Some considerations of submerged tunnelling

Ir J. BRAKEL

Ir J. Brakel

I propose to deal with one very important problem in submerged tunnelling, namely measures to avoid the harmful effects of deformations caused by shrinkage, temperature, creep and settlement.

86. When deformations by temperature or shrinkage are prevented from occurring, high stresses may develop, and when those stresses are tensile they can give rise to cracking of the concrete. In the case of unequal settlement of the subsoil in the longitudinal direction of the tunnel, high stresses may also be caused when the tunnel is rigid. The stresses may give rise to cracking, and sometimes to more serious deformation. *Cracking and other deformations are potential sources of leakage in a tunnel, not least on account of the high water pressure of some 20–30 t/m² or more. Therefore, appropriate measures have to be taken to reduce or avoid the harmful effects of shrinkage, temperature and settlement.*

87. The concrete of the walls and roof will shrink more than the concrete of the floor, which will have been cast four or five weeks earlier and shrunk to some extent. This differential shrinkage, together with the difference in temperature of the older floor and the more recently cast walls and roof (caused by the hydration of the cement) will cause high tensile stresses, particularly in the lower part of the walls. These tensile stresses sometimes give rise to one or two vertical cracks in the lower part of the walls. These cracks are particularly dangerous from the point of view of leakage because they are open throughout the full thickness of the wall. Only an outer membrane of sufficient strength is able to bridge such cracks, and an outer membrane is applied in all rectangular tunnels.

88. The 15–20 m sections can be cast against each other with continuous reinforcement through the joints, for the elements should have sufficient strength to be transported. But then again the problem of shrinkage arises. Therefore, in some tunnels shrinkage joints have been used between the sections. They have a width of 1–1.50 m and allow free shrinkage of the sections for one or two months. When most of the shrinkage has occurred the joints are concreted. The reinforcement is made continuous through the joint by overlapping bars. By connecting the sections in this way a rigid element is obtained which has sufficient strength to be transported for sinking.

89. However, in the event of unequal settlement, great stresses may develop which may give rise to cracking or even to rupture at any arbitrary place. It is better to have these places determined beforehand, so that appropriate measures can be taken. Therefore, when the probability of unequal settlement is relatively high, the joint between the sections is not rigid but flexible. The sections are temporarily united to a rigid element, generally by prestressing, for transportation and sinking. After that the prestressing is released and the joint between the sections allows a small rotation for unequal settlement, and a moderate longitudinal displacement to allow for temperature, shrinkage and creep (Fig. 13). Watertightness is ensured by a rubber seal with a vulcanized iron strip. In addition there is a bituminous membrane which is made continuous over the joint and which is specially reinforced.

90. It can be concluded that the modern sunken tunnel in the Netherlands will be a more or less flexible concrete tube with 'hinges' every 15–20 m, which allow small rotations (mainly for unequal settlement) and small longitudinal displacements (in the

Fig. 13. Joint between sections of outer wall Benelux Tunnel

main for temperature, shrinkage and creep). In the detailing of these joints great care is taken to ensure watertightness.

91. I have attempted to show the great importance of some apparently insignificant and common phenomena such as shrinkage and temperature on the constructional details of tunnel structures. But this is what makes submerged tunnelling so attractive and interesting for the civil engineer. Submerged tunnelling *is* civil engineering in all its various aspects.

Professor A. L. L. Baker, Imperial College

The Paper gives valuable specialized information needed in Great Britain to appraise the pros and cons of submerged and bored tunnels and bridges, and the various combinations of them, as optimum structural designs for carrying motorways over estuaries, sea-inlets and, more particularly, of course, the English Channel.

93. I was first convinced of the great advantage of the submerged tunnel when I spent a day in Jutland in 1969. There moored against a jetty was the next length of a tunnel to be positioned and joined. A reinforced concrete box, 100 m long and about 27.5 m wide, and with two tubes, each for three lanes of traffic, was floating in the water with about 0.15 m of freeboard. During the day the unit was towed into the middle of the fiord and carefully lowered into the sea-bed, manoeuvred into position and joined up, and by 10 p.m. there were another 100 m of tunnel on an almost finished roadway for six lanes of traffic. As one who had worked on the first Mersey Tunnel, with water streaming in and men hacking away at rock day after day doing about 30 ft in a week, I considered that in the right circumstances, this was the modern civilized way of making a tunnel.

94. It is 30 years since the first submerged tunnel was constructed in Holland. The Author has referred to 30 submerged tunnels built since then in various countries, and I believe there are over 50 in total. The construction of submerged tunnels has become a sophisticated technology. I do not believe that geological formations in Great Britain account for our preference in all cases in the past for bridges or bored tunnels. However, British contractors are now submersing a tunnel in Hong Kong, and I believe the first one to be built in Britain will be across the river at Thamesmead.

95. The Author refers to a project to connect Sweden and Finland. Recently in the discussion on General Sverdrup's lecture,¹ the Secretary-General of the French Road Union said that in his opinion the use of ferries to cross the Channel should be expanded from ports spread out between Hull and Southampton, but by 1985 a motorway across the Straits of Dover would be necessary to deal with the traffic. A bridge the whole way for this purpose is a possibility, but the piers could be obstructions in the deep water shipping lanes, where submerged tunnels rising from deep water to artificial islands on the Varne and Le Colbart Banks would leave two 6–8 km wide clearways for supertankers. The risk of tankers running aground or colliding could be considerably reduced by the provision of powerful navigation guides on either side of these broad, deep channels.

96. The scale of the work would justify the use of specially designed plant to reduce the total cost by facilitating the pre-casting of large units and their erection and jointing. Most of the work could be regarded as following standard practice largely developed by the Dutch, Danes, and Americans. There are, however, some difficulties requiring further study, and perhaps the Author would kindly add some comments to what he has already written.

97. I would like to put four questions to him. First, what is the best system of construction in deep water, say, over 50 m, which occurs over short lengths in the Channel? Secondly, has launching tunnel units out over the joined units and positioning by a submarine, gantry-controlled from the face of the tunnel, yet been tried? Thirdly, has shielding to deflect currents been tried? Fourthly, if trench dredging passes through gravel down to the upper chalk, can a cutter-suction dredger cope at a depth of 50 m?

98. A possible layout would take advantage of the Varne and Le Colbart Banks, which are shallow, to bring the tunnel up on the British and French sides. The foreshore projects on the British side and French side with water only about 16 m deep to a distance of about 5 km, so it is probably cheaper and better to bridge, coming out as a pier from each coastline, out over the foreshore, and to descend from an artificial island to a submersed tunnel under the shipping lane reserved for ships of deep draughts, say, from 10–15 m draught. This gap for the large ships is 5–6 km wide. On the French side there would be a similar shipping lane of about 6–7 km wide. Coastal shipping can go through special spans under bridges if necessary, and it is not difficult to devise a whole system of shipping routes for ships of various draught and height so that the whole of the shipping can be controlled properly in the Channel to avoid collisions, which now occur nearly every week. Fig. 14 gives one a better appreciation of the layout.

99. For coastal shipping there could be special spans as in the Chesapeake Bay scheme, where fair size ships can pass between the artificial islands, the construction of which can be seen where the tunnel goes down in an incline. They may be constructed in concrete, and they vary in length from 0.75 to 1.50 km.

100. The whole Channel is over 30 km wide, and the width of the solid constructions would not be more than 4 km. The effect on velocity of tidal flow in the Channel would be very small indeed. The construction would have to be taken down into the chalk, but it seems to be a possible and practical construction.

101. There is one section about 50 m deep on the French side, and a similar section on the British side, and it would be an advantage if one could carry out the erection of the submersed tunnel by launching the new unit over the top of the completed unit by using a submarine gantry which surrounds the two units and which is run forward on wheels on the tunnel already completed (Fig. 15). This could cantilever about 100 m ahead of construction because it includes buoyancy tanks. A new unit can be floated up to the roof of the gantry and propelled forward until it is in position and lowered by filling the buoyancy tubes in front of the tunnel as constructed, and the joining up can then be carried out in the usual way. Such a machine could be designed and the whole process would be controlled from the tunnel as built, because

Fig. 14. Channel Bridge-Tunnel

Fig. 14—(continued)

Fig. 15. Pilot gantry : A, buoyancy tubes ; B, partially buoyant gantry ; C, streamline shield to tidal current ; D, plinth for wheels of gantry ; E, prepared subgrade ; F, face of completed tunnel ; G, additional element

it is a case of controlling electrical winches and pumps to vary the buoyancy in the tanks in the various units. The gantry itself could be floated to the surface for repair if necessary, and the current could be deflected so that the unit was in slack water by means of curved shielding at the sides.

102. The Paper now makes the 1963 Government White Paper, *Proposals for a fixed channel link*, a dated document, requiring revision and expansion for the benefit of the bankers and politicians. The problem concerns not only experts in tunnelling and bridge design, but dredging, navigation, tidal flow, erosion and silting, traffic, artificial island construction and caisson-sinking. While the ferry traffic expands, I suggest there is time for a comprehensive feasibility study and publication of a report for wide discussion and consideration of an environmental balance-sheet of the shrinking Kent countryside before final decisions are made.

Mr A. H. Beckett, Sir Bruce White, Wolf Barry & Partners

Mr Brakel has made a very important type of civil engineering appear to be commonplace in countries outside Britain.

104. Professor Baker referred to the fact that the White Paper on the Channel Tunnel appears to be outdated by the techniques developed for submersed tube tunnelling, and perhaps the Author could give us some indication of the cost ratio between bored and immersed tube tunnels, having regard to the fact that a bored tunnel would lie at a greater depth, so that there would be a longer routing of tunnel than for an immersed tube.

105. I wonder also whether it is possible to couple together immersed tube units without using divers in the very deep water of the English Channel?

106. The Author has mentioned a number of arrangements for jointing the immersed tubes, and I should like to know the measures to prevent leakage in the event of excessive settlement such as would break the rubber joint.

107. Lastly, does the Author see a universal application of the immersed tube tunnel to the virtual exclusion of the bored tunnel when it comes to marine conditions?

Mr K. W. Innes, Scott Wilson Kirkpatrick & Partners

In his introduction the Author referred to flexible joints between the segments forming the rectangular reinforced concrete tunnel units. It appears that these joints are formed as spigot-and-socket connexions. Because of friction between the adjacent concrete surfaces there can be little free movement at these points if settlement occurs and it is therefore difficult to understand how this detail contributes to the flexibility of the design. Could the Author let us know more about the detailed design of these joints and give information on any observations which may have been made concerning their behaviour?

109. I should like to refer to §§ 64-74 in which a comparison of circular and rectangular tunnel sections is made. In considering the costs of the two basic types of tunnel construction, it is important to give due regard to the problems associated with the provision of casting basins. Being close to a river or the sea, these are generally constructed in waterlogged ground and involve the normal hazards associated with such excavations. Also the risks and problems occurring are magnified by the various flooding and dewatering operations that are required when constructing units in batches. Thus it must be appreciated that the basic price is high and as mentioned in § 68, it clearly becomes more economic if the basin can be used for the construction of units for other tunnels, or for some other purpose, for example, providing ship docking facilities as on the Deas Island Tunnel or a yacht basin as with the Marseilles Tunnel. Other costs that should also be included in any budgeting exercises are the cost of the land and its reinstatement if it is to be removed on completion of the contract. These points should be borne in mind in comparing costs of tunnels constructed by the various techniques described in the Paper, and it should also be remembered that the extent to which a casting basin can be used for other purposes after the construction of the tunnel will make comparisons between the costs of different tunnels a difficult exercise.

110. I have been responsible for much of the civil engineering design work on the Hong Kong Cross Harbour Tunnel. In 1966 when it was expected that work would begin in the following year, tenders were invited for constructing a casting basin ahead of the main contracting works. Tenders showed that the cost of this basin was likely to be well in excess of £1 000 000, but in the event this was not built, mainly because of the political troubles in Hong Kong at that time. However, it should be noted that the intention was that by letting an advance sub-contract for the basin the contract time for the construction of the tunnel would have been reduced. This would have been a way of overcoming one of the programme difficulties mentioned in §§ 64 to 67 of the Paper.

111. For this project, whilst tenders were invited for reinforced concrete rectangular units, the successful tender proved to be based on a twin steel tube design. Work began on this project in September 1969. The steel units are being fabricated on slipways constructed adjacent to the tunnel site specially for this project. The steelwork subcontractor has set up a fabrication yard and is currently launching steel units at a rate of about one a month. There are fifteen tunnel units. Progress on the construction of a tunnel in this form is very satisfactory as with this approach the construction of the circular tubes is relatively straightforward, and can be planned as a production line manufacturing process. There is no need for a casting basin and the advantages in the slipway where the units are built and launched as they are required and are available singly rather than in batches are most significant, particularly, as the Author has pointed out, from the point of view of programme.

112. When planning a submerged tunnel project, the possibility of fabricating tunnel units in an existing shipyard should be carefully considered. There is no need

DISCUSSION

for this to be close to the site of the tunnel, and, as has been stated in § 36, tunnel units were towed over 2700 km of open sea for the Chesapeake Bay Tunnels. At one stage in planning for the Hong Kong Tunnel there were proposals for towing tunnel units from Japan, through areas subject to typhoon conditions. The units would have been ballasted to minimize their windage, and, with suitable radar warning devices, it was considered that in an emergency they could have been cast adrift if storms were encountered during the tow. Because of the low windage, little drift would have occurred, and the tugs could have returned after the storm, homing on a signal beacon.

113. For tunnel projects in Great Britain and on the northern seaboard of Europe, I am of the opinion that there could be considerable advantages in manufacturing steel units in shipyards in development areas such as Tyneside and the Clyde and towing them to tunnel sites.

114. Whilst in the Paper the Author implies that steel units can only be used for circular sections, my firm has carried out studies for designs of rectangular units in steel, and these show that four or six lane tunnels can be built at costs comparable to similar reinforced concrete designs. Thus it is possible to combine the advantages of the rectangular section with its designed duct shapes and its minimal construction depth with those of the steel fabrication techniques.

115. In conclusion, I consider that the cost of casting basins can be very high, and this can sway the balance in considering the economics of various forms of construction. Would the Author agree with this statement? Further, there would appear to be advantages in planning for tunnel units to be constructed in development areas, where there is capacity for steel fabrication, later towing them to the tunnel site. This could be important for tunnel construction development in Europe, should the negotiations for Britain's entry to the Common Market prove to be successful. Finally it is my view that the steel shell design approach is not limited to a circular shape or to two-lane tubes, as steel designs of a rectangular shape are practicable and comparable in cost to reinforced concrete design. Would the Author care to comment on this statement?

Mr C. W. N. McGowan, Consultant, formerly Chief Civil Engineer, Kuwait Oil Company Ltd and Superintending Civil Engineer, Admiralty

I should like to confine my remarks to one or two points of view.

117. I would refer to the lecture by General Sverdrup on the Chesapeake Bay Crossing, which is just such a combined bridge-tunnel utilizing submerged tubes as those described by the Author. Like General Sverdrup, Mr Brakel has stressed the achievement in carrying out so large a project in a situation fully exposed to the open Atlantic, and has asserted that the secret lies in most careful planning, engineering, design, and organization, from start to finish. I think we might feel that if a project such as that can be successfully achieved in the face of open Atlantic weather, the same sort of project can be achieved anywhere else in the world.

118. In § 32 Mr Brakel refers to the combined bridge and tunnel proposals for the fixed link between England and France, an idea which has blown hot and cold, so to speak, since early in the last century. The Author has two such proposals in mind, both of which utilize submerged tubes for the undersea sections. The earlier one was put forward in 1961 by the French Channel Bridge Study Group or SEPM. This proposes high-level all-steel bridges between each shore and two artificial islands. There would be one deep-water shipping channel only between the islands, beneath which would be a submerged tube 7600 yd long, allowing a free passage of $2\frac{1}{2}$ miles. At several points in the bridges there would be wide spans for coastal shipping. Accommodation throughout would be provided for eight road lanes and two outside rail tracks.

119. The more modest one, to which the Author has referred, is a more recent

proposal, dating back to early 1967. This comprises precast, prestressed, reinforced concrete low-level bridges over the shallow waters, built on the unit principle as for the Oosterschelde and Chesapeake bridges, again with short, high-level sections for coastal traffic. Both schemes could be developed for recreational and tourist facilities, and the brochure by SEPM suggests remarkable developments in the way of recreation, marinas, motel accommodation and service centres on the two islands.

120. In the second proposal the accommodation would be either six lanes for road traffic only, or four lanes for road traffic and two rail tracks if desired. In this latter proposal there would be not one only but two deep-water shipping channels, each not less than 4 miles wide, and with islands at each side of the channels. Advantage would then be taken to utilize, not only the Varne, as in the case of the earlier proposal, but also the Le Colbart banks for two of the four islands. It is felt more and more that if there is to be a Fixed Channel link between Britain and France, it should be primarily for road traffic, in view of the enormous increase in road traffic density during the last decade.

121. Both proposals are a clear challenge to both Governments. Both are a challenge to the enterprise and to the engineering and organizing ability of our profession in Britain and France—a crossing 22 miles in length between Folkestone and Calais in a shipping zone world famous, or notorious, by reason of the collisions, sinkings, and groundings. It would be the first time that Britain had entered the field of submerged tube construction on a really big scale.

122. Members of Parliament and others have already declared in reference to the 1967 proposal, that the introduction of control points on the islands and bridge-ends on the edges of the two 4 mile-wide channels, as well as elsewhere along the structure, properly equipped with the very latest navigational aids, would materially increase the safety of ships by providing full guidance control in all weathers, as is done at Heathrow for aircraft. I am sure that we have to arrive at a situation whereby shipping in the Channel is properly under control. The present chaotic situation has got to be ended.

123. How can submerged tubes be laid in the Channel with 800 ships passing through it daily? This will be a task calling for perfect co-operation and timing, coupled with a slice of ingenuity. The trenches having been already prepared by the latest in deep-sea dredgers, the sections could be sunk into position by either (a) carefully timed diversion of shipping, (b) the method of lowering from walking platforms, or (c) undersea methods of traction and handling now being investigated by underwater technological research. As the Author has said, the last word on these problems has not yet been said. Perhaps he would care to give us his ideas on the laying of such tubes in the Channel.

124. The submerged tunnel units would be fabricated on shore under factory conditions, so ensuring continuity of progress and reliability of quality, all of this being conducive to saving construction time. There is an ample site not far from Folkestone for the making of the tubes and the bridge units. As the Author suggests, a site such as that would be available for similar production for tunnels elsewhere in the United Kingdom and in Europe if economics so allow.

125. Perhaps the Author could give us some typical examples of the cost of recent works. Lastly, he may have rightly emphasized the final solution to the fixed Channel link problem and, perhaps, also before it is too late.

Mr R. Stelfox, Greater London Council

For the last five years I have been intimately connected with the estimating side of the proposed Woolwich river crossing, and I should like to ask the Author if he would enlarge on his statement that in certain circumstances the tunnel can be cheaper than a bridge. It was pointed out that the sunken tube tunnel should be situated where there are low embankments, which makes it as economical as it is possible to be, and

equally in such circumstances the bridge is as expensive as it could be. We have these circumstances at the Woolwich river crossing, and our researches and experience do not in fact agree with this. I am referring to the cost of one traffic lane construction. The compressed air tunnel costs about £1000/ft of traffic lane, while a free air tunnel costs about £500/ft. We have done a great deal of research into the sunken tube tunnel, and the cost range is somewhere between £400 and £800/ft of traffic lane. If the average is about £600/ft complete, this gives a cost of around £50/sq. ft average for one 12 ft traffic lane.

127. Against that there is the price of a bridge. A comparable bridge must be the Severn or Forth, where the cost per square foot is something of the order of £25. One therefore has a bridge, which would be acceptable, and which could be built for £25/sq. ft against a tunnel which is likely to be about £50/sq. ft.

128. Our eventual scheme including all approach roads which went to the Department of the Environment compared a tunnel scheme costing roughly £23 million with a bridge for around £15 million. I would assure you that we did not produce our prices by taking the square foot price, but carried out research and costed the bills accurately. I would have thought that the tunnel would always be more expensive on any typical river crossing.

Mr I. S. Greeves, Director, Mowlem (Civil Engineering), Ltd

During World War II I was engaged upon the construction of a variety of reinforced concrete floating units, among them sections of the Mulberry Harbour. Of those built in London, some were partially built in basins excavated along the banks of the Thames and completed afloat in the calm waters of the enclosed docks. Others were completely built in docks or basins specially dewatered for the occasion.

130. Although the Port of London Authority has recently abandoned some of the older docks, and there is plenty of space available in them, I doubt whether the lock entrances would be wide enough to accommodate the proposed units for the Thamesmead Tunnel. It would be necessary to find a site along the Thames side where a construction basin could be excavated.

131. When we adopted this procedure in 1943 at Surrey Dock, we found a layer of soft peat overlying the sand and gravel just at the level required for constructing the units. We did not consider this acceptable as a material upon which to found. It was necessary to remove it and to provide a shallow well dewatering system to keep the sand and gravel dry during construction.

132. As this layer of peat is found in most parts of the Thames Estuary I suspect that a similar method would have to be adopted for the larger and heavier units proposed for a submersed tunnel. I would like to have the Author's views on the importance of a firm foundation on which to build the units, bearing in mind the high cost of site dewatering during the construction period.

Mr K. J. Prangnell, Chief Design Engineer, Costain Civil Engineering Ltd

I believe that the first work on immersed tube tunnels was on the experimental tunnel sections built by John Isaac Hawkins (M) in 1811.

134. The Thames Archway Company began their attempts to make a crossing of the Thames at Rotherhithe in 1800, engaging Vazey and then Trevithick, who drove a pilot tunnel by conventional methods almost to the opposite bank before an inrush of water stopped work in 1808. Trevithick commented that a series of caissons across the river might be formed into a tunnel, this echoing the 1803 proposal by Mottray for the Channel Tunnel. The company subsequently staged a competition, in which Charles Wyatt gained the £200 prize for his scheme of a series of 50 ft long cylinders constructed of bricks and Parker's patent cement. The company commissioned John Isaac Hawkins to evaluate this idea.

135. Hawkins first tested the materials thoroughly, starting with Malm pavours, bricks which he found to be so hard that they did not even chip when dropped from

a height of 6 ft on to an iron bar. To test the patent pozzolanic cement, seven of these bricks 'were cemented together end to end forming a prism 5 ft 2 in. long, $4\frac{1}{2}$ in. wide and $2\frac{3}{4}$ in. thick'. This prism was damp cured for a month and then tested as a beam, laid between two props 5 ft apart, and it eventually failed by a fracture of the centre brick under a central load of 35 lb. Finally, a careful study showed the suitability of puddle clay as a material for sealing the joint between cylinders.

136. Having by these tests satisfied the majority of the Directors of the feasibility of the project, Hawkins was authorized

'to build two cylinders of bricks and Roman Cement, each 25 ft long, 9 ft internal diameter, and 11 ft 3 in. external diameter, and to sink one of them in a horizontal position, lying crosswise of the stream, at about low water, in the bed of the River Thames, near the Horse-Ferry stairs, and the other, having its axis in the same vertical plane as the first, the two cylinders meeting end to end; but the second so inclined to the horizon that it might be entered through a Manhole near the higher end, while 3 ft of water covered the place of meeting of the two Cylinders and thus that the passage of water through the junction might be observed'.

137. The construction of the cylinders in turn, on a 40 ton barge, occupied 10 weeks, and each was launched by sinking the barge and they were left floating with about 2 ft of freeboard in the Grand Surrey Canal Basin, where they remained for five months, adverse winter weather conditions preventing the construction of the scaffold in the river. Over-excavation of the river bed had partly filled with a soft mud which would not support the cylinders, so 1200 tons of gravel had to be placed to the correct level as a foundation. Excavation of the river had been carried out at high water, in order to reproduce as closely as possible the conditions which might obtain in mid-stream, using ordinary ballast barges, with crab engines and steel mouthed leather bags, each holding 12 cwt, directed by a handle 50 ft long.

138. Hawkins had to evolve an ingenious boom defence system for his lay platform, to guard against the heavy traffic in the river. It took several experiments before an efficient system was perfected, and Hawkins described his low opinion of the abilities of all the other parties involved, from the ships' masters to his expert advisers. When the scaffold platform and his defences were complete, the first cylinder was brought from the basin on 4 April, 1811. Water was introduced into the cylinder to give it small negative buoyancy and it was lowered by several sets of windlasses to the bottom of the river. It was raised and lowered two or three times to test the systems and it was on the third time that a distraction allowed the windlasses to get out of step, the water in the cylinder flowed to one end and it adopted a vertical position. It fortunately proved possible to lower it into the excavation again to a horizontal position and the water ballast was then largely replaced by pig iron and the trials resumed.

139. When testing was completed to Hawkins's satisfaction, the laying of the gravel bed and the final sinking of the cylinder to its design position was carried out, these operations occupying a little more than an hour, and locking fill was placed on top of the cylinder.

140. The lay platform was moved to its second position, with some difficulty, and the second cylinder brought from the basin and lowered into position. The trench was, however, obstructed and the cylinder had to be raised again for the excess material to be removed. On the second lowering the tops of the cylinders made contact, but at the bottom there was still a gap of $1\frac{1}{2}$ in. Pressure by the Conservators of the Thames to hurry the tests and clear the river forced Hawkins to accept this as good enough and to attempt his puddled joint between the cylinders. This joint, when it was completed, gradually sealed itself and became impermeable and the whole concept was then accepted as feasible. However, at the adjourned Annual General Assembly of the Proprietors of the Thames Archway Company at the Globe Tavern,

Fleet Street, on 27 November, 1811, the Directors reported that although the experiment was a success, due to 'accidental and unforeseen circumstances arising from the crowded state of the River', the costs had far exceeded the estimate and it seemed that the cost of the full tunnel would be such as to make an economic return unlikely. There was some general depression of the money market at that time, so finance for the Thames Archway, as for other major public works of the time, was not available and the scheme faded into somewhat acrimonious obscurity.

Mr M. M. McLean, Greater London Council

The Author referred to a tunnel blanket of 1.50 m to protect against water currents. Has the question of ship sinking been considered at all?

142. Secondly, I should like to know whether any work has been done in Holland on the deflocculation of silts.

Ir J. Brakel

I very much appreciate the many most interesting contributions, comments and questions, which show how seriously the Paper has been studied, or perhaps better, how deep is the interest of British engineers in submerged tunnelling. Many of the contributions provide a most welcome extension and often expert amplification of the Paper, particularly with regard to the Channel and Hong Kong tunnels.

144. **Professor Baker**, whom I would particularly like to thank, suggests that over 50 submerged tunnels have been built since the construction of the first submerged tunnel in the Netherlands (completed in 1941). He may be correct if he includes open cut, shield and bored tunnels (with subways included it would be far more than 50), but the number of trench type sunken tunnels is not much more than the 30 I have referred to. With the exception of three or four of the oldest, of which only Michigan Central Railroad (about 1910) is mentioned in the Bibliography, and perhaps some tunnels of minor importance on which I have no information, I have mentioned all trench type tunnels for motor and railway traffic that have been built to the present date.

145. However, the exact number of existing submerged tunnels is rather unimportant; what is more important is the need for new tunnels in the near future, and this need is increasing even more as motor traffic increases. Here the predictions have always been far behind the real development. What must be kept in mind in the design of the Channel crossing is what does modern traffic want and need in the very near future? People want to drive on and not lose time waiting at ferries, hovercraft or railway transits. People will not be happy driving in a tunnel of extreme length; after some 10 minutes they should again be in the open air for a while. A crossing is needed that fulfills these conditions. Therefore the proposal of Professor Baker for a bridge-tunnel connexion should be very carefully studied. In the Netherlands there are fully developed designs and plans for at least a doubling of the existing number of submerged tunnels (seven to date) in the next 10 years, and in the rest of the world there will certainly be the same tendency.

146. The four questions of Professor Baker I should like to answer as a whole. For tunnel construction in deep water (50 m or more) the following procedures may be considered:

- (a) the normal sinking procedure, with barges or floating cranes, as applied at present for most submerged tunnels (Fig. 6 and 7);
- (b) placing by platforms on spud piles (Fig. 16);
- (c) placing by a submarine gantry, as illustrated by Professor Baker (Fig. 15).
A similar submarine gantry, but one also equipped with an excavating machine to dig the trench, has been designed by a well-known Danish firm of contractors.

147. Launching the tunnel units over the completed tunnel and positioning them by a submarine gantry has not yet been tried, but there is no doubt that it will be

Fig. 16. Excavation of trench and placing of tunnel elements by platforms on spud piles

possible and probably even economic for greater tunnel lengths. Since all operations occur deep under the water surface, shipping will meet no obstacles and placing can go on unhindered. Placing by platforms has been done at the Parana River Tunnel (§ 78) (because of the strong current), at the outfall sewer of the Hyperion sewage treatment plant in Los Angeles (to a depth of 60 m), and has been proposed for a design of the Channel Tunnel (Fig. 16).

148. The normal sinking procedure has not so far been used in water deeper than about 40 m (BART subway tubes) (Fig. 17), because there was no need for it, but under favourable conditions, e.g. little or no current, it will also be possible for greater depths.

149. When the water depth is considerably greater than required by navigation, the possibility of constructing the tunnel as an underwater bridge supported on piles should be considered. A tunnel under water weighs a fraction of its true weight and so the spans, i.e. the distance between the pile trestles, can be great. In very deep water piles cannot be considered, and the weight of the tunnel should be made less than its buoyancy, so that the tunnel can be anchored to the bottom (or to heavy weights). In both cases the only, but very important, danger is that anchoring or sinking ships may damage the tunnel, and for this reason the solution is excluded in places where heavy ships can anchor or sink on it. In certain deep lakes, however, with only light ships, this solution may be attractive.

150. With regard to trench dredging at a depth of 50 m or more, neither a cutter-suction dredger nor a bucket dredger can be considered at present. The first can cope with a maximum depth of about 30 m, the latter with about 33 m. Both can make a trench with a sufficiently level bottom; the bucket dredger generally works to greater accuracy than the cutter-suction dredger. Since the maximum water depth for almost all existing tunnels has been less than 30 m, there have been no difficulties and most trenches have been excavated by one of these methods. The trench for the sunken part of BART, San Francisco, which had a greatest depth of nearly 40 m, was excavated for the greater part by a clamshell dredger, with a bucket of 13 cu yd capacity.² The inaccuracy remained within the acceptable limit of 0.6 m. Dredging

Fig. 17. Placing barge (foreground) and screed barge for BART

a trench at 50 m or more should also be possible with a clamshell dredger, but it will not be an easy job, and with a strong current it may be almost impossible.

151. There are suction dredgers which can cope with a depth of 70 m and more, but their only purpose is in dredging sand or gravel to use elsewhere; they can only make a succession of craters, which does not produce a good trench. Probably the best solution is a machine which can work under water and move on the bottom, or which is lowered from a platform (Fig. 16), or forms part of the submarine gantry, like the already mentioned Danish idea. However, such a costly machine will only be made when a suitable job is available for it, for instance a tunnel trench of sufficient length and depth, exploitation of the sea bottom (e.g. for ores), works in or under the sea bottom (e.g. storage tanks, reservoirs), etc.

152. Shielding to deflect currents and so avoid premature refilling of the trench, has not yet been tried, as far as is known, but it should be kept in mind for appropriate occasions.

153. The cost of a submerged tunnel requested by **Mr Becket** depends on several conditions, and varies roughly between 60 000 and 80 000 fl/m (£2100–2800 ft) for a four lane tunnel. A six lane tunnel will cost 20–25% more under the same conditions. On piles the cost may be increased by more than 50%.

154. For the coupling operation of tunnel elements divers are not needed in principle, as it can be done entirely from the surveying towers on the elements and from the inside. Diver work is only for control, or if there is something wrong. But with modern instruments and equipment control is also possible from the inside of the

elements and in clear water also with television cameras from the outside. For the control of the coupling of the units for BART, divers worked at a maximum depth of almost 40 m below the surface.

155. The forces due to a limited unequal settlement of neighbouring elements can be taken by a dowel construction, as in Fig. 9. As already mentioned (§ 89), in recent tunnels a loose dowel is preferred, to make the joint more flexible. In the event of excessive settlement no arrangement for jointing will be sufficient, as the forces then developed will be so high that no joint construction can resist them. This also applies to the toothed joints of locks and dry docks. When considerable settlements are expected, the tunnel should be founded on piles.

156. There will be circumstances in which a bored tunnel is to be preferred, e.g. in sound rock in which a trench can only be excavated with great difficulty, and others in which a sunken tunnel has the greatest advantages (e.g., in soft soil or bad rock, with serious crevices, cracks, etc.); generally, a bored tunnel also has the disadvantages of its greater depth and length. With increasing length this circumstance becomes less important. In Japan several bored tunnels under the sea have been made. I have heard of an interesting new development in compressed air tunnelling, where the compressed air has been replaced by a fluid in front of the tunnelling machine.

157. I agree with Mr Innes that the price of an excavated casting basin for a rectangular tunnel is high, and that all the factors which he has mentioned should be carefully considered in the comparison of circular and rectangular tunnels. Governmental engineers in the Netherlands have done this more than once, but they have come to the conclusion that for our conditions the rectangular tunnel is still the cheapest solution, despite its delayed building time and other apparent disadvantages in comparison with circular tunnels. The comparison has also been made by some big tunnel contractor consortia, and they have come to the same conclusion for Europe and some other parts of the world. Our engineers are aware that the excavation and preparation of a casting basin is a costly and time-consuming affair, that needs improvement. Nevertheless, I am convinced that under certain circumstances of attractive steel prices, wages, etc. a steel shell tunnel, built under factory conditions by advanced industrial techniques, may prove to be more economic than a rectangular all-concrete tunnel, built in the 'traditional' way in an often expensive casting basin.

158. From the point of view of the engineer it would be very interesting if both kinds of tunnel building could seriously compete with each other. This would undoubtedly stimulate new possibilities and give rise to new developments and improvements in manufacturing and placing techniques. Perhaps the studies of Mr Innes' firm on rectangular tunnels with steel shells will be the forerunner of such a new development. When, however, the rectangular steel shell tunnel is built in the same way as a circular tunnel, with inner structural and outer ballast concrete, I do not see that this structure could be more economic than a rectangular, all-concrete tunnel. I will be glad to hear more about it. With regard to this I wish to remark that it was not my intention to suggest that steel units could only be used for circular cross sections, but that until now they have only been used for this kind of tunnel.

159. Fabrication on an existing shipyard is not attractive for rectangular concrete tunnels, because each element has to be there until it is completed (or nearly), so that the period the shipyard is occupied is several times that for a steel-shell tunnel. In addition, the great weight (20 000 to 50 000 tons) causes high bending moments during launching, which need much additional reinforcement. Also it is not easy to make a rectangular element with sufficient accuracy on a sloped base.

160. Concerning the Hong Kong tunnel, Mr Innes has said that the successful tender was based on a twin steel tube design. I received recently an article by Phillips³ which shows that this was not the cheapest solution. The relevant sentence reads: 'The engineers reinforced concrete design that was put out to tender is the most economic, but, of course, government sponsored funds are nearly always linked with export content quotas and, as this favours high value commodities, the tendency has

been for alternative designs to be of steel, even though this increases the engineering costs. These costs are now estimated to be in the region of HK £220 million'.

161. When the number of units for a rectangular sunken tunnel is below about eight or ten, generally all the units are made together in one dock, which is flooded when all elements are ready. There is little to be gained by first completing half the number, to gain time, for the whole of the sinking operation takes about one week per element (the sinking itself only takes some hours). In the case of the Hong Kong Tunnel, with its 15 elements, it would have been possible to use the dock two or three times and so try to reduce the costs, but undoubtedly the construction time would be increased by doing so, and the economic advantages would be rather dubious.

162. I am much impressed by the launching of one unit a month. However, placing a unit is a question of a week. What is the placing team and equipment doing the rest of the time? The much smaller units of BART were launched one every two weeks, which is already more favourable.

163. With regard to construction time it may be attractive to prepare the construction basin on an advance contract or subcontract. It would be even better to have a permanent, well-equipped construction basin, in which all the tunnel units for one or more countries could be made. Then the most advanced techniques could be applied and it would be possible to reduce the cost of a tunnel by several millions of guilders.

164. To complete the remarks of Mr Innes on the reduction of the cost of a casting basin, the basin of the Danish Limfjord Tunnel will serve as an extension of the harbour, and in Montreal the excavation for one approach was extended so that the tunnel units could be built together with this approach in one open cut.

165. Concerning the first observation of Mr Innes, the joints between the segments every 15–20 m (Fig. 13), allow only a small rotation, but for the settlements to be expected it is sufficient. The observed maximum settlements are about 80 mm but the differential settlements on a segment length of 15–20 m are much less, so that the rotation is only very small. This rotation is possible, because the contact surfaces of the concrete have been covered with a bituminous layer before the next segment is cast. It is clear that no relative vertical or horizontal displacements of the contact surfaces can be allowed, because this would have consequences for the roadway surface; therefore there are spigot and socket joints between the segments and a loose dowel construction between the elements. When considerable settlements are expected, the tunnel should be founded on piles. Then the joint surfaces can be made plane.

166. I am glad that an expert in tunnelling such as **Mr McGowan** is also a champion of a bridge-tunnel crossing primarily for road traffic. In my comments to the contribution of Professor Baker I have already given some ideas of laying tunnel tubes in the Channel. I fully agree with what Mr McGowan says in § 124 on the fabrication of tunnel units and I emphasize again the desirability of co-operation of tunnel building in Europe, or at least between neighbouring countries, not only to make better use of the know-how, experience and equipment that is available, but also to start co-ordinated research. There are already national groups on tunnel building in Western Germany, England and recently also in the Netherlands, and in my opinion, the time is ripe to establish an international organization on this basis. I believe it not exaggerating if I state that in the last three decades of this century some hundreds of submerged tunnels will have to be built all over the world.

167. With regard to the Channel crossing I should like to make the following comments, which refer to the contributions of both Professor Baker and Mr McGowan.

168. Construction of a bored tunnel for vehicular traffic will certainly be possible. With regard to the future it should contain at least eight road lanes. These could be distributed over four tubes with a diameter of about 9 m, three tubes with a diameter of about 12 m, or in two layers in one tube with a diameter of about 16 m. However,

all these solutions will be much more expensive than the construction of a bored, two-track railway tunnel with a diameter of about 10 m, and I am almost sure that they will also be more expensive than a sunken tunnel of the same capacity.

169. The difficulty will be to provide sufficient ventilation. With a great number of ventilation towers the dimensions of the ventilation ducts will be relatively moderate, but the danger of ship collisions will be great. A small number of ventilation towers means expensive ventilation ducts of excessive dimensions, and a decreased, but still existing danger of collisions. The length of a bored vehicular tunnel will only be 1–2 km more than that of a sunken tunnel; this difference is of minor importance over such a great distance.

170. A bored tunnel for railway traffic only, with special trains for car transport, will be the cheapest solution, but it will not satisfy the conditions of modern vehicular traffic, particularly in the near future.

171. A steel bridge over the whole length, with elevated parts and great spans over the navigable passages, will be almost as expensive as a submerged tunnel, certainly when maintenance is included. A similar concrete bridge will have smaller maximum spans (200–300 m) and can be cheaper, as it is less sensitive to corrosion. But in both cases there is the danger of ship collision with a pile, particularly during fog or stormy weather. For the steel bridge the probability is a little lower than for the concrete bridge, but in a case of serious damage the bridge will be out of service for a considerable time (cf. Chesapeake Bay, Maracaibo). This cannot be allowed and therefore piles in the navigable passages should be totally avoided by making a tunnel there.

172. A combination of a tunnel under the deep navigation channels and a concrete bridge with moderate spans (100–200 m) over the shallower parts will be the best solution, both from the point of view of the users as well as shipping. Shipping should be rigorously controlled by the measures described by Mr McGowan (§ 122). How far this can be internationally arranged will not be easy to predict. There should be two navigable passages of sufficient width, one for each direction.

173. For the transition of bridge to tunnel (and the reverse) I prefer islands over the ingenious concrete structure of Professor Baker, because the current will be better guided by a well designed island than by the concrete wall Professor Baker proposes. In addition, the islands can be used for recreation, and also for harbour, airfields, industry, etc. They can be made at a reasonable cost in 15–20 m deep water, as has been suggested at the Conference on Offshore Structures in the Netherlands⁴. The length of the tunnel parts will be such that no intermediate ventilation towers are necessary. The driving time will be between five and ten minutes, so that the user knows that he is always within walking distance of the ends in cases of emergency; in a tunnel almost 40 km long this could give rise to panic.

174. The true costs of tunnels cannot be easily compared, because the circumstances are different for each one. It is not only a question of rising wages and prices in the course of time, but also of variations from country to country. It further depends on how many additional works, such as connecting roads, bridges, enlargement or deepening of the waterway, etc., are included in the contract. It also depends if it is a four-lane or a six-lane tunnel; if the slope of the ramps is 3.5 or 5%, for example; if the foundation is on piles or not; if special measures have to be taken with regard to the drainage and/or soil improvement of the casting basin or the trenches for the approaches; if there are difficulties with shipping, with silt, etc. Although for these reasons a comparison of the costs of some recent tunnels hardly gives a useful indication, some figures are given in Table 1.

175. The cost of the Benelux Tunnel, which has practically the same cross section as the Coen Tunnel, has been increased by almost all the factors mentioned. From this it can be seen that it is dangerous to compare costs, if all the circumstances that have been of influence cannot be taken into consideration. For this reason also the prices of the Scheldt, Elbe and Hong Kong Tunnel are given without comment.

DISCUSSION

176. **Mr Stelfox** refers to a cost-comparison of a bridge and a tunnel, both for the Woolwich river crossing. As already stated it is very difficult to compare tunnel costs, as there are so many factors which can be different from one case to another. Furthermore, the price of a tunnel is not linearly proportional to the number of traffic lanes, because there are several factors that increase far less, for instance the excavation of the casting basin, the formwork, the sinking procedure, the backfill, etc. This also applies to a bridge, but much less than to a tunnel. So an increasing width is in favour of a tunnel. The sunken part of a four lane tunnel will cost roughly between 60 000 and 80 000 fl/m; the cost of the open approaches is in the neighbourhood of half of this (but on piles it may be considerably increased).

177. An elevated long-span bridge with four traffic lanes will cost between 1500 and 2000 fl/m², or roughly between 30 000 and 40 000 fl/m. The ramps will cost between 20 000 and 30 000 fl/m. However, the length of the ramps of an elevated bridge will soon be twice the length of the approaches of a tunnel. In addition, in the Netherlands with its poor soil conditions, the foundation of such a bridge is a costly affair. The fuel costs for a tunnel are much lower than those for an elevated bridge (both over the same distance) and the time saving is also in favour of a tunnel. All this can be expressed in money. This is not possible for fog, ice, snow, wind, the danger of collision of ships against the piles of a bridge, and aesthetic considerations. They are also in favour of a tunnel.

178. Not in favour of a tunnel are the costs of operation (ventilation, lighting, supervision, cleaning, fire-brigade); maintenance, however, is much cheaper than for a steel bridge. The very rough prices above will give an idea of when a tunnel may be cheaper than a bridge, and when not. The average of the prices does not differ much from the averages of Mr Stelfox, if the price of a four lane tunnel is assumed to be four times that of one lane, or £2400/ft (70 000 fl/m). The same applies to the bridge prices. It is clear that only a serious cost estimation and a weighing of the non-profitable factors can definitely decide which is the best solution. In his article on the construction of the Limfjord Tunnel Havnø⁵ states that: 'the tunnel proved to be only slightly more expensive than the bridge, required considerably less foreign exchange, and furthermore, there would be considerable saving in fuel costs'.

179. Dutch engineers have come to the conclusion that a tunnel will often be

Table 1

Tunnel	A m	B m	C	Construction period	Cost, fl × 10 ⁸
Coen	587	1273	4	1961–1966	38*
Benelux	795	1300	4	1962–1967	77*
Heinenoord	614	1064	6	1965–1969	49*
Metro, R'dam	1040	1040	2	1963–1968	45†
Scheldt	690	‡	6 ÷ 2	1964–1969	~220
Elbe	1056	1773	6	1968–	~130§
Hong Kong	1580	1830	4	1970–	~160 ⁶

A = length between portals (or end of section considered)

B = total length

C = number of traffic lanes

*Electrical and mechanical installation (10 to 15% of basic sum) excluded

†Double track subway, founded on piles.

‡Not exactly determinable.

||Six traffic lanes and double track railway tube

§Only Part I (sunken part and one approach).

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cheaper and is seldom considerably more expensive than an elevated, long-span bridge. However, tunnels are preferred also for reasons of shipping, traffic interests, aesthetics, etc. Even when there are no seagoing vessels, so that a low bridge with a movable part seems to be an acceptable solution, this will not be chosen in the future, because modern traffic cannot accept a waiting time of several minutes, causing congestion of several kilometres. And an elevated bridge, under which all ships can pass, will disturb the landscape in an intolerable manner.

180. The suggestion of **Mr Greeves**, of using old docks for the construction of tunnel units and so reducing the cost of the construction basin, certainly deserves to be considered further. Soil conditions in the construction basin should be or be made such that deformations from unequal settlement are limited to an allowable extent, not only with regard to rupture and cracking, but also in view of permanent deformation. When a complete element has been in a deformed state for some time, e.g. from warping, it will not return to its original form and shape, and it is doubtful if the joints will be still fit sufficiently well.

181. The bottom surface of the basin should always be covered with a layer of permeable material (e.g., coarse sand or pea gravel) about 1 m thick, not only to make a good working base, but also to ensure floating of the elements after flooding of the dock. The cost of dewatering depends not only upon the permeability of the soil, but also on possible damage to neighbouring foundations, agriculture, water purification plants, etc. With regard to soil conditions, the location of the dock can be chosen at a suitable place, because the elements can be transported over a considerable distance (see also § 36).

182. The historical note on the oldest sunken tunnel units of **Mr Prangnell I** highly appreciate, and we should admire the more these well-considered and ingenious attempts when we compare the primitive materials and equipment with which these engineers had to work with the resources we have at our disposal.

183. Concerning the question of **Mr McLean**, the 1.0–1.5 m thick cover or blanket on a tunnel serves less to protect the tunnel against currents as against ship anchors thrown out in emergencies, and against dredging. There are, however, recent tunnels with a less thick blanket and some even without one altogether. Then the upper corners of the cross section are sloping and/or rounded (Fig. 2).

184. Ship sinking is taken into consideration. In normal circumstances, when the tunnel is sufficiently embedded in its trench and is covered with a layer of soil or stone 1 m thick or more, there is no danger. A serious situation arises when the tunnel roof protrudes from the river bottom and the ship comes to rest on it as a cantilever. Generally, the ship will break then, but also the tunnel can be loaded near to its ultimate strength. The occurrence of such a situation should be avoided by protection of the river bed on both sides of the tunnel. However, the situation seems worse than it is in reality, for the minimum cover exists only at the sides of the shipping profile, where the tunnel roof is nearest to the bottom. In the middle of the shipping profile the cover is generally several metres more. The Benelux Tunnel has been designed to resist the load of a sunken ship of 40 000 tons.

185. Research on deflocculation of silt, i.e. removal of silt by chemical means, has not been done in the Netherlands to date. Under certain circumstances deflocculation certainly could have advantages and it should be further studied. However, in the tunnel trench in the flowing water of a river, continuously new deflocculation substance would have to be added and it is doubtful if this would be an economic method. Besides, silt also settles without flocculation, but with flocculation settlement is increased.

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