphalt, 2 in. thick, followed closely behind the concrete, and asphaltic concrete on the footways, 1 in. thick above the troughs.

The completed roadway was now utilised as a working space for the timber decking on the railway tracks. The ironbark transoms and sleepers were dressed and lifted over the parapets, bolted in place on the steel stringers carrying the tracks, and followed by hardwood planking forming the decking between the rails.

Rail and guard rails were delivered on the roadway, with all permanent way material, sleeper plates, bolts and spikes, hoisted over the parapets and spiked in position. The permanent way details call for rail expansion joints to take up the movements of the bridge, the main joints allowing an expansion of 12 in.

The rail expansion joint between approach spans consists of a cast manganese steel expansion bar bolted against the web of the rail on the outside and projecting slightly on a ramp above the top of the head of the rail, part of which is cut away on the outside. The tread of the wheel is carried by the bar over the rail gap, the bar having slotted holes on one side for the purpose of allowing the expansion to take place. When the wheel has been carried over the gap, the ramp of the bar allows the true rail to take up the load. The car wheels will thus be carried over the rail gap smoothly without any pounding. Heavy built-up checks guide the flange of the wheel past the joint.

The main span rail expansion joint is similar in principle to a switch except that the switch can never open, but sliding motion is allowed between the fixed switch rail and the moving rail alongside. The switch rail is bolted down to a solid base plate by means of steel castings; similar castings provide a guide for the sliding rail. With this arrangement there is no gap to be traversed, and continuous smooth running is assured. Heavy built-up check angles ensure the alignment of the wheels passing the joint.

For the present only two of the four tracks will be used for railway traffic as the maximum number of trains passing over the bridge in an hour will be 24, which can be easily dealt with on two tracks. Not until the traffic reaches about 40 trains per hour will the other two tracks be necessary for the trains. Cabinet has given a direction that trams as well as trains shall run across the bridge. The trams will be carried on the two easternmost tracks, leaving the western pair of tracks for the railway traffic.

The bridge will have been thoroughly tested before opening for traffic by means of locomotives and tenders placed on the bridge to develop the worst conditions likely to occur in regard to loading. After a full series of deflections and extensometer readings under the weight of the arch itself the locomotives were placed on the bridge, covering all four tracks for a distance of 1,100 ft. over the centre of the main arch, and a further set of deflections and stress measurements were performed. The most severe test was that which followed, viz., to place the locomotives on all four tracks so that they covered one-half of the arch span only, when deflections and stresses were observed. The testing occupied about four weeks in the month of February, after which the locomotives were withdrawn ready for the opening day on March 19.

Asphalt Construction on the Sydney Harbor Bridge

On the main arch, steel approach spans and roadway approaches of the Sydney harbor bridge, three types of asphalt construction have been employed. These include natural rock asphalte, standard sheet asphalt and mastic asphalte.

Natural rock asphalte, a pulverised limestone naturally impregnated with bitumen, forms the wearing surface of the main roadway 57 ft. in width extending over the arch and approach spans, a total length of 3,770 ft. The area involved is 24,000 sq. yd. The surface of the concrete previously laid in the steel troughing of the bridge deck was first lightly waterproofed

Fig. 1. Southern Approach Crescent of 3-in. Sheet Asphalt Laid by the Sydney City Council

with Curcrete, a natural bitumen emulsion. On this, the rock powder, heated to a temperature of about 250 deg. F., was spread and screeded evenly and lightly rolled with a hand roller weighing about 6 cwt. It was then compressed by ramming with heated 60-lb. tampers and afterwards rolled with a heated hand roller weighing about 16 cwt. A final smoothing and finishing was effected with heavy, hot smoothing irons, the compressed thickness being 2 in.

An important feature of the bridge roadway is the mastic asphalte margin or gutter. This is laid 9 in. wide on both sides of the road throughout the entire length of the bridge and provides a run-off for surface water. Floated into place by hand in advance of the compressed asphalte work, this mastic construction enables accurate setting of iron gullies leading to the down-pipes.

Footways

Over the footways of the main arch and steel approach spans a sheet asphalt wearing surface has been provided. These footways are 10 ft. in width, one each side of the bridge, their area totalling 8,400 sq. yd. The steel troughing which forms the deck was first painted with bituminous paint and then filled with the hot sheet asphalt mixture. Upon this was placed the 1-in. asphalt surface, care being observed to maintain the requisite camber. Compression was effected with a 2½-ton tandem roller which was found to be better suited than the three-wheeled type for preserving the surface contour in the confined space in which the work had to be done. The fillet along the edges, where the pavement meets the steel, is composed of hot mixture worked into place with wooden floats, thus providing a watertight joint.

The asphalt mixture for the footways comprised approximately 11 per cent of bitumen (soluble in CS_2), 10 per cent of filler passing 200-mesh, and 79 per cent of sand complying with the requirements of standard sheet asphalt grading. The penetration limits of the asphalt cement (Trinidad) were 35 to 40 (100 g., 5 sec., 77 deg. F.).

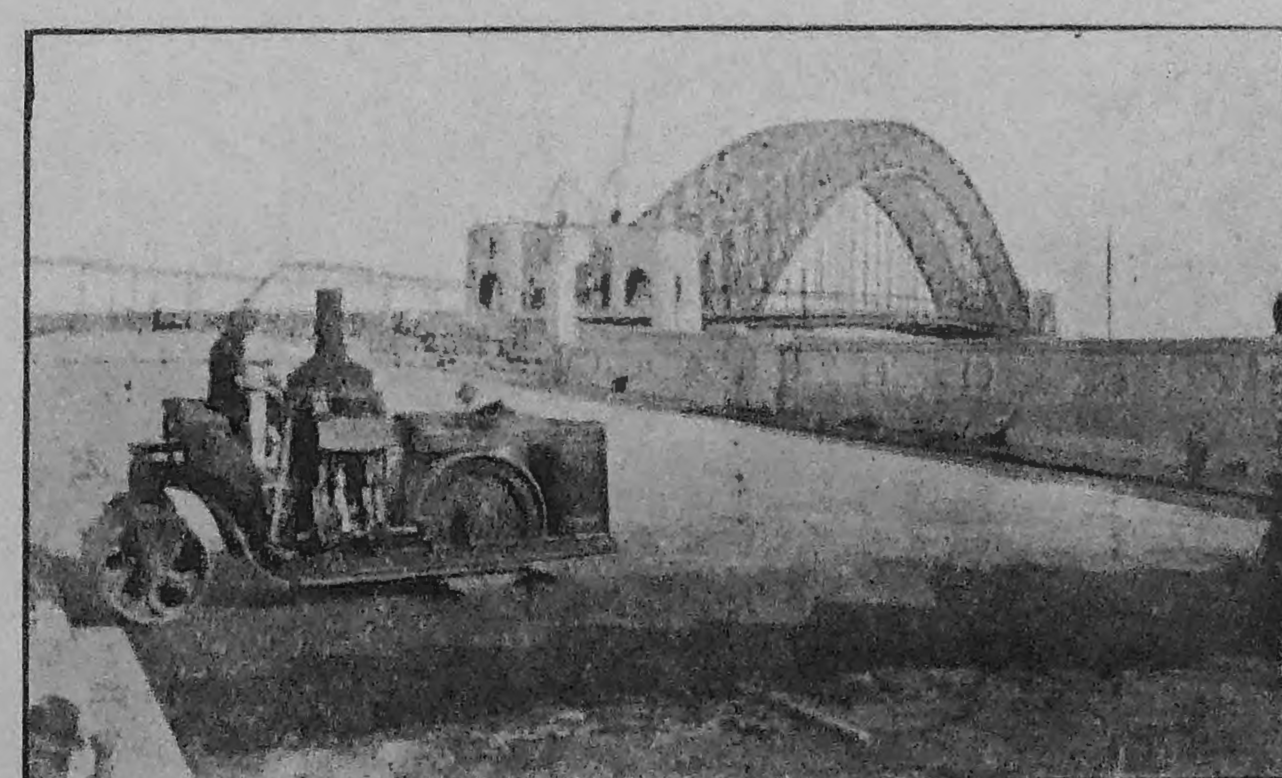

Fig. 2. Compressing Trinidad Sheet Asphalt Wearing Surface on the North Approach Roadway

Roadway Approaches

Sheet asphalt of the standard type, comprising a 1½-in. course of close binder over which is laid a 1½-in. course of sheet asphalt topping, carries vehicular traffic over the northern and southern approaches, each approximately 16,000 sq. yd. in area. The road foundations and the gutters and kerbs are of cement concrete.

For the northern approach, the binder as laid consists of 4 to 5 per cent of soluble bitumen, approximately 20 per cent of asphalt sand, and the balance stone up to 1 in. in largest diameter. Upon the binder is placed the sheet asphalt wearing course, composed of 9.5 to 10.5 per cent of bitumen (soluble in CS_2), approximately 10 per cent of filler passing 200-mesh, and the balance asphalt sand carefully graded to comply with Richardson's limits modified to suit modern traffic requirements. This mixture was delivered at a temperature of between 300 and 320 deg. F., raked evenly and rolled with an eight-ton tandem steam roller, the binder laid each day being covered with surface insofar as practicable. Especial care was observed to adjust the rolling to smooth out any minor irregularities in raking. To accomplish this, the first passage of the roller was usually in a diagonal direction, this being quickly followed by longitudinal, transverse and circular rolling. A light dusting of cement was swept over the wearing surface just prior to final compression, to impart close texture and uniform finish. For the northern approach a daily average of 665 sq. yd. of completed 3-in. surface was maintained.

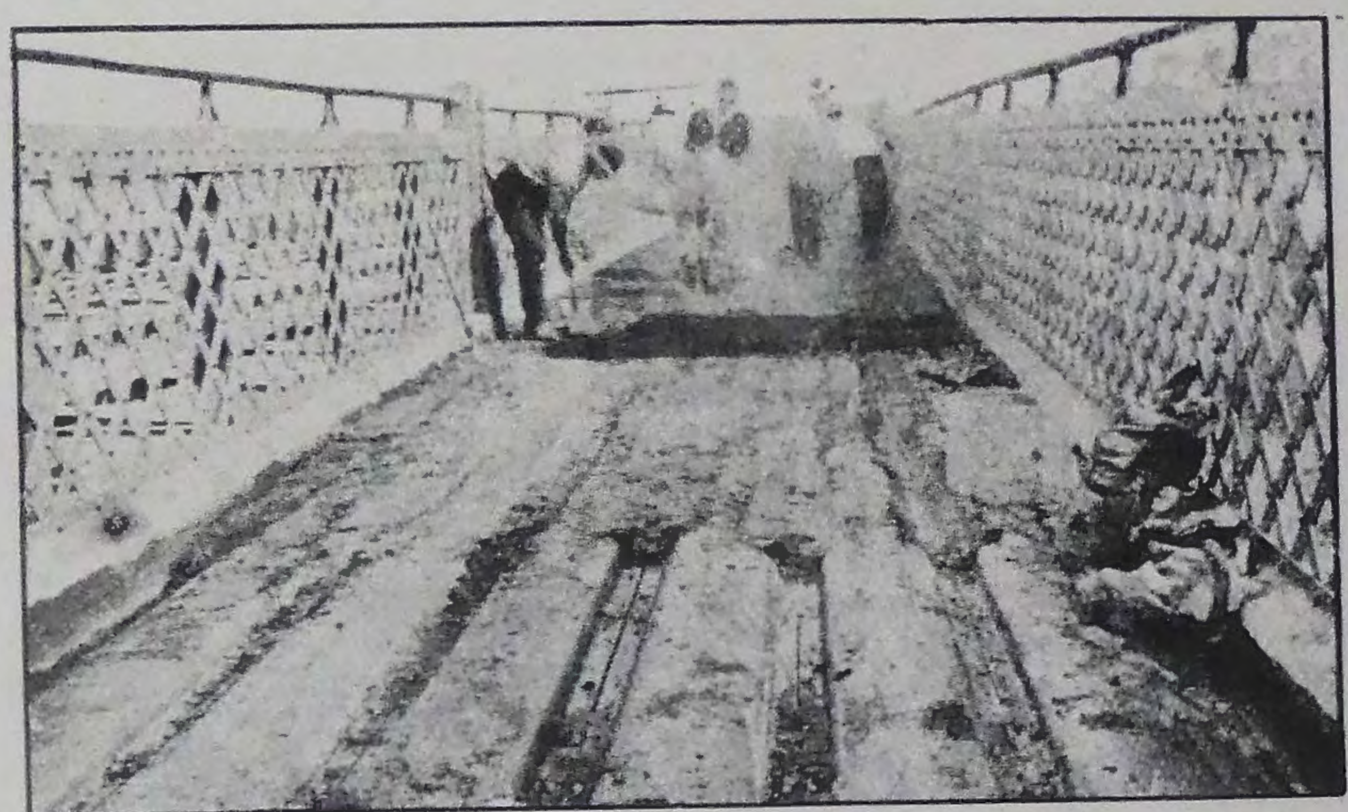

Fig. 3. Placing Sheet Asphalt Surface Mixture in the Bridge Footways

South Approach Crescent

The roadway of the southern approach crescent comprises about 6,000 sq. yd. of two-coat sheet asphalt construction similar to that of the northern approach. The bitumen content of the surface mixture is approximately 10 per cent (soluble in CS_2), filler 12 per cent passing 200-mesh; and the balance asphalt sand of standard grading. Special care in the regulation of time of mixing was observed to secure uniformity. A tandem roller of 8-10 tons weight was used to obtain consolidation. An average of 640 sq. yd. of completed 3-in. surface per day was attained for this section.

The penetration of the asphalt cement (Trinidad) for the northern approach and southern approach crescent was 40/50 for the binder, and approximately 35 for the topping, under standard test conditions, 100 g., 5 sec., 77 deg. F.

In addition to the mastic asphalte margins laid on the bridge roadway, mastic asphalte is also employed for the balconies of the pylons and the transverse crossings between the pylons underneath the roadway level. The thickness as laid is 1 in.

As chief engineer of the Sydney harbor bridge, Dr. J. J. C. Bradfield was in supervisory charge of all asphalt work. The concrete foundations for the approach roadways and crescent were placed by the public works department, and for the roadways over the main span and steel approaches by Messrs. Dorman, Long and Co. Ltd., the contractors for the bridge.

The Neuchatel Asphalte Co. Ltd., as contractors to Messrs. Dorman, Long and Co. Ltd., laid the compressed asphalte and sheet asphalt footways over the main arch and steel approach spans, and also the mastic gutters and mastic asphalte in and around the pylons. As contractors to the public works department, the Neuchatel Asphalte Co. also carried out the asphalt work of the northern approach roadway. The W. B. Carr Construction Co. laid the asphalt of the southern approach roadway. Asphalt construction of the roadway of the southern approach crescent was completed by the Sydney city council under the supervision of Mr. A. H. Garnsey, as city engineer.