Proc. Instn Civ. Engrs, Part 1, 1975, **58**, May, 249–258

7709 DISCUSSION

The Elbe Tunnel, Hamburg: Southern ramp and submerged tunnel

K. HAVNØ

Mr D. R. Culverwell, Freeman Fox & Partners

I have been fortunate enough to have visited the Elbe tunnel, and it is a most impressive piece of engineering. Britain has no such immersed tube tunnels, though there are several planned.

79. I have several questions concerning the Paper. Reference is made in §§ 40, 62 and elsewhere, to forces encountered during the sinking of the units. Would the Author say how much these varied during the sinking and how close they were found to be to the model test and calculation results. Would he also comment on any flutter effect that may have been observed as the unit was lowered into the water and into the trench. In some model tests which were done for my organization on a similar four-lane rectangular concrete box element for the Hong Kong tunnel, it was found that scale effects made accurate prediction doubtful, and I believe at the Lafontaine Tunnel in Montreal quite considerable disparity was found between model test results and the forces actually encountered as the unit was sunk on to the bed.

80. The simple statement in § 69 that units of this size were sunk in 10 h demonstrates a great deal of engineering modesty: this must have required meticulous planning and most careful execution. This is made no less valid by the very frank and useful account in § 59 of the difficulties of controlling the element.

81. I was interested to read of the shipping restrictions (§ 58); would the Author say what time limitations, if any, were imposed by the harbour authorities within which the Contractor had to operate, and also how these restrictions were covered by the terms of the construction contract?

82. In reference to the transverse joints, (§§ 18–27), and to the provision for movement, I would like to know the maximum settlement that was anticipated and the condition, under winter conditions, of the open joints under such settlement. Also reference is made to the possibility of a ship sinking on top of the element: were increased stresses allowed under this exceptional loading?

83. A central two-tube light fitting could have been accommodated in the acoustic ceiling, and I wonder if it might not have been more economic to use this than two lines of single tube fittings in each corner of the highway compartment. The single tube fitting has slightly better overall performance, of course, but the cost of a single tube and a double tube fitting is not very different, being perhaps £30–£40 a time, and thus considerable saving can be effected by using the two-tube fitting. Both were considered for Hong Kong and it was calculated that a single tube fitting saved over £75 000. The average illumination on the roadway there, under service conditions, was about 200 lux with about a 20% variation between the kerb and the centre of the roadway.

Paper published: *Proc. Instn Civ. Engrs*, Part 1, 1974, **56**, (Aug.) 257–274.

84. On the Vlake and Kil tunnels, under construction in Holland, no waterproof membrane is used, but instead special care is taken over the concreting of the units. The mix has been carefully designed with particular regard to the grading and type of aggregate and to the cement and water content and to the use of plasticizers, all with the intention of making the concrete as impermeable as possible. Each 20 m long section of the Vlake and Kil tunnels was concreted in two sections, first the base slab and then the walls and roof in one pour. This would normally lead to cracks in the wall just above the joint with the base slab, but to combat this a cooling system has been built into the wall. This is remarkably simple, comprising a continuous steel pipe about 3 cm in diameter which runs back and forth about six times from end to end of the section, each run being about 0·5 m apart, so that they extend about 2½ m up the wall. After concreting, chilled water is circulated through the pipes for a period of about three days.

85. The Vlake units have been in position in the river for several months and seem remarkably dry, with only two or three damp patches apparent. Nevertheless one should remain sceptical: the membrane is expensive but if it is omitted and leaks occur they are difficult to make good. One may also have doubts over the long-term behaviour and must be very sure about the quality of the concrete. I feel that it would be better to wait and see, and in the meantime to follow the practice adopted for the Elbe and use a substantial membrane.

86. Another innovation on the Vlake tunnel, and one which seems most promising, is sand jetting from the interior of the tunnel rather than externally as shown in Fig. 12.

87. In the Vlake system, which has been developed by the Westerschelde Consortium and the Rujkwaterstaat, the sand and water mixture is pumped from a barge alongside the river bank through a pipe which is taken back from the bank and down into the tunnel. It then bifurcates and each run is led along the centre of the road compartment. At about 20 m intervals there are T pieces leading to holes which have been cast in the base slab, within which there are steel spheres acting as very crude non-return valves. There are also isolating valves on each T and also along the supply pipe, which is about 20 cm in diameter. A comprehensive system of monitoring and control is provided on the barge. The mixture of sand and water is pumped through each hole in the base slab progressively, working from one end, alternating from one side to the other. Islands of sand of increasing diameter are thus built up which merge one with the next and so fill the space under the element.

88. Fig. 14 shows the square hole which has been left in the base slab of the tunnel and the pipework. The upright of the T goes down through the base slab, into a compartment in the lower part of the base slab in which the steel ball is included. The feed pipe comes from the pumping barge which is located on the river bank, the pipe being taken from the barge, over the bank and down through the tunnel entrance.

89. The advantages of the system are minimal plant, good working conditions, total lack of interference with river traffic, and a small work team. At the Vlake tunnel recently the work was being done by seven men, two working in the tunnel on the pipe work, one man on the barge assisting the suction pipe, and two engineers and two technicians in the control hut.

90. Finally I would comment on casting basins. These are large and expensive temporary works, and siting them alongside the river can often be difficult. They are really akin to building a dam of quite a large perimeter which has to withstand about 30 ft of water.

91. For the Tees tunnel which is currently under consideration my organization devised a new method for getting the elements into the water, which it was estimated would give a saving of about £1½ million in the cost of a four-lane immersed tube tunnel of about 900 m total length.

92. Initially a dock is constructed in the river bank, built probably in diaphragm walling. The size of the dock is overall a little larger in plan than the element. There

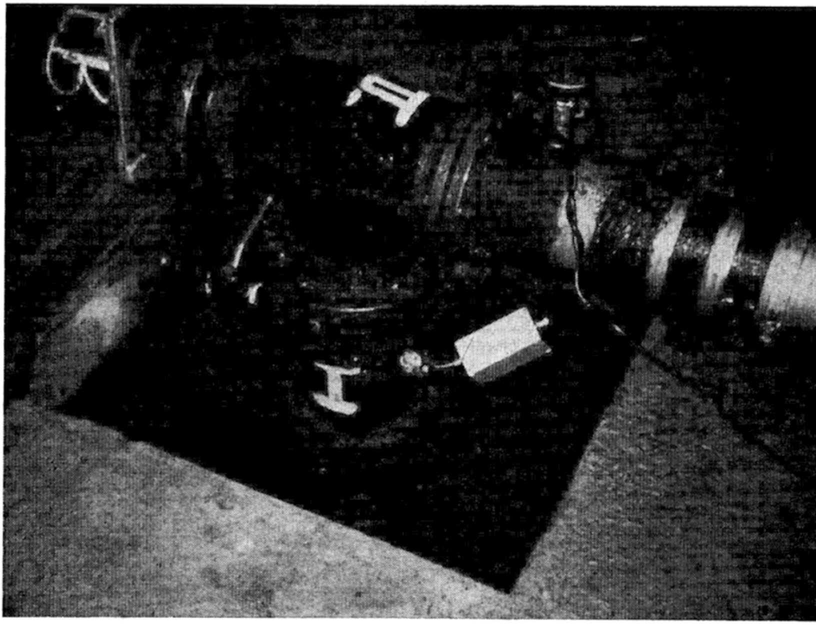

Fig. 14. Hole in base slab of tunnel and pipework

are slots in the side walls of the dock containing the ends of large heavy plate girders which span across. The plate girders are themselves supported by short but heavy crossbeams across the top of the slot and suspended from these by screwed rods passing through hollow ram jacks. Behind the dock there are two rows of large diameter bored piles each of about 500 tons capacity. The width of the element between centre lines of its outside walls corresponds to the width between centres of the two rows of piles. The area between the piles is concreted and provides the base upon which the units are cast.

93. The unit will be cast in five sections which will be stressed together as in the Elbe tunnel. The next stage, having completed the concreting of the element, is to slide it forward on low friction bearings, the unit at this stage being supported by short-stroke hydraulic jacks, one jack being mounted on the top of each pile. The jacks are interconnected so as to provide a compensated base for the unit.

94. The unit is slid forward into position above the dock, being supported at this stage on the transverse beams. Work on the next unit then starts on the casting bed while work on the first unit is completed, i.e. bulkheads, waterproofing and adding tackle for handling and sinking.

95. The Tees units are much smaller than the Elbe units and have a total weight of only about 10 000 tons whereas the Elbe units are 40 000 tons. I do not think one would contemplate, at any rate to begin with, trying to deal with units of large size in this manner.

96. This, I hasten to say, is only a scheme that has been considered; not one that has been used. But it seems promising and might be used for the smaller size of element. It seems to offer useful savings in the cost of the project because it will avoid the use of the very expensive casting basin.

Mr A. Beckett, Sir Bruce White Wolfe Barry & Partners

I found the Paper most intriguing. It is plainly a first-class engineering job. Obviously, Mr Havnø is versatile, since he can build a bored tunnel as well as an immersed tunnel. To make the immersed tunnel work, he has introduced some remarkable joints, his flexible omega joints. I take it that an omega joint is one which by means of its convolutions allows movement to take place.

98. I should like to ask what the life of a rubber omega joint will be in these circumstances and how long the life of the steel joint used as a doubler: also what measures, if any, are to be taken for their renewal? Can they be renewed at all, and if not, is it the omega joint which sets the seal on the life of the tunnel? The ventilation is push-pull; one system pushes in 3000 m^3/s and another pulls out 1900 m^3/s. Why are they different? Is it intended that there should be some compression building up in this tunnel?

99. Another question I should like to ask is about the dredged channel into which the units are laid. This channel runs across the flow of the river, which is silt-laden to some extent. Was there any difficulty in keeping the dredged channel sufficiently clear of silt during the interval between dredging and laying the tubes?

100. The City of Hamburg called for tenders to design and construct. In other words, the offer by Christiani & Nielsen included the design as well as the construction. It would be useful to know, if possible, what percentage of the total engineering cost was spent on design. This would be helpful in solving a controversy regarding the economics of using consulting engineers instead of asking each contractor to include design with his tender. If by this system there are ten tenders and ten designs as well, there is surely a tenfold cost of designing.

The Chairman, Mr Muir Wood

Were the steel omega joints mitred at the corners, or was there some more elaborate arrangement? I would have thought that if any great movement took place, there would be distinct stress raisers at such a change in section. Secondly, I would be glad if Mr Havnø could give more details of the tendering procedure, particularly on the extent to which the job had to be designed before negotiating the tender for it?

102. May I also ask for a little more explanation of the arrangement for the closure joint? I presume that this must have been assembled below water by divers to make up the sleeve around the end of each unit and around the projection from the ventilation building. I was a little confused by Fig. 13 which appears to show the bottom of this seal being supported from above. I presume this was in an intermediate stage of assembly.

Professor A. L. L. Baker, Imperial College

This tunnel passes through a mixture of sand and boulder clay and has therefore been articulated after positioning. This, it seems to me, is an important step forward in the technology of immersed tunnel construction. Although joints have been made in some of the Dutch tunnels I do not think they were quite to the sophisticated design of these Elbe tunnel joints in which bars are incorporated, cut after positioning, and the tunnel is articulated afterwards. This seems to me to be very ingenious.

104. A cross-section through these joints would be helpful since, in such tunnels the joints are the most interesting part of the job. The roofs, the floors and the walls are more or less standard heavy reinforced concrete construction, but it is the jointing system which is really interesting. I am not clear on how the continuous steel sheeting is made watertight over the joint between the units. Perhaps this could be explained a little more clearly.

105. About a year ago I was asked to produce a conceptual design for an immersed tunnel across the Straits of Messina. There, there is siesmic shock, a very steep sided cross-section, with loose material on the slopes, and depths varying from 300 to 900 ft with a current of about 10 knots. So the whole problem is pretty difficult.

106. In my suggested design the embankment on the deep part of the sea bed would be formed of consolidated rock fill, in order to reduce the very steep gradients and to provide a certain amount of protection against seismic shock. The tunnel would be lined with continuous steel sheeting with a tensile resistance very much higher than any frictional forces which could be transmitted through the base by siesmic shock. That could be done by ballasting the tunnel so that the bearing on the embankment was not too high, but just sufficient to stop it floating up. By reducing the friction the risk of seismic shock is also reduced.

107. The joint suggested was flexible with the steel inside all the way through, because I could not see at the time how one could have a steel joint with welding required outside. The joints shown in the Paper are a great step forward. This particular joint was between the units with a corrugated steel connexion, so there was plenty of scope for expansion and relative movement.

108. The Messina tunnel was to be fitted with tubes in the floor through which one could pump weak concrete or mortar, or even, I suppose, sand in the water. Like Mr Culverwell, I would ask whether that is a feasible proposition. It seems to me that it could be a big advantage at great depths. For tunnels about 300 ft down, the external sand jetting device would be too elaborate; it would be essential to pump through the base of the tunnel after all settlement had taken place.

109. The articulated system of the Elbe tunnel provides a splendid answer to those who have argued in Britain against using immersed tunnels across the English Channel, perhaps on an embankment. This may be necessary one day to cross the deep water area of the Straits of Dover to the French coast, to connect up with the Continental road system, and to provide a capacity similar to the Elbe tunnel. This, I am convinced, will come one day in spite of the present oil crisis. After all, the Arab oil reserves are no less today than they were ten years ago. In addition, there is North Sea oil. The only trouble is that the financiers have got it all wrong. The Arabs are now investing their money in British banks and it seems to me they might as well be asked to invest in a channel crossing of a modern type. It would suit them and it would suit us.

Mr M. J. Kenn, Imperial College

Mr Havnø has presented a modest and deceptively simplified outline of some of the problems encountered on this scheme. No doubt his tunnel sections were positioned during calm weather and therefore without significant wave action. However, would he give some information on the maximum wave height and wave length (in terms of tunnel size) which would be acceptable when working in rather more exposed locations.

Mr C. W. Niel McGowan, Consulting Engineer

There are one or two points that I should like to mention briefly.

112. After reading the Paper I was struck by the similarity between the units in the Elbe underwater tunnel and those in the Antwerp E3 link tunnel, built some years earlier and for which I believe Mr Havnø's firm was also responsible. The units in the Antwerp tunnel were 103 m long as compared with 132 m, the width was 49 m as compared with about 42 m, and the height was 10 m as compared with about 9 m. The weight of the Antwerp units was 47 000 t as compared with 46 000 t in the tunnel under the Elbe. Is it probable that the maximum unit weight in any future tunnel will not exceed 50 000 t?

113. In § 3 it is stated that at a speed of 80 km/h the capacity of the tunnel will be 65 000 vehicles every 24 h. Is this in each direction?

114. I am sure that the advantage of a unit with three two-lane carriageways rather than two three-lane carriageways as in the case of the Antwerp tunnel is plain. Three two-lane carriageway tunnels give a more flexible traffic flow by diverting the more intense traffic in one direction into two of the tunnels and that in the other direction

into the third tunnel, whereas in the Antwerp tunnel it is a case of three lanes both ways. In the case of the Antwerp tunnel there is a double-track electric railway in addition, also a cycle track and services duct.

Mr Havnø

With regard to **Mr Culverwell**'s questions, there has been no opportunity of checking the actual sinking forces against the model test which had been made beforehand. The forces measured in the laboratory were for a current velocity in the river of 1·4 m/s, which occurs during tidal ranges somewhere between mean tide and spring tide. This is an extreme case, covering the situation in which the sinking operation took so long that the maximum velocity might be encountered. In practice sinking was completed during slack water when the current velocities were less than 0·5 m/s.

116. As to the shipping restrictions, no time limitations were imposed by the harbour authorities, but of course a time schedule was presented. The periods stated are the averages of those actually used, and it will be seen that the obstruction to the traffic was insignificant. A foggy day in Hamburg can be much more serious. It was necessary to close the Elbe for only half an hour, and from then on shipping could move again. There were no complaints whatsoever.

117. The transverse joints were all furnished with shear keys with a PTFE surface inclined at 1:10. This limits the relative settlement to one-tenth of the width of the opening, which is estimated at 2–3 mm under winter conditions.

118. The possibility of a ship sinking on the tunnel was considered as loading class 3 where steel stresses up to yield strength are allowed.

119. The Contract covered only the civil engineering work, and was not concerned with the mechanical installations, the acoustic ceilings and the lighting. Nevertheless, it was interesting to learn from Mr Culverwell of the economy of using a single line of two-tube fittings instead of two lines of single tubes. There is in fact a small error in the Paper: there is only one row of lighting fixtures at one side of each two-lane road.

120. With reference to the information on tunnel building in Holland, Christiani and Nielsen have a patented method for jetting sand from the interior of a tunnel. It is no doubt a good and cheap method working in a canal where it is certain that no mud will be encountered. But with the internal system it is not possible to be sure the mud is removed. Therefore, I would still advocate the system of sand jetting from the outside when working in a river because it is also a system for removing mud from underneath a tunnel. It was developed at the Schelde Tunnel in Antwerp, where during the sand jetting of the first element, mud with a specific gravity of 1·5 was unexpectedly encountered under the element. Elaborate tests performed beforehand had given no indication of this. Apparently heavy liquid mud had flowed into the trench, probably because of the disturbance caused to the mud on the slopes of the trench by placing the element across the currents. The tower was therefore rebuilt so that the mud could be removed, and this equipment was used also for the Elbe tunnel.

121. I have read discussions in Great Britain concerning the cost of constructing dry docks to provide casting basins and I think this is sometimes exaggerated. The expense on dry docks in my experience has been of the order of 10% of the cost of the concrete going into the elements, and I do not think this is an excessive expenditure. For elements of the size my organization has been constructing, no other arrangements are possible for such a cost.

122. There are advantages in having all elements built in a dry dock; there is continuous work for the labour force in the dock and afterwards a continuous sinking process. However, with the lift method as described by Mr Culverwell or the method used for the Metro in Rotterdam because there was not sufficient space to contain all

the elements (there were two elements at a time in the dry dock), there is a lack of continuity in the work being executed, resulting in extra expense, which has to be taken into account when comparing the different methods. All these remarks refer to large elements and do not preclude the possibility that the lift method may be economical for smaller elements of say 10 000 tons.

123. In reply to **Mr Beckett**, I would like to point out that there are two different types of joint. The joints between the 27 m sections have a steel omega and a rubber waterstop as a doubler. Both were tested for the movements expected for a 100 year period. The joints between the tunnel elements have an outer heavy rubber gasket and on the inside a rubber omega, the lifetime of which has also been proved by accelerated tests to simulate a period exceeding 100 years. Between those two gaskets there is an empty space with pipe connexions to the interior of the tunnel. This means that future generations can inspect for possible leakage through the outer gasket and if the secondary barrier shows any weaknesses it will be possible to inject some sort of plastic sealant into the space.

124. I would not like to guess what kind of material will be available 100 years from now, but undoubtedly there will be much better products than at present. Personally I am convinced that the joints will last as long as the tunnel; if anything should nevertheless happen, it will be possible to carry out repairs during that long span of years.

125. The difference between the volume of fresh air supplied and the volume of vitiated air exhausted is due to the special ventilation system in which there is no exhaust at the central ventilation building. At the tender stage the Client requested a price for an alternative system with exhaust at the central ventilation building. Although cheaper, the Client decided against it for environmental reasons, this ventilation building being close to the Elb-chausse, the residential area and a hospital.

126. Tests made before work started showed that there should be no siltation problems. The results of the tests and the conclusions drawn were submitted as part of the tender documents. Everything went very well until element 8, the last one at the north bank, was reached. Large amounts of silt had to be removed from under the element before any sand could be jetted. It is assumed that the silt originated during heavy rainfall from the purification plant on the right bank of the Köhlbrand. The Köhlbrand flows into the Elbe at such an angle that the silt was washed into the trench at the northern bank. This was a situation which could not be foreseen at the time of tendering and the delay caused was covered by an additional payment under the Contract.

127. On the question of design and construct and the percentage cost of the design, I cannot quote actual figures, but I think it is useful to point out that there is a big difference between the cost of the tender design and the detail design which is needed only after the contract has been awarded. In the case of the Elbe tunnel the Client paid 60 000 DM to each group of prequalified bidders, but this in no way covered the actual expense. Without wanting to engage in a discussion about the merits of one method compared with another—consulting or design and construct—there is one very clear advantage to the client in calling for tenders to design and construct; he gets different ideas and not just one. This can influence the cost of the final construction.

128. **Mr Muir Wood** asked about the corners of the steel omega. These were not mitred but made in a circular form. A corner was specially tested in the 100 year test because of the stress concentrations in corners.

129. With regard to the tendering procedure, five groups prequalified and each received a specification of the Client's requirements regarding horizontal and vertical alignment, free profiles, ventilation, etc. and reports on soil conditions and on the hydrology of the river. The tender covered not only section 1 dealt with in the Paper but also sections 2 and 3 and the mechanical installations.

130. Six months were given for the preparation of the tender. The Contract for

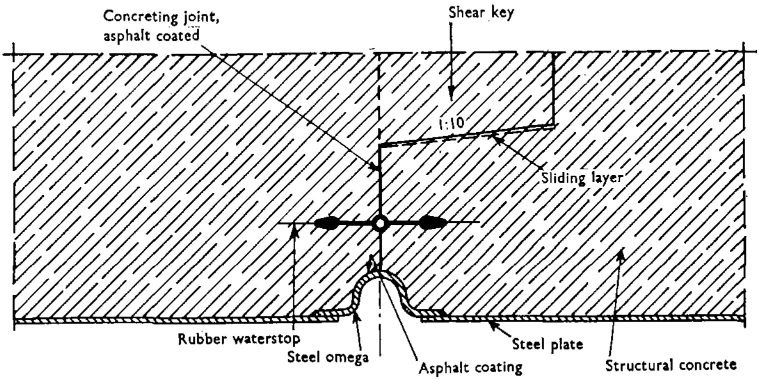

Fig. 15. Joint between 27 m sections: bottom slab

the short section 3 at the very northern end was awarded at an early date. Only two groups remained in the running for section 1, the submerged tunnel, and section 2, the bored tunnel. They were both given an opportunity to retender based on certain additional requirements by the Client: for this another six months were allowed. Finally one group was selected for the submerged tunnel and the other for the bored tunnel. The installations, which included lighting, ventilation, acoustic ceiling, painting, etc., were let as separate contracts.

131. Figure 13 does indeed show the bottom enclosure before concreting of the joint. This bottom panel was placed before element 8 was sunk. After the sinking the side panels were placed on the ends of the bottom panel protruding outside the tunnel walls, and finally the top panel was placed. Through openings in the top panel a diver went down and fixed the temporary suspending wires. The bottom and top panels were then tightened together by turning the nuts on the tightening rods. The joint could then be emptied of water, the rubber seals being further compressed by the external water pressure.

132. The questions of **Professor Baker** regarding the joints have partly been dealt with in the answers to Mr Beckett. The continuity of the steel sheeting at the 27 m joints is obtained by welding the steel omega to the sheets while the two rubber gaskets maintain the continuity in watertightness at the joint between elements. Details of these joints are shown in Figs 15 and 16.

133. In my answer to Mr Culverwell I have commented on the method of injecting sand through the floor from the interior of the tunnel. If Professor Baker's remarks concerning weak concrete or mortar for the tunnel foundation arise from a need to meet seismic conditions, I may mention that my organization has patented a method for stabilizing jetted sand by means of a hydraulic binder, which is considerably cheaper than mortar. This method has been applied in Japan.

134. I am afraid I have no answer to **Mr Kenn**'s question. I have experienced no wave problems when sinking big elements in rivers and canals. Due to the short fetch, the waves have been very short, probably never more than say 35 cm high, and they have no effect on the sinking operation. For tunnel works in more exposed conditions these problems should be thoroughly investigated.

135. In reply to **Mr McGowan** I would state that in choosing the size of an element one is mainly concerned with the length. The width and height are determined by the type and amount of traffic that the tunnel should accommodate and by the water depth. The length one chooses for the elements depends very much on the waterway

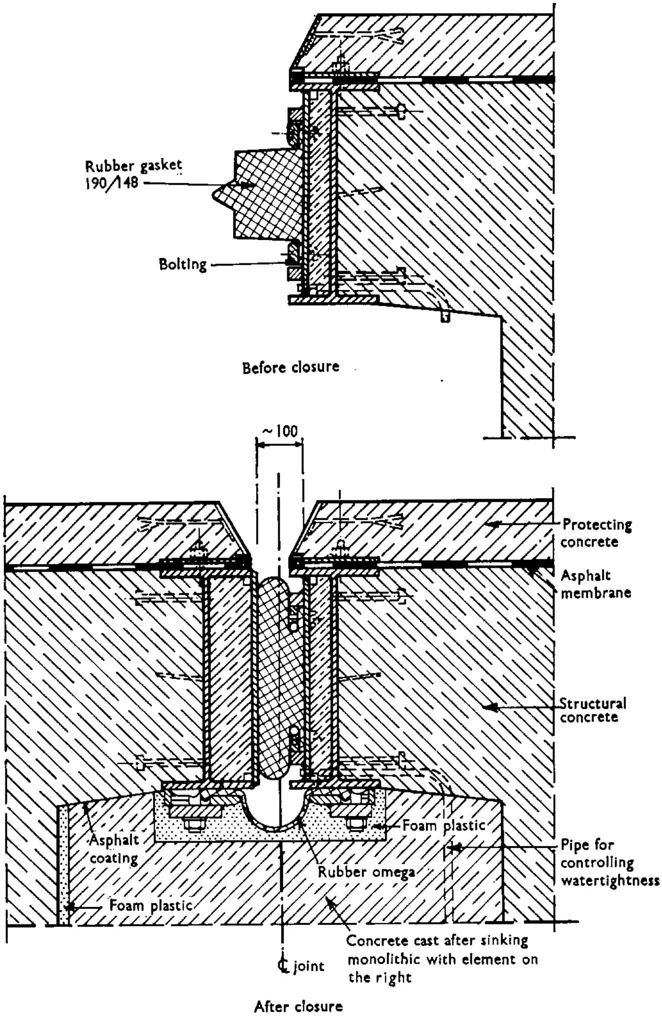

Fig. 16. Joint between elements: top slab

in which one works. Due consideration should be given to the current, the requirements for shipping lanes, the different construction operations such as dredging, sinking, sand jetting and backfilling, several of which will take place simultaneously. To all this should be added the search for the most economical solution.

136. I do not believe that 50 000 tons is the limit on element size, and expect that one day elements of up to 100 000 tons will be used.

137. The tunnel capacity refers to the total number of vehicles in both directions at the design speed. Obviously a bigger capacity can be reached at a lower service

level. For instance the 4 lane Maas tunnel in Rotterdam has under special circumstances carried 80 000 vehicles in 24 h.

138. The choice between 2×3 lanes or 3×2 lanes depends on the local traffic pattern. Both in Antwerp and in Hamburg the tunnels carry the E3 highway, but whereas in Hamburg there is a heavy commuter traffic across the river, this is not the case in Antwerp. Hence the difference in the lane arrangement selected by the clients.