laid bare. Large quantities of clay and material excavated from the tunnels were dumped to form a blanket. The lining was temporarily stiffened against unbalanced pressures at every alternate ring with a horizontal bar 1¼ inches diameter, with sleeve nut adjustment, which was screwed to an initial tension. The work was constructed very expeditiously, and was completed in 1907.

THE PENNSYLVANIA RAILROAD TUNNELS UNDER THE EAST RIVER.—This is one of the greatest subaqueous tunnel works yet undertaken, and comprises four approximately parallel shield driven tunnels, each of 23 feet external diameter, about 3,900 feet long, under the East River

The tubes are of cast iron, lined with concrete, and are 19 feet diameter, inside the lining. The lining is 1½ inches thick, in 30-inch. lengths, each segment weighing about 2,000 lb.

The maximum depth is 90 feet beiow high water to rail, and the minimum thickness of cover over the roof 8 feet, but this was supplemented by means of a clay blanket until the thickness was from 15 feet to 25 feet.

The shields were each 23 feet 6½ inches diameter over all, 18 feet 6 inches long, and weighed about 542,000 lb. They were fitted with 22 rams 9 inches diameter, and two hydraulic segment erectors. The cutting edge was a massive one of cast steel, 30 inches long, drilled above the centre for the connection of a movable semi-circular hood, about 6 feet long. There were two working platforms on the front of the shield, fitted with adjustable extensions for working under the hood, when desired. Two vertical, longitudinal bulkheads divided the shields and working platforms into nine compartments. Each compartment was fitted with an adjustable shutter traversed by a screw of special construction. These shutters could be projected in front of the shield to support the face, or when the shield advanced, they were pushed back under a moderate pressure so as not to retard progress. When the material being excavated was very soft, it could be handled by bars thrust through small apertures in the shutters. The excavated material was shovelled from the back of the shields into dump cars operated by cable traction.

The material passed through in these tunnels varied considerably, including mud, quicksand, boulders and solid rock, requiring at times a pressure of 4,000 tons to advance each shield.

Safety diaphragms were built in the tunnels, and great care taken to prevent injury to the 500 men who were employed under an air pressure up to 35 lb. per square inch.

The tubes were joined in 1908.

THE PENNSYLVANIA RAILROAD TUNNELS UNDER THE HUDSON RIVER.—The internal section of the two shield driven tunnels under the Hudson River is the same as those constructed by the same Company under the East River. The length of the subaqueous section is, however, in this case 5,947 feet, and the design provides for supporting the tunnels over 5,502 feet of this length on screw piles (Plate 2, Fig. 7), placed 15 feet apart, and filled with concrete to a depth of 12 feet below the inverts of the tunnels. The screw piles are 27 inches external diameter, in lengths of 7 feet. A sleeve was provided at the upper end, which cut off the water and allowed of the top length being removed after the pile had been screwed home, when a section of the correct length was inserted. This system of foundations is novel. The tunnels were driven principally through soft silt, with rock at the land ends, but the strata varied very much, including rock over the whole face, gravel, sand over rock, boulders with clay seams, quicksand, sand under silt, and silt over the whole face. It was anticipated that the shields could be driven through without any excavation in front, by closing the doors and applying air pressure, but it was found in practice necessary to take out 25 to 100 per cent. of the excavation. The tubes met in 1906, after which the piles remained to be driven and the lining placed in position.

The author regrets that space will not admit of a fuller description of these most interesting shield driven tunnels under the East River and Hudson River, but members are referred for a more detailed account of these works to recent volumes of the "Engineering Record" and "Engineering News," from which the above brief particulars have been taken.

Reference may also be made to the East River Gas Tunnel, New York, 10 feet 2 inches diameter; the Melbourne Sewerage Tunnels; the Siphon de la Concorde, 7 feet 6½ inches diameter, and the Siphon de l' Oise, 6 feet 8 inches diameter, for the sewerage of Paris; and the Tramway Tunnel under the River Spree at Berlin, 13 feet 2 inches diameter. All of these (see Appendix 1) were shield driven, but space will not admit of a detailed description.

COST OF SHIELD TUNNELLING.—Information of the cost of some shield driven tunnels is furnished in Copperthwaite's standard work, referred to above, from which the following particulars have been principally taken in so far as they refer to subaqueous work.

The following table does not include the cost of the lining:—

	Date.	Internal diameter feet.	Cost lin. yd.	Cost per sq. yd. of internal sec. per yd. forward.
			£	£
1. Greenwich Footway Tunnel	1899	11ft. 9in.	108	9·00
2. Glasgow Harbor	1890	16ft. 0in.	85	3·35
3. Hudson River	1889	18ft. 0in.	300	10·61
4. St. Clair River	1888	19ft. 10in.	200	5·81
5. Blackwall (Section under River)	1892	25ft. 0in.	378	6·93
6. Rotherhithe (Section under River)	1908	27ft. 0in.	412	7·20

Copperthwaite estimates the price as under for iron lined tunnels, exclusive of inside lining, roadway, etc.:—

1. In London clay—£3 per cubic yard of content.

2. In material of fair consistency, without compressed air and with moderate pumping only, up to 16 feet diameter—£3 10s. to £4 per cubic yard of content.

3. In difficult waterbearing strata—£7 per cubic yard of content.

SUBAQUEOUS TUNNELS OTHER THAN SHIELD DRIVEN.

The preceding description of shield driven tunnels has been given as shewing generally what has been done with this method of subaqueous construction. There are, however, in the author's opinion other methods more applicable to the North Sydney connection, where with a depth of 40 feet below L.W.S.T. above the tunnels, a considerable length of the roof of the tunnels will be either out of ground, or with such a shallow cover that it would be necessary to deposit a heavy blanket of clay, before a shield driven by compressed air could be used.

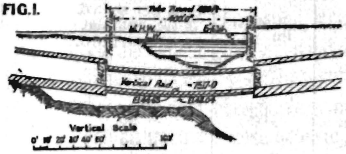
Three notable examples of subaqueous tunnels constructed by means other than a shield are given below:—

THE HARLEM RIVER TUNNEL, NEW YORK.—The New York Rapid Transit Railroad is carried under the Harlem River by means of a double track tunnel 1,500 feet long, of which 641 feet consists of a twin cast iron tube cased in concrete, as shewn in Fig. 1. There is here a maximum depth of about 26 feet at mean high water, while the distance from mean high water to the top of the invert is 46 feet maximum. The bed of the river is of soft mud, overlying clay and quicksand, and it was necessary to keep one half of the channel open for navigation. The work was carried out in five sections. The method adopted for the river section was to dredge a trench to a little below the springing line of the tunnel, and to enclose it on either side with sheet piling. In the trench were driven rows of piles, 8 feet apart, 5 piles in each row, for permanently

HARLEM RIVER TUNNEL

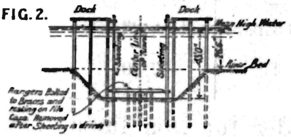
FROM ENGINEERING RECORD

FIG. 1.



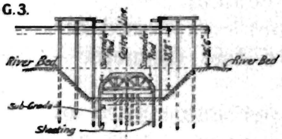
LONGITUDINAL SECTION

FIG. 2.



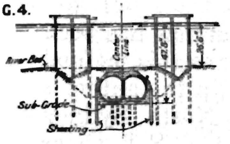
Tunnel Trench, Docks, and Submerged Frame resting on Pile Caps
First Stage

FIG. 3.



Sheeting cut off and upper part of Tunnel Shell in position forming the Roof and Side Walls of a Working Chamber
Second Stage

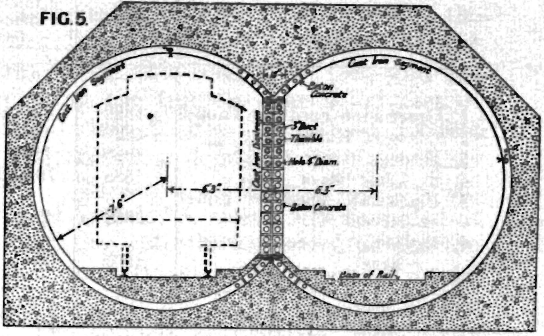
FIG. 4.



Section of completed Tunnel Docks to be removed and Back-Filling completed under them
Third Stage

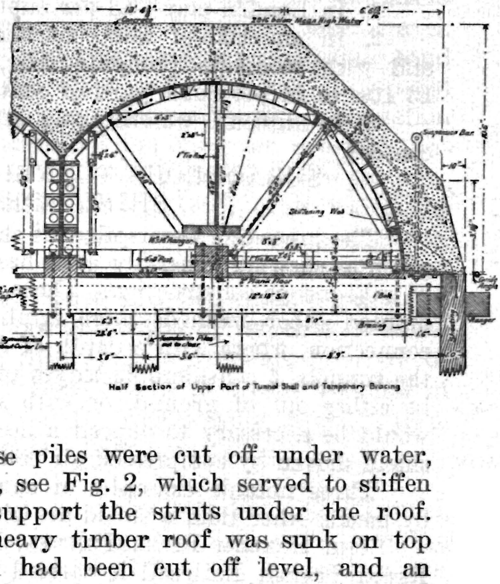
CHARACTERISTIC OPERATIONS IN TUNNEL CONSTRUCTION

FIG. 5.



TRANSVERSE SECTION OF TWIN TUBE TUNNEL.

FIG. 6.



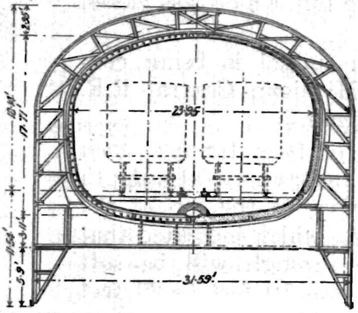
Half Section of Upper Part of Tunnel Shell and Temporary Bracing

supporting the work. These piles were cut off under water, and were connected by caps, see Fig. 2, which served to stiffen the sheeting, and also to support the struts under the roof. In three of the sections a heavy timber roof was sunk on top of the sheet piling, which had been cut off level, and an air-tight chamber was thus formed in which, using compressed air, the invert of the tunnel was excavated and the cast iron lining assembled, and surrounded by concrete. In one section, 264 feet long, the bold expedient was adopted of using portion of the permanent work as a roof, instead of employing a temporary roof of timber. Under this method, after the sheeting had been driven, the upper portion of the cast iron segments was put together on a pontoon in lengths of 90 feet and surrounded with concrete. A false bottom was fixed to the inside above the springing line, and bulkheads were fixed at each end, while manholes were provided in the roof. This construction was floated out and sunk on to the sheet piling (Fig. 3), and connections made by divers with the finished work, after which the false bottom was removed and the excavation of the invert carried out, and the remainder of the tunnel constructed under air pressure as before. The amount of excavation carried out under the roof was about 3 cubic yards per lineal foot (this was exclusive of the quantity previously dredged) while the total amount of concrete required was 7 cubic yards per lineal foot of tunnel. After completion of each section it was back filled. (Fig. 4.)

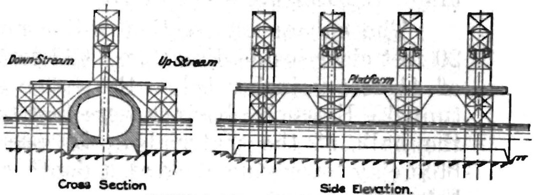
This tunnel, which is described in the "Engineering Record," and other American journals, was successful completed in 1904.

SEINE TUNNEL OF THE METROPOLITAN RAILWAY OF PARIS.—The method adopted for carrying out the tunnel under the River Seine is quite different to that in any of the other tunnels referred to. It was originally proposed to use the shield method with two single line tunnels, but the system adopted provides instead for constructing by means of caissons sunk under compressed air, as shewn.

SEINE RIVER TUNNEL
METROPOLITAN RAILWAY OF PARIS
FROM "LE GENIE CIVIL" OF DEC. 1905.



CROSS-SECTION OF CAISSONS FORMING RIVER TUNNELS.



Cross Section
Side Elevation.
DIAGRAM SHOWING CAISSON AND WORKING STAGINGS.

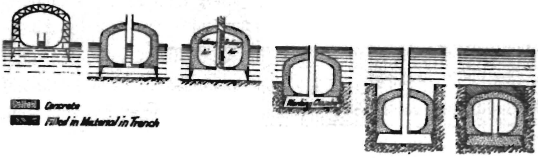


DIAGRAM SHOWING SUCCESSIVE STEPS IN SINKING CAISSON.

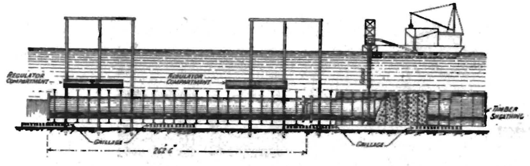
One great advantage of this method over the shield tunnel is the saving of grade. As constructed, the rails are at 36.6 feet below water level, whereas with shield driven tunnels they would have been 9.7 feet deeper, thus necessitating steeper grades in approach. The river section has been constructed with five caissons, which are all similar except as to length. The three caissons for the main crossing of the river were respectively

118.8, 125.4 and 141.7 feet long, while for the smaller crossing of the river there are two caissons each 61.3 feet. The caissons are 23.7 feet wide inside, with 15.58 feet clearance above rail level. The height of the working chambers was 5.9 feet.

Prior to placing the caissons in position, pile stagings were driven and platforms erected. The caissons were then built on shore, launched, and brought to site. The annular space between the lining and shell was filled with concrete sufficient to sink the caisson to the river bottom. As the caisson sank, the working shafts were placed in position. Air pressure was then applied, and the working chamber laid dry, after which the material, which was sufficiently hard to necessitate being broken up by blasts, was excavated under air pressure. The caissons were sunk with a space of about 5 feet between the different sections to allow for any irregularity during sinking. This was closed by building up the ends of the caissons to a rectangular shape, and sinking a small caisson along the side walls of adjacent caissons to close the opening. By means of this caisson a vertical wall was built along either side of the 5 feet opening, and another caisson was then lowered on to the top, which was closed by another section of concrete.

THE DETROIT RIVER TUNNEL.—This tunnel is being constructed to carry the two lines of the Michigan Central R.R. under the Detroit River at Detroit, Michigan.

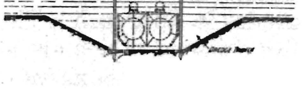
The subaqueous section will consist of twin tunnels, each 20 feet clear inside diameter, 2,622 feet 6 inches long, at a depth of 41 feet 9 inches below the water surface to the top of the tunnel. Extensive borings were first taken, which indicated that the bulk of the material to be passed through will be soft blue clay, overlying rock at a depth of from 10 feet to 20 feet below the invert.



TUBE IN POSITION READY FOR CONCRETING

CONCRETING IN PROGRESS

TUBE SPLICE



The first proceeding was to dredge a trench about 48 feet bottom width, 32 feet deep, with side slopes of ½ to 1. This was excavated by means of a dipper dredge in the upper portion, and a specially designed clam shell dredge in the lower portion of the cut. The bottom of the trench is then levelled off approximately, and steel grillages are sunk, and fixed at the correct level to receive the ends of the sections in which the tunnel is built. These sections are each 262 feet 6 inches long, and a space of 3 inches has been allowed between the ends of adjacent sections to admit of adjustment. Each section consists of a pair of steel tubes, 23 feet 4 inches diameter, ⅜-inch thick, with lapped joints, which are riveted and caulked. The exterior of each tube is reinforced with transverse steel diaphragms, 12 feet apart, formed of plates and angles. The interior is stiffened with temporary bracing to prevent distortion. The sections, which weigh about 550 (short) tons each, are built ashore, sheathed along the outside of the diaphragms with longitudinal planks, fitted with internal bulk heads at either end, launched, and floated to position. They are then sunk between rows of guide piles on to the grillages in the trench. In order to control the sinking, each tube is fitted with two horizontal steel cylinders 10 feet diameter, 60 feet long, which are temporarily fixed to the top of the tubes. Water is admitted to the tubes by means of valves near the bottom of the bulkheads, the confined air escaping through another set of valves situated near the top of the bulkheads, but sufficiently low down to admit of a certain amount of air being retained in the tubes after the latter valves are submerged. This air subsequently escapes slowly through vents, which are operated from the surface, thus regulating the sinking. Finally, sufficient water is admitted to sink the tubes sufficiently deep to bring the controlling cylinders into the water, when further sinking is prevented until the buoyancy of these is overcome. The controlling cylinders are operated by admitting water, or expelling it by compressed air, thus keeping the descent of the large tubes always under control, until they are finally brought to rest at the correct position on the grillages. The controlling cylinders are then removed, and 6:3:1 concrete is deposited within the timber casing, which is fixed on the diaphragms, round the outside of the tubes, by means of tremie tubes worked from punts. Since the timber sheathing is only placed along the sides of the diaphragms, and not along the bottom, the latter is open, and permits of the concrete passing through and filling up any inequalities in the bottom of the trench, thus securing a solid foundation. While this is being done, the tubes are full of water, and the total load on the foundation after the concrete is deposited, and before the water is removed, is greater than after the tunnels are completed.

even allowing for the live load. An advantage of this arrangement is that any settlement in the foundation of the tunnels is more likely to occur in the early stages.

The function of the steel tubes is to serve as a mould for the concrete, and to act as a water-proofing for the lining of the tunnels. The external concrete serves to weight the tubes, and to stiffen them against hydrostatic pressure when pumped out. When sufficient sections have been laid, the water is removed, and the internal lining placed in position under atmospheric pressure, thus permitting of reliable work. The lining is of 4:2:1 concrete, 20 inches thick, reinforced with 1 inch longitudinal steel rods, 18 inches apart, placed 6 inches from the inner surface of the concrete.

This lining constitutes the tunnel proper, and is designed to withstand all stresses whether hydrostatic, or due to dead and live loads in the tunnel.

The jointing between the sections of the tubes is effected by means of sleeve joints with rubber gaskets. At the ends of each section are cast steel sockets bored for 6-inch steel pilot pins, 5 feet long. The tubes are sunk so that the holes in the sockets are opposite to each other, when the pilot pins are driven by divers, and the sleeves grouted up from the punts under pressure, through flexible pipes, a second pipe being provided at each joint to admit of the escape of air and to shew when the joint is filled by the grout rising to the top of the pipe.

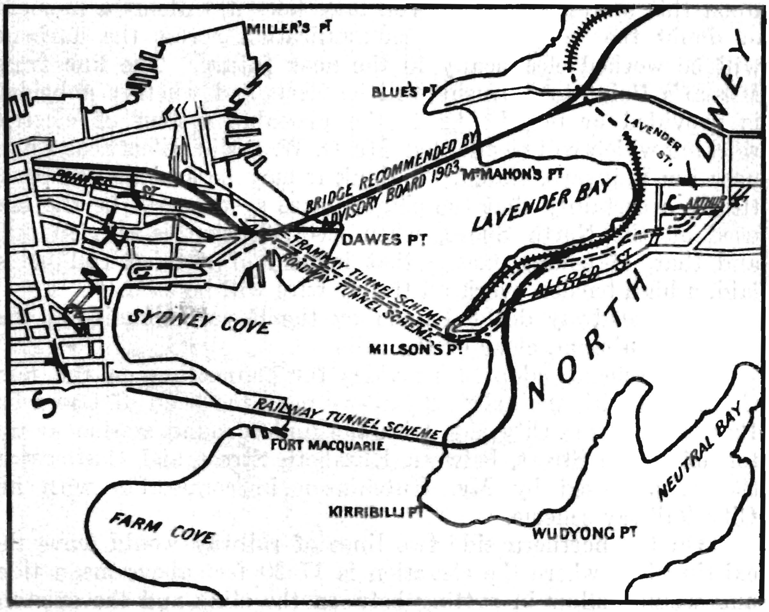
The first of the tube sections was sunk in October, 1907, and the second in the following month. These were joined together without difficulty, the pilot bolt arrangement working very successfully. After concreting round the tubes had been partly completed, navigation was stopped by ice for the winter. During the following season, to November, 1908, five more sections were put in and concreted, making seven out of the ten sections completed, so that completion of the whole work may be looked for in the near future.

This is one of the most interesting subaqueous tunnels yet undertaken, and except as to the depth of water, which is greater than in Sydney Harbour, and in the fact of ice stopping work in the winter, the conditions at Detroit appear very similar to those of the proposed North Sydney connection.

The above represents generally what has been done up to the present in the way of subaqueous tunnelling, practically all within the past 25 years. There are other works, such as the Chicago Tunnels, and doubtless others in Europe and elsewhere of which no mention has been made, but, so far as the author is aware, the methods of construction adopted are not likely to have any important bearing upon the proposed subways to North Sydney, which will now be referred to. The method of construction for these subways will, of course, largely depend upon the depth at which they are built. The Royal Commission wisely kept the roof as near to the surface as possible, and adopted a depth of 40 feet below L.W.S.T. to the top of the subways. This depth, while ample for navigation, admits of a considerable saving in grade on either side of the Harbour, as compared with shield driven subways, unless the latter were built under a heavy blanket of clay, which it would be necessary to subsequently remove. The advantage of saving grade, and consequently working expenses, is obvious.

PROPOSED SUBWAYS BETWEEN SYDNEY AND NORTH SYDNEY.

Various subway schemes were submitted to the Royal Commission. Of these, special mention may be made of the proposal by Mr. A. M. Howarth, Assoc. M. Inst. C.E., for a subaqueous viaduct carried on cylinder piers; of the shield tunnels proposed by Mr. W. Hutchinson, M. Inst. C.E., Chief Engineer for Railway and Tramway Construction, connecting with the City Railway scheme prepared by the same gentleman; and of the shield tunnels suggested by Mr. J. Davis, M. Inst. C.E., Consulting Engineer for New South Wales, London, also connected with a City Railway scheme, but in the latter case requiring special rolling stock, and not connecting with the Hornsby-Milson's Point Railway.



The three schemes recommended by the Royal Commission were selected from a number of proposals submitted by the author, with a modification in the route of the Vehicular Subway, so as to connect with the new road proposed by the Sydney Harbour Trust, as referred to below, instead of bringing the roadway to Barton Street as at first proposed by him.

The clear headway over the roof of all the subways was fixed by the Royal Commission at 40 feet below L.W.S.T.

BORINGS.—A series of borings was taken by the Sydney Harbour Trust, under the direction of Mr. H. D. Walsh, M. Inst. C.E., along the lines proposed for the subways between Dawes Point and Milson's Point, and between Fort Maquarie and Beulah Street, Kirribilli Point.

These borings were carried to rock by means of a water jet forced through a 2-inch galvanised pipe, and shewed that the rock along these lines was, for the greater portion of the distance, at much greater depths than had been previously supposed, and quite beyond pneumatic limits. The object of the borings was merely to ascertain the depths to rock, and the method adopted did not admit of determining the nature of the formation passed through, except in a few instances.

PROPOSED RAILWAY SUBWAY.—At the outset, it was decided that any railway connection through a subway must be designed for electric, and not for steam traction.

In evidence given before the Royal Commission, Mr. T. R. Johnson, Chief Commissioner of Railways, stated as follows upon this matter, "I think you may take it without a moment of doubt that any railway communication across the harbour will be worked electrically in the near future. The line from Milson's Point to Hornsby will be electrified whether a bridge is provided or not." As to the probable system of electric working which will be adopted, Mr. O. W. Brain, Electrical Engineer for Railways, stated, "I think it may be accepted as practically a certainty that the single phase system will be the one used on the North Shore, when electrification is carried out, and that, of course, means that instead of a third rail being laid, a high tension overhead trolley wire will be used."

The headway decided upon by the Royal Commission was 16 feet minimum, clear of the rails.

The scheme adopted provides for connecting on the northern side with the existing railway near the head of Lavender Bay, and on the City side with the underground station at the top of Moore Street, between Elizabeth Street and Castlereagh Street, proposed by Mr. Hutchinson in connection with his City Railway scheme.

On the northern side two lines of railway would leave the existing line where the elevation is 17·20 feet above mean tide, and would follow in cutting between the cliffs and the existing