1911

The Detroit River Tunnel Between Detroit, Michigan, and Windsor, Canada

William John Wilgus

Recommended Citation

Wilgus, William John, "The Detroit River Tunnel Between Detroit, Michigan, and Windsor, Canada" (1911). *SWODA: Windsor & Region Publications*. 4.
http://scholar.uwindsor.ca/swoda-windsor-region/4

THE

INSTITUTION

OF

CIVIL ENGINEERS.

SESSION 1910-1911.—PART III.

SECT. I.—MINUTES OF PROCEEDINGS.

---

7 February, 1911.

ALEXANDER SIEMENS, President,
in the Chair.

The Council reported that they had recently admitted as

Students.

Reginald Ernest Barton, B.Sc. (Engineering) (*Lond.*)
Guy Cyril Bedington.
Alfred Cyril Bingham.
Theodore Frederic Carter.
William Garnett Codling, B.Sc. Tech. (*Manchester*).
William Davison, B.Sc. (Engineering) (*Lond.*)
Charles Edward Fairburn, B.A. (*Oxon.*)
Charles Trevor Gooch, B.A. (*Cantab.*)
Harold Hobson.
John George Holtzapffel Holtzapffel, B.A. (*Cantab.*)
William Maximilian Lindley.
Frederick Thomas Littlejohn.
Thomas Ridding Morse, B.Sc. (*Birmingham.*)
Charles Herbert Scarlett, B.A. (*Cantab.*)
Giulio Franco Tosi.
James Rendell Wilkinson, B.Sc. (Engineering) (*Lond.*)
Evan Owen Williams.
Reginald John Zemin.

The Scrutineers reported that the following Candidates had been duly elected as

Members.

Alfred Thomas Blackall.
Raymond de Candolle, B.A. (*Cantab.*)
John Bernard Earle.
Silas H. Woodard.

Associate Members.

Louis George Allison, Stud. Inst. C.E.
Roderick George Bartholomew.
Hugh Linley Byrd, B.Eng. (*Liverpool*).
George Herbert Carter.
Gilbert Cook, M.Sc. (*Manchester*), Stud. Inst. C.E.
Sydney O'Grady Cotton, Stud. Inst. C.E.
Harold Douglas Creedy, B.Sc. (Engineering) (*Lond.*), Stud. Inst. C.E.
Allan Crombie, Stud. Inst. C.E.
James Grimshaw Cunliffe, M.Sc. Tech. (*Manchester*), Stud. Inst. C.E.
Richard Grimshaw Cunliffe, M.Sc. Tech. (*Manchester*), Stud. Inst. C.E.
John Reginald Hare Duke.
Frank Goldie Engholm, Stud. Inst. C.E.
Basil Prockter Fletcher.
Raymond Gill, Stud. Inst. C.E.
William Cory Goddard, Stud. Inst. C.E.
Isaac Harpur, Stud. Inst. C.E.
Frederick Guy Hill.

Associate Members—continued.

George McCausland Hoey, B.A., B.E. (*Royal*), Stud. Inst. C.E.
Alfred Harry Huddart, Stud. Inst. C.E.
Wilfrid Drake Lancaster, Stud. Inst. C.E.
Henry Scott Manisty, Stud. Inst. C.E.
Eric Walton Merrall.
George Geoffrey Nelson, B.A. (*Cantab.*), Stud. Inst. C.E.
Thomas Hotham Newton, B.A. (*Cantab.*)
William Oliver, B.Sc. (*Edin.*), Stud. Inst. C.E.
John Parr, B.Sc. (*New Zealand*).
Alfred Maurice Paton, B.A. (*Cantab.*)
Philip Louis Pratley, M.Eng. (*Liverpool*).
Samuel Arthur Sayer.
Walter Alfred Scoble, B.Sc. (Engineering) (*Lond.*)
Cyril Spooner, Stud. Inst. C.E.
Frederick William Strickland.
Alfred Samuel Vincent Taylor, Stud. Inst. C.E.
David Halton Thomson, B.A. (*Cantab.*), Stud. Inst. C.E.
Robert Weir, Stud. Inst. C.E.
Douglas Thurburn Wells, Stud. Inst. C.E.
Henry Norman Worth, Stud. Inst. C.E.

Associate.

Francis Vivian Lister.

(*Paper No. 3915.*)

"The Detroit River Tunnel, between Detroit, Michigan, and Windsor, Canada."

William John Wilgus, M. Inst. C.E.

The completion of the Detroit River tunnel between Michigan and Canada, marking as it does the addition of another bond of friendly intercourse between the United States and its neighbour on the north, is an event of more than passing interest, apart from its importance as an achievement in engineering. Stretching for nearly one-half of the distance between the Atlantic and the Pacific, the chain of Great Lakes offers a natural barrier to railway intercommunication nearly 1,500 miles long, except at a few favoured situations where bridges or tunnels are feasible. At Montreal and at Cornwall on the St. Lawrence River, at the Falls and Buffalo on the Niagara frontier, and at Sault Ste. Marie, seven bridges in all carry their burden of railway-traffic from shore to shore. At Sarnia, the outlet of Lake Huron, a single-track tunnel completed the list of crossings until the recent opening of the new tunnel at Detroit, after half a century of agitation, added a ninth crossing to the record.

The vicissitudes of the many projects for crossing the river at Detroit, culminating 5 years ago in the decision to build a double-track electrically-operated tunnel, the salient features of the design and construction of that tunnel, and the final results, are recorded in the present Paper. The scope of the subject, however, embracing as it does corporate policy, construction, and operation, has necessarily dictated the abbreviation or omission of many details which otherwise would have been entitled to more lengthy treatment.

HISTORY OF RIVER-CROSSING PROJECTS.

Controlling over 12,000 miles of line, and serving a territory 1,000 miles long by 600 miles wide, that stretches from Boston on the east to the Mississippi on the west, and from Montreal, Canada, on the north to the junction of the Ohio and Mississippi on the south, the New York Central and Hudson River Railroad, with its principal rival the Pennsylvania Railroad, dominates the traffic of nine of the most populous and prosperous States of the Union. From the Atlantic seaboard to the west its lines converge at the Niagara frontier, where they separate, one group, of which the Lake Shore and Michigan Southern Railroad is the leading member, skirting the southern shores of Lake Erie, and the other, comprising the Michigan Central Railroad and controlled lines, passing north of the lake through Canada, recrossing the frontier at the Detroit River, which falls into the north-west corner of the lake, and running thence to its western terminus at Chicago (*Fig. 1*).

While the northern or "Michigan Central" route has been an important factor in the goods- and passenger-traffic of the New York Central lines, it has necessarily occupied a position inferior to that of its southern competitor, the "Lake Shore" route, because of the handicap that it has suffered at the crossing of the Detroit River. At this point car-ferriage has been required, with the delays, risks, and expense incident to crossing a stream about 50 feet deep, ½ mile wide, with a current of more than 2 miles per hour, and bearing a traffic that exceeds that of any other waterway in the world. Moreover, in the winter months ice and fogs have at times so obstructed the crossing as practically to strangle the railway's through business.

The need for an escape from these limitations on the growth of trunk-line traffic was recognized as early as 1855, when the Great Western Railway of Canada, having completed its line from the Niagara frontier to Windsor on the east side of the Detroit River, opposite Detroit, offered an eastern outlet for the traffic of the Michigan Central Railroad, which had been chartered in 1836 and extended westward to Chicago in 1852. At this time there was a break of bulk at the river, the crossing being effected by small ferry-boats in the open season, and by sleighs on the ice during the winter months.

In 1867 the President of the Michigan Central Railroad, Mr.

James F. Joy, first advocated the construction of a tunnel beneath the river, and 2 years later he retained Mr. E. S. Chesbrough, M. Am. Soc. C.E., to report upon the project. Upon the basis of Mr. Chesbrough's recommendations a company was organized to construct and operate a double-track tunnel with two bores of 18 feet 6 inches internal diameter each, spaced 50 feet apart from centre to centre, and with approach-gradients of 1 in 50. The depth of rail-level under the river was fixed at 80 feet below the water-surface. This depth was adopted so as to afford a thickness

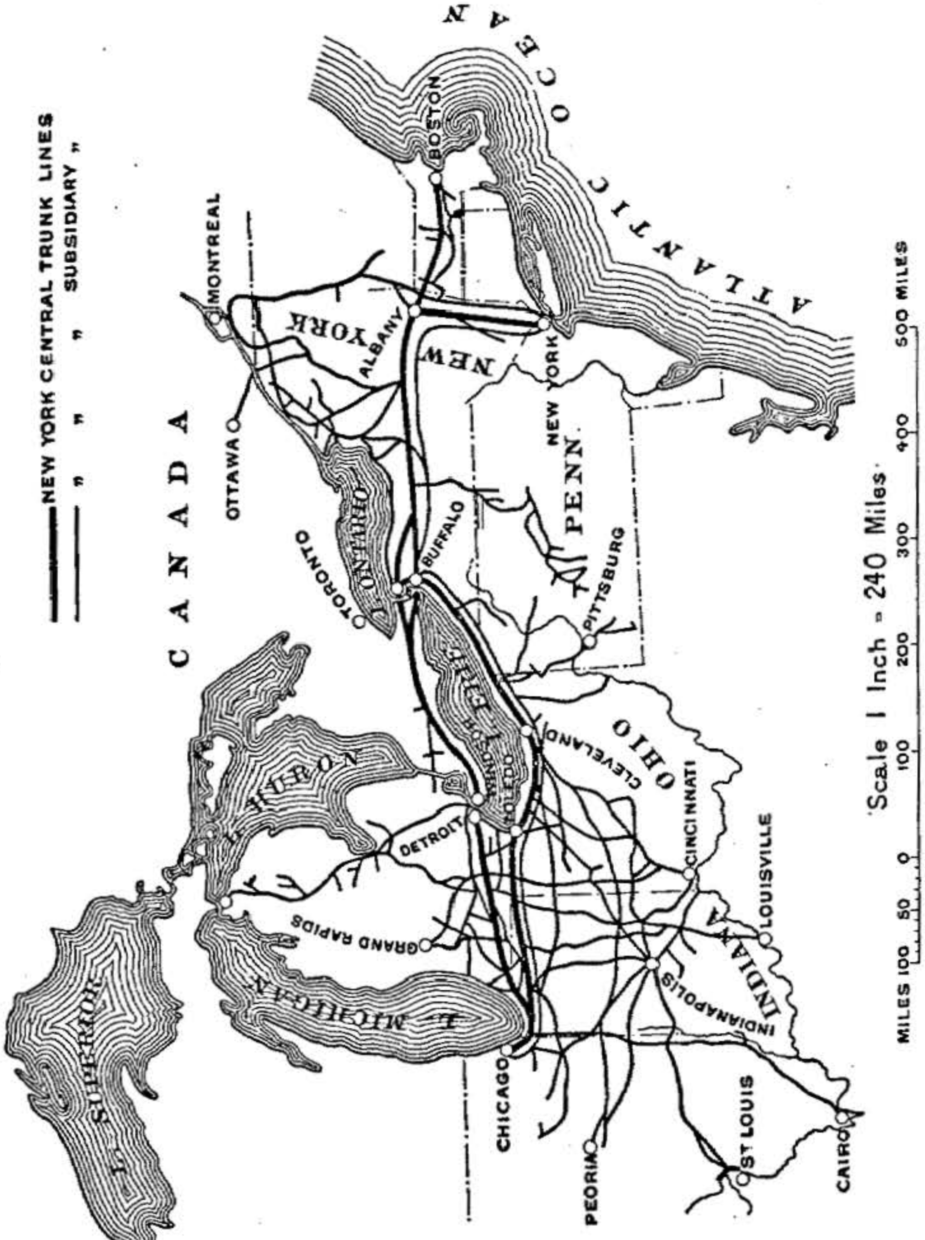


Fig. 1.

of about 20 feet of clay between the tunnel structure and the bed of the river and at the same time provide space between the bottom of the main structure and bed rock for a 5-foot drainage-tunnel. Work was commenced at both ends of the drainage-tunnel in 1870, and the headings were driven through clay, sand, and boulders about 1,220 feet from the American shore and 370 feet from the Canadian side, when work was permanently suspended, in the latter part of 1872, owing to continued inrushes of water and gas and loss of life. Ordinary tunnelling methods with timber lining were employed, as the use of shields and compressed air was deemed inadvisable at such great depths and in such small drifts.

About this time the Canadian Southern Railway, a projected competitor of the Great Western Railway of Canada, fell into financial difficulties, and subsequently, about 1878, it was brought under the control of the New York Central at the time when the Michigan Central passed into the same hands. The common ownership of these two lines, which together constituted an important link in the new system between Chicago and the seaboard, led to renewal of the agitation for a better method of crossing the river at Detroit, although powerful car-ferries had replaced the crude devices of earlier years. About 1885 an unsuccessful attempt was made to secure Government approval of a bridge crossing at a low level, with a draw-span. Some years later an equally unsuccessful attempt was made to secure the consent of the Lake Carrier interests and the two Governments to a low bridge, with a movable span to be used during the winter months and removed in the open season, when car-ferriage would be resumed and the main channel be left unobstructed for river-traffic.

About the year 1900 the President of the Michigan Central Railroad, Mr. H. B. Ledyard, who also exercised jurisdiction over the Canadian Southern Railway, and Mr. Chas. M. Hays, Vice-President of the Grand Trunk Railway, the successor of the old Great Western Railway of Canada, agreed to investigate the feasibility of a high-level bridge for the joint use of their lines, and for that purpose they retained the services of Mr. George S. Morison, M. Inst. C.E.

After Mr. Morison's death, Mr. Alfred P. Boller and Mr. Henry W. Hodge, MM. Inst. C.E., were retained, and they finally reported in 1904 on two alternative double-track crossings, the upper one connecting with the Grand Trunk Railway facilities on the American side, necessitating three river spans of which the channel span was 940 feet, and the lower one, at the Michigan Central situation, involving the use of the same number of river spans, with a channel-opening of 1,140 feet. The required clearance for vessels, 115 feet, fixed the elevation of the track at 125 feet above the water-surface. The adopted gradients of 53 feet per mile on the Canadian side and about 43 feet per mile in Detroit, imposed long approaches, the total length between points of connection with the surface tracks being 3·69 miles at the upper site and 4·38 miles at the lower.

The heavy cost of construction, including the necessary rearrangement of terminal facilities at Detroit as well as in Canada, and the inability of the two railway interests to meet the condition, imposed by the Lake Carriers' Association, that one point of crossing should be agreed upon for joint use, led to the abandonment of the high-level-bridge project.

Finally, about this same time, in the early part of 1904, the promised success of electrification of the New York Central's terminals in New York,[1] of which the Author, as Vice-President of the company, was in charge, induced Mr. Ledyard to consider the feasibility of an electrically-operated tunnel beneath the Detroit River, and a committee, consisting of the late Mr. E. A. Handy, M. Am. Soc. C.E., Chief Engineer of the Lake Shore and Michigan Southern Railway, Mr. W. S. Kinnear, M. Am. Soc. C.E., Chief Engineer of the Michigan Central Railroad, and the Author, were appointed by the Board of Directors of the Michigan Central Railroad to investigate and report upon the problem.

This committee considered the local conditions at Detroit, where the existing joint passenger-station and other terminal facilities cluster along the water-front, the preponderance of eastbound traffic, and the relative costs of constructing various lengths of approaches; as a result of which the conclusion was reached that $1\frac{1}{2}$ per cent. (1 in 66·6) eastbound and 2 per cent. (1 in 50) westbound gradients should be adopted, these inclines lending themselves to the working of maximum-tonnage trains with not more than two locomotives. The committee also advised the construction of two separate single-track tunnels, the use of electricity as a motive power, and the abolition of level crossings at all street-intersections between Detroit and the main yards and shops of the company at West Detroit.

It was also concluded that the construction of the tunnel was entirely feasible, and that marked economies in time and cost, and a general increase of traffic, would result from its completion and the consequent placing of the Michigan Central route in the trunk-

---

[1] Transactions of the American Society of Civil Engineers, vol. lxi (1908), p. 73.

line class. Moreover, the obvious needs of other railways in the vicinity, including the Canadian Pacific, Grand Trunk, and Pere Marquette railways, for similar relief from the embarrassment of ferriage, offered a prospect of future use for the surplus capacity of the tunnel not required for the Michigan Central lines. A plan showing the position finally adopted for the tunnel, and its relation to the various lines near, is given in Fig. 2, Plate 1.

The Railroad Company approved the recommendations of the committee, and a new company was organized, known as the Detroit River Tunnel Company, the securities of which were guaranteed by the Michigan Central Railroad and Canada Southern Railway companies.

ENGINEERING ORGANIZATION.

The construction of the Detroit tunnel line, including its electrification, was, on the 10th July, 1905, placed in charge of an advisory board of engineers, consisting of Mr. Howard A. Carson, M. Inst. C.E., under whose direction as Chief Engineer of the Rapid Transit Commission the subways and subaqueous tunnel at Boston had been brought to a successful conclusion, Mr. W. S. Kinnear, M. Am. Soc. C.E., and the Author as chairman.

Mr. Kinnear was selected to have local charge of construction, with the title of Chief Engineer, to whom reported the tunnel-engineer, Mr. Benjamin Douglas, M. Am. Soc. C.E., with direct supervision over tunnel-construction proper; the electrical engineer, Mr. J. C. Mock, with jurisdiction over electrification; and the terminal engineer, Mr. A. C. Everham, as a representative of the Chief Engineer on matters external to the tunnel-construction, such as the Detroit and Windsor terminals and the elimination of level crossings.

Preliminary plans and specifications for the tunnel, including electrification, were prepared under the direct supervision of the Author at New York, after which the preparation of detail and final plans took place at the Chief Engineer's office at Detroit.

TUNNEL-DESIGN AND CONTRACT.

Preliminaries.—Following the first meeting of the Advisory Board of Engineers on the 12th July, 1905, surveys and borings were commenced, and by early in the autumn sufficient information had been obtained to determine the alignment and profile of the tunnel.

The river at the point of crossing was found to have depths ranging from a minimum of 15 feet at the bulkhead line on the Detroit side to a maximum of nearly 50 feet at a point 1,100 feet from that shore; eastward of this, the main channel extended for about 1,500 feet to the Canadian bank. Current-velocities in mid-channel were found to average 2 miles per hour at the surface, and 1·33 mile per hour at the bottom, a maximum of 2·29 miles per hour occurring at a point 15 feet below the surface.

Upwards of two hundred borings were made with a churn-drill, working inside a $2\frac{1}{2}$-inch diameter casing, while water was being forced through a $1\frac{15}{16}$-inch hollow drill-bar. In addition, four test-pits, two on each side of the river, were sunk to ascertain the character of the material in situ. With the exception of a top layer of yellow clay, varying in thickness from a slight covering to 15 or 20 feet, a stiff blue clay, weighing 135 lbs. per cubic foot and carrying 15 to 18 per cent. of moisture, interspersed with occasional sand and gravel pockets, was found on both sides of the river. The degree of hardness was quite irregular; as a rule, the material on the Detroit side was stiffer than that found on the Canadian side. In the river section, blue clay, quite hard near the shores, and noticeably softer for a width of 1,000 feet in mid-channel, was found to overlie the bed rock, which existed at a depth below water-surface ranging from 90 feet on the Detroit shore to 85 feet on the Canadian side.

Tests demonstrated that the mainland clay in open cuts was capable of bearing safely loads of 5,000 lbs. per square foot. No satisfactory test was made of the bearing-power of the subaqueous clay, but it was calculated that under original natural conditions at the bottom of the proposed tunnel it would carry 2,175 lbs. per square foot, which considerably exceeded the anticipated net load due to the completed tunnel.

In determining the alignment of the tunnel, consideration was given first to proper connections with existing railways on the United States and Canadian sides. This feature, and the desire to avoid interference with important railway-structures, fixed the position of the approach-tangents. The alignment at the river-crossing was then arranged so as to secure a straight line for nearly the entire distance, the angle with the axis of the stream approximating to 71 degrees. Spiralized 2-degree curves (radius 2,865 feet) were adopted for the connection between the approach-tangents and the river-crossing. The alignment as thus laid down permitted surface operations without undue interference with cross-river car-ferry traffic.

Consideration was given also to the possibility of making future connections with the Canadian Pacific, Grand Trunk, and Pere Marquette railways east of Windsor, Canada.

Alternative Subaqueous Designs.—Concurrently with the making of surveys and borings and the determination of the alignment, the Advisory Board considered the type of construction that should be adopted, particularly in the subaqueous section, because of the great difficulty of that part of the work, and the bearing that its depth would have upon the position of the approach-summits and their relation to existing railway facilities.

Having concluded to adopt the recommendation of the committee of engineers, of 1½ per cent. on eastbound and 2 per cent. on westbound gradients, equated for curvature, the Advisory Board recognized the necessity of establishing the level of the track in the subaqueous section as high as the conditions would permit, so as to bring the approach summit on each side of the river as near as possible to the shore. On the Detroit side this was imperative because of the necessity of shortening the reverse movement of passenger-trains between the point of junction with the surface tracks and the existing station on the water-front, and the further necessity of harmonizing with the plans for raising the track west of 15th Street, which had been prepared both with a view to abolish level crossings and with the idea of erecting a new joint passenger-station. In Canada the shortening of the approach-tunnel was desirable in fixing the western throat of the new goods-yard and connections with other railroads as close as possible to the river shore. Moreover, every foot that could be saved in descent beneath the river was recognized as meaning a substantial saving in the cost of working.

It was found that, with the adopted gradients, if due consideration was given to the proper location of the approach-summits in both Detroit and Canada, the greatest thickness of clay that could be obtained between the top of the subaqueous tunnel and the bed of the river would not exceed 3 or 4 feet in some places, thus rendering the use of the compressed-air shield both hazardous and expensive.

It was finally determined that four alternative plans of subaqueous construction should be prepared for tendering, contractors being given the option of selecting therefrom a preferred method, or offering modifications thereof, or submitting entirely new designs; subject, in all cases, however, to compliance with certain general requirements as to material and workmanship.

The alternative methods may be briefly summarized thus:—

(A) A "trench-and-tremie" method proposed by the Author, involving the dredging of a channel across the river, of the desired size and depth; the placing therein to proper line and level of cores or forms; the deposition of concrete around, beneath, and on top of the forms, by means of tremies operated from scows; the unwatering of the space within the cores or forms in sections, and the lining thereof with reinforced concrete so as to secure the desired watertightness and continuity of strength. This method was considered to be open to the objection that it was untried; but on the other hand it offered the advantages of freedom from the use of compressed air, and the feasibility of raising the tunnel-structure so that the top would even project above the bed of the stream as far as might be desired, with due regard, of course, to the requirements of navigation.

(B) A pipe method proposed by Mr. Carson, who had had a satisfactory experience with the floating and sinking in place of completed sections of sewer-tunnel in the vicinity of Boston. This method, while having the merit of permitting the raising of the track-level of the tunnel, was open to debate, because of the difficulty in making joints below water in a manner that would guarantee watertightness and continuity of strength.

(C) A modification of A in minor details.

(D) A compressed-air-and-shield method, using a segmental cast-iron shell and concrete lining, similar to the method employed under the River Thames, under the Detroit river at Sarnia, and under the North and East rivers, New York City, the objections to which, for this particular problem, have already been mentioned.

Preliminary plans were prepared, embracing the four alternative subaqueous methods, as well as the approach-tunnels, open cuts and shafts, all based on a clear headroom of 16 feet above the top of the rail, and a length between portals of 7,852 feet, of which the subaqueous portion measured 2,624 feet. In the final plans accompanying the contract, the headroom was increased to 18 feet, the Canadian portal was moved eastward 458 feet and the subaqueous section was lengthened 43 feet.

Preliminary specifications were prepared, containing full descriptions of all four of the alternative subaqueous designs, of which but one was embodied later in the final contract plans. The specifications gave in detail all requirements as to material and workmanship that applied equally to all designs.

In accordance with the policy of requiring each tenderer to select or nominate the design on which his proposition was to be made, thereby requiring him to assume responsibility for the completion of a tunnel, in the preparation of the final plans and specifications of which he was to have a voice, the following clause appeared:—

"The purpose of these specifications is to furnish information to the bidders to afford them knowledge of the general conditions under which the tunnel is to be constructed and the results desired by the Tunnel Company. With this knowledge it is expected that each bidder will carefully study the plans and specifications and select therefrom or propose a design or designs which he considers can be most cheaply constructed consistent with safety, expeditious completion, continuity of strength, watertightness, and all other elements which may enter into the delivery by the contractor to the Tunnel Company of a finished structure within the time mentioned in the proposal, ready for operation by the trains of the Tunnel Company. It is expected that the bidders will prepare and submit additional plans and supplemental specifications which in their opinion may be necessary to more clearly explain the manner in which they propose to carry out the work, which if accepted will be embodied with and form a part of these specifications."

Lump-sum tenders were requested for each section of the work, namely, the western open cut, the western approach-tunnel, the subaqueous section, the eastern approach-tunnel, the eastern open cut and the Detroit and Windsor shafts; also for the work as a whole. In addition to the lump sums, unit prices were requested for the various items entering into the work, for the adjustment of minor changes that might be found necessary after the awarding of the contract.

Invitations to contractors were issued on the 1st February, 1906, and on the date of opening, 26th March, 1906, nine tenders were submitted, of which two were based on design A, one on design B, one on design C, one on design D, and four on independent designs. The contract was awarded on the 30th July, 1906, to the lowest responsible bidder, the Butler Brothers Construction Company, which had selected as the basis for its proposition design A, at a price more than $2,000,000 less than the tender that was based on design D. In addition to this saving from the use of the trench method, an increase of headroom of 2 feet was obtained for the passage of trains.

Final Specifications and Plans.—The final specifications, with the exclusion of reference to the rejected methods B, C, and D, practically differed in no respect from the preliminary issue. The final plans, of which the essential features are illustrated in Figs. 2–12, Plate 1, embody the preliminary plans, corrected for the increased headroom and lengths, and the modifications proposed by the contractor, consisting of wooden sides and cross diaphragms on the subaqueous section for restraining the flow of exterior concrete, and certain details intended to facilitate construction.

The physical features and dimensions of the tunnel are described in Table I of the Appendix.

General provisions were made for proper administration of the work, the supply of certain minor features by the Tunnel Company, care and medical attention for workmen, compressed-air facilities if used or required, and the quality of cement, sand, broken stone and gravel, which, as a rule, accorded with New York Central standards.

The method of construction of the subaqueous portion of the tunnel was outlined in the specification, considerable latitude being allowed to the contractors in regard to certain details of the work. The principle on which the work was carried out will be generally apparent from Fig. 18, Plate 2. The operations comprised, first, the dredging of a trench across the river and the placing of supports on the bottom to receive the forms at their correct levels and gradients. The forms, constructed of steel and coupled together in pairs, were then floated out and sunk into position on the supports. They were in convenient lengths of about 260 feet, and great care was taken in making the joint between adjacent lengths so as to ensure watertightness and equality of strength with the remaining portion of the tube. Concrete was then deposited around the forms from scows, by means of tubes or "tremies" reaching down from the surface of the water. After several lengths had been constructed, each was in turn unwatered, all leaks were stopped, and an inner tube of concrete, reinforced with steel rods, was constructed, thus completing the tunnel.

Other clauses described in detail the requirements of dredging, constructing the forms or tubes, depositing concrete under water, and lining, with a view to secure the desired strength and watertightness.

The excavated material from open cuts and approach-tunnels was required to be delivered upon cars at the tunnel-summits, whence the Tunnel Company agreed to dispose of it in neighbouring yard-construction. Dredged material from the subaqueous trench was to be utilized for back-filling and for depositing at certain points to be designated by the Tunnel Company.

Concrete was specified for tunnel-construction and retaining-walls, of the following classifications:—

Class A, consisting of 1 part of cement, 2 parts of sand and 4 parts of broken stone or gravel, for interior lining, copings, and at other points where an especially rich material was required.

Class B, in the proportions of 1 : 3 : 6, for exterior subaqueous concrete, for the lower portions of the approach-tunnels, and for the main portions of retaining-walls.

Class C, of proportions 1 : 1 : 2, for special situations.

Class D, proportioned 1 : 4 : 7½, for the bottom layer or bed in the subaqueous trench, for footing-courses of retaining-walls, and for other places where a cheaper grade of concrete was suitable.

Four classes of waterproofing were specified :—

(A) Three layers of felt and four layers of coal-tar pitch ; largely for use in the approach-tunnels.

(B) and (C) Five layers of felt and six layers of pitch, and ten layers of felt and eleven layers of pitch, respectively ; for use in special situations.

(D) A swabbing of coal-tar pitch of at least $\frac{1}{8}$ inch in thickness ; for the rear surfaces of retaining-walls.

The rolled steel for use in the forms or tubes was required to accord with "Manufacturers' Standard Specifications" as given in the Pocket Companion of the Carnegie Steel Company for the year 1903, especial care being required in the caulking of joints and rivets for ensuring watertightness. Steel bars for reinforcing concrete were required to be of open-hearth medium steel, with an ultimate strength of 55,000 to 65,000 lbs. per square inch, and in other respects to accord with the "Manufacturers' Standard Specifications."

Ducts and drains were described in detail with a view to secure material and workmanship best adapted to the purpose.

The contract, which was dated the 1st August, 1906, had the usual provisions for the mutual protection of the parties thereto, particular stress being laid on the obligation by the contractor to provide a watertight tunnel of the accepted design, and the assumption by the Tunnel Company of the burden of any patent claims that might arise by reason of the employment of the plans and methods specified in Design A.

The agreed date of completion was the 1st June, 1909, with such extensions as the Tunnel Company might grant for causes beyond the contractor's control. For each day that the work was completed in advance of the date of agreed completion, Sundays and legal holidays excepted, the Tunnel Company was to pay to the contractor $1,000 (£200), and for each day (with similar exceptions) of non-completion a like sum was to be paid by the contractor to the Tunnel Company.

OPEN-CUT CONSTRUCTION.

In the excavation of both open cuts (Figs. 5 and 6, Plate 1) the contractor used Bucyrus steam-shovels, the material being delivered to the railway-company on standard-gauge cars for use in neighbouring yard-construction and elimination of level crossings. Retaining-walls, drains, ditch-paving and the sodding of side slopes followed, with little of special interest. The Tunnel Company installed vertical blind drains in the side slopes, which, in conjunction with the sodding and thorough sub-drainage, are expected to check the usual tendency to slips in deep tunnel-approaches through clay. The progress of this work is shown in the following Table:—

	Item.	Commenced.	Completed.
Western cut	Excavation	23 Sept. 1906	1 June, 1908
	Concreting	26 July, 1907	22 July, 1909
Eastern cut	Excavation	17 Oct. 1906	21 Apr. 1908
	Concreting	22 Nov. 1907	9 Sept. 1909

CONSTRUCTION OF APPROACH-TUNNELS.

Shafts.—The excavation for the two permanent shafts near the river-banks in Detroit and Windsor was carried out by the Tunnel Company, the permanent lining thereof being provided for in the contract. The Detroit shaft and sump (Fig. 9, Plate 1) were completed without special incident. At the Canadian shaft, however, on the 11th September, 1907 (Fig. 11, Plate 1), before the concrete lining could be placed above the elevation of the sump, the temporary timber lining collapsed, necessitating the transfer of the position of the shaft to a point about 175 feet eastward, where no further difficulty was experienced.

In order to facilitate construction, temporary elevator-shafts were sunk on both sides of the river, two on the Detroit side, 400 feet and 1,250 feet respectively from the permanent shaft, and three on the Canadian side, 700 feet, 1,540 feet, and 3,080 feet respectively from the original permanent shaft. In addition to the elevator-shafts, small gravity shafts for delivering material were provided at several points.

Tunnels.—The contractor originally intended to excavate for the approach-tunnels (Figs. 8 and 12, Plate 1), with the exception of the cut-and-cover portions, by means of a four-story drift for the centre wall and a three-story drift for each side wall, after which the inverts and arches were to follow, all with temporary timber lining and without the use of air (Figs. 13, Plate 2).

On the Detroit side, westward from the permanent shaft, the harder nature of the clay permitted the use of this method for the centre drift for a distance of approximately 1,360 lineal feet. Compressed air, at pressures ranging from 5 lbs. to 22 lbs. and averaging 7 lbs. per square inch, was used for a short distance (400 feet) near the eastern end, for the prevention of undue surface settlement.

On the Canadian side, after the lower level and a part of the second level of the centre drift had been completed for the larger portion of the distance between the permanent shaft and the 3,080-foot shaft, the pressure of the clay became so great as to crush and distort the timber lining, making desirable the use of a hydraulically-driven shield, which was pushed forward on top of the concrete already laid in the lower level of the drift (Figs. 14, Plate 2).

The centre shield started from the temporary 3,080-foot shaft at the west end of the cut-and-cover section, and was driven westward for a distance of 2,013 feet, beyond which, for 1,061 feet, the original method of drifting was employed as far as the permanent shaft. Considerable difficulty was experienced with this type of shield because of its light construction and a tendency to work out of line, the latter trouble being aggravated by the necessity of chopping away portions of the previously-constructed timber drift.

The high pressures that developed as the excavation progressed, and the surface settlement that followed excessive inflow at the faces of the headings, led to the abandonment, in March, 1907, of the original method of constructing the side walls, inverts, and arches, and the adoption in both approaches of hydraulically-driven side shields, guided and partially supported by the previously-constructed centre walls, in which channel-bars had been inserted for that purpose.

In the Canadian approach the side shields were started from the same shaft as the centre shields, and used continuously for 3,052 feet to a connection with the short section constructed by the original drift method eastward from the permanent shaft. Compressed air, at pressures varying from 6 to 20 lbs. and averaging 11 lbs. per square inch, was required for the entire distance.

In the United States approach the side shields were started at different points and pushed eastward to the permanent shaft, the distances for the north and south tunnels being 1,606 feet and 1,166 feet respectively. No compressed air was required on this side of the river, except for the short distance in the centre drift as already mentioned.

Considerable difficulty was experienced in the driving of the side shields because of light construction that necessitated frequent repairs and strengthening, and the inexperience of the men in regulating the movement so as to maintain alignment. Ultimately these faults were corrected so that progress was quite satisfactory, the average daily movement of each shield being approximately 9 feet.

Cut-and-Cover Sections.—On the Canadian side the eastern 382 feet of the approach-tunnel was constructed by the ordinary cut-and-cover method. On the Detroit side the same method was used at the western end for 436 feet and 714 feet on the north and south tunnels respectively. About 200 feet of the southern track east of the cut-and-cover section was built according to the original plan.

Subaqueous Connections.—Connections between the shore approaches and the subaqueous tunnel were treated differently on the two sides of the river.

On the United States side the centre drift was completed to the west end of the subaqueous tunnel, and the apron was completed for the west end of Section I. The difficulties encountered led to the use of a coffer-dam 66 feet long, 104 feet wide, and 54 feet deep, which was built between the shore and the west end of the previously-deposited subaqueous section, and the connection as far as the shaft, 53 feet in length, was then constructed in the dry (Figs. 15, Plate 2).

On the Canadian side the full-sized approach-tunnel was built, by the use of successive small timber drifts and compressed air, each way from a temporary shaft sunk near the shore 18 feet west of the original permanent shaft, after the latter had collapsed. After the portion west of this temporary shaft, about 45 feet in length, had been completed and bulkheaded, the river trench was dredged to its western face and the junction there was made with the subaqueous section. Eastward from the shaft the portion constructed by this method was extended for 32 feet, and a junction was effected with the portion constructed by the side-shield method from the east.

General.—As a rule, the face of the concreting of the approach tunnels was kept within 30 to 60 feet from the tail of the side shields, the intervening space being completely lined with 10-inch and 12-inch timber "cants" or blocks, sheathed on the inside with 2-inch planking, upon which the waterproofing was placed in advance of the concrete.

In the Table on p. 17 are given the lengths of double-track approaches constructed by the various methods. The western approach was commenced in October, 1906, and completed in May, 1910; the eastern approach, commenced at the same time, was finished 4 months earlier. The progress per 24 hours made with the shields was a maximum of 20 feet, with an average of about 9 feet.

The actual quantities excavated in the approach-tunnels exceeded the net quantities for the section within the exterior outlines of the masonry section by about 39 per cent., the totals for both tunnels

	Western Approach.		Eastern Approach.		Total.
	Feet.	Feet.	Feet.	Feet.	Feet.
Cut-and-cover—					
North tunnel	436		382		
South ,,	714		382		
Average		575		382	957
Side shields—					
North tunnel	1,606		3,052		
South ,,	1,166		3,052		
Average		1,386		3,052	4,438
Original method—					
South tunnel	200				
Average		100		..	100
Subaqueous connection		53		77	130
Shaft		18		..	18
Totals		2,132		3,511	5,643

being 295,500 and 212,650 cubic yards respectively. This excess was due to the additional space needed for the timber lining, to inflow, and to cut-and-cover work near the portals.

CONSTRUCTION OF THE SUBAQUEOUS TUNNEL.

The tunnel under the river itself was of course the most important and expensive portion of the work, involving the greatest risk, and calling for ingenuity and resourcefulness on the part of the engineers and contractor in promptly solving the problems and emergencies that arose from day to day, especially as the selected method was a departure from those hitherto in use. As already mentioned, the work of the contractor was performed in five separate stages, namely, dredging, construction of tubes, sinking of tubes, tremie concreting, and lining.

Dredging.—The trench across the river, 2,667 feet in length, had a depth ranging from 26 to 46 feet, and a bottom width of 48 feet for tube Sections I to IV inclusive, IX, and X, of the eleven sections into which the whole length of tube was divided, and of 60 feet for Sections V to VIII inclusive (Figs. 10, Plate 1). The depth of the bottom of the trench below water-surface ranged from 58 feet at the Detroit shore to 74 feet under mid-channel, with an extreme depth of 79 feet for a short distance at the sump.

Excavation by the sub-contractors, the Dunbar and Sullivan Dredging Company, was started with a dipper dredger capable of working in 45 to 65 feet of water; but constant breakages of spuds soon led to its abandonment and the substitution of a clam-shell dredger with a dipper-capacity of 2 cubic yards. This dredger has excavated as much as 1,400 cubic yards of material in a day of 12 hours, and had an average daily output of 700 cubic yards.

Dredging started from the Detroit shore on the 1st October, 1906, and was continued during the seasons of open navigation until completed in August, 1909. The face of the trench was advanced eastward with sufficient speed to avoid interference with the successive sinkings of the tube-sections. The dredged material was loaded into scows having a capacity of 400 to 500 cubic yards, and the portion not required for back-filling was towed to dumping-grounds distant about 5 miles both up-stream and down-stream.

Experience in similar material at other places in the chain of Great Lakes led to the expectation that the side slopes of the trench would stand at ½ to 1, on which basis the quantity of excavation was estimated at 245,000 cubic yards. In the result, the slopes gradually assumed a considerably flatter angle, averaging 1·41 to 1, and the actual quantity excavated approximated to 350,000 cubic yards. Near the shores the clay was found to be very stiff in texture, dredged masses falling from the bucket to the scow without disintegration. At the centre of the river, for a distance of 1,000 feet where the trench was shallowest, the clay was found to be much softer.

Steel Tubes.—The steel forms or tubes, as designed by the contractor, were constructed at the shipyard of the Great Lakes Engineering Company, at St. Clair, 50 miles north of Detroit on the west bank of the river. Each of the eleven sections—numbered I to XI, starting from the Detroit shore—consisted of twin tubes 23 feet 4 inches in diameter, made of ⅜-inch riveted steel plates, and fastened together by transverse rectangular diaphragms of steel plates and angle-bars spaced 12 feet apart, as indicated in Figs. 10, Plate 1, and Figs. 16, Plate 2.

Nine of the sections, weighing 490 tons[1] each, were built with a length over-all of approximately 262 feet 6 inches; one (No. VI), weighing 446 tons, with a length of 238 feet 6 inches; and the eleventh, which served as a closure at the junction with the eastern approach-tunnel, weighed 125 tons, and was 65 feet in length.

Longitudinal planks fastened to the exterior vertical edges of the diaphragms acted as walls for restraining the outward flow of tremie-deposited concrete. The combination of the tubes, diaphragms,

---

[1] The English ton of 2,240 lbs. is used throughout this Paper.

and wooden sides formed a rectangular cellular bottomless box enclosing the twin tubes, each cell having a length along the axis of the tunnel of 12 feet and a width of 55 feet 8 inches, within which the deposition of concrete would be capable of regulation and control. It should be added that while the sections first built had the lower part of the outer plank sides inclined inwards, those constructed later (V to VIII inclusive) had vertical sides for the full depth, so as to overcome the difficulty that was experienced in manipulating the outer tremies at the angles.

The necessary buoyancy for floating the sections to the site of the tunnel was secured by closing the ends of the tubes with temporary timber bulkheads, in which valves were provided for the ingress and egress of water. Interior temporary "semi-bulkheads" 45 feet from the ends of each tube, afforded two cushions of air at the top, 7 feet deep, for checking a too sudden or unbalanced immersion. Interior spiders of radial rods, opposite each diaphragm, prevented distortion of the tube during launching and sinking, and were removed after exterior concrete had been placed and the sections unwatered.

Pilot-pins at the western end of each section, with the exception of Nos. I and XI, were arranged so as to fit into bell-shaped sockets in the eastern end of the neighbouring section (Figs. 16a, Plate 2). Telescopic joints with rubber gaskets were provided with matched holes for bolting together adjoining sections after sinking. The ends of adjacent sections were carefully fitted together and tested at the shipyard before the final assemblage, so as to ensure tight connections in the finished work.

Removable steel masts, graduated for readings, were fastened to each section for fixing line and level during the process of sinking.

The tubes were constructed by the same method that is followed in building lake cargo-vessels, known as the "universal system of the Great Lakes." They were launched sidewise, temporary sheathing being used on the bottom for about 15 feet inwards from the launching edge of the timber side, to afford the necessary buoyancy while passing down the ways into deep water. The neglect of this latter precaution with the first two sections occasioned some damage that necessitated repairs in dry dock. After launching, the sections were towed to the site of the work, where they were moored until the prepared trench was in readiness for sinking.

The building of the tube sections gave employment to about 300 men for nearly 2½ years.

Sinking of Tubes.—The principal apparatus used in tube-sinking consisted of a "tremie scow" 155 feet long, 35 feet wide, and drawing about 6 feet of water, for depositing exterior concrete and manipulating the tubes; and a derrick scow for general use. The tremie scow was equipped with two derricks for unloading sand and gravel from neighbouring boats to overhead bins; a conveyor for handling cement from adjoining craft to the mixing platform under the bins; three concrete-mixers on the main deck beneath the mixing-platform, so arranged as to discharge their contents into buckets in the hold; and vertical leads 82 feet high for guiding the buckets to points of automatic discharge into the hoppers of the adjustable tremies. Each of the three tremies, having a length of about 80 feet and a diameter of 12 inches, was controlled by suitable lines operated from the hoisting-engines, of which there were two for various operations on the scow. Both the tremie and the derrick scows were furnished with extensible spuds capable of reaching to maximum depths of water, for fixing the scows firmly in any desired position.

Before sinking, four air-cylinders were attached to each section (I to X inclusive) for controlling their gradual subsidence and adjustment to the exact desired position (Figs. 16, Plate 2). These cylinders were 60 feet in length and 10 feet 2 inches in diameter, and were divided into three compartments, into which water could be admitted or expelled at will by the use of compressed air from the tremie scow.

The calculated weight of the mass was then as follows :—

	In Air. Tons.	In Water. Tons.
Metal in tubes	490	433
Wooden sheathing and bulkheads	302	−7
Four air-cylinders	100	87
Total	892	513

The weight of the entire mass in water, when (with the exception of the air-cylinders) entirely submerged, was approximately 527 tons, including the cylinders.

In advance of the sinking, a grillage of I-beams, measuring approximately 38 feet along the axis of the tunnel and 43 feet at right angles thereto, and with downwardly-projecting spuds of varying lengths (usually 17 or 18 feet), was suspended from the scow by long rods and placed, with the aid of a pile-driver, in the bottom of the trench at the correct height for receiving the ends of adjoining sections, the space beneath and around the grillage being filled with tremie-placed concrete.

The section was then floated into position and properly secured, and lines were passed from the hoisting-engine on the scow through the bell sockets in the end of the previously-deposited section to the pilot-pins of the section that was about to be sunk, after which the 14-inch valves in the temporary bulkheads at each end were opened, and the section was permitted gradually to sink until the air-cylinders were partially submerged, so as to suspend the entire mass, with its bottom 20 to 30 feet above the grillage-supports. Water was then admitted into the middle compartments of the air-cylinders until the weight of the whole mass was sufficiently greater than its displacement to cause it to sink slowly, readily controlled at all times by a lift of 5 tons each on the derrick-lines. The section was then permitted to touch gently the top of the grillage-support at each end, and the necessary tension on the end lines drew the section longitudinally until the pilot-pins entered the sockets of the adjoining section, so that the circumferential holes matched. A diver then easily inserted the bolts, keyed the pilot-pins, and completed the joint.

After the outshore end had been swung into line and wedged to the proper level on the grillage-support by the diver, and one or more of the centre pockets had been weighted with concrete so as to anchor the section, the air-cylinders were removed for use in the sinking of succeeding sections.

The twin tubes after sinking were then supported at correct line and level above the bottom of the trench, ready for the placing of exterior concrete.

The first section, No. I, on the Detroit side of the river, was successfully sunk on the 1st October, 1907, one more section following the same season. Sections III to VII inclusive were sunk in the open season of the succeeding year, and the remaining four, VIII to XI inclusive, in 1909, the last section being in shape for the passage of men on the 18th October, 1909. Had the time of starting the tunnel been spring instead of autumn, it would have been possible to sink all eleven sections in two seasons.

The actual operation of preliminary sinking of each section usually took a day, of which about 2 hours were required for filling the tubes. Final sinking and connecting with the previously-placed section were usually effected within 3 to 9 days after preliminary sinking.

External Concreting.—After the tremie scow had been placed at right angles to the tunnel, with its spuds resting firmly on the bed of the stream, one tremie was passed down between the tubes and one on each side of them within the outer plank walls. The first operation was to cover the bottom of the trench for a sufficient height to engage with the bottom of the transverse diaphragms, sealing the lower part of the pockets or cells and anchoring the mass, after which each cell was filled to the top.

The maximum daily 24-hour capacity of the tremie-scow was 1,000 cubic yards, but the ordinary practice was to make the output of a working-day 360 cubic yards, which was just sufficient to complete the filling of a pocket. Altogether, approximately 100,000 cubic yards were deposited by the tremie process.

As the placing of the concrete progressed, back-filling was placed between the plank sides and the slopes of the trench. Gravel and sand filling was used at the bottom of the space, and clay for the upper parts and for top covering.

The utmost care was taken, by the aid of the diver, to keep the outlets of the tremies at all times submerged in the flowing concrete, so as to avoid the exposure of the moving material to the washing action of water. The men became so expert that, after a few initial mishaps, there was not an instance of a loss of charge in the tremies during the entire work, the filling of each pocket progressing continuously by a gradual raising of the concrete from the bottom upwards.

That the results were satisfactory was shown in a variety of ways. Several core borings were taken from top to bottom of the mass. The concrete cores not only disclosed a surprising density and homogeneity, but the results of crushing-tests compared favourably with those obtained from air-made concrete, as shown in the following Table:—

COMPARATIVE STRENGTH OF AIR-MADE AND TREMIE CONCRETE.

	Class of Concrete.	Position.	Depth below Water.	No. of Tests.	Size of Samples.		Age of Sample.	Compressive strength.
					Area.	Length.		
			Feet.		Sq. Ins.	Inches.	Months.	Lbs. per Sq. Inch.
Air-made.	1:3:6	Ret. wall	..	5	19·64	..	16	2,277
Tremie-made	1:3:6	Sect. I	45	4	17·16	7	13	3,239
„ „	1:3:6	„ I	45	2	18·63	7	13	1,509
„ „	1:1:2	„ V	60	2	36·00	6	10	4,040
„ „	1:2:4	„ VI	60	8	35·55	6	10	1,980

The removal of plates from the tubes in several instances also disclosed similarly good results, leading to the conclusion that the tremie-placed concrete was much better than was considered necessary for the purpose for which it was used, and that, with suitable means of mixing and depositing concrete under water, this mode of construction has a wide range of application. The density and strength is accounted for by the pressures to which the material is subjected, due to the hydrostatic head in the tremie, the hopper of which was usually at considerable heights above the river-surface, and to the high specific gravity of the column of concrete in the tremie. Homogeneity of the material is attributed to the restraint of the flow of concrete within comparatively small limits, without exposure to current- or wave-action.

The soft material in the bottom of the trench for a distance of 1,000 feet at mid-channel led to the use of the tremies for prodding holes into the clay to the underlying hard stratum, and the filling of the holes with concrete as the tremies were withdrawn. In this manner three lines of concrete columns or piles were built in place, one line between the tubes and one on each side, the piles being spaced longitudinally about 6 feet apart.

Lining.—Section I, which had been sunk to its final position by the 1st October, 1907, was unwatered about the end of June, 1908, by pumping into the river through temporary shafts at the west end, after the placing of additional sections to the east had made that course safe. The interior was found to be in excellent condition, and practically watertight, especially at the joint with Section II. In fact, throughout the subaqueous tunnel, even where modifications in the original plan of connection had to be made to meet local conditions, the joints were free from leakage.

As the sections were successively unwatered, all leaks and seepage at joints and rivets in the steel shell were effectually stopped by caulking.

Lining with reinforced concrete was not commenced until the 11th February, 1909, working from the centre of Section V westward, after Sections VII and VIII had been sunk and partially concreted in place. Upon effecting a junction of the lining with the east end of the Detroit approach-tunnel, work was resumed in Section V, and the lining was pushed eastward to a junction with the Canadian approach-tunnel in January, 1910, 4 months after the tunnel had been opened for continuous passage to pedestrians. Bench-walls were completed in the month of March, 1910.

It should be mentioned that careful observations before the placing of the lining disclosed a gradual settlement of the subaqueous section for a length of about 1,000 feet in mid-channel. The conclusion was reached that this was due to the unsettled condition of the surrounding material and to the "bleeding" of water from the clay through minor leaks in the unfinished tunnel, so as to lower the hydrostatic pressure; and that the adjustment of the tunnel to new conditions, and the closing of all leaks upon the completion of the inner lining, would cause the movement to cease. This hypothesis was found to be correct, the full hydrostatic head being restored and all settlement ceasing several months before the track was laid. The necessary final adjustment of level was easily effected between the vertical curves without encroaching upon the overhead clearance.

The progress of various portions of the subaqueous tunnel is given in detail in Table II of the Appendix. It will be noticed that 3 years elapsed from the time of commencing the first section of tubes at the shipyard in February, 1907, to the completion of lining in the same month in 1910.

Leakage.—Before lining was started, short 1-inch pipes in the top and bottom, spaced 12 feet apart, were connected with holes bored in the steel shell, with which connection could be made, after the completion of the lining, for forcing grout into all cavities and spaces between the shell and the exterior concrete, and between the shell and lining. This same procedure was followed in the approach-tunnels to stop leaks in the extrados of the arches. Grouting under a pressure of 75 to 100 lbs. per square inch was carried out in the spring of 1910, with the result that the minor leaks that had resulted from imperfect caulking and waterproofing were closed, the total leakage between portals in both tunnels being less than 10 gallons per minute, equivalent to 0·85 gallon per day (24 hours) per lineal foot of single bore. Even this slight leakage is gradually diminishing and promises soon practically to cease.

Casualties.—While there were on the subaqueous section a number of casualties incidental to the magnitude of the work, such as carelessness of employees and minor accidents, there was not a single fatality attributable to the adopted method of construction, nor, of course, was there any trouble with "bends," as the use of compressed air, except for divers, was avoided.

TUNNEL QUANTITIES AND COSTS.

The history of an undertaking like the Detroit River tunnel would be incomplete without a statement of costs of the portions of the work that involved the use of new methods. The approximate quantities and actual costs of the tunnel-construction, *exclusive of contractor's profits,* are given in Table III of the Appendix, these being taken from inspector's reports, with 15 per cent. added for overhead charges. The total cost from summit to summit will be seen to amount to $4,775,306 (£995,000).

The current prices of labour, tools, and material were as follows:—

Unskilled labour	15 to 30 cents (7½*d.* to 1*s.* 3*d.*) per hour, average 18½ cents per hour.
Skilled labour	25 to 45 cents (1*s.* 0½*d.* to 1*s.* 10½*d.*) per hour, average 32½ cents per hour.
Cement	$1·16 to $2·25 (4*s.* 10*d.* to 9*s.* 5*d.*) per barrel, average $1·35 per barrel.
Sand and gravel	60 cents (2*s.* 6*d.*) per cubic yard.
Steel in tubes delivered on site of work	5 cents (2½*d.*) per pound (£23 6*s.* 8*d.* per ton).
Dredging, based on "pay quantities," with slopes of 1 to 1, beyond which no allowance was made for removed material	40 cents (1*s.* 8*d.*) per cubic yard.
Steam shovels, each	$5 (£1 0*s.* 10*d.*) per day.
Cars, each	$1 (4*s.* 2*d.*) per day.
Scows, derricks and miscellaneous tools, at prices to cover interest, depreciation and replacement.	

It will be noticed in Table III that the cost of excavation in the western open cut was $1·33 per cubic yard, as contrasted with 39·3 cents per cubic yard in the eastern cut, the difference being due to smaller quantities, a larger proportion of hard digging, and the care required to avoid disturbance of adjoining temporary track-supports at the former place. In the approach-tunnels the use of compressed air on the Canadian side largely accounts for the cost of $5·54 (23*s.* 2*d.*) per cubic yard for excavation as compared with $4·73 (19*s.* 9*d.*) on the Detroit side. The subaqueous cost of 50·3 cents (2*s.* 1*d.*) per cubic yard includes dredging, coffer-dam excavation, back-filling, riprap and other work connected with the excavation and refilling of the trench, with the exception of the coffer-dam itself, which is included under "Miscellaneous."

The item of iron and steel appears most prominently in the subaqueous section, where 5,000 tons was required in the tubes and the balance, 528 tons, in grillages and reinforcing rods. The approximate cost of the tubes in place was:—

	Net Cost per Ton.			
	$	£	*s.*	*d.*
Steel tubes delivered on site ready for sinking	112·00	23	6	6
Labour of sinking and placing	8·40	1	15	0
Plank sides	6·10	1	5	6
Overhead charges (15 per cent.)	19·00	3	19	0
Total	145·50	30	6	0

The cost of concrete per cubic yard varied, of course, with the classification and with the conditions under which it was placed, the cost of forms having much to do with the differences, as will be noted in Table IV of the Appendix.

Class A concrete (1 : 2 : 4) was the most uniform in cost, averaging \$10·76 (44*s.* 9*d.*) per cubic yard, the highest reaching \$12·74 (53*s.*) per cubic yard in the subaqueous tunnel-lining where the comparative thinness of the ring and the presence of reinforcing rods increased the labour item. Class B concrete (1 : 3 : 6) ranged from \$6·17 (25*s.* 8*d.*) to \$6·97 (29*s.*) per cubic yard in the open-cut retaining-walls, and from \$8·54 (35*s.* 7*d.*) to \$9·40 (39*s.* 3*d.*) in the approach-tunnels; while in the river section the cost fell to \$4·42 (18*s.* 5*d.*) per cubic yard, because of the use of tremies and the absence of forms other than the tubes and appurtenances that are provided for under iron and steel. Class D concrete (1 : 4 : 7½) cost \$4·75 (19*s.* 9*d.*) to \$5·28 (22*s.*) per cubic yard in the open-cut retaining-walls, and \$3·72 (15*s.* 6*d.*) per cubic yard in the foundation-course of the subaqueous section, where the increase from the calculated quantity, 6,800 cubic yards, to the actual quantity of 21,000 cubic yards, is accounted for by the large amount of "prodding" that was required in the soft clay near mid-channel and the excess excavation beyond the neat lines of the trench.

A subdivision of the tunnel-costs given in Table III into labour, material, and overhead charges, appears in Table VI of the Appendix, the items of dredging and steel tubes ready for sinking appearing in subaqueous "material," because they were subcontracted, and therefore their labour-costs did not show on the reports of the principal contractor's operations.

It may not be amiss to compare these results with those obtained in subaqueous-tunnel practice elsewhere in the United States during the past 20 years. For this purpose the cost of the tunnel between portals per lineal foot of single track and per cubic foot of contents within the internal circumference are given in Table V, the latter unit being of special value in comparing the costs of tunnels having different dimensions. While, of course, the comparison shown in the Table on p. 27 is of little precise value, owing to differences in local conditions, varying prices of labour and materials, the inclusion in some instances and the omission in others of contractor's profits and losses, and uncertainty as to the strict accuracy of the cost data, still it has considerable interest as indicating in a general way the results obtained in different materials by various methods.

Summarizing, it appears that tunnel costs per cubic foot of contents, within the internal circumference, may be said to have ranged from 90 cents, as at Detroit, to \$1·08 and upwards, in soft clay;

$2·27 and upwards in sand and rock; from $1·65 to $2·38 in silt; and 61 cents in firm clay free from water.

SUBAQUEOUS TUNNELS: ROUGH COMPARISON OF COSTS PER CUBIC FOOT OF INTERNAL CONTENTS.

Place.	River or Harbour.	Nature of Material.	Method of Construction.	Internal Area of Each Bore.	Cost of Tunnel Proper.	
					Per Cubic Foot.	Per Lineal Foot, Single Bore.
				Sq. Ft.	$ s. d.	$ £ s.
Detroit[1]	Detroit River	Soft clay	Trench and tremie (no air) . . .	314	1·057=4 5	332=69 6
			Side shield (no air)	309	0·757=3 2	228=47 12
			Side shield and compressed air .	309	0·853=3 7	257=53 13
			Average . .	. .	0·896=3 9	273=57 0
Sarnia[1] [2]	St. Clair River	Soft clay	Circular shield and compressed air .	309	1·08 =4 6	333=69 10
Boston .	Harbour	Stiff dry clay	Roof shield and compressed air .	395	0·61 =2 7	241=50 8
New York City[1] .	North River	Silt	Circular shield and compressed air .	182	1·65 =6 11	300=62 12
New York City .	East River	Sand and rock	Circular shield and compressed air .	165	2·27 =9 5	375=78 6
New York City .	Harlem River	Silt and sand	Trench and compressed air . .	164	2·38 =9 11	390=81 10

The Author believes that the subaqueous method used at Detroit may be utilized with marked reduction of cost and hazard in many locations where the employment of shields and compressed air has hitherto been considered obligatory, and where the gradients and proximity of portals to shore-lines make desirable or necessary the raising of the top of the structure up to or above the water-bed.

PERMANENT-WAY EQUIPMENT AND VENTILATION.

Track-work and Drainage.—It was realized at an early stage of the work that, in the interests of economy, of maintenance, and of safety to employees, a type of permanent way should be adopted in the tunnel that would dispense with the need of section-gangs for the frequent repairs and adjustments that are usual with ballasted track. After experimenting for several years on the main tracks of the railway-company near Detroit, the Advisory Board reached the conclusion that it would be proper to use in the tunnel a permanent type of construction consisting of 8-inch by 11-inch sleeper-

---

[1] Contractor's profits or losses not included.

[2] Constructed about 20 years ago. Costs embrace all expenses between portals.

blocks, 3 feet long and 24 inches apart from centre to centre, under each rail, these to be embedded in and rest directly upon the reinforced-concrete base of the tunnel, with a centre ditch between them for drainage to sumps (Figs. 10, Plate 1, and Figs. 17, Plate 2). Experience demonstrated that bolting down the blocks was unnecessary, dowels being sufficient to prevent lateral movement.

In the open cuts standard Michigan Central Railroad permanent way was adopted. On the road-bed a 9-inch course of gravel was laid, on top of which was placed crushed stone ballast, 9 inches in thickness beneath the bottom of the sleepers.

The rail adopted weighed 100 lbs. per yard, and was in standard 33-foot lengths, with splices conforming to the Railroad Company's practice, especial care being taken to secure a quality of material that would guard against breakage under heavy traffic. East of the boundary-line at the centre of the river open-hearth steel rail was used, containing:—

	Per Cent.
Carbon	0·65 to 0·75
Manganese	0·90 „ 1·10
Silicon	0·10
Phosphorus, not exceeding	0·04
Sulphur, not exceeding	0·05

West of the boundary, a Bessemer-steel rail was supplied, containing:—

	Per Cent.
Carbon	0·45 to 0·55
Manganese	0·95 „ 1·15
Silicon	0·13 „ 0·20
Phosphorus, not exceeding	0·10
Sulphur, not exceeding	0·075

Ferro-titanium was added as an alloy, and 19 per cent. discard was required from the tops of ingots to eliminate faulty material.

In order to divert surface water in the eastern open cut so as not to burden the sumps, a long sewer was built from the Detroit River eastward, to a point 1,400 feet to the west of the Canadian summit, where connection was made with the road-bed ditches. Westward of this point of interception, surface water in the open cut is led in sub-drained paved open ditches to the sump at the portal, where it is raised by automatically-controlled electric pumps to the sewer, and thence to the river.

In the western open cut similar ditches convey surface water directly to the Detroit portal-sump, from which it is pumped electrically into a neighbouring city sewer.

Within the tunnel any surface water that may pass the portal-sumps, as well as seepage-water, will be caught in sumps near the two shafts and at the centre of the river, and be pumped thence electrically to the surface.

Signalling and Safety-Devices.—Complete installations of electric automatic signals and electric interlocking plants with alternating-current track-circuits were installed by the Tunnel Company with purchased materials, all devices complying with the requirements of the New York Central Lines for safeguarding traffic.

An independent telephone-system for the use of transportation- and maintenance-employees connects the tunnel substation with portals, shafts, and subaqueous sump, and also with the signal-towers near the summits at which sectionalized circuit-breakers are placed.

The Advisory Board concluded that provision should be made for the prompt cutting off of propulsion-current, and for a supply of water under pressure, in the event of accidents in the tunnel. In accordance with this policy a continuous "pull-cord" and "break-glass" boxes have been placed in both tunnels, by means of which any passenger or employee may send an alarm to the substation operator, who in turn will cause the fire-pump in the substation at once to be started and water under pressure to be supplied through a 5-inch main in each tunnel to hose-connections spaced about 100 feet apart. At the same time the substation operator will notify the men in charge of the signal-towers to open the circuit-breakers controlling the affected section and cut off the supply of propulsion-current to the third rail. With these precautions, supplemented by the use of the independent telephone-system, it is possible on short notice immediately to interrupt the supply of propulsion-current, secure fire-pressure in the pipe-lines, and take any other measures that may be required for the comfort and safety of passengers and employees.

An automatic train-stop, devised by the Author, was installed experimentally to secure, if possible, means by which rear-end collisions, due to carelessness or disability of employees, would be rendered impossible. The improper passing of a home signal results in the de-energizing of a normally-closed air-brake magnet on the locomotive, thereby venting the train-pipe and causing the brakes to be applied. The de-energizing of the air-brake magnet is effected by the automatic cutting off of the supply of propulsion-current to a short movable section of working-conductor at the home signal, when the block ahead is occupied. As the device depends for proper working upon a closed circuit, any defect or injury thereto will result in the application of the brakes.

Artificial ventilation in the tunnel is considered unnecessary, because of the adoption of electricity as a motive power, the access to outer air at shafts and portals, and the running of trains in one direction through single-track tubes acting as pistons to expel foul air in front, and draw in fresh air from the rear.

ELECTRIFICATION.

Electricity as a motive power was adopted at the beginning, and, in fact, it was the recognition of its applicability to steam-railway conditions, based on the promised success of the New York Central installation at New York, that led to the decision to construct the tunnel.

Operating Requirements.—The problem to be solved involved the electrifying of the tunnel-zone extending from a point $\frac{3}{4}$ mile west of the Detroit summit to a point $1\frac{1}{4}$ mile east of the Canadian summit, a total distance of $4\frac{1}{2}$ miles, and embracing 18 to 20 miles of single track in main line and yards.

The service to be handled, exclusive of future additions from foreign lines, was estimated to consist of twenty goods-trains and eighteen passenger-trains daily, the former ranging in weight, exclusive of locomotives, from 1,366 to 1,685 tons, and the latter from 134 to 535 tons. The conditions of operation were assumed to necessitate at times the simultaneous movement on the ascending gradients through the tunnel of a 1,800-ton goods-train in each direction at a speed of 10 miles per hour, plus assumed main-line and yard movements beyond the summits. The number of cars to be moved daily approximates to 1,200, or about 400,000 per annum.

Provision was also required for the working of sump-pumps, and for lighting the tunnel and yards.

Choice of System.—The fiercely-asserted rival claims made by the advocates of various methods of electrification rendered imperative the adoption of a means of reducing arguments to some measurable basis that would be equally fair to all, and afford the Advisory Board justification for selecting an electric propulsion-system that would combine safety and reliability with economy.

In compliance with this policy, specifications were prepared, setting forth the physical conditions as to alignment and gradients, the speed, frequency, and weights of both classes of trains, the lighting and pumping, and all other information that would be required by those tendering propositions, to produce the results desired by the Tunnel Company.

Each tenderer, therefore, was to submit a proposition for a definite scheme to meet these conditions, the designs being prepared with a view to cause the Tunnel Company a minimum amount of expense for meeting the growth of traffic. It was mentioned that if the foreign railroads used the tunnel route the traffic would be approximately doubled, and the proposed method of providing for this had to be stated. Any tenderer who deemed the requirements of the general specifications prohibitive to the free exercise of his best skill in meeting the conditions was invited to offer suggestions for the consideration of the Company.

Attention was called to the clearance provided in the tunnel above the top of the rail, and notice was given that the cost of enlarging the tunnel to afford additional space for any system involving the use of overhead working-conductors would be considered as a charge against such system in making comparisons with other systems not requiring enlargement.

As the annual cost of operation should have equal consideration with first cost in determining which system was to be adopted, tenderers were required to insert in the specifications their estimate of the annual costs, both fixed charges and working-expenses, of the system upon which they tendered, whether direct-current, single- or three-phase alternating-current, or any other system that they considered properly adapted to the conditions. In order that the tenders might be properly compared, the cost of maintenance and operation was to be calculated in accordance with a specified method, and before the contract was finally awarded, a form of guarantee was required, protecting the Tunnel Company against a higher cost of maintenance and operation. These annual costs comprised interest-charges, taxes, insurance, risks, depreciation, operation, and maintenance.

Other clauses of the specifications described in detail the general requirements applicable to any or all systems, among the principal items being the power-station and substation buildings and machinery, the duct-system, cables, working-conductors, track-bonds, lighting, locomotives, and pumps. As a rule, the specifications in force for the electric-zone improvements of the New York Central Railway at New York governed the workmanship and material.

Invitations to contractors were issued on the 1st March, 1906, and on the 15th August of the same year proposals were received from three companies, a comparison of which follows on p. 32.

It was therefore apparent that for this particular problem direct current was respectively 12 per cent. and 32 per cent. less expensive in first cost than the three-phase and single-phase systems, and 4 per cent. and 20 per cent. less expensive annually, apart from the avoidance of necessity for encroaching on tunnel-clearances. The adoption of the single-phase system in this instance would have

System.	Locomotives for Specified Service.			[1] Comparison of Costs. Omitting Batteries.				
				First Costs.				Annual Costs. Including Fixed Charges, Operation and Maintenance.
	No.	Weight each.	Aggregate Weight.	Gen. Station.	Distr. System.	Locos.	Total.	
		Tons.	Tons.					
Direct current .	8	89¼	714	100	100	100	100	100
Three-phase[2] .	8	72¼	578	96	167	103	112	104
Single-phase[2] .	16	53½	856	121	104	167	132	120

imposed upon the Tunnel Company an added burden of nearly $40,000 (£8,000) per annum.

Moreover, the Advisory Board considered that direct current possessed elements of greater reliability, this feature being emphasized by the demand of the operating department of the railway-company for the installation of storage-batteries as a reserve in case of power-interruption.

Power-Supply.—Further consideration of the subject led to the decision that the best interests of the company would be served by the purchase of power from the Detroit Edison Company, which, with its multiplicity of generating-plants, offered a favourable price and a reliability of supply that could not be guaranteed with an isolated station of the Tunnel Company. A 10-year contract was executed accordingly, for the delivery at the substation of the Tunnel Company, on the Detroit side of the river near the shaft, of three-phase alternating current, at a pressure of 4,400 volts and a frequency of 60 cycles. Two cables from the power-stations are provided for the exclusive use of the Tunnel Company, each cable having a capacity of 2,120 kilowatts, and there are two additional cables for emergency use in common with other consumers.

At the commencement of each calendar year the Edison Company agrees to set apart in its generating-stations the kilowatt capacity designated by the Tunnel Company as needed for its maximum demands for the ensuing year, such capacity to be within a minimum of 450 kilowatts and a maximum of 2,000 kilowatts; the Tunnel

---

[1] Traction only. Direct-current costs, 100 assumed as basis for comparison.

[2] In making this comparison of cost no charge has been made for the enlargement of the tunnel if found necessary for overhead conductors.

Company having the right at any time, on due notice of an emergency, to call for an increased supply, for a short period, not exceeding twice the designated capacity.

As compensation the Tunnel Company is to pay a price per kilowatt-year for the capacity so designated, to cover fixed charges which are unaffected by the volume of consumption, plus a kilowatt-hour rate to defray working- and maintenance-costs, which of course vary with the quantity of current consumed.

The use of a storage-battery by the Tunnel Company was imposed in order to ensure reliability of service and for regulating the short periodic fluctuations of demand for primary alternating current for traction purposes to within 300 kilowatts above and below the capacity agreed upon from time to time.

The substation building, covering a space 50 feet by 207 feet, and suitably arranged for the installation of motor-generators, booster, and battery, together with the fire-pump and appurtenances, was constructed near the Detroit shaft, down which ducts were provided for the thirty-two cables of the distributing- and telephone-systems (Figs. 9, Plate 1). Two motor-generators, each with a capacity of 1,000 kilowatts, are installed, with space for a third; these transform the 4,400-volt alternating current to 650 volts direct current for the track. The battery consists of 312 cells, and has a capacity of 1,500 kilowatts on an hourly rating; it was supplied under a maintenance-agreement for a long-time period at a fixed annual cost.

Third Rail.—The 650-volt third-rail working-conductor is of the underrunning protected type devised by the Author in collaboration with Mr. Frank J. Sprague, M. Inst. C.E., and first used on the New York Central Railroad[1] (Figs. 17, Plate 2). In this type the 70-lb. bull-head steel rail is clasped in porcelain insulators made in two halves and fastened to cast-iron brackets spaced 11 feet apart. Between the insulators the rail is sheathed in a wooden insulated covering so that only the lower surface is exposed to contact, thus guarding against accidents to employees and interruption of service from sleet and snow. This covering is in three pieces as shown, the lower two pieces being fixed to the upper by long screws when in place.

Locomotives.—The contract for supplying six electric locomotives, with an option for two additional ones, was awarded to the General Electric Company, the selected type being adapted to both goods-

---

[1] Transactions of the American Institute of Electrical Engineers, vol. xxvi (1907), pp. 726 to 735.

and passenger-service within the limits of the electric zone. Each locomotive is capable of hauling a goods-train weighing 800 tons, exclusive of the locomotive, on the ascending maximum 1-in-50 gradient at a speed of not less than 10 miles per hour, and of hauling a passenger-train weighing 310 tons, exclusive of the locomotive, on the same gradient at a speed of not less than 20 miles per hour. Each locomotive weighs 90 tons and is equipped with four motors aggregating 1,120 HP. on nominal rating. The principal characteristics of the locomotive are given in Table VI of the Appendix.

Extensive tests of the first locomotive were completed on the experimental 6-mile track of the New York Central Railroad near Schenectady, New York, before construction of the remainder was started, and final tests on all were made at the same place, before they were accepted by the Tunnel Company.

Lighting and Pumps.—The contract for lighting included the furnishing and installation of all parts necessary for lighting the tunnel and yards. Duplicate lines of lighting in each tunnel are supplied from an independent 4,400-volt alternating circuit so as to be unaffected by interruptions of propulsion-current, the 16-candle-power lamps being spaced 40 feet apart on each line. One hundred and twenty-four series arc-lights on steel poles were installed by the Tunnel Company in the yards and tunnel open cuts.

Automatically-controlled motor-driven sump-pumps of the submerged vertical centrifugal type were installed. Particulars of their situation and other data appear in the following Table:—

	Aggregate Capacity.	Capacity of Sump.	Gravity Head.	Outlet.
	Gallons per Minute.	Galls.	Feet.	
Detroit portal	1,400	43,000	29	City sewer.
,, shaft	700	20,000	69	River.
Mid-river sump	500	37,000	91	,,
Windsor shaft	700	20,000	87	,,
,, portal	4,500	53,400	40	Tunnel Company's sewer.

Electric Zone Operation.—To facilitate the change of locomotives from steam to electric, and vice versa, ample yard facilities have been provided beyond the tunnel-summits on both sides of the river. Eastbound passenger-trains on the Detroit side proceed under steam to the existing station near the water-front, thence back to the yard at the junction with the tunnel line near the summit, where the motive power is changed to electricity, and thence they proceed to the Windsor yard, where steam-locomotives are again attached. Westbound passenger-trains drop their steam-locomotives at the interchange yard at Windsor and proceed by electricity to the Detroit yard, where the change is made to steam and the train is backed into the station.

Goods-trains are handled in the same manner as the passenger-service, excluding, of course, the back movements at the joint station.

When the new joint station at the western summit is completed back movements will be obviated, and the change of motive power of passenger-trains will be made at the station while the loading and unloading of passengers, luggage, mails and parcels, are being effected.

As Detroit is a division-point, necessitating an exchange of locomotives on all trains from both the east and the west, the use of electricity in the tunnel imposes but one extra change of power, for which the average time required is between 4 and 5 minutes per train.

The saving in time that results from the use of the new method of crossing the river, as compared with car-ferriage, averages 15 to 20 minutes for passenger-trains and 3 to 4 hours for goods-trains, without taking into consideration the elimination of the absolute stoppage of traffic that formerly occurred in winter months when running ice was particularly heavy.

CONCLUSION.

On the 26th July, 1910, not quite 4 years after ground was first broken, the initial electric train passed through the tunnel, the fruit of 50 years of endeavour to conquer Nature's obstacle to a continuous rail connection between the East and the West, via Detroit.

From this improvement, costing with contiguous work between \$10,000,000 and \$15,000,000 (between £2,000,000 and £3,000,000), the public will reap the benefits of greater safety, reliability, and speed that will result from the substitution of an electrically-operated tunnel for the uncertainties and dangers incident to car-ferriage across a pathway encumbered in summer and autumn with a traffic of more than 60,000,000 tons annually, and rendered hazardous in winter by storms and ice. The railway in turn will profit by savings in time and cost of working, and in a larger sense, from the increase of traffic that will inevitably follow growth of public favour, and the removal of a handicap to competition for trunk-line traffic.

In conclusion, it may be added that this record will be incomplete without reference to the persistent advocacy by Mr. Ledyard of the far-sighted policy of securing a rail connection between the lines of his company heretofore separated by the Detroit River; to the ripened judgment and wise counsel brought by Mr. Carson to the solving of the many problems that arose during construction; to the skill of Mr. Kinnear and his staff in bringing the work to a successful conclusion; and to the resourcefulness of the several contractors in overcoming the many difficulties that arose from day to day during the progress of the work.

The Paper is accompanied by ten tracings, from which Plates 1 and 2 and the Figure in the text have been prepared; there are also a number of photographs.

APPENDIX.

TABLE I.—PARTICULARS OF TUNNELS.

General—

Number of single-track tunnels	2
Assumed live load per lineal foot of single track	6,000 lbs.
Clear height above top of rail	18 ft. 0 ins.
Width between bench walls	11 ft. 6 ins.
Height, top of rail to top of bench wall	5 ft. 3 ins.

Lengths of double track—	Open Cut. Feet.	Tunnel. Feet.	Totals. Feet.
Western approach	1,540	2,132	3,672
Subaqueous section	..	2,667	2,667
Eastern approach	2,942	3,511	6,453
Totals	4,482	8,310	12,792= 2·42 miles.

Alignment of Centre Line—	Curve. Feet.	Tangent. Feet.
Tangent[1] from Detroit terminus eastward to first curve	..	2,791
2° curve to right, spiralized, central angle 20°	1,329	..
Tangent across river	..	2,150
2° curve to right, spiralized, central angle 19° 9′	1,257	..
Tangent from second curve to eastern terminus	..	5,265
Totals	2,586	10,206
Percentages of total length	20%	80%

Profile (eastbound)—	Length. Feet.	Fall. Feet.	Rise. Feet.
Vertical curve at Detroit terminus	346	5·1	..
Descending gradient, 2 per cent. equated	3,822	75·7	..
Vertical curve	680	8·5	..
Ascending gradient in mid-channel, 0·186 per cent.	860	..	1·6
Vertical curve	720	..	3·7
Ascending gradient, 1½ per cent. equated	6,034	..	89·6
Vertical curve at Canadian terminal	330	..	3·3
Totals	12,792	89·3	98·2

Quantities—

Excavation	848,500 cubic yards.
Concrete	247,760 ,,
Iron and steel	5,740 tons.

---

[1] The transition from 13-foot centres in the western open cut to 20-foot 6-inch centres in the approach-tunnel is effected by 1° reverse curves, spiralized, in the southern track, within a distance of 570 feet from the portal.

Open Cuts—	Eastern Cut.	Western Cut.
Distance between track-centres at portal	20 ft. 6 ins.	20 ft. 6 ins.
Distance between track-centres 570 feet from portal	..	13 ft.
Distance between track-centres at summit	20 ft. 6 ins.	13 ft.
Distance centre of track to wall	8 ft.	8 ft.
Length of walls	342 ft.	1,190 ft.
Depth, top rail to bottom of footings	6 ft.	6 ft.
Depth of footings	4 ft.	4 ft.
Width of coping	3 ft.	3 ft.
Height of wall above footings at portal	22 ft.	22 ft.
Height of wall above footings at end	5 ft. 5 ins.	3 ft. 6 ins.
Ratio of base of wall to height (about)	$\frac{5}{10}$	$\frac{5}{10}$
Width of road-bed, including ditches	49 ft. 6 ins.	42 ft.
Width of road-bed, inside of ditches	38 ft. 6 ins.	31 ft.
Formation-level to top of rail	1 ft. 8 ins. to 2 ft.	1 ft. 8 ins. to 2 ft.
Length of invert adjoining portal	307 ft.	339 ft.
Strut spacing beyond invert	15 ft.	13 ft. to 17 ft.
Maximum load on clay per square foot	2,000 lbs.	2,310 lbs.

Approach-Tunnels—

Distance between track-centres on tangent	20 ft. 6 ins.
Distance between track-centres at junction with subaqueous section	26 ft. 4 ins.
Radius of semi-circular top	8 ft. 3 ins.
Thickness of arch at crown (average)	2 ft. to 2 ft. 7 ins.
Thickness of centre wall	4 ft. to 9 ft. 10 ins.
Maximum load per square foot on clay, ignoring friction, arching action of clay, and hydrostatic pressure	5,600 lbs. to 7,800 lbs.

Subaqueous Tunnel—	Ft	Ins.
Distance between track-centres	26	4
Inside diameter	20	0
Thickness of inside lining	1	8
Thickness of steel shell	0	$0\frac{3}{8}$
Diameter of steel shell	23	4
Exterior thickness of concrete outside of shell—		
Top	4	6
Sides	3	0
Bottom	4	6
Distance of water surface to top of tunnel in mid-channel	41	9
Distance of water surface to top of rail in mid-channel	65	11
Distance of water surface to bottom of trench in mid-channel	74	1
Height of section out to out of metal frames	30	0
Height of section out to out of concrete	32	4
Bottom width of section (maximum)	56	8
Bottom width of section (minimum)	45	0
Maximum load on clay per square foot, crediting full hydrostatic pressure	1,680 lbs.	

	Detroit.		Windsor.	
Shafts—	Ft.	Ins.	Ft.	Ins.
Height from top of coping to top of rail	56	9	72	0
Length of oblong opening over each tunnel bore	16	6	16	6
Width of oblong opening over each tunnel bore	11	0	13	6
Minimum thickness of walls	2	0	2	0

TABLE II.—PROGRESS OF WORK, SUBAQUEOUS TUNNEL.

Item.	Sect. I.	Sect. II.	Sect. III.	Sect. IV.	Sect. V.	Sect. VI.	Sect. VII.	Sect. VIII.	Sect. IX.	Sect. X.	Sect. XI.
Commencement of tubes . . .	10 Feb., 1907	29 June, 1907	19 Aug., 1907	30 Sept., 1907	31 Oct., 1907	5 May, 1908	26 June, 1908	23 July, 1908	28 Aug., 1908	16 Sept., 1908	10 April, 1909
Launching. . .	20 Aug., 1907	29 Sept., 1907	26 Oct., 1907	13 Nov., 1907	24 June, 1908	22 July, 1908	22 Aug., 1908	15 Sept., 1908	21 Oct., 1908	17 Nov., 1908	29 May, 1909
Sinking . . .	1 Oct., 1907	25 Nov., 1907	27 May, 1908	9 July, 1908	27 Aug., 1908	10 Oct., 1908	19 Nov., 1908	3 May, 1909	8 June, 1909	4 Aug., 1909	14 Sept., 1909
Bolting joints. .	..	3 Dec., 1907	5 June, 1908	15 Aug., 1908	30 Aug., 1908	15 Oct., 1908	25 Nov., 1908	12 May, 1909	12 June, 1909	13 Aug., 1909	..
Exterior concrete—											
Commenced .	10 Oct., 1907	6 Dec., 1907	5 June, 1908	23 July, 1908	8 Sept., 1908	19 Oct., 1908	24 Nov., 1908	13 May, 1909	11 June, 1909	9 Aug., 1909	18 Sept., 1909
Completed . .	29 April, 1908	30 Aug., 1908	23 Sept., 1908	24 Sept., 1908	23 Nov., 1908	22 Dec., 1908	13 April, 1909	11 June, 1909	3 July, 1909	28 Aug., 1909	7 Oct., 1909
Lining—											
Commenced .	31 Mar., 1909	26 April, 1909	24 April, 1909	28 Mar., 1909	11 Feb., 1909	1 July, 1909	17 Aug., 1909	17 Oct., 1909	20 Oct., 1909	26 Nov., 1909	6 Dec., 1909
Completed . .	18 Feb., 1910	28 July, 1909	28 June, 1909	24 May, 1909	23 Nov., 1909	12 Feb., 1910	15 Dec., 1909	4 Jan., 1910	19 Jan., 1910	18 Jan., 1910	12 Jan., 1910

TABLE III.—APPROXIMATE TUNNEL QUANTITIES AND COSTS (*Exclusive of Contractor's Profits*).

(Electrification, Tracks, Safety Devices, Terminals, and Right-of-Way not included.)

Items.	Unit.	Western Open Cut.			Western Approach.			Subaqueous.		
		Quantity.	Unit Cost.[1]	Cost.	Quantity.	Unit Cost.[1]	Cost.	Quantity.	Unit Cost.[1]	Cost.
			$ s. d.	$		$ s. d.	$		$ s. d.	$
1 Excavation .	Cubic yard	39,300	1·33 = 5 7	52,304	109,500	4·73 = 19 8	518,261	350,000	0·50 = 2 1	175,950
2 Iron and steel	Ton	..	.. ..	3,075	98	92·23 = £19 5*s.*	9,039	5,520	136·45 = £28 10*s.*	753,065[2]
						s. d.			s. d.	
3 Concrete A . (1 : 2 : 4)	Cubic yard	260	11·45 = 47 7	2,977	27,557	10·11 = 42 0	278,494	27,170	12·74 = 53 0	345,978
4 " B .	" "	5,210	6·97 = 29 0	36,288	12,091	8·54 = 35 6	103,400	79,100	4·42 = 18 6	349,830
5 " D .	" "	4,597	5·28 = 21 6	24,253	..	.. ..	..	21,000	3·72 = 15 6	78,049
6 Waterproofing	100 square feet	248	2·00 = 8 4	494	2,741	14·62 = 61 0	40,064	..	.. ..	..
7 Ducts . .	Lineal feet	26,004	0·187 = 0 9	4,864	121,956	0·131 = 0 7	15,957	178,124	0·097 = 0 5	17,349
8 Miscellaneous	..	..	.. ..	163	..	.. ..	5,750	..	.. ..	52,223[3]
9 Totals . .	Lineal feet, single track	3,080	.. ..	124,418	4,264	227·71 = £47 10*s.*	970,965	5,334	332·29 = £69 0*s.*	1,772,444

[1] Unit costs obtained by dividing total costs by quantities, and are therefore approximate.

[2] Includes plank sides.

[3] Includes coffer-dam for making westerly connections with approach-tunnel.

TABLE III—*continued.*

Items.	Unit.	Eastern Approach.			Eastern Open Cut.			Totals.	
		Quantity.	Unit Cost.[1]	Cost.	Quantity.	Unit Cost.[1]	Cost.	Quantity.	Cost.
			$ s. d.	$		$ s. d.	$		$
1 Excavation . .	Cubic yard	186,000	5·54 = 23 3	1,030,927	163,700	0·393 = 1 8	64,400	848,500	1,841,842
2 Iron and steel .	Ton	129	131·20 = £27 7*s.*	16,941	..	.. ..	1,983	5,745	784,103
3 Concrete A (1 : 2 : 4) .	Cubic yard	51,353	10·08 = 42 0	517,396	75	9·04 = 37 9	678	106,415	1,145,523
4 ,, B .	,, ,,	14,507	9·40 = 39 2	136,504	2,490	6·17 = 25 8	15,368	113,398	641,390
5 ,, D .	,, ,,	..	.. ..	..	2,350	4·75 = 19 10	11,164	27,947	113,466
6 Waterproofing .	100 square feet	4,463	11·38 = 47 6	50,716	110	1·18 = 4 11	130	7,562	91,404
7 Ducts . . .	Lineal feet	205,175	0·141 = 0 7	29,034	7,040	0·132 = 0 6	928	538,299	68,132
8 Miscellaneous .	..	..	.. ..	19,985	..	.. ..	11,325	..	89,446
9 Totals . . .	Lineal feet, single track	7,022	256·55 = £53 10*s.*	1,801,503	5,884	.. ..	105,976	25,584	4,775,306

---

[1] Unit costs obtained by dividing total costs by quantities, and are therefore approximate.

TABLE IV.—DETAILED COSTS OF CONCRETE PER CUBIC YARD (*Exclusive of Contractor's Profits*).

Class of Concrete.	Subdivision.	Western Open Cut.		Western Approach.		Subaqueous.		Eastern Approach.		Eastern Open Cut.	
		$	$	$	$	$	$	$	$	$	$
	Concrete { Labour . . .	4·26		2·57		5·63		2·74		3·45	
	Concrete { Material . . .	3·05		3·92		4·33		3·84		3·52	
A	Concrete { Overhead charges.	1·09		0·98		1·50		0·99		1·04	
		——	8·40	——	7·47	——	11·46	——	7·57	——	8·01
1 : 2 : 4	Forms		3·05		2·64		1·28		2·51		1·03
	Total		11·45		10·11		12·74		10·08		9·04
	Concrete { Labour . . .	1·50		2·82		0·85		2·94		0·81	
	Concrete { Material . . .	2·80		3·39		2·99		3·71		3·14	
B	Concrete { Overhead charges.	0·62		0·93		0·58		1·00		0·59	
		——	4·92	——	7·14	——	4·42	——	7·65	——	4·54
1 : 3 : 6	Forms		2·05		1·40		..		1·75		1·63
	Total		6·97		8·54		4·42		9·40		6·17
	Concrete { Labour . . .	1·65				0·73				0·68	
	Concrete { Material . . .	2·48				2·50				3·22	
D	Concrete { Overhead charges.	0·62				0·49				0·58	
		——	4·75		..	——	3·72		..	——	4·48
1 : 4 : 7½	Forms		0·53				..				0·27
	Total		5·28				3·72				4·75

Table V.—Costs of Tunnel per Lineal Foot of Single Track and per Cubic Foot of Contents

(*Exclusive of Contractor's Profits*).

Location.	Length of Single Track.	Area within Internal Circumference.	Costs per Lineal Foot of Single Track.									Costs per Cubic Foot within Internal Circumference.
			Excavation.	Iron and Steel.	Concrete Class A.	Concrete Class B.	Concrete Class B.	Water-proofing.	Ducts.	Miscel.	Totals.	
	Feet.	Square Feet.	$	$	$	$	$	$	$	$	$ s. d.	$ s. d.
Western Approach	4,264	300·80[1]	121·54	2·12	65·31	24·25	..	9·39	3·74	1·36	227·41=47 10 0	0·757=3 2
Subaqueous	5,334	314·16[2]	32·98	141·18[3]	64·86	65·59	14·63	..	3·26	9·79	332·29=69 0 0	1·057=4 5
Eastern Approach	7,022	300·80[1]	146·81	2·41	73·68	19·44	..	7·22	4·13	2·86	256·55=53 10 0	0·853=3 7
Total between portals	16,620	..	..	..	..	..	..	..	..	..	273·46=56 18 9	0·896=3 9

[1] Internal section 20 feet high by 16 feet 6 inches wide.

[2] Internal section circular, 20 feet in diameter.

[3] Plank sides included.

TABLE VI.—PROPORTIONATE LABOUR, MATERIAL AND OVERHEAD CHARGES.

Location.	Labour.	Material.	Overhead Charges (15 per cent.).	Total.
	$	$	$	$
Western open cut	61,018	47,174	16,226	124,418
Western approach	487,377	356,941	126,647	970,965
Subaqueous	341,820	1,199,435	231,189	1,772,444
Eastern approach	952,666	613,859	234,978	1,801,503
Eastern open cut	45,993	46,163	13,820	105,976
Totals	1,888,874	2,263,572	622,860	4,775,306

TABLE VII.—PARTICULARS OF LOCOMOTIVES.

Length inside coupler knuckles	39 ft. 6 ins.
,, of main cab	16 ,, 3 ,,
Width of cab.	10 ,, 2 ,,
Height to top of cab	12 ,, 6 ,,
,, of cab floor	5 ,, 6 ,,
,, to top of trolley, retracted	14 ,,10 ,,
,, ,, ,, extended	15 ,, 6 ,,
Maximum width	10 ,, 2⅝ ,,
Rigid wheel-base	9 ,, 6 ,,
Total wheel-base	27 ,, 6 ,,
Span of third-rail shoes	22 ,, 8 ,,
Diameter of drivers	48 ins.
Total weight	200,000 lbs.
Spring-borne weight	145,000 ,,
Weight per axle	50,000 ,,
Horse-power per ton of weight, nominal rating, tractive effort 35,200 lbs.	12·5
Horse-power per ton of weight, overload capacity, 2 to 5 minutes, tractive effort 60,000 lbs.	18·25
Number of motors	4
Nominal rating of each motor, on 600 volts	280 HP.
,, ,, ,, locomotive on 600 volts	1,120 ,,
Overload capacity of each locomotive	1,630 ,,
Type of motors	Geared, commutating pole.
Voltage of motors	600
Gear-ratio	4·37
Weight of motor complete	11,600 lbs.
Type of control	Sprague-General Electric.
Air-brakes	Westinghouse.
Maximum speed in miles per hour	30
Instantaneous tractive effort at slipping point	50,000 to 60,000 lbs.
Ratio of weight to normal tractive effort	5·62
Capacity behind two locomotives in multiple unit on 2 per cent. gradient (1 in 50) at 10 miles per hour, continuous service with 15 minutes' layover at each end without undue heating	1,600 tons.
Ventilation	Forced.

Discussion.

The President.

The PRESIDENT, in moving a vote of thanks to the Author for his interesting Paper, stated that, unfortunately, the Author's business engagements in America did not permit of his crossing the Atlantic to be present that evening. He thought it would be of interest to mention that the Author had formerly held for a long time the office of Vice-President of the New York Central Railroad, which was, of course, a very important position. The Paper described a novel and highly ingenious method of building what he would not call a tunnel, but a subaqueous connection between Canada and the United States, and contained information in regard to its construction and cost which would be of great value.

Mr. Moir.

Mr. E. W. MOIR observed that in many respects the Paper was a difficult one to criticize. The details were so new and so bold that it seemed presumptuous for any engineer to say anything about them but praise. About 5 years ago he was one of the unfortunate beings who struggled with an estimate for the scheme dealt with in the Paper. His firm, Messrs. S. Pearson and Son, did not get the contract; but he noticed, from the statement of cost given in the Paper, that they would have made a very handsome profit at their price if they had been as clever as the firm who obtained the work. The various firms who tendered for the contract had issued to them in New York what he thought could best be described as a "brain poultice" in connection with both the tunnel and the electric equipment. Nine schemes were put in for the consideration of the consulting engineers, but those who tendered never heard how their schemes had succeeded. In the plan put in by Messrs. Pearson it was proposed to use sunken tubes, but not to put the concrete round the outside as was shown in the diagrams. Messrs. Pearson proposed to launch the tubes with the concrete complete inside, except for a few feet at the ends, to make the junction with air-locked ends to the tubes, and then to complete the internal lining. The only credit that his firm deserved was that they were bold enough to say they could complete the work at a price, as the successful firm had done. It appeared to him from the diagrams given that a great deal of concrete had been put around the tubes that might have been saved. The quantity necessary to overcome the buoyancy or to retain the tubes in their place was nothing like the volume there was outside the $\frac{3}{8}$-inch steel casing.

Mr. Moir. Messrs. Pearson's scheme involved filling the surrounding space with sand instead of with concrete, which he thought would have met the case; it would not have been so strong, but he thought it would have made an equally efficient job. Possibly, however, it would have prevented any serious settlement of the structure in the trench, to which the Author referred, which in a structure of that kind was somewhat dangerous. In the scheme put forward by Messrs. Pearson there was to be a continuous support, levelled by a diving-bell, to place the tubes on, and it was hoped by that means to avoid any settlement. It seemed to him rather risky, in a current flowing at 3 knots per hour, to dredge a trench at right angles to the stream and fill it with concrete, without being sure that all the silt had been removed from the bottom. The test-results given in the Paper seemed to show that the concrete was of excellent quality; it had been passed through water and had set in water; and therefore it seemed to him the samples proved that concrete nowadays was made unnecessarily rich in cement. Engineers had been worrying contractors about cement-specifications for many years, making them more stringent all the time. During the last 30 years the quality had been improving very much, but engineers still specified a 2-to-1 mixture for mortar, or 6-to-1 concrete, as if cement were lime. The specification in this case called for 4-to-1 concrete inside the tubes, while only 6-to-1 material was required for that lowered through the water. Two of sand and 4 of broken stone amounted practically to 4 to 1, and he submitted that that was an exceedingly rich mixture. The costs given in the Paper were very interesting, and were seldom obtained in the Proceedings of The Institution—he was afraid, for trade reasons. In America the staffs of the engineers of the railway-companies invariably took the time on the whole of the works. Their inspectors were young engineers who had graduated at universities; they acted, among their other duties, as timekeepers, and the cost of every piece of work, whether contract work or day work, was recorded. For that reason he thought that American Papers, giving, as they did, actual data, were often more interesting than English Papers. Referring to the question of costs, it was stated on p. 27 that the Detroit tunnel had cost $332 (£69 6*s.*) per lineal foot of single track. The St. Clair tunnel, one of the earliest subaqueous tunnels, crossing at Sarnia, a little farther up the same river, had cost $333 per lineal foot of single track, whereas the North River tunnel in New York City, where prices were notoriously higher than at Detroit, and which had been built under compressed air, had cost only $300 (£62 12*s.*) per lineal foot. Turning to p. 40, it would be seen that

Mr. Moir. the cost per cubic yard of excavation of the subaqueous portion of the Detroit tunnel was only 50 cents, whereas he expected the cost of excavation in New York would be more like 10 to 15 dollars per cubic yard when dug out. There was evidently room for cross-river connections on this system—and probably at much lower cost; and there was no doubt that in many situations the method would be exceedingly useful. He fully anticipated that some day the English Channel would be subaqueously "bridged" by a system on the lines of the work carried out at Detroit. Many years ago the same plan was suggested for connecting Denmark and Sweden—he thought by a Swedish engineer, shortly after leaving the employ of Messrs. Fowler and Baker on the Forth Bridge; and he understood that Mr. Barlow suggested many years ago a similar method for crossing Rio de Janiero harbour. If engineers were ultimately able to fix the maximum draught of ships, it would appear that some such scheme, suspended, like Mohammed's coffin, between heaven and earth, might be used to bridge many channels, if masses of foundation could be dropped into water which was too deep to permit of their being laid properly by divers. He noticed from the Paper that the contractors had been unable to carry out the shore approaches by the method of timbering suggested in the preliminary specification. Messrs. Pearson's tender did not endorse that part of the suggested scheme at the time, and they suggested making the shore approaches by means of circular shields in two distinct tracks. The contractors began to build their shore approaches with a series of headings, but ultimately they had to give up that plan and adopt what would appear, from the progress made, to be a somewhat inefficient makeshift, considering that an advance of only 9 feet was made per day with a shield, which was a very slow rate at the present day. The scheme as a whole, however, was full of new suggestions, and inasmuch as the Author gave such great credit to the contracting staff, Mr. Moir was sorry to see that the names of individual members of it did not appear in the Paper. When Messrs. Pearson made their tender, the joints, for instance, were not designed, and a great many details that appeared in the Paper did not appear in the original specifications. The Author frankly admitted that the contractors designed many of the details of the scheme, and Mr. Moir therefore wished that their names had been given, so that they might appear on the record as having done such good work.

Mr. Burge. Mr. C. O. Burge remarked that the question of crossing Sydney Harbour had been considered in Australia, and much discussion had taken place as to whether a bridge or a tunnel would

Mr. Burge. be the proper means to adopt. The Royal Commission which investigated the subject about 2 years ago came finally—guided largely by the success of the Detroit tunnel—to the decision to adopt the system set out in the Paper. As in the present scheme, they were limited in depth. The railways on each side of the river could not be approached with a gradient steeper than about 1 in 50; consequently it was necessary to adopt a shallow tunnel. The scheme had been before Parliament, and he believed the work would probably have been commenced by the present time, but for the dissolution of the State Parliament, which had thrown parliamentary proceedings somewhat out of gear. When the Australian engineers came to design the work, no doubt they would be greatly guided by the present Paper and the discussion upon it. The question he desired to ask was, what necessity was there for having longitudinal reinforcement in the lining? The tubes appeared to have stood for 7 months without any lining or reinforcement after they were unwatered. It seemed to him that the whole massive concrete structure, strengthened longitudinally by the tube itself, would be fully sufficient to meet all the stresses that were likely to come upon the structure in a longitudinal direction. On the 29th April, 1910, an article appeared in the *Railroad Age Gazette*, in which the statement was made that one of the tubes on the Detroit tunnel had gone out of position when being sunk, but that, by a very extraordinary circumstance, a large steamer passing over caused such a movement in the water as to get it exactly into its right position! If that report had appeared in an ordinary journal it would have been less surprising, but it had appeared in a technical paper, and therefore he thought it would be interesting if the Author were able to say something about it. Details of the five tunnels which it was proposed should be made across Sydney Harbour for railway, tramway, and road, had appeared in *Engineering*[1].

Mr. Thomson. Mr. T. FRAME THOMSON remarked that he had had the pleasure of going through the Detroit tunnel in the first passenger-train which traversed it. The Author made somewhat of an apology for not dealing at greater length with all the details of the subject which were of interest; but Mr. Thomson thought very few Papers had been read at the Institution in which every aspect of the subject had been so fully and clearly dealt with as in the present instance. There was one feature of the tunnel which was of special

---

[1] Vol. lxxxviii (1909), p. 673.

Mr. Thomson.

interest to British engineers at the present time, when reciprocity was so much to the fore. The Michigan Central Railroad was the best line in the whole of the North American continent for high speed. It was laid with rails rolled in Canadian mills, and it was laid in Canadian territory; and the new 16-hour trains between New York and Chicago were to be run over that road. He thought it was reciprocity indeed that the best express trains of the United States should run over Canadian territory. Mr. Moir had made a comparison of the cost of building the Detroit tunnel with the North River tunnel in New York, so far as the excavation was concerned. He presumed the tunnel to which Mr. Moir had referred was excavated, but the Hudson River tunnels were not excavated, because the material was so soft that the shields could be driven through with an admission of only 5 to 10 per cent. of the mud through the face of the shield, and that might vitiate any comparisons. The comparisons made by the Author of the relative merits of the direct-current, three-phase, and single-phase systems were extremely interesting. Referring to the subject of signalling, he did not know whether the latest methods of signalling on the New York Rapid-Transit Railway had been brought to the notice of The Institution. He had seen on that railway an apparatus which had struck him as being peculiarly ingenious. A series of short blocks approaching the stations were arranged to operate at certain time-intervals, so that if a train passing between any two of the blocks took less than a certain time, the brakes were applied and the train was pulled up before it reached the platform.

Mr. Hudleston.

Mr. F. Hudleston remarked that he had read the Paper with a great deal of interest, because it dealt with an entirely different class of subaqueous tunnels from those constructed in England, and therefore it naturally appealed to an English engineer. Mr. Moir had already pointed out that, so far as the costs were concerned, these did not come out any better than for shield-driven tunnels. In the present case he thought the costs would have been distinctly higher if it had been necessary to construct the tunnel under similar conditions to those that had to be faced occasionally in England. For instance, if the tunnel had had to be made in an open trench, in a river which had very strong currents, and a good deal of sand moving about in it, it would probably have been found almost impossible to keep the trench open long enough to sink the various sections of the tunnel. On the other hand, in a river like the Detroit River, where apparently there was no movement of sand, and where it was desirable to keep the tunnel as high as possible, engineers

Mr. Hudleston. would be driven to devise some arrangement of the kind adopted, because it would be almost impossible to drive a shield through bad soil of the description mentioned, within 3 or 4 feet of the river-bed. The shallowest tunnels constructed in England had been at least 7 or 8 feet below the bed, and even then more solid stuff was met with than the half-clay and half-silt present in the Detroit River. As the Author pointed out, there were many advantages in the method adopted. For instance, it was possible to get nearer the surface; the approach-tunnels were therefore shorter, and generally the mere fact that they were shorter made the work a good deal easier. Nevertheless, he did not think such a tunnel could have been constructed across the Thames, as the interruption of traffic caused by the presence of the dredgers would have been prohibitive. In sundry other estuaries in England the flow of sand was so large, and the movement of the sandbanks was so considerable, that in practice it would be impossible to keep the trench open long enough to sink the tunnel. He differed from Mr. Burge's view that the concrete lining of the tunnel need not have been reinforced. Had the engineers not reinforced the lining, but tried to keep it tight by caulking, sooner or later there would have been very severe hydrostatic pressure at the back, and if there were any movement through the concrete, the skin of the tube would have no power to resist such pressure. He would not say anything as to the exact amount of the reinforcement, but he considered that in principle the reinforcement was perfectly correct in such a case. During the time the tunnel was under construction it did not much matter if water did get in, because that could be relieved by drilling holes through, but to have left the tunnel unlined on the inside would, in his opinion, have been an impossible proceeding. With regard to Mr. Moir's remarks about settlement, he did not quite understand why there should be much settlement in the tunnel, because the pressure per square foot on the ground below the tunnel would not be very different from what it was before, unless the ground was extraordinarily soft. If settlement did occur, it would be rather awkward, because the leaks would be appalling; but he did not think there would be much settlement, because he noticed from the drawings that the tunnel was set down first on fairly strong grillages, and then, as the whole thing was concreted up, a very even pressure was obtained over the whole of the foundation. The pressure could not be much, because there was only 20 feet of solid concrete, which did not amount to much per square foot. The Paper was so full of detail that it was difficult to criticize it exhaustively. The only other point to which

Mr. Hudleston. he wished to refer was the eminently simple method by which two adjacent sections of the tunnel had been connected (Figs. 16A and 17). There was a long pilot pin to guide the tube into place, and a spigot joint, which was a fairly easy piece of work. That was very elastic and would allow for a considerable degree of movement and settlement during construction and before the tunnel was finished. After it was finished and concreted up, it was difficult to conceive that there would be much settlement.

Mr. Read. Mr. R. J. G. READ thought the Paper was exceedingly interesting, and the work to a large extent very original. A similar work had been carried out in Paris for the crossing of the River Seine, at two places, by the Metropolitan Railway. The tunnel was sunk into the bed of the river from the surface, but not exactly in the same way as that carried out by the Author. The French enclosed their tunnel—a single tube with two tracks—in a caisson, which was built round it in skeleton ironwork and concreted before sinking; when concreted it was sunk on to the bed of the river, and further depth was attained by excavating in an air-chamber under the bottom of the caisson. That work had been accomplished very successfully. As had been pointed out, a very large quantity of concrete had been used in the Detroit tunnel, but nothing like that quantity had been used in the French tunnels. After the River Seine had been crossed, the excavation was continued with a shield, in a manner somewhat similar to that adopted in constructing the tunnels under the River Thames. He noticed that in making the contract for the carrying out of the Detroit tunnel it was stipulated that the date of completion was to be the 1st June, 1909, and that a penalty was imposed on the contractor if he did not complete it by that time, while he was to receive a bonus of £200 per day if he completed it sooner. It was stated in the Paper that the tunnels were not completed till February, 1910, the first train running through on the 26th July of that year. He would like to know whether the penalties had been imposed, and, if not, what had been the reasons given for non-completion to time.

Mr. Hay. Mr. DAVID HAY expressed his appreciation of the work and of the boldness, ingenuity, and skill displayed in carrying it out. Mr. Hudleston had spoken of the difficulty of carrying out such work in Great Britain, on account of the high velocity of the tides, and the consequent silting up. To a certain extent Mr. Hay agreed, but he thought this would only entail a little more dredging in the first instance or clearing out of the silt immediately before the tubes were placed in position, and the method would be well worth considering under certain conditions. About 40 years ago he

Mr. Hay. remembered seeing drawings of a scheme for tunnelling the Channel by submerged tubes. The idea, he believed, originated with Mr. J. Somes Story, M. Inst. C.E. The success of any such scheme, however, must be entirely dependent upon the feasibility of depositing the concrete under and around the tubes, and the system described by the Author, which was new to Mr. Hay, seemed to be admirable for its purpose. In a work where the main difficulty had been so successfully met, it seemed rather ungracious to criticize adversely any of the minor works, but he wished to say a word on the subject of the approach-tunnels. The work had evidently been carried out in three stages: first a tunnel for the centre wall, and then the two side tunnels. That must have been a very expensive proceeding, and opening the ground three times must have caused serious subsidence and consequent damage to the property above. It would have been more economical, he thought, to have constructed two entirely separate tunnels on each side of the river. The 18-foot headway above the rails appeared large, but no doubt there was reason for it. Although not familiar with American prices, he thought two tunnels 20 feet in internal diameter, with cast-iron lining, might have been constructed, apart from contractors' profits, for £200 per lineal yard for the double tunnel. In that way the 1,800 yards of tunnel would have cost about £360,000, as against the actual cost of £572,000, a difference of over £200,000, apart altogether from the damage to property, which must have been very considerable.

Mr. Copperthwaite. Mr. W. C. Copperthwaite thought the Paper described a remarkable instance of the value of imagination in engineering. Given certain conditions, the work had been so arranged that it had been carried out exactly in a manner suited to those conditions. He was not, however, prepared to say, as the Author did, that the system was in any sense a substitute for the English method of driving subaqueous tunnels by means of a shield and cast-iron lining—a method connected with the name of Mr. Greathead. It seemed that the conditions under which the work had been done were entirely special. In order to carry out such a work satisfactorily it would have to be done under a waterway where there was no very rapid current, or, at any rate, where there was a regular current; secondly, it must be in a waterway where the material of the river-bed would not silt up; and thirdly, and perhaps as important a point as any, the waterway must be under the control of authorities who were tolerably complaisant. He could not imagine obtaining such special privileges on the River Thames, nor could be imagine that any trench dug in the Thames in the manner shown by the Author could possibly be kept clean enough to enable concrete to be laid down which would

Mr. Copperthwaite.

be in any degree watertight. Neither could he imagine mooring on a river like the Thames, say between Vauxhall Bridge and London Bridge, where the current ran at times at the rate of 4 knots per hour, barges depositing concrete in a comparatively limited space underneath. But, of course, this criticism did not affect in any way the extraordinary merit of the method described in the Paper, in the particular place where it had been carried out. It had been proposed twice in England to carry out a large subaqueous tunnel-work by lowering a tunnel, so to speak, in blocks. The first case was on the Humber, and the scheme was prepared by the late Sir Benjamin Baker, Past-President Inst. C.E., who proposed to lower a double brick tunnel, in lengths of about 50 or 60 feet, into places dredged for them, and, having joined them as closely as possible, to cover the joints with lead sheeting placed on by divers. Then the water was to be pumped out and the tunnel gradually closed. He accepted the information given to him by Sir Benjamin, but had a feeling that he would rather be directing the work from the surface than from underneath. The other case was in connection with the Blackwall Tunnel. One of the numerous schemes considered by the Engineer of the London County Council was a project for lowering the tunnel in one length. It was suggested that a trench should be dredged and a steel tube built and lowered into it. That scheme was put on one side on account of the natural difficulties of the river, and the tunnel was carried out by the now ordinary English method. There was one matter upon which he would like to have some information, namely, the shields. Mr. Hay had already criticized the method of carrying out the approach-tunnels, and it did look extraordinary. Two separate tunnels would probably have been much better, and certainly they would have been easier to make. As he understood the Paper, the approach-tunnels were commenced with the idea of building them by timbering. He could not understand why, when the engineers found they had to use a shield, they built a shield which was certain to give trouble in guiding. It seemed to him, from his experience of shield work, that if, instead of being made semicircular, the shield had been made with a flattened base, it would have travelled much more easily and have kept in line. No doubt the engineer had had a good reason for making it in the way he did, but it could not be in order to save material, because the saving in that respect would be very slight in comparison with the trouble and labour involved in keeping the shield in line. With regard to the question of cost, the Author stated that the tunnel under the Detroit River worked out at 4*s.* 6*d.* per cubic foot of content. It might be of interest to

Mr. Copperthwaite. give the cost of some similar work in London. In ordinary London clay, where for certain reasons it was necessary to work under compressed air, an ordinary "tube" railway-tunnel cost about 3*s.* per cubic foot of content. That included nothing for rails or roadway, the 3*s.* being the actual cost of making a reasonably watertight tunnel. In the case of a tunnel like those at Blackwall and Rotherhithe the prices ranged between 4*s.* 2*d.* and 5*s.* 1½*d.* per cubic foot of content. Then there was the curious case—particularly interesting in connection with the subject under discussion, and especially in connection with Mr. Hay's suggestion that it would have been much cheaper to build two separate tunnels—of the Glasgow tunnels, which consisted of three tunnels side by side. Instead of building one large tunnel for the roadway and footway tunnels they built two road-tunnels, one for the traffic in one direction and one for the traffic in the other, and a footway tunnel. The cost of those tunnels was only 2*s.* 6*d.* per cubic foot of content. Adding 50 per cent. for American prices, in a case such as that described by the Author, where the labour cost nearly as much as the material, the cost of the Glasgow tunnel was something under 4*s.*; and the Author only claimed that the cost of his tunnel was 4*s.* 6*d.* Under similar conditions, therefore, there was very little difference between a 16-foot tunnel constructed in Glasgow and a tunnel with an 18-foot headway constructed in Detroit by the particular method described.

Mr. Monkhouse. Mr. E. W. MONKHOUSE endorsed what had been said as to the importance of the Paper and the care that had been taken to overcome the difficulties. Some of the arrangements appealed to him, as a mechanical engineer, very strongly. He had tried to put himself in the position of the man who had to lower the tubes into the water and connect them up, and had tried to see the difficulties to be overcome to get them into position. Although a great many details of those difficulties were set out in the Paper, there were others which it would be of advantage to have noticed. To lower a tube 250 feet long on to a grillage, as the tubes had been lowered at Detroit, so that the holes of the adjacent ends of two tubes came opposite one another, must have been very difficult; and the whole of the slinging arrangements must have been extraordinarily accurate in order that the pilot-pins might be of use in getting the tubes into their exact places. The diaphragms around the tubes must also have been made very accurately, because if the tubes had been the least bit off the square neither the pins and their sockets nor the bolt-holes of adjacent sections would have come opposite to each other. Again, if the tubes had been a very

Mr. Monkhouse.

small amount out of level across the river, they would have had to be raised, and a 250-foot tube could not be hove up by bolts without probably tearing the flange off, because the tube was only of $\frac{3}{8}$-inch metal and the flanges were not large. Therefore, the tubes must have been set very accurately in level and line. The difficulties of fixing barges so as to lower tubes of that kind on to the bed of a river in a tideway were very great. He had had some experience of mooring ships and other things in dry docks, and he knew something of the difficulty of getting any ship or structure affected by the wind to settle down in a particular position. The scows were standing on four legs which did not seem to be raked at all. The moorings must have been very rigid, otherwise there would seem to be a danger of the spuds "capsizing." The barges in the Thames which worked with hand-dredgers for dredging up ballast were fixed by spuds, but those spuds were inclined at an angle. The barges were moored by anchors fore and aft, and were fixed sideways by the spuds; otherwise the dredges would slue them out of their proper position. The Detroit spuds were said to be extensible, and he would like to know what the mechanical arrangement was for extending them, and whether, in order to get the derrick properly fixed on the spuds, the weight of the scows was taken on the spuds, and what means were adopted for doing this, so as to get a firm seating on the ground. The profile of the tunnel was more or less curved, and he would like to know whether the lengths of tube had been made to fit that profile, or whether the radius was so long that the tubes could be hove up together so that the joints met. The rubber joints would no doubt give a little, but it did not seem to him they would give enough if there were any considerable curvature in the profile. The method of getting the concrete to the bottom of the river was very ingenious, but how had the concrete been got underneath the tubes? It seemed easy to get it in between them or at the sides, but not so easy to get it underneath them, or to ensure that the concrete underneath the tubes was really solid. Had the divers pushed it under, or had it been left to chance to flow under? The Author spoke of prodding holes in the bottom of the river so as to get in concrete piers on which to put the concrete raft, and Mr. Monkhouse would like to know what those prodding tremies were like; he thought they must be some kind of boring-machine. If a tube of any kind were prodded into the clay, the core would have to be removed from the tube before the concrete was put down, but nothing was said about that in the Paper. He would like to know what means of communication were adopted between the divers and the men on the

Mr. Monkhouse. scows, and between the divers themselves, as it would seem that some communication would be necessary, especially in the process of setting the tubes. As to the electrical arrangements, he agreed with the Author in his adoption of continuous rather than alternating current; not because he thought alternating current was in any way less reliable than continuous, but because, for the work under consideration, continuous current seemed to be quite as good as alternating and somewhat less complicated. One of the reasons given for making a contract with the Detroit Edison Company for the supply of current was that the Tunnel Company would be able to call on the supply-company at any time for any power they wanted. The contract might have been wise, because it had saved the Tunnel Company from spending capital on a generating-station, but it did not seem that with the arrangements made they could call on the Edison Company for any quantity of power at a moment's notice. The Edison Company supplied three-phase current, and had installed at the tunnel two 1,000-kilowatt motor-generators. Motor-generators of that size transforming from three-phase current at a certain pressure down to continuous current at some other pressure were not to be bought over the counter, so that the Edison Company could not really be called on for any excess power at a moment's notice. From the point of view of reliability, therefore, there did not seem to be much in it, as the power that would be necessary to take an 800-ton goods-train up the incline of 1 in 50 at 10 miles per hour was just under 890 kilowatts, which was fairly near the full load for one machine, so that there was only one machine to spare. It would be interesting to know what price was paid per kilowatt-year to the Edison Company, and also what price was paid per unit; but perhaps that was a question that should not really be asked.

Mr. Moir. Mr. E. W. MOIR thought that Mr. Copperthwaite might have taken his figures from the gross prices including contractor's profit, whereas the Author quoted net prices. Further, the Author had added only about 15 per cent. for certain charges which were undefined. It would be interesting to know what that 15 per cent. covered. If it was supposed to cover contractor's profit, depreciation of plant, and so on, it appeared to be less than any figure that he would consider sufficient for that purpose.

Mr. Tripp. Mr. W. B. TRIPP mentioned that in 1873 there was a severe contest in the Houses of Parliament over a scheme for the Humber. It was a very ingenious design, on the principle of ordinary bridge-piers, sunk by means of the pneumatic process. It was considered that it would be just as easy to make a section of tunnel through the air-chamber of the caisson as it would be to fill it with Mr. Tripp. concrete; and that by sinking a sufficient number of piers in line with one another, it might be possible to get a succession of sections of a tube, so that when they were completed all that would have to be done would be to join them up and withdraw the caissons. That was worked out for the Humber, the scheme involving the use of three working-vessels, each 160 feet long. The middle vessel was to be a pontoon 160 feet long, 42 feet wide, and 12 feet deep. Underneath the pontoon there was the ordinary air-chamber, and elevated above it on columns was a working-deck clear of the water. That was to be floated out at slack water of flood-tide and sunk. There was various apparatus connected with the vessels, and screw-piles to support and give an even bed in the river. When sunk down about 24 feet below the river-bed the top of the pontoon would be level with the bed of the river, and a number of air-tight ballast-barges were to be sunk on to the top of the pontoon, serving to weigh it down and also to prevent the sand from accumulating on the top and preventing the caissons from being floated. The lower half of a pair of single-line railway-tunnels was then to be constructed in the caisson; they were to have a head wall at each end, the inner half of the wall to be of brickwork and the outer half of weak mortar. When the lower half had been built, the caisson was to be lifted and the upper half built in the same way. Puddle was to be put into the cavities left by the columns of the air-chamber. One section was to be completed and the ballast-barges floated off, and then the vessel was to be floated up and sunk again as near as possible to the end of the completed section. The end of the caisson was to shear through the weak mortar that had been left to keep out the sand, and then the new section was to be proceeded with in the same way. The novelty was in the joining up, which was to be done by raising the caisson 9 inches at a time, and the bricklayers were supposed to reach out underneath the end of the caisson and fit the bricks into the toothing of the last section. It was said there would be no difficulty in doing that because it had been practically carried out. Then another section would be done, and the whole thing thus carried right across the Humber. The scheme passed the House of Commons after a fight, but was thrown out by the House of Lords on the ground that it was impracticable. It was an ingenious scheme, and some of the details might not be unworthy of being placed on record.

Mr. W. M. Mordey remarked that, like most modern engineering problems, the one under discussion was partly electrical, and Mr. Mordey. electrical engineers would have been very glad if the Author had

Mr. Mordey. added to his interesting Paper more details of the methods employed and of the reasons that had led him to the choice of his system of driving. It was satisfactory to find that it was a recognition of the possibilities of electric driving that had led to the construction of the work. In the Paper a little Table was given showing a great difference in capital cost and in working-cost between the direct-current system, the three-phase system and the single-phase system. According to that Table the capital cost of the single-phase system was about 32 per cent. higher than that of the direct-current, and the annual working-costs were about 20 per cent. higher. He was not speaking as an advocate of alternating-current work or of single-phase working, but he thought the Table taken by itself, in view of the conditions of the work, might lead to some misapprehension. He would like to direct attention to the problem the Author had to solve. It was quite a simple problem, namely, to work a railway 1½ mile long with less than forty trains per day. That was a very different problem from railway electrification in the broad sense. It might be remembered that 9 years ago Mr. Bernard Jenkin and he had the honour of reading a Paper at the Institution on the Electrical Working of Railways. They examined all the known systems with a view to find out which was the system having the fewest disadvantages for railway electrification generally, and they arrived at the conclusion that although the single-phase system had serious disadvantages in some directions—disadvantages that had been partly removed in the last 9 years—that system offered fewer disadvantages than any other electric system for railway working on a broad and comprehensive scale. They directed their attention to finding out what was the best method, not merely of working a short town section with a very heavy traffic, but of making that town section part of a large railway system, and they came to the conclusion that in dealing with problems of railway working—dealing with them of course as electrical engineers only, and considering main-line working, long-distance traffic, express trains at high speeds, frequent trains with many stops and with rapid acceleration and rapid retardation, and so on—on the whole the direct-current system, necessarily more or less low-tension, was not as good as a high-tension alternating-current system capable of simple transformation; and that of the various alternating-current methods the single-phase system offered the fewest disadvantages. He did not put it higher than that. The Author had not helped towards the elucidation of that problem, and indeed had not set out to do so. Mr. Mordey wished to ask members not to take the little Table on p. 32—which he had no doubt was perfectly accurate

Mr. Mordey.

and fair—showing a very unfavourable comparison between direct- and alternating-current working, as necessarily condemning the latter system. It merely showed, he thought, that the Author had been perfectly right in choosing the former system for the limited and quite simple requirements that he had before him.

Mr. Sayers.

Mr. J. Sayers concurred in the remarks of the last speaker. Unless it was remembered that the Detroit work was a very special and limited problem—the working of a short section of line in the middle of a steam line—the Table in question would be very misleading. He also held no brief for any particular system of working railways, but he happened to have had experience of single-phase work, and he certainly could not imagine how, even for that length, those figures had been obtained. He referred particularly to the cost, and without questioning the accuracy of the Table he would be very pleased to have some details, if possible, of the respective rival tenders. Those remarks applied to maintenance as well as to capital cost. It was stated in the Paper that in estimating for the single-phase or three-phase equipments the contractors had to allow for any extra cost in increasing the headway, and that he could not understand. The tunnel as made allowed plenty of headway for a high-tension conductor, because there was 18 feet from the top to the rail-level. On the Heysham branch of the Midland Railway there was only 13 feet 10 inches in places, and it had been rather a difficult problem there because on a steam railway allowance had to be made for the steam-engines; but with 18 feet there would be plenty of room for insulation. Really and truly, the problem was not between continuous current and alternating current, but between high pressure and low pressure. At present the continuous current for the third rail had necessarily to be at a low pressure on account of difficulties of insulation, but if a continuous-current system could be worked directly from the contact-wire at high pressure, he thought it would be the simplest problem of all. He was not quite clear what the ducts shown in the diagram were for. As there was only one contact-rail, he concluded that the current came back by the running-rails. It was generally understood to be the better practice to have the return-current brought back by a conductor-rail.

Mr. Hudleston.

Mr. F. Hudleston thought Mr. Sayers was under a slight misapprehension. The American loading-gauge was much larger than the English, and there was nothing like the clearance there would be in a tunnel of that size with the English loading-gauge.

Mr. Moir.

Mr. E. W. Moir believed the East River tunnels were about 16 feet 3 inches from the rail to the underside of the crown.

Mr. Dawson. Mr. WILLIAM DAWSON remarked that 18 feet was about the standard headway of American tunnels measuring to the crown of the arch. The maximum height of a locomotive in England was 13 feet 6 inches, but in America they were built up to 16 feet high. The Paper specially interested him because about 5 years ago, in travelling from Niagara Falls to Chicago by the Michigan Central Railroad he had to cross the river at Detroit. The train of twelve coaches was run on to ferry-steamers in three rows of four coaches each, and the operation took about 35 minutes. Mr. Kinnear, the Chief Engineer of the Detroit Tunnel, happened to be travelling in the same train and told him they were about to construct a tunnel underneath the river; and he thought the manner in which the work had been done reflected great credit, not only on the designers, but also on the contractors who carried out the works. It did not seem to him that the method of holding the sleeper-blocks down was altogether satisfactory, as they rested in a channel of concrete, secured only by a small dowel. He would have thought that the upward movement on the conductor-rail and the downward movement on the running-rail would have produced a tendency for the sleeper-blocks to become loose. The flat-bottomed rail was adopted, he presumed, because sleepers of hard wood, such as oak, cedar, or chestnut, were used, whereas in England chairs had to be used in order to distribute the weight over the softer sleeper, which consisted mostly of northern pine (*Pinus sylvestris*). He thought the Americans were gradually coming to the English type of permanent way, because on many of their roads they placed a flat plate underneath the rail for the purpose of distributing the weight over the sleeper, and they also fixed brackets alongside the rail around curves, which practically corresponded with the English chairs. He noticed that the percentage of carbon in the rails was much higher than was adopted in England, the upper limit being as high as 0·75 per cent. He would like to know whether the determination had been made by total combustion, or by what was known as the Eggertz colour-test: 0·75 per cent. seemed a very high percentage in rails for passenger-lines; it was 50 per cent. more than was recommended by the British Engineering Standards Committee.

The Author. The AUTHOR, in reply, expressed his gratification at the courteous reception of his Paper by The Institution and by those who had been good enough to participate in the discussion. No difficulty had been experienced in keeping the subaqueous trench free from silt or drifting material. Just before sinking the tubes, any loose

The Author.

material was removed by dredging; and later, in advance of the depositing of concrete by the tremie, all sediment was sucked out by pumping from the scow above. He had observed that even in such loose materials as river-silt in the vicinity of New York, comparatively little trouble was experienced from sloughing in of the sides of the dredged channels after the slopes had reached their proper angle. As to the settlement referred to by Mr. Moir, this had been experienced more or less in all subaqueous tunnels through soft materials during the period of adjustment to surrounding conditions, as, for instance, in the several tunnels at New York City and elsewhere. Since the establishment more than a year ago, of the final levels, and the commencement of regular traffic, there had been no settlement whatever, and in fact, as remarked by Mr. Hudleston, it was not to be expected, seeing that the load per square foot on the underlying material (1,680 lbs.) was no greater—indeed even less—than it had been under the original conditions (2,175 lbs.). The adoption of the reinforcement referred to by Mr. Burge had arisen from the desire to secure a structure that would distribute loads without danger of cracks from unequal settlement or changes of temperature, especially in anticipation of possible corrosion of the steel tubes in after years. The insistence upon an inner lining continuous from shore to shore and of sufficient strength to distribute stresses as well as to resist hydrostatic pressure, had been one of the reasons that had led to the rejection of other trench methods involving the use of jointed lining. In connection with the remarks of Mr. Moir and Mr. Read, the employment of a permeable material, such as sand, around the exterior of the tubes had been discussed but not considered permissible, as a surrounding envelope of sufficient strength and watertightness was needed to prevent the collapse of the steel tubes after they were unwatered and pending the placing of the interior continuous lining or tunnel proper. Referring to the comments of Mr. Monkhouse, the care used in the shipyard in regard to the bolt-holes, pilot-pins, and sockets, and the temporary stiffening by radial rods and bulkheads, had prevented difficulty in joining the sections in situ. Cables anchored to heavy concrete "dead men" sunk to the river-bottom had held both scows and tubes in place against the force of the current. Little trouble had been experienced in operating the spuds by means of suitable devices on the scow. The radii of the vertical curves in the profile were so long that it was not necessary to build the tubes other than straight. No trouble had been experienced in working the concrete beneath the tubes, as the concrete had been mixed "wet" so as to flow easily under and around the tubes, rising gradually in each pocket to the full

The Author. height in such manner as to guarantee a solid mass. Prodding had been performed by the ordinary tremies, which were first permitted, while empty, to sink by gravity in the soft underlying clay, and then were slowly withdrawn as the concrete was fed in from the top, the weight of the column of concrete driving out the core of clay and at the same time pressing sideways so as to enlarge the hole and build up a column shaped somewhat like an inverted Christmas-tree. Communication between the divers had been effected by signals with which the men became very proficient, the telephone having been tried and abandoned. As to the episode mentioned by Mr. Burge, it had happened in one instance that the swell of a passing steamer, together with the efforts of a tug, had moved a misplaced section sufficiently to approximate to its correct position without lightening the load through the agency of the auxiliary cylinders. While all the contractor's details for achieving the specified result, including the method of building and sinking the tubes and connecting them by means of pilot-pins and circumferential bolts, had proved highly successful and well adapted to their purpose at Detroit, they were not necessary to the application of the general scheme in other places where the surrounding conditions or the ingenuity of the contractor might render desirable the employment of other details; as, for instance, the separation of the sections so as to permit the exterior concrete to flow not only around but also between them, and to form bulkheads that might be excavated later as the sections were unwatered. With regard to the approach-tunnel design referred to by Mr. Hay, Mr. Copperthwaite, and Mr. Moir, the use of the centre wall had been imposed by the necessity for keeping the two tracks as close together as possible, so as to not unduly spread apart the twin tubes of the subaqueous section; to facilitate the construction of the cross passages; and also to minimize the width of the open cuttings and thereby avoid interference with adjoining surface tracks. But for these considerations the use of separate tunnels would undoubtedly have been preferable. In answer to Mr. Moir's comparison of costs, the Author would explain that the section of the North River "McAdoo" tunnel, for which a cost of \$300 per lineal foot of single bore had been given, was about 60 per cent. of that of the Detroit tunnel-section, and that instances at New York more nearly comparable with Detroit would be those of the Pennsylvania Railroad tunnels, some of which, with a somewhat smaller cross section, were reported to have cost considerably over \$500 per lineal foot of single bore, exclusive of contractor's profits. The most rational comparison would be to take the Sarnia tunnel, having practically the same cross section

The Author.

and passing through similar material. The cost of this tunnel built by day labour, about 1890, with no contractor's profits, was said to have been $333 per lineal foot of single bore, this applying not to the under-river portion alone as taken by Mr. Moir, but to the entire distance between the portals, including both approaches. Compared with this amount the cost at Detroit was $273 per lineal foot of single bore, which sum, by the way, had included 15 per cent. for overhead charges but no contractor's profits, thus corresponding with the basis adopted for the "McAdoo" and Sarnia tunnels. Taking into account increases of 10 to 25 per cent. in the cost of labour and materials during the past 15 or 20 years, it might be conservatively stated that the cost of the Sarnia tunnel, on the basis of prices and costs during the period of the construction of the Detroit tunnel, would not be less than $350 to $375. Applying the lower of these prices to the situation at Detroit, in conjunction with the greater length of tunnel imposed by the necessity of placing the approach-tunnels about 10 feet lower, the comparative cost of construction, excluding contractor's profits, would be somewhat as follows:—

Compressed-Air-and-Shield Method Based on Up-to-date Sarnia Costs.

	Feet.
Length of Detroit tunnel between portals as built .	8,310
Extra length	1,167
	9,477

Total length of single bore, 18,954 feet at $350 . . = $6,633,900

Adopted Method.

Total length of single bore as built, 16,620 feet at $273 = 4,544,900

Excess cost of compressed-air-and-shield method $2,089,000

Not only had there been this saving of more than $2,000,000 from the use of the method adopted, but also avoidance of danger to workmen from labouring in high air-pressures and poisonous gases which existed in the clay overlying bed-rock at this place, the saving due to not having to lift the traffic an additional 18 feet, and non-interference with existing tracks and stations in the neighbourhood of the tunnel-summits. While under suitable conditions the adopted method offered marked advantages as to cost, gradients, and efficiency of working, as remarked by Mr. Copperthwaite, it should not be considered applicable to situations where the compressed-air-and-shield method was peculiarly adapted. Every problem, of course, required the treatment best suited to its particular needs.

The Author. In reply to Mr. Read's inquiry, the penalty had not been collected, in view of the satisfactory work of the contractors and of certain delays that were beyond their control. With regard to the electrification, the net height of 18 feet in the tunnel was required by the railroad for equipment clearances, and therefore the cost of securing any greater height for overhead conductors had been considered to be a proper charge against the system requiring it. The contract for power gave to the railroad-company a range of demand ample to cover its greatest possible needs, the battery in the substation "floating on the line" so as to regulate sharp fluctuations as well as to store energy for the needs of service in excess of the capacity of the motor-generators, which, by the way, were built for 100 per cent. overload. As remarked by Mr. Mordey, it could not be claimed that the adoption of the direct-current system on a 4½-mile link in a trunk-line railroad could be considered as necessarily having any bearing on problems elsewhere with entirely different conditions; but it seemed proper to say that the result at Detroit pointed to the danger to the best interests of shareholders in a blind acceptance of the teachings of those who advocated the adoption of any one electrical system as a standard to be used in all cases, to the exclusion of other systems. As stated in the Paper, the adoption of that policy might have meant a loss to the company of about $40,000 per annum. The ducts referred to by Mr. Sayers were for high- and low-tension cables for propulsion, lighting, and pumping purposes, as well as for telephone- and telegraph-wires. The running-rails were utilized for the return of the propulsion-current, as that was the practice in America. The Author regretted that he was not at liberty to furnish the details of the rival tenders for electrification. In response to Mr. Dawson's question, the carbon determinations for the steel rails had been made by the colour-test, occasionally checked by total combustion. High percentages of carbon were found to be proper with open-hearth steel having low percentages of phosphorus and sulphur. In conclusion, the prices mentioned in the Paper did not purport to cover the total cost to the Tunnel Company, as they did not include the contractor's profit They did, however, embrace labour, materials, plant, and payments to sub-contractors, plus 15 per cent. for overhead charges. Those using the figures should, of course, vary them to suit local conditions, and a suitable amount should, of course, be added for profit if the work was to be done by contract, or for contingencies if it was to be done by day labour.

Correspondence.

Mr. A. P. **Boller**, of New York, had read with keen interest the account of the construction of the Detroit Tunnel, one of the most important transportation problems in the United States. Having been concerned with the prolonged investigations which had had in view a bridge crossing of the Detroit River, he considered that the tunnel solution, with the approach and terminal question involved, was the correct one from all points of view, the efficiency of electric traction in trunk-line service having been established. The design of the tunnel adopted formed a radical departure from established shield methods, and it was certainly novel in conception. When the Author first proposed his design, Mr. Boller discussed with him the practicability of its execution; he then saw no reason why it should not be a feasible proposition, and he so advised the Author. The clay bottom of the Detroit River was of admirable consistency for the application of the design proposed, and the river not being a silt-bearing stream, there was little or no probability of any river-deposit dropping into the great trenches which had to be dredged and kept open during comparatively long-continued concreting operations. Tremie methods of depositing concrete under water had long been established as giving satisfactory results in quiet water, and this had been fully borne out by the tests on the sample cubes which had been taken out of the actual work. As to the wisdom of adopting this novel tunnel construction in preference to long-established methods, it had been wholly a question of cost, time, and gradients, but the figures given appeared to vindicate the plan adopted. The Detroit Tunnel cost of 90 cents (3*s.* 8*d.*) per cubic foot seemed low, and while accurate costs could be computed on the basis of materials and labour, it was difficult for an inspector to obtain particulars of all the labour and incidental costs that a contractor paid out to make up the grand total. Nevertheless, the difference in cost between a shield-driven tunnel in rapidly penetrated silt at $1·65 per cubic foot and the Detroit system even at $1 was remarkably great. As to the shallower level at which the Detroit system had permitted the tunnel to be built, involving as it did the very important question of the gradient and length of the approaches, the Detroit system in a bottom adapted to it, appeared to have an advantage over the shield system. While it was true the level of a shield tunnel could be raised by blanketing the river-bottom on the tunnel-line to hold Mr. Boller.

Mr. Boller. the air during driving, this involved a mound of material over the tunnel-roof and sides that might interfere seriously with river-flow or navigation. As to time, 3 years had been taken to complete the aqueous portion of the Detroit Tunnel, which, in his opinion, could certainly have been done by the shield system in two-thirds of that time. On the whole, the Detroit system of tunnelling for that crossing, under all the conditions of the problem, had been boldly and wisely conceived, and skilfully carried out; and the Author was to be congratulated on the successful accomplishment of a very novel undertaking, as well as on the admirable Paper in which he had recorded the particulars of this great work.

Mr. Carson. Mr. H. A. CARSON referring to foreshadowings of the Detroit work, pointed out that in 1845 De la Haye, of England, suggested making submarine railways by constructing wrought-iron tubes above water, and then sinking them to a suitable bed. In 1869 Martin and le Gay, of France, proposed a tunnel, between France and England, consisting of metal tubes sunk to the bed of the Channel and surrounded by concrete. The Martin–le Gay scheme provided also for outer frames attached to the tubes, and for boarding to prevent too great a lateral spread of concrete. These early projects were schemes merely. He did not know of any actual construction that followed De la Haye's suggestion until Mr. Belgrand, in 1866, made a pair of small pipe-tunnels for sewers under the Seine in Paris. Each had a diameter of 1 metre (40 inches), was 156 metres (510 feet) long, and was made of iron plate. Since then there had been numerous examples of sunken iron water-pipes. The first masonry tunnel of the De la Haye class, and also the first of this kind large enough for men to walk through erect, was believed to have been made by Mr. Carson himself, assisted by Messrs. W. Blanchard and F. B. Smith, when, in 1893–94, he built the Metropolitan sewer in the outer portion of Boston harbour.[1] Those tube sections laid in 1893 were of brick, with exterior skins of iron plate, had external diameters of a little over 8 feet, and were 50 to 65 feet in length; temporary watertight bulkheads were inserted at each end, and external flanges for bolting contiguous sections end-to-end were provided. These bulkheaded sections were tested for airtightness, and inferentially for watertightness, by exhausting air from within and measuring the degree of rarefaction with a vacuum-gauge. The weight of the sections relatively to their displacement was such that they would barely float in sea-water. They were made on the upper portion of a sloping beach and, when completed,

---

[1] Described in the Annual Reports of the Metropolitan Sewerage Commissioners of Massachusetts for 1893 and 1894.

Mr. Carson.

were moved down the beach on rollers and timbers to where the incoming tide would nearly cover them with water. Each section was towed at high tide, by floating cranes, to a suitable position above a trench dredged in the gravel bed of the harbour. A section was then lowered, by admitting sufficient water, to nearly its final position, saddles to receive it being accurately placed in the bottom of the trench. When a contiguous section had been laid a few inches from its predecessor, the two were bolted together end-to-end by divers. A rubber gasket was provided at each end between the flanges. The subsequent operations were the backfilling of the trench around and over the pipes, the successive removal of the bulkheads, beginning at the land sections, and the pumping out of the water. At each joint between two consecutive sections, a short closing length of masonry had to be put in, joining the interior adjacent brick walls. This was accomplished without difficulty, as the outside gaskets had made the joints perfectly watertight. As the rubber gaskets were outside the masonry, the fact that they would become disintegrated in time was not a matter of consequence. In progressing with the work next season a rather different method was adopted, the tube sections, weighing 100 tons each, being made in cradles above water, alongside of a wharf. After completion and bulkheading they were lowered by long vertical screws moved by steam-power. The sections were then towed ½ to ¾ mile to their positions for lowering—also on to saddles placed in the dredged trench. These later sections had a skin of wood 4 inches thick, inside of which was a 6-inch thickness of Portland-cement concrete, and an interior ring of brickwork 8 inches thick. It was found that all the tunnel was perfectly watertight at the joints and elsewhere, true to line and level, and satisfactory in every way. When Mr. Carson became a member of the Advisory Board of the Detroit tunnel, he naturally proposed a similar method, referred to on p. 10 as method B. He thought that the joints, although larger, would be as tight at Detroit as at Boston, and that the strength could be made as great as might be desired. He did not propose an outer surrounding volume of concrete, on account of its expense. It must be admitted, however, that a large expense was justifiable in protecting a tunnel whose top was brought up to the very bottom of a river with such an enormous floating traffic. The possibility of a foundered vessel resting on the top of the tunnel had never been lost sight of by the Advisory Board. The scheme proposed by the Author for Detroit was not merely a re-invention of that of Martin and le Gay; it possessed in addition thick inside walls and other important features.

Mr. Carson. In 1877 William Sooy-Smith, an American engineer, proposed to tunnel under the river at Detroit by sinking pneumatic caissons such as were used in making piers. These caissons were to touch one another end-to-end under the river, and in them the tunnel was to be built. It was an interesting fact that the general features of the French scheme of Martin and le Gay had been recently used at Detroit at the very same time that the American plan of Sooy-Smith was being used in Paris, in connection with the crossing under the Seine of the Metropolitan subway. Each scheme had been re-invented with important modifications.

Mr. Dawson. Mr. **Philip Dawson** had read with great interest the very able Paper which Mr. Wilgus had prepared, and wished to make a few remarks in connection with the electrical equipment of the tunnel and its approaches. It was obvious that in the present case the only point for consideration had been the system of electric traction that would be the most suitable for a short section of line, of which—as far as could be gathered—there was no likelihood in the near future of any extension. Further, the line was all in a tunnel which, from an economical point of view, it was advantageous to keep to the smallest possible dimensions. Under these circumstances the choice of the continuous-current system finally selected seemed to be fully justified. At the same time he felt obliged to take issue with the Author on his very general statement that "direct current was respectively 12 per cent. and 32 per cent. less expensive in first cost than the three-phase and single-phase systems, and 4 per cent. and 20 per cent. less expensive annually." The conditions laid down in the specification, on which the tenders for the various systems had had to be based, were not stated, nor were the reasons for stating the additional annual cost; without such particulars it was impossible to offer any detailed criticism. All he could say was that the Sarnia tunnel had been equipped with the single-phase system and appeared to be working satisfactorily. He knew that, at the commencement, the New York, New Haven and Hartford Railroad had a great deal of trouble with the single-phase system which they installed—trouble which, he ventured to think, might have been avoided. They seemed, however, quite satisfied with their present results, as was proved by the extensions of the single-phase system which they proposed to carry out shortly. The success of single-phase current for general electrification had been proved without a doubt on the Continent of Europe, and all the principal railway-authorities of France, Switzerland, Austria and Sweden, and also on the various German State railways, had, after the most careful investigation, unanimously decided in favour

Mr. Dawson. of the single-phase system; they considered it the only possible solution when the electrification of an existing railway that included urban, suburban, and interurban sections had to be carried out. The results obtained by Mr. Dawson on the London, Brighton and South Coast Railway were entirely opposed to the statements made by the Author as regarded the comparative results of the various electric-traction systems; and further, many well-known American engineers did not agree with the Author's views as to the merits of the various systems. Thus, Mr. George Westinghouse, in a Paper read last year before the Institution of Mechanical Engineers in London, had been all in favour of the single-phase system considered from every point of view. Mr. Dawson also disagreed altogether with the opinion expressed by the Author that the continuous-current system presented elements of greater reliability than the single-phase system. He did not claim that the former was not reliable, but he emphatically claimed, as the result of over 2 years' operation (including experimental running) on the Brighton Railway, that the single-phase system was, at least, quite as reliable as any continuous-current system.

Mr. Jacobs. Mr. C. M. Jacobs congratulated the Author on his excellent description of the first important trench-built tunnel that had been brought to a successful conclusion. When, however, he made certain general assertions, such as that on p. 27, where he expressed the belief that "the subaqueous method used at Detroit may be utilized with marked reduction of cost and hazard in many locations where the employment of shields and compressed air has hitherto been considered obligatory," there was room for some question whether the shield and compressed-air method—if applied to the conditions described by the Author—would not have resulted in economy of either time or money, or both. This was not to be taken to imply that the methods employed at Detroit might not point to a useful method of tunnelling in certain other conditions, e.g., where suitable ground existed with so great a depth of water that the air-pressure in the working-chamber would exceed that at which it would be feasible for men to work. Before discussing this phase it might be questioned whether, in his "History of River-Crossing Projects" the Author had not been misinformed on one detail. He said:—

> "Work was permanently suspended in the latter part of 1872, owing to continued inrushes of water and gas and loss of life. Ordinary tunnelling methods with timber lining were employed, as the use of shields and compressed air was deemed inadvisable at such great depths and in such small drifts."

Probably the fact that the modern combination of shield and

Mr. Jacobs. compressed air was still untried and unknown at that date, might also have had something to do with this decision. It was true that a tunnel-shield and lining were described by Brunel in a patent specification in the year 1818, and that a shield was used by him in the original Thames tunnel from 1825 to 1828, and again from 1835 to 1843. The next tunnel driven by the shield method was in 1869, when the London Tower subway was built. In 1870 Mr. Beach drove his Broadway tunnel in New York City, and in 1872 short pieces of tunnel were driven by shield at Cincinnati and Cleveland, Ohio. All these tunnels were driven without the use of compressed air as a means of supporting the ground. In 1830 Cochrane took out his patent for the use of compressed air for expelling the water from water-bearing ground during the excavation of shafts and tunnels, in the manner in which it was used at the present day. The system was first used in 1839 in a French coal-mine shaft. The first tunnels driven by the use of compressed air were constructed in 1879, simultaneously at New York City and at Antwerp. In both these cases no shield was used. The first time the shield method was combined with compressed air in the tunnel was in the case of the City and South London Railway in 1886. This point was of no real importance except in an historical sense, and unless the records showed that in 1872 actual discussion as to the use of shield and compressed air had occurred, it was difficult to understand how such a method could have been considered inadvisable at that time, as it certainly was unprecedented.

To turn to the Author's contention that in this particular case the trench method adopted was superior to the shield method, he stated that the former method was adopted because the latter was considered too hazardous and expensive, owing to the very small depth —about 3 or 4 feet—of cover, and also because the lowest tender on the trench system was $2,000,000 less than the one on the shield system. It must be confessed that this latter reason was a fairly conclusive one, and yet it might be possible to show that these tenders were based on misapprehension, especially due to the odium and fear which seemed to attach to the idea of using compressed air, which nevertheless in moderate pressures—say, up to 30 lbs. per square inch—was not at all a thing to be alarmed at, in the light of present-day knowledge and with proper medical provision. It would be noticed that in this case the pressure due to the whole hydrostatic head would almost certainly not have been needed, and 25 lbs. per square inch would have sufficed. It was therefore possible that these tenders did not afford any solid grounds for believing that the trench method was necessarily superior to the shield method in this particular case. The depth of water Mr. Jacobs. at the place where the cover became so small appeared from Fig. 4, Plate 1, to be about 41 feet. As the draught of the lake vessels using this waterway was only about 19 feet, it would seem that there would have been nothing to prevent the placing of a clay blanket over the tunnel had the latter been driven by compressed air, and had the natural cover not been strong enough to prevent blows. It might be remembered that the Hudson River tunnels of the Hudson and Manhattan Railroad, in New York, were within 5 feet of the river-bed in some places, the material there being a soft mud much less strong than the tenacious clay of the Detroit River; and to turn to examples nearer home, the Blackwall tunnel across the Thames came within 5 feet of the river-bed, and in open gravel and ballast at that. It was useless to labour the question of the practicability of applying the shield method here, as to anyone conversant with this type of construction it was obvious, and it only remained to consider whether the shield and compressed-air system or that used would have been the more economical of time or money. This was altogether apart from the fact that by the use of the shield there would have been no interruption to the heavy shipping traffic using this waterway, and that the work would have been entirely independent of any delays due to severe winter weather. It would seem that even the Author's own figures decided in favour of the shield as regarded economy. It would be noticed that after the first method of driving the approach-tunnels had proved a failure, a second method was adopted, in which a middle drift was first put through, the centre wall being built, and the section then completed by driving side shields under compressed air. It would be readily admitted by anyone conversant with tunnel work how much more expensive it was to build a tunnel in several operations than by two separate tubes in one operation. The chief expense with the latter was the cost of the iron lining, which was offset by the delay and expense of the other piecemeal method. As it was, the cost of the approach-tunnels was stated to have been \$228 per lineal foot of single bore built in normal air, and \$257 built in compressed air, while the trench-built tunnel under the river had cost \$332 per lineal foot of single bore. It thus appeared that the under-river portion exceeded the approach-tunnels (expensively built as the latter were) by \$75 per lineal foot of single bore, or \$150 (£30) of double bore. As there was about 2,600 feet of under-river work, this amounted to \$390,000 (£78,000), which was probably five times as much as the provision of a clay blanket would have cost. In case it might be feared that

Mr. Jacobs. the river-current would sweep away the blanket, he might state that on the East River tunnels of the Pennsylvania Railroad at New York City, the blanket had been successfully used in a current of 4½ miles per hour, whereas at Detroit the maximum was stated to be 2·29 miles. The velocity of the ebb-current in the North or Hudson River, in which also clay blankets had been used, was about 3·22 miles per hour in a low-river season. This current-velocity would be increased by an increase in river-discharge. Some detailed estimates of the time and money required to build these tunnels by the compressed-air and shield method might be presented for the purpose of comparison with those actually incurred. They were based on the use of two shields on each side of the river, so that advance could be made simultaneously from both shores. The average rate of progress, in the compact "silt" under the land, of the 23-foot diameter shields of the North River tunnels of the Pennsylvania Railroad was 225 feet per month. This material was the nearest approach to the Detroit clay which these shields experienced. In the silt under the river, in which an average of 33 per cent. of the total displaced material was brought into the shield, progress had been delayed by a good deal of experimental work, but the average rate had reached 405 feet per month. The old St. Clair tunnel, 21 feet 6 inches in external diameter, which seemed to have been driven through ground closely resembling that found at Detroit, and in fact crossed this same river about 57 miles north of the tunnel described in the Paper, achieved an average rate of advance of 207 feet per month in normal air and 263 feet per month in compressed air, a maximum advance of 308 feet being made in one month. This tunnel was built in 1888, comparatively early in the history of tunnel-shields, and was, in fact, the most ambitious of any attempted up to that time. It was reasonable to expect that at Detroit the shields would make an average progress of 250 to 300 feet per month per shield. Each shield would have 4,155 feet to travel, namely, half the total distance of 8,310 feet from portal to portal. At the rate of 250 feet per month, this distance would be covered in 16¾ months, and at 300 feet per month in 13¾ months. On the North River tunnels of the Pennsylvania Railroad into New York City, the putting in of the concrete inner lining (delayed by a considerable amount of steel-rod reinforcement) took 7 months for the total length of 12,200 feet of single tunnel. At the same rate of progress the 16,620 feet of the Detroit tunnel would have taken, say, 10 months. The total time, therefore, on the basis of progress at the rate of 250 feet per month would be 26¾ months, or, allowing 10 per cent. for unexpected delays, 29½ months; and, on the assumption of 300 feet per month, this time would be reduced to 26¼ months. As far as could be gathered from the Paper, a period of not less than 42 months had elapsed between the time of breaking ground and finishing the concrete lining. A considerable saving of time for the shield method was, therefore, indicated, even on the basis of using only four shields and driving from each portal. It would be a question of economy whether it would pay to install additional shields and drive the approach- and river-tunnels simultaneously from intermediate shafts, thus approximately halving the time required to drive and line the tunnels. Mr. Jacobs.

As to the cost, taking the basis of using two plants and driving the tunnels simultaneously from each portal, with tunnels 23 feet in external diameter, and allowing for the cost and depreciation of plant, engineering, provision of a clay blanket, and all field and administrative charges, but exclusive of contractor's profit, Mr. Jacobs had no hesitation in stating (and this statement was based on two distinct experiences) that the work could have been comfortably carried out for $4,100,000 to $4,155,000 (£820,000 to £831,000), that was, $246·67 to $250·00 (£49 6*s.* 8*d.* to £50) per lineal foot, including a very liberal allowance for the clay blanket. The actual cost seemed to have been about $4,544,912, made up as follows:—

Western approach . . .	4,264 feet at	$227·71 per foot =	$970,965
Subaqueous work . . .	5,334 „ „	$332·29 „ „	= $1,772,444
Eastern approach . . .	7,022 „ „	$256·55 „ „	= $1,801,503
Total . .	16,620 „ „	$273·00 „ „	= $4,544,912

In this connection attention must be directed to the Author's comparative statement of the costs of various subaqueous tunnels. These were grouped and stated in such a way as not only to be of "little precise value," as stated in the Paper, but to be actually—though unintentionally so—misleading to a serious degree. For example, the Detroit tunnel had cost $1·057 per cubic foot and $332 per lineal foot in the under-river portion, while the old St. Clair tunnels cost $1·08 per cubic foot and $333 per lineal foot for the whole length from portal to portal. In the latter case compressed air was not put on until the shields entered the river section, so that the portions corresponding with the approach-tunnels in the former, namely, 1,994 feet on the Canadian side and 1,716 feet on the American, or a total of 3,710 feet, were driven in normal air, against 2,460 feet driven with the aid of compressed air.

Mr. Jacobs. Nearly all the difficulties experienced on the St. Clair work were met with in the normal-air sections, and the ground flowed in through the shields to such an extent that frequently 50 per cent. more ground was taken in than the cubical content of the finished work. It was therefore fair to suppose that, had compressed air been used in the approaches, an appreciably lower cost would have been recorded, though, even so, this old tunnel, built 20 years ago, with every appliance so much less developed than at present, cost only \$0·02 per cubic foot more than the subaqueous portion of the Author's tunnel. Another example which needed serious qualification was that of the North River tunnels in New York City, quoted as costing \$1·65 per cubic foot and \$300 per lineal foot. These figures referred to the tunnels of the Hudson and Manhattan Railroad, and were given, without any qualification, as being in silt. As a matter of fact, this cost was the average for tunnelling both under the river and on land, where the face consisted often of part rock and part silt, which was a particularly difficult and dangerous combination; and it also included very heavy expenses due to heavy buildings in a congested section of the city having to be cared for. Where the tunnel was in the true silt, without admixture of other materials, the cost was \$144 per lineal foot, or \$0·79 per cubic foot of internal bore, and this figure could be reduced, with the knowledge and experience now gained, to about \$130 per lineal foot, or \$0·72 per cubic foot. To take another example, and one not cited by the Author, the Pennsylvania Railroad had recently built two tunnels of 23 feet external diameter, heavily lined with cast iron and concrete, across the Hudson River at New York City. The cost of this work had been much enhanced by a large amount of testing and experimental work in connection with the original design to place pile foundations under the tunnels to support the heavy main-line traffic which they had to sustain in the soft river-bed. These tests and experiments occupied about 18 months, and many expensive details were embodied in the design, which delayed the work greatly. Very careful cost-records had been kept during the carrying out of the work, and these showed that with the experimental features and experimental delays eliminated, the cost of these tunnels had been \$256 per lineal foot, or \$1·04 per cubic foot of internal bore as driven from both sides of the river. Had the tunnels been driven from one side only, as would have been done had no piles been contemplated, the cost would have been reduced to \$245 per lineal foot, or \$1 per cubic foot, of internal bore; and the tunnels would even then have been

Mr. Jacobs. finished in plenty of time to be completed simultaneously with other parts of the system. Of course all this kind of direct comparison between results obtained under totally different conditions, was bound to be misleading and was of very little use; but, if it were used at all, care should be taken to see that the conditions which did obtain in each case were correctly stated.

With regard to the dryness of the completed structure, the Author stated that the leakage was equivalent to 0·85 gallon per 24 hours per lineal foot of single bore. These tunnels were wholly in clay. The shield-driven North River tunnels of the Pennsylvania Railroad were not only in silt, but in gravel (heavily charged with water), sand, and rock—all well below tide-level. The total length of single bore of shield-driven tunnel was 12,196 feet, and the leakage averaged 0·0544 gallon per lineal foot of single tube per 24 hours. It would thus be seen that the leakage into the Detroit tunnel (which leakage, however, was stated to be diminishing and on the way to stopping) was at the date of the Author's writing seventeen times as much as in the shield-driven Pennsylvania-Railroad tunnels. In conclusion, it would seem that the methods used at Detroit displayed greater pains to be original rather than to follow certain well-trodden paths which Mr. Jacobs had no doubt would have quite probably led to the quicker and cheaper accomplishment of the required result. That the Author and all those in charge of the work had every reason to be proud of it and deserved the thanks and congratulations of the profession for a useful, instructive, and successful experiment, was undoubted; but sweeping assertions as to the superiority of the method adopted over others—even in this particular case where every condition was in its favour, and still more so as a general proposition—needed to be very carefully qualified before they could or should be accepted.

Mr. Kernot. Mr. M. E. Kernot had seen the question of tunnel versus bridge for crossing rivers and estuaries frequently raised in various parts of the world, and he thought the Author's work at Detroit had done much to support tunnel schemes. Another much debated point, the question between two single-track tunnels, or one large tunnel for a double railway-track, was decided in favour of the twin tunnel, and this agreed with the result of his own investigations. The saving of fall and rise, and the consequent saving in the length and cost of approaches, by keeping a subaqueous tunnel up to the limit of depth required for navigation, had also been demonstrated. The calling for tenders on a general specification, with designs which tenderers had liberty to modify or depart from, possessed great

Mr. Kernot. advantages for works of unusual character, and appeared to have led to good results in this case. It would have been interesting if some particulars had been supplied as to how the sides of the open cuts were supported while the heavy retaining-walls were being built, as the clay, which required a slope of 1½ to 1 for the slopes above those walls, had to be undercut when the walls were put in. No reason was given for the adoption of different designs for the retaining-walls in the western and eastern open cuts. The walls were shown with different cross-sections, and the concrete had been reinforced in one case and not in the other. The difficulties met with in execution appeared to have been greater in the approach-tunnels than in the subaqueous tunnel, as the latter, though costing more per unit of length on account of the steelwork, seemed to have given little trouble, while in the case of the approach-tunnels changes of working-method became necessary while they were in progress. With regard to the subaqueous tunnel, it was stated on p. 23 that for a distance of 1,000 feet in mid-channel the tremies were used for prodding holes in the clay to the underlying hard stratum, and for filling these holes with concrete, thus apparently giving solid support to the tunnel; but at the bottom of the same page it was mentioned that there had been a gradual settlement of this section. This suggested that the tremies had not been effective in reaching a sound foundation, and that they should not be much relied on for such work. The thickness of concrete used for the subaqueous tunnel appeared to be large. At Chicago the tubular method was being used in the construction of the La Salle Street tunnel, which had 27 feet of water over it, and a thickness of 2 feet of special waterproof concrete inside the steel tube was considered sufficient; while at Detroit, with 41 feet 9 inches depth of water, the total thickness of concrete was about 6 feet on top and 4 feet 6 inches on the buried sides. The reason given for not adopting the tubular or "pipe" method of construction (Method B, p. 10) was the difficulty of making the joints below water, but this objection would have been met by tubes with ends made with diaphragms and casing exactly as used by the Author. And it should be noted in this connection that at Chicago it was considered practicable to do most of the concrete lining in the tubes before they were sunk, thus largely reducing the cost of that part of the work. The whole scheme bore the impress of a bold conception, with highly intelligent and masterful execution, and the Author and his co-workers deserved congratulations on their success, which marked a notable step forward in subaqueous tunnelling. Mr. Kernot, who was President of a recent Royal Commission on the question of traffic-connections across Sydney Harbour, found that the recommendation of that Commission for the abandonment of a bridge scheme in favour of separate subaqueous tunnels for railway, tramway and vehicular road-traffic, in situations which were in many respects similar to those at Detroit, had been supported and strengthened by this successful work. Mr. Kernot.

Mr. Lavis. Mr. Fred Lavis, of New York, considered the Paper to be extremely interesting, as describing a novel method of construction that had been carried to a successful conclusion. The utility of this method and its adaptability to other cases of subaqueous tunnelling was very largely a matter of cost. It would naturally occur to engineers connected with work of a similar nature to make a comparison between the method described in the Paper and that of using a shield and compressed air. In considering the Author's statement that the lowest tender for construction by the shield and compressed-air method was about $2,000,000 higher than that for the design adopted, it must be remembered that the position of the tunnel, with reference to the bed of the Detroit River, was such that contractors had probably been led to the conclusion that the use of the shield method was practically prohibited by the terms of the specifications, except under very severe restrictions. It seemed reasonable to inquire whether, if a lower depth for the tunnel had been adopted, a much lower tender might not have been made for a shield-driven tunnel; and whether such lower tender might not have been sufficiently below the actual cost of the tunnel as built to have compensated for a higher cost of operation. Assuming that the summits were unchanged and that the gradient was increased from 1·5 to 1·75 per cent., the section under the river would have been lowered about 15 feet, which would give sufficient cover for fairly safe and economical construction by the shield method in the stiff clay found at this site. The increase in the gradient would not be a very serious consideration in this problem, in view of the fact that electricity was used as the motive power. The only important additional working-cost would be the actual power required to raise the weight of the trains passing through the tunnel through a height of 15 feet. Very little, if any, greater plant or engine-capacity would be required, and the only additional item of any importance would be fuel to produce the power. Various assumptions might be used to calculate the additional cost of this 15 feet of rise and fall, and for the traffic assumed by the Author —namely, twenty goods-trains and eighteen passenger-trains per

Mr. Lavis. day, the additional cost of working would be between $2,000 and $5,000 (£400 and £1,000) per annum. These were wide limits, but assuming the maximum and assuming double the traffic, the justifiable expense to eliminate 15 feet of rise and fall would be $200,000 (£40,000), (interest at 5 per cent.). With electrical operation under the favourable conditions obtaining at Detroit, and for the amount of power consumed, it was believed that operating-expenses would be much lower than that, and it was to be hoped that the Author, who doubtless had access to correct data, could give some further information on this phase of the subject. Turning now to the question of the cost of the work, Mr. Lavis estimated that a shield-driven tunnel at the lower depth could have been built for, approximately, $225 (£45) per lineal foot. The cost of the water section of the East Boston tunnel—a double-track tunnel 25 feet high and 29 feet wide, outside dimensions—which had been driven through stiff blue clay under Boston Harbour, amounted to $240 (£48) per lineal foot. Mr. Copperthwaite[1] estimated the cost of a shield-driven tunnel, 21 feet 2½ inches inside diameter, in London clay, at about $175 (£35) per lineal foot unlined, the lining adding about $60 (£12) to this. With the steeper gradients proposed, the approach cuts would be shortened, but might be a little deeper at the portals. It would not be unfair to assume the cost of this portion to be unchanged and to take the length of the shield-driven tunnels at about 8,800 feet each, as against 8,310 feet actually built, at a cost of $4,544,912 for the tunnel section. The 8,800 feet of shield-driven tunnel at $225 per lineal foot would cost for the two tunnels $3,960,000, showing a saving of about $600,000 in construction to offset the increased operating-charges, capitalized, as shown, at a maximum of $200,000 for double the present traffic. The question of time had also to be considered: 12 months might be allowed from the time of letting the contract until the shields were ready to work, another 12 months for driving each of four shields 4,400 feet, 6 months for lining and 6 months for contingencies, all of which seemed to be ample, in view of the favourable conditions at Detroit as compared with the work done on the North River tunnels at New York. The total time then would be 3 years as against nearly 4 years actually required. He recognized, of course, that in this class of work there were many contingencies which could not be foreseen and might increase both the cost and

---

[1] "Tunnel Shields and the use of Compressed Air in Subaqueous Works," p. 368. London, 1906.

Mr. Lavis. the time, but he believed sufficient had been said to show that there was hardly that immense difference of cost in favour of the method employed on the Detroit River tunnel, which the difference in the amount of the tenders might possibly lead one to think.

Mr. Lindenthal. Mr. **Gustav Lindenthal** considered that the method of building the tunnels described by the Author had the merit that it was happily adapted to the special local conditions. These were: first, the necessity of keeping the level of the subaqueous tunnel so that its roof would almost be level with the bottom of the river, which just had the necessary depth for navigation and no more; and secondly, the fact that the clay bottom of the river permitted the operation of dredging to be done with rather steep slopes and at comparatively little cost. If the bottom had been sand, mud, or other easily flowing material, that method would not have proved so efficient as the usual shield method with compressed air. This could readily be seen when the clay bottom of the Detroit River was compared with the mud bottom of the North River at New York, or with the mud, sand, and rock bottom of the East River. Dredging a trench in such material would have been very expensive, if not impossible, because of the soft bottom material flowing into the trench, or of the necessity of excavating submarine rock by one of the several methods in use—all of them, however, more expensive than the dredging in clay at the Detroit River. The successful and cheap completion of the tunnel under the Detroit River showed the correct judgment used in the selection of the method for the particular circumstances, for which too much credit could not be given to the Author. There was one detail in the completed tunnels on which more information would be welcome, namely, the construction of the tracks, consisting of wooden tie-blocks embedded and dowelled into the concrete with a drainage-gutter between the rails. Rapid corrosion of the rails due to the condensation of locomotive-gases, would, of course, be absent in this tunnel; and the formation of the track was such as also to permit of easy cleaning, a very important matter in sanitary respects. He would like to inquire, however, if the fastening of the tie-blocks in the concrete under the heavy tracks showed permanency; or whether any weakness had been observed which would indicate that the tie-blocks should occasionally, say every fourth or sixth, be in one piece, crossing the gutter. Experience on this question of tunnel-track was important in view of several other forms of construction now being experimented with, partly in the electrical subways of Philadelphia and New York, partly in the electrical Pennsylvania Railroad tunnels, and partly in tunnels used by steam-trains, wherein the

Mr. Lindenthal. track was subject to rapid corrosion from condensed locomotive-gases. For the electrical equipment in the Detroit tunnel the use of a storage-battery was a very suitable arrangement for the regulation of the periodic fluctuations in the electrical current. It was not yet a usual feature in electrical installations for traction purposes, because of its large first cost, but nevertheless it was a wise economy.

Mr. Manton. Mr. A. WOODROFFE MANTON was specially interested in the costs of this bold method of carrying out the tunnel work, such figures being so seldom given in English papers. He did not think, however, that the Author had fully proved the methods adopted in both the approach and subaqueous tunnels to be more economical than the shield-and-clay-blanket method. This method which had been used in connection with the East and North River tunnels at New York, was first suggested by Mr. E. W. Moir, M. Inst. C.E., in 1891, when he obtained permission from the United States Government to dump clay over the Hudson tunnel as it approached the New York shore; and it was used by him again in connection with driving the Blackwall tunnel, by consent of the Thames Conservancy. To Mr. Manton the material at Detroit seemed to be almost ideal for the use of a shield, without the hazard and expense suggested by the Author; in fact, he would imagine that the method adopted ran the risk of possible failure, was much less speedy, and was at least quite as expensive, if not more so. With reference to the nearness of the tunnel extrados to the bed of the river, the East River tunnels at one point had a similar small cover, but a clay blanket (the clay for which had in that case to be brought about 60 miles) surmounted the difficulty very satisfactorily and economically; and, in fact, the East River tunnels were a much more hazardous undertaking. The two North River tunnels of the Pennsylvania Railroad in "Hudson silt" had evidently been constructed under very similar conditions to the Detroit River tunnels, and the shield system adopted had the great advantage that it was a very well proved one, and was not in any sense experimental: further, it could be carried on with speed and economy at all seasons of the year, being independent of currents, ice, and storms, which affected that river. Undoubtedly, the shield method would have been a much quicker one, and it must be remembered that each day was worth at least $1,000 to the railway company. This was the contractors' penalty, but probably it did not nearly represent the value to the company. The completion of these subaqueous tubes had been about 9 months behind the contract time, and taking the value of that period at only $1,000 per day, an extra cost of $275,000, Mr. Manton.

or more than \$50 per lineal foot of single tube, was involved. The sinking and external concreting had occupied about 730 days—that was to say, the progress had been approximately 7 feet 4 inches of single tube per day of 24 hours, or about half the average progress made in the North River tunnels in the soft material. In the case of the approach tunnelling the average progress of the side shields per day per tube, after all the difficulties had been surmounted, was only 9 feet without compressed air, while the average progress in the North River tunnel with the standard shield was 14 feet under compressed air. With the adoption of shields no river-edge shafts need have been sunk. With reference to costs, Mr. Manton found it very difficult to understand how the "overhead charges," which were said to have been a uniform charge of 15 per cent. on labour and material, over the whole of the open cut, approach, and subaqueous work (of such different classes) could be as low as this. It would be interesting to know whether the inspectors' reports would be likely to include in this 15 per cent. the items of depreciation of equipment, timber, fuel, stores, repairs and renewals, workmen's compensation and other insurances, and office administration (both local and chief). The administration and workmen's compensation and other insurances would alone amount to nearly this percentage. In the case of the North River tunnels, the overhead charges, that was, the cost in addition to labour and material, must have amounted to between 30 and 35 per cent. Thus the cost, exclusive of contractors' profit, as worked out from the full information given in the Transactions of the American Society of Civil Engineers (1910), including the whole of the foregoing items, and costs for ordinary cast-iron lining and bolts, heavily-reinforced internal concrete lining (the reinforcement costing about \$11 per lineal foot of single tube), grouting, ducts, steelwork, etc., averaged, in soft ground, about \$345 (£69) per lineal foot of single tunnel. The cost of the rather larger Detroit River tunnel (and it did not seem quite clear why it should be larger than the Pennsylvania Railroad tunnels for third-rail operation) was \$332 per lineal foot, allowing only 15 per cent. for overhead charges on labour and material alone. The latter cost, as given in the Paper (p. 29), was practically the same as that of the shield-driven St. Clair tunnel, of about the same cross section, constructed in probably similar material about 20 years ago, since which time very considerable advance had been made in experience of the construction and equipment of such tunnels, with corresponding reduction of cost. In conclusion, the shield method, with the precautionary clay blanket, would seem to Mr. Manton to have been a more certain method of carrying out this work, Mr. Manton. especially as regarded speed, and consequent final economy to the railroad-company, to whom the rapid completion of this tunnel and its approaches was undoubtedly a matter of the highest economical importance.

Mr. Meem. Mr. J. C. Meem, of New York, felt that the Paper would be of great interest to engineers, and would make a valuable addition to the literature on the subject of tunnelling. His own interest in submerged tunnelling went back to the first published description of the construction of the submerged sewer-siphon under Shirley Gut in Boston, by Mr. Howard A. Carson, which work was alluded to on p. 10. Following this, he had made a study of submerged tunnels on a large scale, and in 1896 he read before the Brooklyn Engineers' Club[1] a Paper embodying the results of this study. In effect, the method proposed was to build a large wooden barrel with an inside diameter of 18 feet, to sink this in position on sills set by divers to approximate line and level in a dredged trench, to surround this barrel with concrete (deposited in loose bags) and afterwards to unwater the tube and build the tunnel inside. Except for the fact that a wood lining was used instead of a lining of metal, and other minor modifications, this project was in effect a rough forecast of a portion of the work described in the present Paper. Especial interest, however, attaching to the publication of this study in its relation to the present Paper, lay in the fact that, during the progress of the Detroit work described, Mr. Carson, in correspondence with Mr. Meem, had stated that a contractor, by virtue of having obtained a patent in connection with some submerged tunnel work which he had done, claimed a right to a royalty. Mr. Carson asked for some information concerning the matter from Mr. Meem, who sent him a copy of the Paper containing the study referred to, and although Mr. Meem did not know that it ever became necessary to use it, it showed how the publication of similar studies might be of value to the general engineering profession in such cases. In adopting the wooden barrel as the integral part of his scheme, Mr. Meem had been influenced by his connection with, and interest in, the construction of wooden-barrel sewer-outfalls under many of the piers of New York City. These barrels were usually 4 to 6 feet in diameter and circular in section, though some had been made oval. They were generally built of staves 4 inches thick, cut to radial lines and bound together by galvanized-iron bands, spaced at suitable intervals. They rested

---

[1] Brooklyn Engineers' Club, 1897 (Annual), "A Study of a Proposed Method of Building a Submerged Tunnel."

on sills bolted to the piles supporting the piers, and were held in place by capped timbers similarly affixed. Either short sections abutting were used, or preferably the lengths were made continuous, with the staves breaking joints at irregular intervals. The staves were creosoted for use in the New York waters, and this type of sewer gave very satisfactory results in every way, besides having a very low coefficient of friction. Mr. Meem had also used one of these wooden-barrel sewers to carry a temporary flow of storm-water, pending the breaking out of a large storm-sewer during the construction of a subway, the special advantages being that it was carried with absolute safety on timbering, while the material was available for use a second, or even a third time. He noticed the Author's allusion on p. 18 to the nature of some of the dredged material, and in connection with the usual assumption in regard to submerged structures, he would call especial attention to this remark, as showing that submerged structures bedded in clay or similar material could not possibly be under aqueous pressure over the whole area. Mr. Meem.

Professor C. L. DE MURALT, of the University of Michigan, was especially pleased with the part of the Paper which referred to the electrical equipment. It seemed to him that the specifications forming the basis for the tenders for this equipment had been drawn up in a particularly happy manner. They laid down in clear terms the general requirements with reference to electrical operation, and yet left to the various bidders the greatest possible freedom in the choice of details. Thus the various electric systems were placed on a strictly fair and at the same time on a directly comparable basis. He was slightly disappointed that the Author did not see his way clear to give the actual figures of the various tenders, but presumed there were good reasons against his doing so. After all, the percentage figures in the Table of comparison, taken together with the fact that the electrical equipment actually installed had cost in the neighbourhood of $1,000,000 (£200,000), gave a fair measure of the advantages of the three tenders, and of the three systems of electric traction which they represented. This comparison ended in a clear victory of the continuous-current system over the single-phase, the difference against the latter being 32 per cent. in first cost, and 20 per cent. in annual operating-costs (including fixed charges, operation, and maintenance). Considering the conditions under which this railway was worked, everybody, except single-phase enthusiasts, would have expected this to be the case. It was very interesting, however, to find the generally accepted view borne out so accurately in Prof. de Muralt.

Prof. de Muralt. a case of actual competitive bidding. The difference between the continuous-current system and the three-phase system was less prominent. The limited stretch thus far electrified did not bring out fully all the advantages of the latter. If the electric zone were extended to include, on either or both sides of the tunnel, sufficient additional track to make an electrical section, say, 100 miles in length, its advantages would be much more pronounced, and the comparison might end differently. The weight-characteristic of the three types of locomotives was also brought out very clearly by the three tenders. Three-phase locomotives were the lightest in weight, continuous-current locomotives came next, and single-phase locomotives were the heaviest of the three, the relation being as 1 : 1·23 : 1·48. This was a very important factor in heavy service. The extra weight carried in a single-phase locomotive, or to put it the other way, the smaller useful load which it would haul, was a very serious matter in the electrification of any railroad with dense traffic. There was not only the extra expense of carrying excess weight, but the capacity of the tracks was affected by limitation of the maximum useful load which could be passed over the line in a given time. A concrete example, which forcibly illustrated the importance of this locomotive weight-factor in any railway problem, had recently come to his notice in connection with the study of the advisability of introducing electric motive power on a western trunk-line where a fast through service had to be maintained over a section with severe gradients. The specified requirements of the electric locomotives were that they should be able to haul a trailing load of 400 tons at 50 miles per hour against a 1½-per cent. gradient (1 in 66). The steam-locomotives in use at present weighed approximately 150 tons including the tender, and even two of them were hardly adequate to maintain the specified speed on the gradient in question. It was found that the requirements could be satisfactorily met by a three-phase locomotive weighing about 68 tons or a continuous-current locomotive of about 95 tons. For the single-phase system the most practicable solution proved to be the adoption of locomotive-units of 105 tons each. Two of these, or a total locomotive-weight of 210 tons, were necessary to fulfil the service requirements on the 1½-per cent. gradient, although a single unit might be used on other sections of the line where the conditions were less severe. This meant in concrete terms that under steam operation 75 tons of locomotive had to be hauled for each 100 tons of revenue-bearing weight, with the single-phase system 52½ tons, with the continuous-current system 24 tons, and with the three-phase system 17 tons. All told, engineers must be very grateful to the Author for having brought out these points so clearly, and Professor de Muralt trusted that this very direct comparison would have the good effect of quieting some of the system-enthusiasts. When once the fiercely-asserted rival claims were silenced, they would all have a better opportunity to devote themselves to the real work of actually installing electricity as a motive power on main-line rails. Prof. de Muralt.

Mr. Wilson. Mr. H. RAYNAR WILSON remarked that this tunnel was an international work, affecting both the United States and Canada. Having regard to the scare—set up by military men and politicians and not by engineers—as to a tunnel between England and France, it would be interesting to hear whether the respective Governments had been consulted as to the Detroit tunnel, and, if so, what reply had been given. With regard to the track, some information as to how lateral movement of the sleeper-blocks was guarded against would be useful. He presumed that no appreciable difference between the two types of rails used in the tunnel could yet be noticed.

Dr. Zollinger. Dr. A. ZOLLINGER, of Berne, noticed that it seemed customary in America, in tunnelling under water, to employ single-track tunnels, grouped in various ways. It was true that in marly, clayey, or sandy soils, where timbering had to be resorted to, the single-track tunnel possessed the advantage of facilitating the excavation and work of lining, in consequence of the lower pressure encountered; but where a shield was used, or an advanced heading in reinforced concrete was driven, it became advisable to consider whether it would not be better to employ a double-track tunnel, rather than a twin single-track one. The cost would certainly be less for the double-track construction, which enabled the centres of the two lines of railway to be kept at the minimum distance apart, and would materially reduce the expense of the permanent way. From the maintenance point of view the double-track tunnel was less costly than two single-track tunnels. The natural ventilation in the case of a single-track tunnel was easier, as it was effected by the passage of the trains. The system adopted for crossing beneath the Detroit River was very ingenious, and enabled the number of the workmen to be greatly diminished, because nearly all the operations were conducted by mechanical power. Here a very important question arose: when the Mont Cenis tunnel was being constructed, as also in the case of the St. Gothard, it was still possible to find miners, timber-men, and skilled masons who had practised nothing else but those trades all their lives. At the present time it was very difficult to obtain expert workmen, and it became necessary to

Dr. Zollinger. make use of labourers. This rendered it obligatory to employ mechanical devices in the work to a much larger extent than formerly. In building the Lötschberg tunnel they had been compelled to execute almost all the excavation by machine-drilling because no miners were to be had. The same difficulty had been encountered in constructing the tunnel-lining because masons were not procurable. It would soon become necessary to make use of reinforced concrete, in order to obviate the employment of masonry with natural stone, which needed good artificers, otherwise the work was badly executed. The more recourse was had to the use of machinery, the more the man himself became a mere machine, and eventually the skilled craftsman would disappear. Comparing the cost of the under-water portion with that of the approach-tunnels, it appeared that in the former case the cost of the labour was only 20 per cent. of the total outlay, while in the latter case the cost of labour amounted to 50 to 53 per cent. of the total. The expenditure on a tunnel under water by the system adopted would be the same as for a tunnel through the ground, making use of the shield or of compressed air, but the system of submerging tubes rendered it practicable to keep the structure high and thus diminish the length of the inclined approaches. The tests of the concrete mixed in various proportions did not furnish very brilliant results. In his own practice greater strength was demanded; thus with Portland-cement mortar mixed in normal proportions (1 to 3 by weight), the compressive strength at 28 days should amount to a minimum of 3,129 lbs. per square inch. Concrete mixed in the proportion of $1 : 1\frac{1}{2} : 3$ should show in compression, after 28 days, 2,844 lbs. per square inch, and a mixture of $1 : 1 : 2$ would give a strength in compression of 3,556 lbs. per square inch. For the purposes of electric traction, continuous current on the third-rail system was employed which, though more costly in the equipment of the conductor, was preferable from the maintenance point of view in the case of a tunnel. The third rail did not interfere with the reconstruction work, as was found to be the case with overhead conductors, which, moreover, required a larger sectional area of tunnel in order to provide space for the trolley-bow involving extra cost in the construction of the work. Continuous current gave specially favourable results in the case of short runs with a heavy traffic. He did not know why it was contemplated in the Detroit tunnel to provide for few trains heavily laden. There was no necessity for this so far as goods-trains were concerned, because they could be formed up in the two adjoining stations. Express passenger-trains, whose composition had to remain unchanged, Dr. Zollinger.

were the only ones which needed to pass through from side to side with a heavy load. There was always a desire evinced to carry out electric traction under the same conditions as steam traction; but this was a fallacy, because electric traction, if it was to be economical, must be conducted under suitable conditions; and that was the case only where numerous light trains running at a high speed were employed, and where the current was not called upon to propel certain trains five times as heavy as the average train. Heavy trains made too great a demand upon the power, and would not permit of the application of electric traction with more economical results than were obtained with steam traction.

The Author.

The AUTHOR, in reply, expressed regret that umbrage had been taken at his reference to the possibility of the use of the Detroit method under conditions where hitherto the employment of the shield had been obligatory, and especially so in the case of Mr. Jacobs, whose success with the shield had been so marked. He had intended merely to point out the applicability of the trench method to problems in which the air-shield had certain disadvantages. The authority for the reasons given for ceasing work on the original tunnel-scheme in 1872 was Mr. Chesbrough.[1] In estimating what the tunnel might have cost by the air-shield method, Mr. Jacobs had no doubt taken into consideration the increase in prices for materials and labour since the St. Clair tunnel was built more than 20 years ago; but apparently he had not borne in mind that, even ignoring this possible cause for disparity, the St. Clair tunnel had cost $1·08 per cubic foot between portals, as compared with $0·89 within the same limits at Detroit. It was possible, too, that he had overlooked the necessity of a larger tunnel had the air-shield method been adopted. Experiments with the permanent type of track at Detroit had demonstrated the need for an underlying, shock-absorbing mass of concrete, which was present in the trench design but absent in the cast-iron-lined type of tunnel advocated by Mr. Jacobs. Hence, to provide the 18-foot headway above the rails, considered by the operating department of the railway as necessary for goods- and passenger-traffic, and also space for ballast under the sleepers as a cushion to obviate the chance of injury to the cast-iron lining, the internal diameter would have had to be increased from 20 feet to 21 feet, involving about 10 per cent. increase in the cubical contents, with a resulting increase in cost that would have far outweighed even Mr. Jacobs's assumed saving.

---

[1] Transactions of the American Society of Civil Engineers, vol. ii (1874), p. 235.

The Author. In reply to Mr. Jacobs's criticism that the Author's Table of comparative costs was in effect misleading, though not so intended, the information had been merely given for what it was worth, as a sidelight on the subject, and for the further purpose of stimulating discussion and drawing out just the kind of valuable data produced by Mr. Jacobs, of which too little appeared in technical proceedings for the advancement of the profession. It was interesting to note the difference in cost per cubic foot between the small-sized Hudson-Manhattan tunnels and the large-sized Pennsylvania Railroad North River tunnels which had been driven through material of the same character, and it was to be regretted that similar information had not been given for the Pennsylvania Railroad East River tunnel, the cost of which to the railroad company had been understood to largely exceed the North River costs. It was also to be regretted that the Author was not at liberty to disclose the contractors' profits on the various New York tunnels and at Detroit, as indicative of the margin that was considered proper to cover the risks of the two methods. The advantage in this respect had appeared to be in favour of the Detroit work. As to the Boston tunnel referred to by Mr. Lavis, it should be borne in mind that it was built through firm clay, practically free from water, without many of the onerous conditions that obtained at New York and at Detroit. However, discussion as to what might have been done at Detroit appeared to be academic in the face of what had actually occurred. After a peculiarly vigorous and open competition among the most experienced contractors in the country, several of whom had had wide experience with the air-pressures mentioned by Mr. Jacobs, and, moreover, had had the advantage not only of studying the situation on the ground but also, in at least one instance, of close personal knowledge of the subaqueous conditions at the time the first attempt was made to construct the tunnel in 1872, the trench design was selected at a price to the Company about $2,000,000 less than was actually bid on the air-shield design. The work had been successfully completed in accordance with the adopted design, without the interference to navigation about which Mr. Jacobs expressed concern, without accident, without injury to the health and life of employees, and with eminent satisfactory results to the Tunnel Company. It could, of course, now be said that with the air-shield method a blanket might have been used on the river-bed to prevent "blowing," and that thereby the cost might have been less; but the nine contractors who had tendered for the work had not so viewed the matter, evidently realizing that blankets

The Author.

imperfectly held air, obstructed waterways, and involved certain risks; that the cost of construction where these designs were then in use, as in the case of the East River Tunnel of the Pennsylvania Railroad, was liable to be excessive; and that the danger to the health and life of employees in the use of the air-shield at Detroit would have been accentuated by the presence of poisonous gases in the underlying material. As the work progressed the impression grew among those in responsible charge of the work, both engineers and contractors, that these fears were well grounded and that they had been well escaped by the adoption of the trench design. As stated by Mr. Jacobs, the accumulation of a great many years of experience with the air-shield design would, no doubt, in the future result in reduction of the cost of that type. For the same reason it might be expected that the building of future tunnels by the less aged Detroit method would show similarly happy results. Mr. Lavis had suggested that steeper gradients might have been used than 2 per cent. west-bound and 1½ per cent. east-bound, so as to provide a thicker roof over the tunnel. This had not been favoured by the Advisory Board because of the desire to minimize the strain on couplings and draw-bars, and the hazards and expenses always incidental to the frequent movement of long and heavy trains on steep gradients. Even with the adopted gradients the greatest care was required to prevent trains from breaking in two, especially when it was necessary to start a stalled train on an ascending gradient. As to the question of time, referred to by Mr. Boller and others, it was true that a year might have been saved in the tunnel-construction proper if the rate of progress had been attained that had been found possible with air-shield methods, but it was equally true that the same saving could have been effected at Detroit, had the Tunnel Company so desired, by requiring the contractor to employ more equipment and work from both ends. External conditions that developed after the commencment of the work, such as delays in acquiring property for the new Union Station, and in the elimination of neighbouring level crossings, rendered this requirement unnecessary. Even so the total time from beginning to completion of the work, 4 years, did not compare unfavourably with other tunnels, as for instance those constructed by the Pennsylvania Railroad under the East and North Rivers, each of which occupied approximately 5 years. The watertightness of the North and East River tunnels of the Pennsylvania Railroad was remarkable. In this connection the Table of comparative tunnel-leakages on the following page was given:—

The Author.

Order of Water-tightness.	Location.	River or Harbour.	Leakage, in Gallons, per 24 hours.	
			Per Sq. Ft. of ~~Superficial~~ Gross Sectional Area.	Per Lineal Ft. Single Bore.
1	New York[1]	North River Pennsylvania Railroad	0·0005	0·15
2	Detroit	Detroit River	0·0027	0·85
3	Boston	Harbour	0·0034	1·35
4	New York[1]	East River Pennsylvania Railroad	0·0035 to 0·0070	1·00 to 2·00
5	Sarnia	St. Clair River.	0·0080	2·46
6	New York	East River Battery	0·0102	1·68
7	New York	North River Hudson-Manhattan	0·0264	4·80[2]

The 15 per cent. for overhead charges, about which Mr. Manton inquired, included administration and general expenses only, as the other items he mentioned were provided for in the labour and material costs. In response to the queries of Messrs. Lindenthal and Wilson as to the stability of the permanent track construction, short dowels in the concrete projected upwards into the tie-blocks so as to prevent lateral movement. No need had developed for bolting down the blocks, nor for occasionally extending ties in one piece across the gutters. Mr. Carson's and Mr. Meem's remarks were particularly interesting as bearing on the history of the art, especially as those of the latter had now first been called to the attention of the Author. Mr. Carson had well covered the reasons for finally favouring the adopted design, but for the information of Mr. Kernot it was explained that the requirement of continuity of strength from end to end of the subaqueous section had been considered best served by placing the reinforced lining without joints after the sections had been unwatered. As to electrification, interestingly touched upon by Professor de Muralt, Mr. Dawson, and Dr. Zollinger, extracts from the specifications would be too lengthy for inclusion in this Paper, but the Author

---

[1] Based on data furnished to the Author, 17th March, 1911.

[2] Mr. C. M. Jacobs has since explained that although this figure was correct when his Paper on "The Hudson River Tunnels of the Hudson and Manhattan Railroad Company" (Minutes of Proceedings Inst. C.E., vol. clxxxi, p. 169.) was written, the leakage now is at the rate of 2·28 gallons per 24 hours.—SEC. INST. C.E., Sept. 1911.

The Author.

would repeat that the terms laid down therein had given the fullest opportunity for contractors to select and tender upon the system they preferred. The result had proved conclusively that for this particular problem the direct-current system was the cheapest in both operating and capital costs. That the system so selected was preferable from the standpoint of reliability had been shown in the data made public at the recent annual meeting of the American Institute of Electrical Engineers. Mr. E. B. Katte, of the New York Central Railroad, in comparing statistics for the direct-current electric zone of his company with those given for the alternating-current installation of the New York, New Haven and Hartford Railroad, gave the following figures:—

	New York Central.	New York, New Haven and Hartford.
Train-minute delays, due to electric troubles, last 6 months 1909	427	2,076
Locomotive-miles per locomotive-failure . . .	26,655	15,700

The Tunnel Company considered that, by the adoption of the direct-current system for this particular problem, there had been achieved the desired ends of economy, safety, and reliability, with the fullest opportunity for the future expansion of the electric zone, and with the avoidance of the large additional expenditure that would have been required for enlarging the tunnel had overhead conductors been adopted. The remarks on the fallacy of adapting "steam" methods to electric traction were applicable to lines worked entirely by electricity, but in the Detroit instance the electric zone was but a link in a chain of steam-traction, which rendered necessary the carrying through of trains unbroken.

14 February, 1911.

ALEXANDER SIEMENS, President,
in the Chair.

The discussion upon Mr. W. J. Wilgus's Paper, "The Detroit River Tunnel, between Detroit, Michigan, and Windsor, Canada," was continued and concluded.

21 February, 1911.

ALEXANDER SIEMENS, President,
in the Chair.

The PRESIDENT announced that the Council had heard with regret that day of the death of one of the Honorary Members of The Institution, Mr. Octave Chanute, of the United States. The Council had passed the following resolution: "That the Council record the regret with which they have learned of the death of Mr. Octave Chanute, who has been an Honorary Member since May, 1895."

(*Paper No. 3923.*)

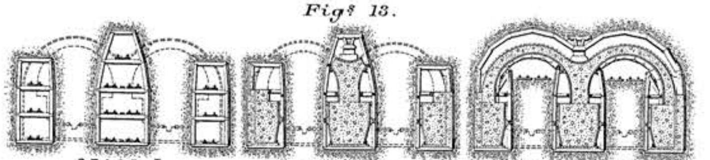
"Coast-Erosion."

By WILLIAM TREGARTHEN DOUGLASS, M. Inst. C.E.

THE Author proposes to discuss in this Paper the various causes which operate in the erosion of foreshores and of the bed of the sea in their vicinity. The principles which should guide the engineer in designing works useful for defensive purposes will also be dealt with; including the pitfalls to be avoided, the circumstances which have to be permanently borne in mind, and the limitations which Nature imposes on all human activities that aim at restraining the working-out of her laws. From what has been accomplished already in different parts of the country, remedial and other effects may reasonably be expected to ensue on the construction of soundly-designed sea-defences over isolated sections of the coast. Lastly, expenditure, with its necessary variations according to differing local conditions, and the financial requirements of the situation as it affects the United Kingdom as a whole, will be taken into consideration.

THE DETROIT RIVER TUNNEL.

Figs 13.



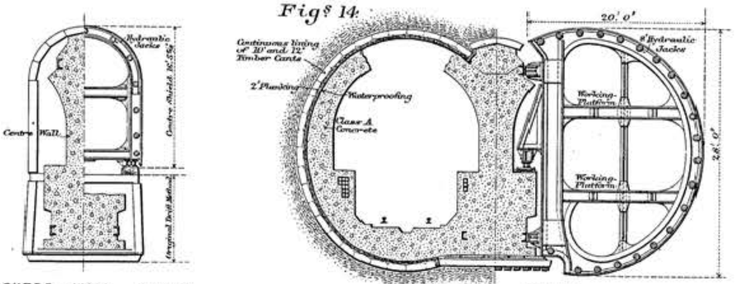
STAGE I

STAGE II

STAGE III

APPROACH – TUNNEL; ORIGINAL METHOD OF CONSTRUCTION

Figs 14.

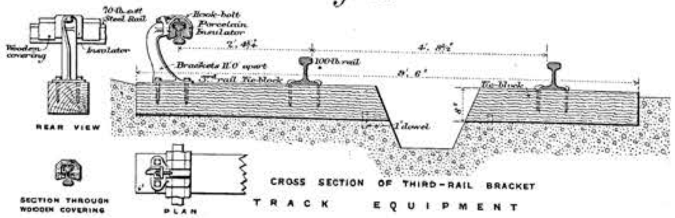


CENTRE – WALL SHIELD

SIDE – WALL SHIELD

APPROACH – TUNNEL SHIELD METHODS OF CONSTRUCTION

Figs 17.



REAR VIEW

SECTION THROUGH WOODEN COVERING

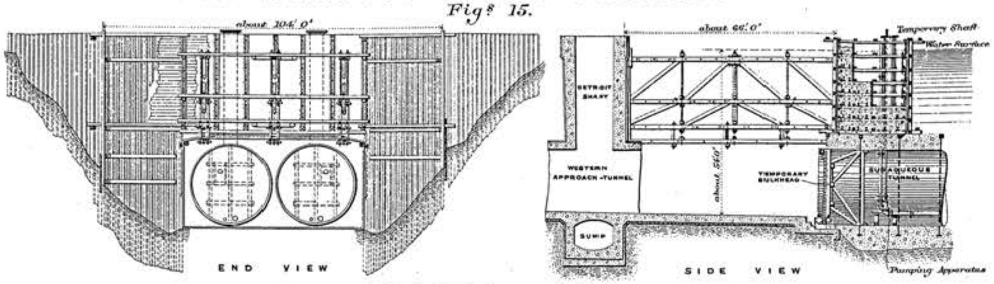
PLAN

CROSS SECTION OF THIRD-RAIL BRACKET

TRACK EQUIPMENT

THOS KELL & SON, LITH. 40 KING ST COVENT GARDEN.

Figs 15.

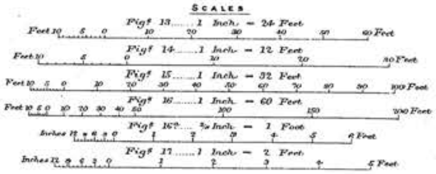


END VIEW

SIDE VIEW

COFFER DAM

SCALES



Figs 13……1 Inch = 24 Feet

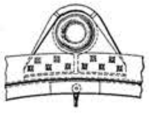
Figs 14……1 Inch = 12 Feet

Figs 15……1 Inch = 32 Feet

Figs 16……1 Inch = 60 Feet

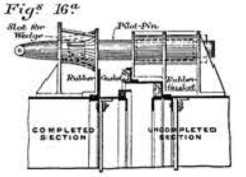
Figs 16a…… ⅜ Inch = 1 Foot

Figs 17……1 Inch = 2 Feet

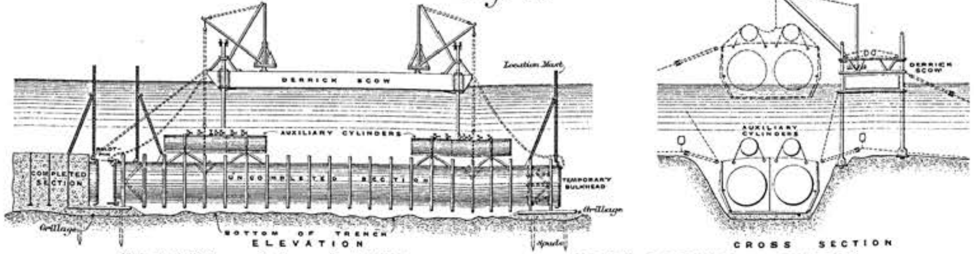


DETAIL OF PILOT – PIN AND JOINT

Figs 16a.



Figs 16.



ELEVATION

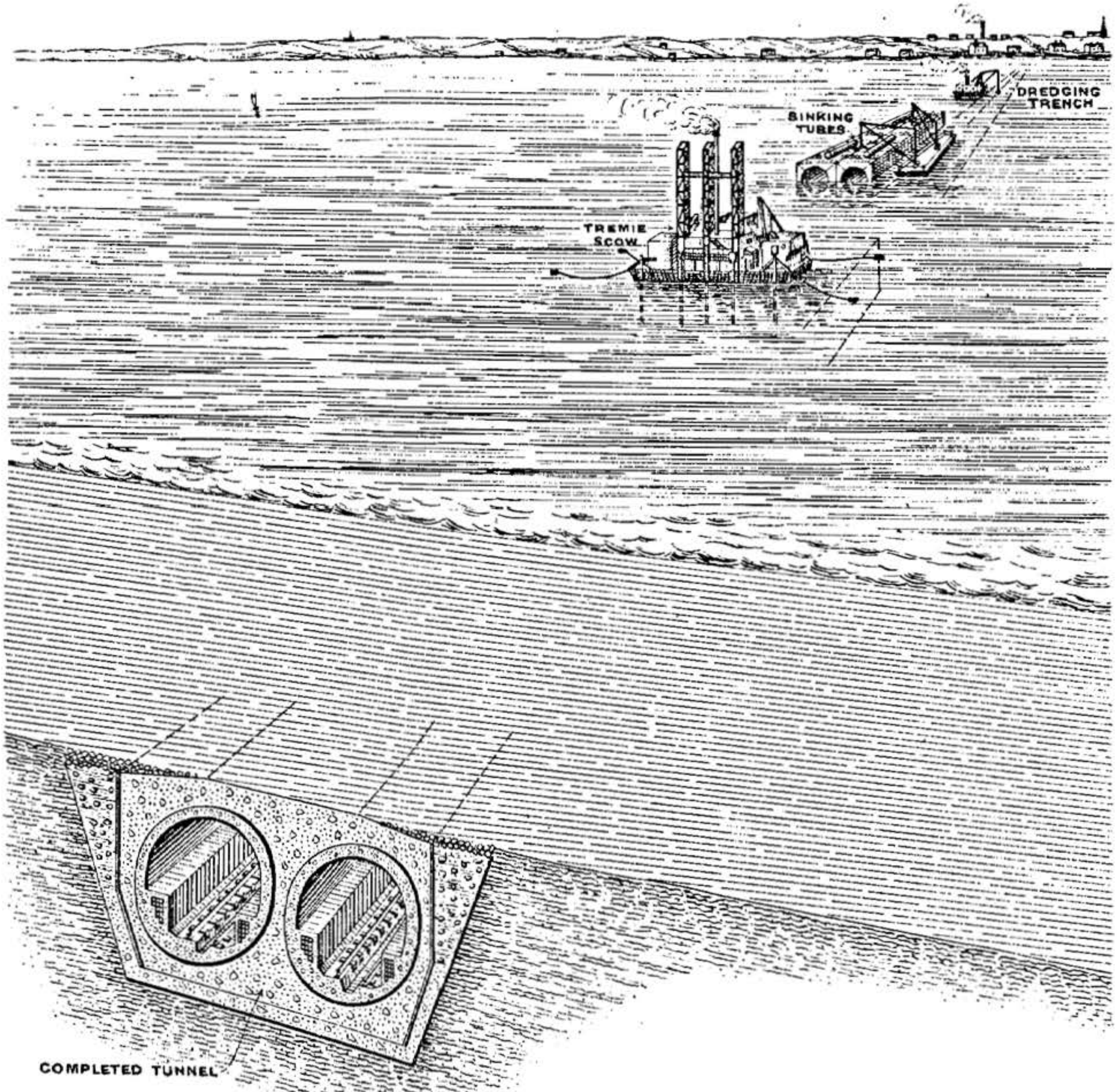
CROSS SECTION

METHOD OF SINKING AND CONNECTING TUBES

Minutes of Proceedings of The Institution of Civil Engineers, Vol. CLXXXV Session 1910-11. Part III.

PLATE 2.
DETROIT RIVER TUNNEL.

Fig: 18.



ORTHOGRAPHIC VIEW SHOWING
STAGES OF SUBAQUEOUS CONSTRUCTION

W. J. WILGUS.