A new design of flap gate for No. 4 Dock, Malta, G.C.

by

T. F. D. Sewell, B.Sc.(Eng.), A.M.I.C.E.

and

N. H. Searle, B.Sc., A.M.I.C.E.

Mr R. Thomas (Resident Engineer, Messrs G. Maunsell & Partners) said that he would confine his remarks to some aspects of the construction of the gate which might be of interest.

60. The Contractors were essentially ship repairers and they had treated this contract as a ship repairing operation. In spite of some misgivings, it had worked very well.

61. They had constructed the supporting staging using keel blocks and welding grillages, but what he had found most interesting was their method of lining up the hinges on the gate using a Taylor-Hobson micro-alignment telescope. This instrument, normally used for aligning stern tubes and the like, enabled a flat plane to be established independent of gravity. The plane was adjusted to pass through three known heights on the surface to be set and a travelling target enabled the height of all other parts of the surface to be measured relative to this plane, and by adjustment the whole area could be brought into a common plane. It had been a tedious operation but it had been successfully carried out by the contractors, well used to this type of equipment.

62. It had been natural enough to ask Lloyd's non-marine department to supply one of their surveyors to inspect the work and particularly the welding. All critical welds had been X-rayed to ensure that they were up to specification. Lloyd's, as part of their service, had inspected all the steel supplied to the job at the source. This had been a great help as earlier samples of the N.D.I. steel sent to the site for use in testing welders were found to have pronounced laminations which came to light when examined with an ultrasonic tester on site. A great deal of time could have been lost waiting for replacements for defective steel. He had a feeling, too, that the presence of a Lloyd's surveyor at the works had a salutary effect on the manufacturers.

63. Another useful aid adopted by the Contractors was a scale model of the gate and the entrance. This had proved invaluable in determining the location of the winches and blocks to obtain the best leads for the ropes used in the stepping and unstepping operations. These site model tests had been complemented by tests on the winches and blocks to see whether they were capable of withstanding the loads to which they might be subjected. The workmen, too, had been thoroughly rehearsed, particularly the divers. These detailed preparations had certainly paid dividends.

64. He concluded by mentioning a phenomenon noticed after the gate had been in use for some time. On this occasion the usual drill had been carried out to close the gate, but it had seemed to be reluctant to move. Watching the gauge one could see that the gate started to move, then there would be a burst of bubbles on the surface of the water and then, according to the gauge, the gate would settle back on

its supports again. Several attempts had been made with the same result, added to by the horrible sinking sensation most engineers experienced when something went wrong.

65. However, a close examination of the pressure gauge had revealed that the pressure was slightly in excess of 23.5 lb/sq. in. A slight adjustment to correct the operating pressure and the gate had performed as sweetly as ever.

66. The conclusion seemed to be that when the operating pressure was increased, the air, instead of displacing the water, 'piped' through it and escaped without doing its work. This seemed to be a very useful safety device to prevent operators from trying to speed up the gate closing operation. They would just have to be patient.

Mr G. A. Cain (Works Manager, Malta Drydocks) said that members would have noticed on the last page of the Paper that the Client and the Sub-contractor for the gate contract were one and the same—namely, Bailey (Malta) Ltd, now trading as Malta Drydocks.

68. He had been technical manager at the time of the gate construction and his drawing offices had been concerned with the production of the detailed drawings of the gate and the production of a stepping procedure programme, while the construction programme had been in the hands of one of their senior ship repair managers, Mr William Begg, who had served as a project manager. At the meeting he was permitted to speak in the dual role as representative of the Contractors and of the users of the gate.

69. Initially it had been felt that the dual role would lead to some conflict of interest, in other words, cost versus quality, but in fact it had served to iron out various difficulties in that everyone concerned had had a first-hand knowledge of how to get things done in the yard.

70. The yard was in the process of building up commercial ship repairs as well as contributing to its own material development. It had been of great assistance to those concerned in the gate construction to know the share which they could expect of the available facilities and resources.

71. The Paper referred to the need to modify the naval dockyard to enable it to attract commercial cargo tanker trade to the island. No. 4 Dock had been selected for major conversion to the bigger size due to its position and to its being already almost long enough to meet the specified requirements for tankers of 90 000 tons deadweight. One vessel of 92 400 tons deadweight had in fact been dry-docked shortly after the opening of the new dock.

72. No. 5 Dock, which was adjacent, had been lengthened to 710 ft by rebuilding the head of the dock, and it now accepted vessels up to 35 000 tons/deadweight.

73. Improved facilities had been built into these docks, in the way of salt and fresh water services, electric power, pneumatic services, heavy cranes, dock lighting, piped oxygen and acetylene cutting gases, welding points and pneumatically operated bilge-blocks in No. 4 Dock. This disposed of the outmoded wood bilge-blocks and side shores leaving the dock clear to facilitate ship repairs and painting.

74. The streamlining of the docking down of vessels enables the labour force to bring into action quickly all facilities within the dock, and similarly, efficient undocking enabled work to be resumed quickly at the afloat berths.

75. The former procedure of handling the previous caisson gate into position involved a small powered tug with four men and a shore gang of six attending for more than an hour before dock pumping could commence. Similar time and labour was spent in the removal of the caisson gate, and this included incorporating mobile pumps to pump out the buoyancy chambers to enable the gate to be floated up before it could be towed away. Weather sometimes prolonged this procedure. The new No. 4 Dock needed only one man to attend to the air control valve. The gate rose to the closed position in about 12 min, the time varying according to the wind. There were three men who connected the pneumatic turning machines on to

FIG. 13: LOWER SECTION OF SKIN PLATE WITH SECONDARY BUOYANCY TANK

the control spindles of the penstocks and removed or replaced the gate fender. There were no other men involved. The dock pumping commenced after a further ten minutes and traffic resumed over the gate five minutes later. This was a considerable asset because it avoided a quarter-mile journey round the docks.

76. The maintenance of the gate was equally simple and inexpensive. A simple survey procedure had been devised on a six monthly cycle and this was carried out when the dock was dry. Divers examined the outer skin from time to time to see that there was good paint preservation on the harbour side. At the six months survey the rubbers were examined by skin divers to ensure that all were securely in position. There had been initial leakage from the penstocks due to deflexion of the gate under hydrostatic load, whereas the penstock surfaces had been levelled during construction. By fitting the temporary blanking plates to the penstock apertures, when the gate was stepped and under load, it was possible to realign the surfaces under working conditions and the leakage was eliminated.

77. The Paper briefly described the construction. While the construction had been quite conventional, the sequence of the construction was considered worthy of mention. Fig. 13 showed the lower section of the skin plate with the secondary buoyancy tank. The assembly bed was made up of conventional dock blocks from the old docking system. The skin plate was laid lengthwise to the full length of the gate. The secondary tank was formed of rolled plates, welded together and welded to the skin

STAGE 3

STAGE 4

FIG. 14: FABRICATION OF THE BUOYANCY CHAMBERS

STAGE 5

FIG. 15: SUPERSTRUCTURE AND HINGES INSTALLED

plate. Finally, the unit was lifted up and levelled in the cradle and the second skin plate was placed along, giving the extra depth. The skin plate stiffeners were then installed.

78. The next step concerned the bottom of the buoyancy chambers, as shown in Fig. 14. The outside plate was placed on and the various stiffening sections were set in position at that stage. The remaining stiffeners were fitted to the bulkheads, followed by the operating tank ballast and permanent buoyancy tanks plating.

79. Finally, as shown in Fig. 15, the top plating was fitted, then the superstructure, the roadway girders and the timber decking. The hinges were positioned, aligned

FIG. 16: GATE STEPPING IN PROGRESS

and bolted up. Mr Thomas had referred to the Taylor-Hobson optical equipment. This was used to align the hinge pins so that they were co-axial to within 0.005 in. The machined castings constituting the lower half of the bearings were also set in the same manner to the same degree of accuracy.

80. The enclosed chambers of the gate were each water-pressure tested to 30 lb/sq. in., and the overall construction was carried out under the scrutiny of a Lloyd's Register of Shipping, Land Department, surveyor seconded to the Consulting engineers.

81. The Paper and the film gave details of the stepping procedure. Fig. 16 showed the compressed air and water supply control panel with the valve system which allowed water to be admitted or rejected from the secondary buoyancy tanks, the wing ballast tanks and the operating tank. There was also a requirement for the skin to be flooded by hose before water was admitted to the secondary tank.

82. The temporary handling wires were secured onto a capstan and a winch on each side of the dock. There had been a cross-over system of wires, with one eye on the capstans and one eye on the winch. It was then possible to pull the gate down or to hold it back.

83. There was thus a combined ability to flood or drain tanks at will and to draw the gate up or down on wires, ensuring a high degree of control on movement. The top of the gate could also be drawn backward or forward by wires which were manually operated whilst the vertical control wires were power operated. The pneumatic and water control valves were orthodox lever cocks and screw down types. A water meter was fitted in the supply main which recorded the amount of water fed into the secondary tank or the flooding tank. This provided information for future reference to avoid overloading the wires in future stepping operations. There was virtually the same rig for the unstepping operation except that tanks were pneumatically evacuated instead of flooding.

84. In conclusion No. 4 Dock had been in operation for just on 700 days and it had been utilized for 643 days, the other remaining days indicating lack of vessels

for docking due to seasonal operations. During that time 123 large ships had been docked and undocked. The new gate had proved itself in that time to be a very efficient innovation. Malta drydocks were very pleased to possess this dry dock feature and looked forward to many years of good service from it.

Mr A. F. Gee (Chief Structural Engineer, W. S. Atkins & Partners; formerly of G. Maunsell & Partners) said that since the Authors' excellent Paper had been mainly concerned with the operational aspects of the gate, he was very grateful for an opportunity to amplify the comparatively brief description of the structural design.

86. As stated in § 24 the standard grillage programme which was used for the primary structural analysis was limited to a framework of 18 joints. The equivalent framework adopted was shown in Fig. 17. All joints were fully fixed: the member 1-2-3-4-5-6 represented the main horizontal beam; the members 1-7-13 represented the vertical meeting face stiffener; each of the members 2-8-14, 3-9-15, 4-10-16 and 5-11-17 represented a group of five stiffeners and the member 6-12-18 represented half of the central stiffener. The inertia of these members was, therefore, made equivalent to the sum of the inertias of the various stiffeners they represented, and advantage was also taken of the fact that it could be changed at each joint. The section of the actual stiffeners in the gate varied twice in their heights but the inertias of the representative members of the framework could, of course, be varied only once. Similarly, although the section of the main beam varied at five places, these were not coincident with the positions of the joints in the equivalent member, but it was not considered that these discrepancies would seriously affect the accuracy of the analysis. The loads were applied to the equivalent framework by means of fixed-end moments

FIG. 17: THE GRID FRAMEWORK

and reactions at each of the joints. The programme calculated the rotation and deflexion of each joint and the shear, torsion and end-moments in each member.

87. The comparative analysis by means of an equivalent plate referred to in § 23 used the opposite principle: the stiffness of the equivalent plate was made equal to the average stiffness of the stiffeners divided by their spacing. The main horizontal beam was represented by a uniform member having flexural and torsional stiffnesses equal to the average values for the beam. Analysis was based on the solution of a large number of simultaneous linear equations resulting from the expression in finite difference form of the general flexure equation at each node on a network covering the plate.

88. It was at first intended to analyse an equivalent isotropic plate and it was necessary, therefore, to use a square net. It was considered that because of the proportions the plate would effectively span vertically from the lower meeting face to the upper horizontal beam, and the fact that the gate had comparatively little horizontal stiffness would not have any significant effect. Since it was intended to solve the simultaneous linear equations on the English Electric Deuce computer and it was known that the cost of the solution would rise sharply if the number of equations exceeded about 90, a 5 ft 2 in. network was found to conveniently cover the gate.

89. It was later decided, however, that the analysis of the equivalent anisotropic plate would eliminate any possible inaccuracy and it was found that the arithmetic was not after all too fearsome.

90. Using the basic biharmonic equation

$$D_x \cdot \frac{\partial^4 w}{\partial x^4} + 2(D_1 + 2D_{xy}) \cdot \frac{\partial^4 w}{\partial x^2 \partial y^2} + D_y \cdot \frac{\partial^4 w}{\partial y^4} = -q$$

one equation was obtained for all nodes having a finite deflexion and further additional equations at all boundaries. Conversion of the biharmonic to a finite difference equation involved the deflexion of twelve other nodes surrounding the one considered. Consequently, two more rows of imaginary nodes were required outside the boundaries of the gate itself. On a simply supported edge—the lower meeting face—however, all deflexions were zero and because there was no moment and therefore no curvature across this boundary, the deflexions of the imaginary nodes on the next row were equal and opposite to the deflexions of the nodes immediately inside.

91. On the axis of symmetry—the centre line of the gate—the deflexions of the imaginary nodes were equal to the deflexions of the symmetrical real nodes. On both the free edge—the vertical meeting face—and the elastically supported edge—the upper horizontal main beam—two equations were obtained expressing the boundary conditions and these were combined in pairs to eliminate the second row of imaginary nodes.

92. The network was, therefore, reduced to that shown in Fig. 18. This was

FIG. 18: THE NETWORK FOR THE PLATE ANALYSIS

basically a 6×15 net having, therefore, 90 unknown deflexions but four of these unknowns A, B, C and D were eliminated. The deflexion at B was zero and consequently the deflexion at A did not appear in any of the equations so that both of these unknowns were eliminated: since the main beam was considered as simply supported—in flexure—at B, the deflexion at D was equal and opposite to the deflexion at node 14. Similarly the deflexion at C was either equal or equal and opposite to the deflexion at node 28 according to whether the beam was considered to be torsionally free or fixed at B. These were the two conditions which it was decided to investigate as described in § 25 of the Paper, since it was felt that because of the rubber meeting face units the true condition was probably somewhere between the two.

93. It was interesting to compare the deflexions obtained by the two different methods of analysis assuming the two different degrees of fixity. Fig. 19 showed, for the case where the beam was torsionally restrained, the deflected form of the equivalent plate on six lines of the network selected to correspond as near as possible with the members of the equivalent framework. The ringed points on the two dotted lines showed the deflexions of the joints of the equivalent framework. The respective spacing along the gate of the lines of the network shown and of the members of the equivalent framework were given in Table 2.

TABLE 2: SPACING OF THE NETWORK LINES

	Equivalent plate	Equivalent framework
1	0	0
2	10 ft 4 in.	8 ft $7\frac{1}{2}$ in.
3	25 ft 10 in.	24 ft $10\frac{1}{2}$ in.
4	41 ft 4 in.	41 ft $1\frac{1}{2}$ in.
5	56 ft 10 in.	57 ft $4\frac{1}{2}$ in.
6 (C.L.)	67 ft 2 in.	67 ft $1\frac{1}{2}$ in.

94. The deflexions plotted were for the combined loading from a hydrostatic head of water 31 ft 3 in. and a nominal static load of 100 tons applied horizontally to the main beam on the centre line of the gate. Agreement could be seen to be remarkably good except for the deflexion of the vertical meeting face. The reason here was that the load assumed to be carried by the appropriate member of the equivalent framework was too small.

95. Referring again to Fig. 17 it could be seen that by taking equal loads, proportional to a length of 16 ft 3 in. along the gate, on each of the central members of the framework, the load applied to the member at the meeting face was proportional to a length of only 6 in. along the length of the gate. The stiffness of the member 1–7–13, however, was proportional to that of a whole stiffener, or an equivalent length of 3 ft 3 in.

96. The structural action of the gate was clearly seen in Fig. 19. The stiffeners near the meeting face received a positive fixing moment from the main beam since the latter was prevented from rotating. Towards the quarter-point of the gate the stiffeners became effectively simply supported, obtaining no restraint from the main beam, whilst near the centre of the gate the beam was actually applying a negative moment to the stiffeners.

97. Fig. 20 showed the same comparison for the case where the main beam was allowed to rotate at the meeting face. This time the agreement between the deflexions obtained by the two methods was not quite so good, but again the structural behaviour of the gate was quite clear. Less restraint was applied to the stiffeners and consequently less load was attracted to the main beam, so that the deflexion and thus the moments in the stiffeners were greater, particularly near the meeting face.

FIG. 19: COMPARISON OF DEFLECTED FORM OF EQUIVALENT PLATE AND EQUIVALENT NETWORK

98. The reason for the poorer agreement in this case lay in the relatively greater effect of under estimating the load on the equivalent framework member at the meeting face. There was thus a very much smaller moment tending to twist the beam away. In fact, the figures showed a very small negative rotation of the beam and a resulting small negative deflexion of the meeting face compared with a distinct positive rotation in the case of the equivalent plate. The maximum deflexion for the framework was consequently slightly greater in this case than for the fixed-ended case. However, the generally close agreement and, more significantly, the very similar general form of the results obtained for the two cases showed that whether the beam was assumed to rotate or not had very little effect on the moments in either the beam or the stiffeners.

99. To the seven places of decimals supplied when one used a computer to do one's calculations, the maximum deflexions actually obtained at the centre line of the beam for the fixed-ended case—for a hydrostatic head of 31 ft 3 in. and 100 ton load—were respectively 2.5721328 in. for the framework and 2.6516138 in. for the plate, or a difference of less than 3%.

100. The framework was analysed only for the combined loads but these effects were considered separately in analysing the plate. The calculated maximum deflexion of the centre line of the beam under the hydrostatic head of 31 ft 3 in. only was almost

FIG. 20: THE SAME COMPARISON AS IN FIG. 19 WITH THE MAIN BEAM ALLOWED TO ROTATE

exactly $2\frac{1}{6}$ in. in the free-ended case and $2\frac{7}{8}$ in. in the fixed-ended case. It was of interest to note from § 47 of the Paper, therefore, that the actual recorded deflexion under a hydrostatic head of 29 ft was $1\frac{7}{8}$ in.

101. The calculated rotation of the centre line of the beam for the fixed-ended case was 0.00140 for the framework and 0.00130 for the plate. For the reasons stated, agreement was not so good for the free-ended case, the framework showing slightly more rotation than in the fixed-ended case, and the plate slightly less. It would, nevertheless, be interesting to know the value of the observed rotation referred to in § 47.

102. Finally, referring to § 51, the Authors had said they considered that operational considerations might limit the application of this type of gate in its present form. However, they gave two overseas examples of applications of a presumably similar structural design in winch-operated gates, and it would be interesting to know whether the cost of this gate indicated whether or not the structural design concept was justified for other than operational reasons.

Mr B. R. Piggott (Scientific Officer, Design Advisory Service of the British Welding Research Association) said that his organization were asked to carry out certain strain measurements during the operation of the gate. He was therefore rather perturbed

by the remark of one of the Authors that there were such things as lies, damned lies and strain-gauge measurements! He realized, however, that measurements which were not accurate and not carried out correctly were worse than having no measurements at all.

104. The conditions under which the gauges had to operate were nothing like laboratory conditions. Not only had they to operate under water, which was quite a common thing, but they had to stand up to the feet of many workmen during the floating down operation of the gate, and also many people climbing about and pulling wires before they had been connected to the recording equipment.

105. Many civil engineers were quite familiar with strain gauges and measurements but probably some were not. The strain gauge measurements were based on the well-known theory that if an electrical conductor was stretched, its cross-sectional area changed and so did its electrical resistance. The wire chosen for this job was sensitive to strain and unfortunately, in some cases, very sensitive to thermal effects. The wire had to be of a reasonable length, but since this was not very practical in a strain gauge it was condensed into a very small grid. In the type of gauges used on this gate, the grid was sandwiched between wafers of paper which enabled one to handle these delicate elements.

106. Because of the limited time available—the BWRA team arrived only a short time before the operation was due to commence—they had to carry out the job of the attachment of the gauges in two days.

107. The surfaces had been prepared with equipment similar to a rotary sander and had been finished by hand to give a flat surface which was completely de-greased. The gauges had been bonded to the structure with a quick-drying cement and the water-proofing operation had been begun by producing a small Bostik sealing strip mould round the gauge. The lead wires from the gauge had been soldered to the gauge and led through the walls of the box mould. Into the mould they had poured a bituminous sealing compound which was often used in electrical junction boxes. The whole had been completely covered with a sheet made from the Bostik sealing strip, similar to that used by the do-it-yourself men. The complete installation had been coated with a Bostik No. 6 sealing compound followed by a final coat of bituminous paint.

108. The lead wires, which were of considerable length, had been run in a harness up to a high point on the gate, and this had been stowed until the gate was stepped. After the stepping operation the lead wires had been led out along one of the hoses.

109. Consideration had had to be given to compensating gauges. It was necessary to have compensating gauges because of the temperature effects; without them, it was impossible to differentiate between the effects of strain and the effects of temperature change. Compensating gauges were mounted on strain-free plates and water-proofed in a similar manner to the active gauge. They were located alongside the active gauges.

110. The means of detecting the resistance change was the well-known Wheatstone Bridge principle. This was used with the static strain indicator shown in the film and also the dynamic indicator. The static indicator was a portable single channel instrument with scales marked directly in terms of strain. Half the bridge was accommodated in the indicator and the other half of the bridge was composed of the active and the dummy gauges. The active and dummy gauges were switched in turn to the strain indicator so that each gauge could be read in turn. The dynamic recorder was a multichannel ultraviolet recorder, with an ultraviolet light source focused on to small galvanometer mirrors which reflected spots on to ultraviolet sensitive paper charts. As the galvanometer mirror deflects, so the spot moves across the chart, which is driven at a constant speed, giving a continuous record. Chart speeds of up to 9 to 10 ft/s and galvanometers of different frequency responses can be used with these recorders.

111. For these reasons wire gauges, which are reliable in operation and easy to apply, were bonded to the structure with a quick setting adhesive.

112. Both recording instruments used were calibrated before use. A strain gauge selected from the batch used on the job, was bonded to a four point loaded constant moment calibration bar and connected to the recorder with long lead wires in circuit. By this method site wiring arrangements could be simulated and known strains applied to each recorder.

113. The calibrations obtained for each galvanometer were then used to convert the appropriate chart trace directly into terms of strain and then to stress by multiplying by Young's modulus.

Mr J. MacKay (Assistant Engineer, Messrs Binnie & Partners) said that the Paper was most instructive and contained information which was of interest to engineers concerned with gates for irrigation and hydroelectric purposes as well as for docks.

115. The use of bearing units, seals and shock absorbers all made of rubber was noted and it would be useful to have details of the mechanical and chemical properties of these items, and why the different rubbers were chosen. It would also be interesting to hear why an extruded rather than a moulded shape had been selected for the soft seal as a moulded shape was generally considered to be more consistent dimensionally. It was noted from Fig. 4 that the clamping plates for the soft seal appeared to have sharp edges. If this were so, had this given trouble in operation?

116. The gate had been in operation for two years and it would be interesting to hear whether any of the rubber seals, bearing units or fenders had had to be replaced. If not, had a life been estimated for these items, either in terms of time, or in number of opening and closing operations? Could the Authors state whether the oil in the harbour water had had any serious effect on the seals, or load-bearing units?

117. Stainless steel studs had been used for fixing the meeting face rubber bearing units and presumably for fixing the rubber seals and other bearing units. It would be of interest to know the grade of stainless steel used, and whether stainless steel had been used for the nuts. If stainless steel nuts had been used, had any precautions been taken to prevent the cold welding which could take place between stainless steels in contact under pressure? Such precautions could have been to use a dissimilar stainless steel for the nuts and coating the threads of the nuts and bolts with a substance which would inhibit cold welding. Molybdenum disulphide had been named for such a purpose.

118. A most comprehensive set of model tests had been carried out and, as one would expect, the results had proved to be most valuable in arriving at a satisfactory design. It would be interesting to know the resultant cost of these tests.

119. The horizontal deflexion of the box girder was observed to be $1\frac{7}{8}$ in., which was approximately equal to span/865. Would the Authors please state what was the theoretical deflexion? In hydroelectric practice this usually varied between span/600 to span/1250, depending on the function of the gate, and the corrosion allowance was often deducted before the deflexion was calculated.

120. However, when arriving at the dimensions of the structural members, instead of specifying a thickness to be allowed for corrosion, the German standard on hydraulic structures DIN 19704 stated that a reduction in stress could be used, thus dispensing with a thickness allowance. This simplified calculations and detailing and one could guard against over-thin members by specifying a minimum thickness. Would the Authors like to comment on this?

121. Protection against corrosion was a problem of which all were aware and it would be of interest to have more details of the non-oxidizing petroleum based preservative used on the interior surfaces of the gate.

122. The problem of leakage must be considerable on a gate of this size and it would be of interest to know whether tests had been made to ascertain the leakage

quantities past the gate and if so, whether these compared with any calculated leakage quantities.

123. The method of operating the gate would no doubt be repeated and it would be interesting to hear of future developments where the problem of overcoming large tidal variations was tackled.

124. The question which he had asked had a bearing on the subject of hydraulic gates in general rather than dock gates in particular, but in hydraulic gates there were many aspects which were common to all its branches and he thanked the Authors for a Paper which was no doubt of interest to those who were concerned with dock gates and certainly of interest to those concerned with other hydraulic gates.

Mr W. R. Thorpe (Sir William Halcrow & Partners) said that in § 26 it was stated that the air pressure was kept at a constant value of 23.5 lb/sq. in. Mr Thomas had said that this was a very important point. As the gate neared the closed position and the operating tank was finally emptied of water, the excess air pressure would escape through the flooding pipes. Could the Authors state whether the air was automatically shut off when this point was reached or was it manually operated?

126. In § 29 the steel quality was described as being in accordance with B.S. 2762. What values of permissible working stresses were adopted? Would the Authors consider the use of high yield stress steel either to B.S. 968 or alternatively of ship-building qualities A.H.2 and D.H.2 if they were designing another gate of this type?

127. The gate had been fabricated in the dock since the necessary skills and equipment were available. But many gates were fabricated far from the dock and had to be towed by sea. Would the Authors agree that a single skin gate would require extensive temporary strengthening for such a sea voyage?

128. The Paper described how to build cheaper dock gates, first by reducing the weight of steel and secondly by dispensing with the operating winch. The single skin gate undoubtedly saved steel, although a gate of this kind was bound to be more flexible than its double-skin counterpart. The flexibility raised problems of seal between skin plating and sill and quoin but in the gate described in the Paper the difficulties had been successfully overcome.

129. If one wished to retain the inherent stiffness of the double-skin flap gate it was possible to reduce the weight of the structure by introducing a box beam near the top of the gate. A design incorporating this principle had been evolved for the entrance gate for a large dry dock now under construction in Tema, Ghana. Fig. 21 showed in simple form what had been done. The dock was 910 ft in length, the entrance width was 150 ft, and the depth from mean high water neaps to sill was about 29 ft. The lower portion of the gate was in the double-skin construction, parallel sided, with 4 ft between the skin plates. Five tapered buttresses were provided to strengthen the double skin and to connect it to the 14 ft deep by 8 ft wide transom box at the top of the gate. Permanent ballast and buoyancy spaces were provided in the double skin. Most of the transom box was free flooding except for the upper compartments of the two intermediate buttresses. The gate rested on two open bearings of cast steel. Two anti-lifting linkages were provided to guard against accidental uplift forces. When open the gate rested on two concrete plinths. There were 370 tons of steel in the gate including 70 tons of high-yield stress steel in the central portion of the transom box. The balance was mild steel. The gate was opened and closed by a single 50 hp winch and the operating time was 8 min.

130. The savings to be achieved by leaving off the winch were substantial since normal gate operating machinery costs might amount to 12% to 15% of the total. He looked forward to further developments of this type of gate, in particular where there was a large tidal range.

131. In conclusion, he suggested that it would be excellent if there could be some standardization of the design of such gates—not one standard design for all docks

FIG. 21: BOX BEAM FLAP GATE AT TEMA

but possibly a basic two or three designs. He was sure that the Paper had given a glimpse of at least one of the standard designs of the future.

Mr M. J. Kenn (Senior Lecturer, Department of Civil Engineering, Imperial College, London) commented on the hydraulic-engineering aspects of this most interesting and enterprising project and, especially, on the importance of the hydraulic-model studies. These studies had been invaluable in investigating the influences of gravity, wave action and ship movements on the gate. If the model studies had been carried one stage further, the dash-pot effect during gate opening might have been more fully developed and the need for rubber shock absorbers entirely eliminated.

133. Concerning the gate movements arising from the overhead passage of ships, Mr Kenn was curious to know whether these were essentially due to the pressure differentials, across the front and back of the gate, established simply from differences of water levels, ahead and astern of the ships, as a result of the ships behaving as 'loosely-fitting pistons' in the dock entrance. Such effects would be expected to force the gate down when a ship entered the dock and to exert a lifting force on the gate as a ship departed, regardless of the presence of any baffle wall.

134. The novel gate described by the Authors appeared to have many applications and Mr Kenn was reminded of a somewhat similar type of gate conceived in Canada some 15 years ago for the prevention of salt-water intrusion into a river estuary. The latter gate comprised a small horizontal bottom cylinder (with hinges) suitably joined with plates to a large horizontal top cylinder. Air could be pumped into the large cylinder, as required, and the gate would then rise and fall with the tide but still allow the discharge of fresh water over the crest.

The following contributions were received in writing:

Mr W. R. Cox (Sir William Arrol & Co. Ltd) wrote that the Authors were to be congratulated on their comprehensive description of all aspects of the gate design and construction. There was very little published material on flap type gates and the information given in the Paper would be of great interest to all engineers concerned with such structures.

136. There were, however, a few points on which further clarification would be helpful. Would the Authors explain why the lower skin plate had been positioned some 2 ft back from the meeting face? If it were 3 in. away from the meeting face, the uplift on the gate, with the dock dry, would be reduced by about 145 tons thus alleviating the problems of anchorage at the hinges and shear strain in the rubber meeting face. If access were required to the hinge bracket bolts, this could have been achieved by means of an access box sealed on the sea side but open on the dock side.

137. In § 8, it was stated that the introduction of a 'soft' seal down the lower stretches of the vertical meeting face eliminates the tendency of the lower corners to distort outwards. Was this correct? The flexural distortions of a gate of this type, when acting as a dam, were indicated in a very simplified fashion in Figs 22, 23 and 24. Fig. 22 showed a vertical cross section through the gate at the centre of the dock before lateral loading is applied. Fig. 23 also showed a vertical section at the centre but with the dock dry and external water pressure acting. This hydrostatic loading causes the top box girder to deflect laterally and the torque imposed on the box by the sill reaction causes it to twist as shown. The sill reaction was not uniform across the sill, but increased to a maximum at the centre of the dock since it was dependent, at any particular section, on the lateral and rotational displacement of the box and on the flexural stiffness of the vertical ribs. Fig. 24 showed a section near the end of the gate assuming that the lower corners are not prevented from distorting outwards. At the ends the flexural deflection of the top box was zero, but the torque caused by

FIG. 22

FIG. 23

FIG. 24

the sill reaction might have had to be resisted by a shear S in the horizontal sill girder if the resultant line of action of the end shear in the top box fell above the top of the gate end plate. It appeared to be the foregoing effects which caused the lower corners of gates to distort outwards, rather than lack of bearing down the end plate. In a conventional gate, the hinges were usually located at the lower corners thus providing resistance to lifting off at these points.

138. It would appear, in fact, that there might be a greater tendency for the corners of the Malta gate to move outwards than is the case in a conventional gate since the hinges are not at the corners and since the rubber meeting face permits a certain amount of rotation at the ends of the top box girder. This does not necessarily mean that the corners of this particular gate would move outwards since each structure has its own characteristics but it would be interesting to know what was the direction of the reaction at the lower corner obtained from the computer for the case in which the top box girder was free to rotate at the ends.

139. Regarding the simplified grid adopted for computer analysis, it was stated in § 24 that the vertical ribs spanned from the mid depth of the box to the sill. Did this assumption not make the vertical ribs too flexible since the 20 in. deep ribs actually extended only up to the underside of the box; some 3 ft 6 in. less than in the assumed grid? The computer may thus have indicated rather more loading on the top box girder and less on the sill than would actually be the case, but this was an error on the safe side so far as the design of the box girder was concerned.

140. The use of rubber meeting faces on the gate was very interesting. The dressing of the normal greenheart timbers was a slow and expensive procedure and in any case, it was usual practice to fit some sort of rubber seal on the greenheart to improve watertightness. Since the rubber should tend to take up irregularities in the dock sill and quoins would the Authors agree that a relaxation in normally accepted tolerances on these surfaces is acceptable when using rubber in this way? What tolerances were specified for the dock meeting faces? Would the Authors recommend rubber meeting faces even in polluted and oily waters?

Mr P. B. Lindley and Mr A. G. Thomas (Engineering Consultancy Service, Natural Rubber Producers' Research Association) wrote to comment on some of the design aspects of the rubber pressure pads. These pads must support the force of the water on the gate, prevent leakage, and be able to accommodate rotations due to the flexibility of the gate at the same time.

142. Rubber, of course, was widely used as a sealing medium in civil engineering. Examples include waterstops, sealing rings in flexible underground pipe joints, linings for reservoirs, etc. It was not surprising, therefore, that it should be used here to provide the seal.

143. However, to transmit the pressure from the gate to the dock, it was originally intended that stainless steel spheres should be used as these would also accommodate rotation. Because of NRPR's experience with other load bearing rubber components they were able to suggest that correctly designed rubber units could be used. As well as providing a seal they would also serve the same function as the spheres. In this latter respect, i.e. supporting the load and accommodating movement, rubber is in widespread use in the bearings of bridges, for which the design principles are fully understood.^{3,4}

144. The ability of rubber to support high loads is due essentially to its high bulk modulus, E_{∞} (Table 3). Its flexibility, which enables it to accommodate rotation and to seal effectively, is due to its low Young's modulus E_0 and shear modulus G .

145. To be flexible in compression rubber must have room to deform. Because of its high incompressibility in bulk, deformation takes the form of bulging at the force-free surfaces. By limiting its freedom to deform the rubber gets stiffer. A quantitative measure of this is the shape factor S , which for a block of rubber is defined as the ratio of cross-sectional area to the total force free area. When the

rubber is in the form of a continuous strip, width b , thickness t , its shape factor S is $b/2t$ and the dependence of the compression modulus E_0 on S is⁶

$$E_0 = 4E_0(1 + kS^2)/3 \quad (1)$$

where k is a compression factor (Table 3). At high shape factors there is a contribution due to bulk compressibility which has been ignored in equation (1). A slightly different relationship

$$E_0 = E_0(1 + 2kS^2) \quad (2)$$

is used for blocks of circular, square and near-square section.⁶

146. The load-deformation relationships of rubber in compression are approximately linear up to about 10% to 15% compressive strain. Reproducible load-compression characteristics of rubber generally require that the loaded surfaces do not slip. Normally this is achieved by bonding to metal. If, however, the rubber is perfectly free to slip at the loaded surfaces, then there are no shape factor effects.

147. From the above the average compression of the rubber strip along the lower meeting face can be calculated. The rubber hardness is 52 ± 2 IRHD giving, from Table 2, $E_0 = 370$ lb/sq. in. and $k = 0.69$. The strip is 6 in. wide and $1\frac{1}{2}$ in. thick, hence $S = 2$. The outer $\frac{1}{8}$ in. of rubber is unsupported by metal plates and is not included in the width; the $\frac{1}{8}$ in. thick layer below the metal plate is for bedding purposes, and has too high a shape factor to contribute materially to any compressive deformation. From equation (1), therefore, $E_c = 4 \times 370(1 + 0.69 \times 2^2)/3$ lb/sq. in. = 0.83 ton/sq. in. The total force on the bottom support strip, of length 135 ft, is 964 tons giving an average compression of $964 \times 1\frac{1}{2}/(135 \times 12 \times 6) \times 0.83 = 0.178$ in.

148. The measured values* of the compression were $\frac{3}{16}$ in. at the centre and $\frac{1}{32}$ in. and $\frac{1}{8}$ in. at the ends. Assuming a parabolic form for the deformation of the strip along its length, Simpson's rule gives the average deflexion as 0.151 in. The calculated value agrees quite closely with the measured values, considering that the $\pm 2^\circ$ tolerance on hardness corresponds to a $\pm 20\%$ variation in stiffness. The above calculations assumed that no slip occurred at the unbonded load interface. In view of the good correlation with measured values it would seem that this was the correct assumption at the lower meeting face.

149. The effect of slip on stiffness is difficult to predict. This is so in the case of the support pads at the ends of the box section. For these the hardness is 65 ± 2 IRHD ($E_0 = 830$ lb/sq. in., $k = 0.54$) and the effective rubber dimensions 92 in. $\times$ 18 $\frac{1}{2}$ in. $\times$ 1 $\frac{1}{2}$ in. The shape factor $S = 6.1$, and, from equation (1), $E_0 = 10.4$ tons/sq. in. Hence the average deformation of the rubber pads under 328 tons maximum load on each end of the box section is 0.023 in.

150. Rotation of the box section at the ends through an angle α will increase the compression of the rubber at the inner face by $\frac{1}{2} \alpha l$, where l is the width of support (18 $\frac{1}{2}$ in.), and reduce the compression at the outer face by a similar amount. A value for α can be obtained by assuming the deformation of the box section to be parabolic. At the centre of the 135 ft span its deformation, as given in § 47 of the Paper, is $1\frac{1}{8}$ in. The slope at each end can therefore be determined as 0.0046 radians. The change in compression at the edges of the rubber is therefore $\frac{1}{2} \times 0.0046 \times 18\frac{1}{2} = 0.043$ in. Thus the rotation is seen to remove all the compression from the outer edge. This allows slip to occur and invalidates the deformation calculations.

151. The amount of slip depends largely on the coefficient of friction of the rubber on the contact surface. Contamination of surfaces or oxidation can reduce the coefficient of friction. In some recent tests⁷ its value dropped from unity for new rubber against polished steel, to less than 0.2 for aged rubber against smooth but oxidized steel plate. The Authors of the Paper have calculated a value of about

* The measured deformations of the rubber units were made available to the Writer by Mr T. F. D. Sewell, B.Sc.(Eng.), A.M.I.C.E.

0.04, which is probably not unreasonable in view of the conditions existing at the meeting faces.

152. Timber pressure pads could not be used because they would have been attacked by a marine organism peculiar to the Mediterranean. Rubber, however, has been used in docks and harbours all over the world in fender units. Some, installed at the Pittsburg & Corneaut Dock Co., Ohio, U.S.A., 30 years previously, were still in use. Nowadays rubber compounds can include the most efficient protective agents. Even in the absence of these, rubber can last a long time. Recently a main sewer at West Ham had to be replaced. Its expansion joints, still operative, contained the original rubber sealing rings which were installed over 100 years previously in 1861. Apart from some surface degradation, the rubber was in very good condition.⁸

TABLE 3: HARDNESS AND ELASTIC CONSTANTS OF RUBBER⁹

Hardness* IRHD ± 2	Shear modulus G lb/sq. in.	Young's modulus E_0 lb/sq. in.	k	Bulk modulus E_∞ lb/sq. in.
30	43	130	0.93	142 000
35	53	168	0.89	142 000
40	64	213	0.85	142 000
45	76	256	0.80	142 000
50	90	310	0.73	146 000
55	115	460	0.64	154 000
60	150	630	0.57	163 000
65	195	830	0.54	171 000
70	245	1040	0.53	180 000
75	317	1340	0.52	189 000

Based on B.S. 1154 natural rubber spring vulcanizates.

* International Rubber Hardness Degrees (IRHD) = British Standard Hardness degrees ($^{\circ}$ BS) $\approx$ Shore Durometer 'A' Scale readings. (Hardness is subject to an uncertainty of about $\pm 2^{\circ}$.)

Mr D. J. D. Reid (Stanford University, California, U.S.A; formerly of G. Maunsell & Partners) wrote that one of the features during the design stage of the gate was the continual attention that had to be given to weight and centre of gravity changes. Minor design changes and items such as paint made a considerable difference to the acting moments. The position of the hinge axis was critical and the hinge bearing details were left until the rest of the gate was fully designed. It is interesting to note that a minor change after the gate was in service impaired closing operations to a considerable extent and that a small alteration of kentledge corrected the fault.

154. The balancing of the model took several days. The weight and the centre of gravity of the model had to simulate those of the prototype both in air and under water. This was accomplished by attaching slabs of wood and sheet lead to the brass plate model on the dock side of the main skin. The model was weighed and balanced on a knife edge both in air and under water.

155. The model testing was a good example of how money spent on pre-construction investigation is repaid many times in economies in construction and a better finished job.

Mr D. Perfrement (British Transport Docks Board) wrote to offer the Authors his congratulations upon a most interesting Paper. He was impressed with the application of hydraulic model testing to determine the optimum design of the flap gate. He was rather surprised that this aspect of the Paper had aroused little interest at the

discussion, since most of the speakers were interested either in the structural design of the gate or the materials used in its construction. The great importance of hydraulic model testing, the scope of which increases with the development of more effective techniques, was somewhat overshadowed.

157. He was also concerned that, as detailed in § 12 of the Paper, the gate had tended to come off its open hinges when approaching the horizontal position in conditions of small counterweight force. It was fortunate that in the prototype the opening and closing times were not critical. It occurred to him, however, that in any other applications where shorter operating times were required, the uplift at the hinge could assume excessive proportions, particularly if the gate was forced open or closed by a crank or pulley mechanism instead of allowing the out-of-balance forces to form the operating medium. The dashpot effect of the gate recess could also result in additional uplift being exerted at the hinge unless a very large counterbalance was applied. All this would add up to the mass of the gate with consequent effect upon the operating times.

158. The questions thus resolved into the following points.

- (a) Was any attempt made in the model, by using heavier kentledge, to improve upon the operating time of the gate—and if so, with what effect on the hinge?
- (b) Were any tests carried out during the early experiments with gaps at the baffle wall at the head of the gate recess to reduce the dashpot effect which might have had a useful application in scavenging the gate recess for sedimentary deposits? This point would readily be demonstrated by the use of lines of the blue dye used to demonstrate the layers of water maintained against the outer face of the gate during the process of lowering.

Mr J. A. Williams (Partner, Sandford Fawcett, Wilton & Bell) wrote that a new design for a conventional structure always aroused excitement, more especially when the proposal was so essentially simple as the operation of a flap gate by compressed air. In consequence, he had begun reading the present Paper with keen anticipation. However, as the study progressed a sense of disappointment crept in, resulting finally (and regretfully) in the following critical comments.

160. Basically—and he wondered whether the Authors themselves did not feel this—the initial simplicity of conception was lost, albeit unavoidably, as the detailed design developed. For instance, the gate became hung about with flexible piping and flooding gear; a secondary buoyancy tank had to be added; fairly complex valving was required to control air pressures; a complex counterweight system had to be introduced; and so on.

161. More especially, a model study was an essential part of the design which should surely be added to the gate cost, both in terms of time and money. Just how essential the model study was, was demonstrated by the points which emerged and which, the Writer submitted, implied even further inherent disadvantages:

- (a) Sensitivity to the thickness of timber decking;
- (b) the possibility of the gate leaving hinges (which then introduced divers' working during stepping and unstepping);
- (c) the tendency of the open gate to lift under certain circumstances (necessitating the introduction of a baffle wall, which again should really be added to the gate cost).

162. On the 'credit' side it was acknowledged that the model allowed the counterweight system to be omitted!

163. Yet even after computer analysis and model testing the prototype required no less than 18 tons of kentledge for final adjustment.

164. Referring now to the structural arrangement and details, the Writer had two further criticisms.

- (a) It appeared from the cross-sectional shape (Fig. 2) that during unstepping and dry-docking for maintenance, the gate might be cumbersome to handle and it looked vulnerable to distortion in the dry; also at some stage of the operation it might become top heavy.
- (b) The heavy box girder, with plate thicknesses up to $1\frac{1}{2}$ in., introduced welding complexities (e.g. pre-heating) not found in conventional gates.

165. It must not be overlooked at this stage that as every problem of detail was overcome in developing the design, however neat each individual solution was in itself, the overall fundamental object was merely the avoidance of a winch. What, after all, was so terrifying about, say, a 40 ton winch, either in installation, operation or cost? If the answer lay in cost and if the chosen design could show a dramatic saving, the whole of the foregoing criticism might well largely be invalidated. This, however, did not seem to be the case. As the 'gate sub-contractor' was also the Client, the cost of £84 000 could presumably be taken as the absolute minimum figure for such a gate. There was also the matter of model tests and baffle wall costs previously mentioned. From available data the Writer would have expected tender figures from 'outside' firms, for a conventional gate and winch, including installation, of about £90 000. This did not indicate any likely saving of significance with normal competitive tendering. Therefore, while respectfully saluting a new design the Writer remains unconvinced that this has, in the event, proved superior to a conventional flap gate. In fact would the Authors, in similar circumstances, unhesitatingly adopt this design again?

166. In conclusion the Writer ought, perhaps, to acknowledge some possible bias in this matter, having received early training in dock gate work on Tyneside from men who were colleagues of the late Mr Edward Box, M.I.C.E., who designed the original 'Box', or flap gate!

Mr R. P. Torr (Technical Manager, Andre Rubber Co. Ltd) wrote that as technical manager of the designers and manufacturers of the load bearing rubber pads and strips he felt it might be of interest to give details of the static test results and to comment on their group behaviour.

168. The 31 in. long pads at the ends of the box girder when tested separately to $\frac{1}{4}$ in. compression gave an essentially linear force/deflexion characteristic, resulting in a compression stiffness of 230 tons/in. (calculated value 222 tons/in.). Tests on scale model pads when grouped similarly to the dock gate installation (3×3), gave an increase in stiffness by a factor of $3\frac{1}{2}$ over the increase obtained by multiplying the pad stiffness by the number of pads. Thus an overall installation compression stiffness of 7250 tons/in. might be expected at each end of the box girder.

169. The 39 in. long pads forming the strip bearing seal at the bottom of the gate when tested separately to $\frac{1}{4}$ in. deflexion gave a compression stiffness of approximately 150 tons/in. (calculated value 110 tons/in.), i.e. 3.84 tons/in. per in. run.

170. All tests were carried out with the pads placed between dry steel plates in the 'as rolled' condition. The deviation in test stiffnesses compared with calculated values are thought reasonable considering the difficulties in assessing the slip effects at the unbonded faces.

171. Site measurements of deflexion of the pads were taken at one edge only because of access difficulties, and in consequence actual mean deflexions could not be established. However, the results appeared consistent with the calculated reactions and slopes due to bending of the gate, plus some distortion due to fabrication.

The Authors, in reply, would like to enlarge upon the point made by Mr Thomas concerning the fortuitous escape of air from the operating tank when the supply pressure had been increased above the specified value. This incident had occurred on the occasion described in § 46, when the operating tank was nearly fully blown. Apparently, when the gate had failed to rise, due to the weight of steelwork that had

just been added to the structure, the operator had altered the setting of the constant pressure control valve in a mistaken attempt to raise the gate. When the pressure had subsequently been lowered to below the normal figure and then gradually increased, water flowed and the last part of the tank was de-watered and the gate rose.

173. It was interesting to note that during the model experiments something similar had occurred. On that occasion the cause had been fairly obvious because the intermediate transverse diaphragms in the operating tank were provided with only small interconnecting holes and hence the section which included the air inlet point was blown in advance of adjacent sections, allowing air to escape without doing any further work. In the case of the prototype, with its relatively small stiffeners and free access between tank sections, the Authors considered that the significant feature was not so much the increase in pressure as the increase in air velocity which had disturbed the water surface in the region of each inlet point to such an extent that air was able to pass direct through the exit ports. When the differential pressure was made very small, as described above, the water surface was undisturbed allowing the last few inches to be expelled. Under normal circumstances, of course, the gate would have started to rise long before this point was reached.

174. In future designs the Authors felt confident that the air inlets would be more numerous and of larger diameter and additional exit ports would be provided such that even if full mains pressure were utilized at the operating pit, water would be forced out of the operating tank at a rate which would prevent the differential head from becoming excessive, thereby avoiding overstress in the tank plating. Removal of the pressure limitation would save the cost of the control valve and give faster operating times, should these be required.

175. The Authors wished to thank Mr Cain for coming from Malta to attend the meeting. In his dual role as the sub-contractor Mr Cain had been able to furnish a number of interesting details on the methods used for construction and installation.

176. The Authors were grateful to Mr Gee for elaborating on certain aspects of the design analyses. One statement required correction, however, and this referred to the allocation of load to the end stiffener (§ 95). The width taken in the grid analysis had not been 6 in. but 1 ft 9 in. and the stiffness of member 1-7-13 in Fig. 17 was that of the smaller 1 ft 9 in. stiffener. Similarly, the width allocated to member 1-8-14 was not 16 ft 3 in. but 15 ft 6 in. The differences between the results obtained by the two methods could not therefore be attributed to errors in load allocation. The fixed ended case had been taken as giving the worst conditions for design and in this instance the differences were negligible, but in the free ended condition it was difficult to account for the divergence.

177. Quantitative measurements of the rotation of the beam on the prototype were not of great assistance in this matter as it had been discovered that thermal changes during the filling of the dock had affected the readings but nevertheless it was possible to come to certain conclusions. Initially the structure behaved in a manner between the fixed and free ended conditions and between the plate and grid analysis predictions, in that the rotation at the end of the beam was of different sign to that at mid-span, but after a year's operation the structure had noticeably bedded down.

178. Mr Piggott had made helpful comments about the strain gauges and it was useful to have his contribution on a subject of which many engineers had only limited experience.

179. Mr MacKay had shown considerable interest in the manner in which various rubbers had been employed and the Authors felt that the manufacturers would be the best people to approach for additional details of their chemical and mechanical properties. The choice of natural rubber for the main bearing pads had followed upon the suggestion of the Natural Rubber Producers Research Association and on the recommendation of the Andre Rubber Co. Ltd, to which latter company credit was given for the final design. There was no evidence that oil or other pollution had affected these units or any of the other seals fitted to the gate.

180. The possible dimensional inconsistency of the extruded neoprene rubber seals described in § 39 had been allowed for in the development of a suitable shape. Further allowances had also been made for permanent set in the rubber and the elastic deformation of the gate. An adaptation of an existing extrusion was employed on the recommendation of the Dunlop Rubber Co. Ltd, whose interest and assistance was much appreciated. The clamps used to retain the seal on the gate were not sharp edged and there was no evidence of any distress in the rubber.

181. The stainless steel used for the fixing studs contained 18% chromium and 8% nickel and the nuts were made from aluminium bronze alloy.

182. The shock absorbers were a standard product obtained from the U.S. Rubber Co. Ltd, in which butyl rubber was used on account of its hysteresis or slow recovery properties.

183. The Authors were pleased to record that after nearly three years' service no water was leaking past the meeting faces and no units had required replacement. The estimated minimum life had been between five and ten years and replacement units were kept in store in the dockyard for this and other eventualities. Also in the stores were kept a spare penstock and other items of equipment so as to minimize the cost of delays from any cause.

184. Mr MacKay had raised the question of the cost of the model tests but this could not be given in precise terms. The hydraulic investigation had been done jointly by the Consulting Engineers and the Hydraulics Division of George Wimpey & Co. Ltd, working as a team, and it was difficult to differentiate between what was design work and what was model work but nevertheless it was considered that the cost of the construction of the model and its calibration and operation was between £3000-£4000.

185. In answer to the query concerning the theoretical deflexion of the box girder under the design loading given in § 21, the Authors stated that it was approximately $2\frac{1}{2}$ in. or span/617. This was calculated before the corrosion allowance was added. The method adopted in the German standard DIN 19704 to allow for corrosion was probably just as satisfactory as the practice of adding a constant amount to the thickness of all members but was not quite so logical. This was because a stress change of a given percentage implied variations in the thickness of members by different amounts according to the sizes of such members. Alternatively, the adoption of the German standard meant that if the rate of corrosion were assumed uniform then the factors of safety for the various elements in the structure would vary at differing rates.

186. The non-oxidizing preservative which had been applied to the inside surfaces of the gate was a standard commercial product intended for marine use. It had a somewhat 'tacky' consistency and in that grade was not suitable for application on the external surfaces. One particular advantage was that it could be applied in safety in confined spaces by unskilled labour.

187. In reply to Mr Thorpe, the air supply was controlled manually by means of the L-ported plug valve in the operating pit.

188. The maximum tensile stress due to bending, taken for the steel to B.S. 2762, was 10.5 tons/sq. in. The adoption of high yield stress steel in any future design of single skin gate would have to receive very careful consideration. The welding of thick plates of this material was still a matter for rigorous control in a workshop to avoid cracking in the welds. The Authors were grateful to Mr Thorpe for giving details of his firm's design for the 150 ft wide flap gate at the new Tema dry-dock and noted the bold use of high yield stress steel in the central portion of the transom box. It must be borne in mind, however, that the structural element of the No. 4 Dock gate had been designed prior to 1962, when B.S. 968 underwent revision, but nevertheless it was doubtful whether high yield stress steel would be adopted if another gate were to be similarly constructed in the open air, or if the plate thicknesses were to exceed 2 in.

189. The Authors could not offer much comment on the towing characteristics of single skin gates as this aspect had not required serious consideration for the Malta design. With that particular design the provision of the secondary buoyancy tank transformed the floating structure into an elementary form of catamaran and they did not consider that the flexibility of the skin would be a disadvantage requiring excessive temporary bracing.

190. In reply to Mr Kenn's suggestion that the dashpot effect could have been developed, in order to eliminate the need for shock absorbers, the Authors commented that early model tests indicated a gate arrangement in which the angular velocity was sufficiently low to permit the use of inexpensive rubber fenders for absorbing the energy of impact. The addition of a baffle wall, thereby creating a dashpot, reduced the angular velocity still further (Fig. 25) but shock absorbers were still desirable in order to eliminate wear at the contact surfaces.

FIG. 25: ANGULAR VELOCITIES IN MODEL AND PROTOTYPE

191. Some lifting of the gate during the passage of a ship was anticipated as a result of the venturi effect mentioned by Mr Kenn. It was found from the model tests, however, that the inclination of the lines of flow of the water which fills the dock as the vessel moves out was of greater significance than the venturi effect; hence the construction of the baffle wall.

192. The Authors agreed with Mr Cox that the uplift forces, with the dock dry, could be substantially reduced by reversing the skin so that the plating was close to the meeting face and the tee stiffeners were projecting harbourwards, but it would

still be necessary to provide anchorage at the hinges due to the buoyant behaviour of the gate when opening. The hinges would also require placement nearer to the skin to compensate for the loss in initial opening moment and the simplicity and cheapness of the secondary buoyancy tank arrangement would be lost, but nevertheless Mr Cox's suggestion was certainly worthy of closer study in any future design.

193. In considering the elastic behaviour of the structure in qualitative terms the Authors could see some force in Mr Cox's argument but similarly it could be argued that as the natural tendency of the box beam at the ends was to rotate clockwise, as viewed in Fig. 22, this might counter the effect illustrated by Mr Cox to an extent sufficient to change the sign of the rotation in the regions remote from the centre of the gate. The analysis had shown that the reaction was, in fact, always positive along the sill but the Authors maintained that if there had been the added factor of a reaction along the vertical meeting face then some lifting of the lower corners would have been expected. The complication of transverse stiffening of the skin adjacent to the vertical meeting faces had also been eliminated by allowing the skin to deflect. The Authors commented that if the grid analysis were repeated, advantage would be taken of a more powerful computer program now available but it was not thought that the simplifications referred to by Mr Cox had introduced any errors of significant magnitude.

194. Mr Cox had raised the interesting point that if rubber were used for meeting faces could not alignment tolerances be relaxed? The Authors considered that there should be no relaxation of the Specification where it related to discontinuities between adjacent units because even rubber could not be expected to fill the steps thus created. As far as the units themselves were concerned, there was no difficulty in achieving a high standard of finish on the surface of the concrete by the use of steel moulds. It had also been proved that it was no more difficult to align the meeting face units to a high degree of accuracy than to set them to within, say, $\frac{1}{8}$ in. of the correct plane. This had been achieved by building in simple screw jacks and aligning with the help of piano wires and a form of tee square (Fig. 26) which incorporated a slot equal in width to the sum of the wire diameter and the alignment tolerance.

195. In the No. 4 Dock contract the Specification stated that the surface of the concrete meeting face should be accurate to within ± 0.025 in. of a vertical plane and that minor variations on the surface should be such that the maximum depression measured by a feeler gauge under a 10 ft straight edge placed anywhere on the face was not more than 0.01 in. Accurate planarity of the steel structure was more difficult to achieve and the use of rubber permitted some relaxation of normal tolerances. The manufacturers' own tolerance on the rubber units was given as $\pm \frac{1}{64}$ in. and the Specification required the steel surfaces to which these were attached to be within 0.03 in. of a 10 ft straight edge; thus the combined effect could be almost ± 0.05 in.

196. The Authors were grateful to Mr Lindley and Mr Thomas and also to Mr Torr for the detailed contributions on the subject of the load bearing rubber units and considered that there was nothing further which need be added to the information given.

197. The Authors were pleased to have received Mr Reid's contribution as it gave them the opportunity to acknowledge the important part played by him during the model studies and the design period. Whilst obviously agreeing with his observations the Authors wished to correct the impression that might be gained that the gate design was very critical and that it would only operate within narrow limits. In fact, the operating limits were quite large and the minor amendments referred to, by way of additions to the structure, amounted to the not inconsiderable weight of 4 tons, or a moment of 150 tons ft when in the open position.

198. Mr Perfrement was concerned with the magnitude of uplift forces on the hinges during the movement of the gate either under the action of gravity or a mechanism. No attempt was made to measure these forces during the model studies

FIG. 26: ALIGNMENT OF MEETING FACE

as it was considered that, from the observations made during the tests, such forces were not of a large magnitude. It was emphasized that the time during which the gate was actually in motion averaged only $3\frac{1}{2}$ min and there seemed to be little point in decreasing this period in future designs. In consequence the Authors felt that the possibility of increased uplift forces did not arise. If shorter overall operating times were required then the flooding arrangements would require amendment, as discussed in § 174. It would also be appreciated that the installation of extra kentledge, although speeding the downward motion of the gate, would entail the use of a larger operating tank to provide the additional buoyancy needed to overcome the added kentledge and to close the gate in a comparable, shorter, time. This in turn would require more air and the advantages in time would tend to be nullified. The object had been to keep the operating tank as small as possible.

199. Mr Perfrement had made the point that gaps in the baffle wall could have assisted in the removal of sedimentary deposits disturbed by the water flowing out from under the gate during opening. This had not been examined in the model but was worthy of consideration in future designs. Sedimentation was not a big problem in the Grand Harbour and cleaning out was anticipated only at very extended intervals, if at all.

200. Mr Williams had made a stimulating and challenging contribution to the discussion but the Authors, understandably, could not agree with all the points that he had raised!

201. The original concept had, in fact, included a straightforward counterweight system and so its elimination during the design period represented a marked simplification. Similarly, at the earliest stage a secondary buoyancy tank had been considered preferable to temporary, removable, buoyancy tanks and had been designed to provide a simple means of floating the structure and of assisting in the stepping and unstepping operations. The flexible flooding pipes had only been used during

installation and formed no part of the permanent works but a different contractor might, of course, have elected to perform the stepping operation in a different manner.

202. The Authors could not see why the sensitivity of the model gate to changes in the thickness of timber decking was necessarily a disadvantage. It was axiomatic that the more refined designs became, the more sensitive they were likely to be to small changes in any of their constituent elements. The Authors would freely admit, however, that the addition of hinge keeps and the use of divers during installation, whilst not particularly disadvantageous in themselves, had added slightly to the cost.

203. It was important to correct a misunderstanding which might arise as a result of the views expressed by Mr Williams in § 163, concerning the use of 18 tons of trimming kentledge. The design study had revealed in one of the conditions tested that optimum working, that is roughly equal opening and closing times, could probably have been achieved by increasing the ballast by approximately 9 tons, provided there was no significant change in the moment of inertia. Adjustment of the bulkheads and disposition of the tanks could have achieved this, the model test could have been repeated and the prototype built accordingly but this would have left no scope for adjustment in practice; buoyancy could not subsequently have been increased to compensate for possible additions to the structure. In consequence, it had been decided (§ 20) to build the more buoyant design and install 9 tons of cast iron kentledge blocks which were readily available in the dockyard. The model tests also indicated that this design would still function, albeit with widely differing opening and closing times, if a further 9 tons of kentledge were added but this was only of academic interest. It was never envisaged that anything more than minor adjustment would be necessary in practice and in fact no adjustment had been made in the period immediately following the stepping of the gate. The operating times had been nearly equal and had remained so until the occasion referred to in § 46 of the Paper.

204. A comparison of the angular velocities obtained from the model and those recorded during site trials was given in Fig. 25. This indicated that the terminal velocity forecast from the model would have been achieved in the prototype had there been no baffle wall (§ 45). The divergence in values at the beginning of the travel was due to the fact that the tanks in the prototype filled less rapidly than those in the model.

205. The Authors, bearing other cases in mind, did not consider that the gate was any more cumbersome to handle than a conventional flap gate, judging from the experience gained when it was unstepped during the installation procedure (§ 44), and they were confident that the structure would not suffer distortion when being dry docked for maintenance.

206. In reply to Mr Williams's comment that the gate might become top heavy, the Authors stated that this could only happen if, by mischance, several of the buoyancy compartments became flooded simultaneously.

207. Mr Williams's remarks concerning costs were interesting as the Authors had performed the converse exercise of making comparisons with six existing flap gate installations. Allowance was made for the cost of the model tests and the baffle wall, although the Authors felt that the former was a development charge which should be spread over future designs of this sort and the latter would not often recur, as the pit that normally had to be excavated in the sea bed to accept the gate would be sufficient safeguard against uplift effects. Corrections were made for differences in size and in all instances the equivalent single skin gate showed a saving.

208. It was noticeable that for the larger docks, with entrances of 130 ft and above, the gates which incorporated a box beam and a relatively thin "slab" spanning from this member to the sill were more economical in the quantity of steel used. This supported Mr Thorpe's statement in § 129 and answered Mr Gee's query in

§ 102 as to whether the structural design concept was justified for other than operational reasons.

REFERENCES

2. TIMOSHENKO S. P. and WOINOWSKY-KRIEGER S. *Theory of plates and shells*. Second Edition. McGraw-Hill Book Company Inc., Chap. 11.
3. LINDLEY P. B. Design and use of natural rubber bridge bearings. *Tech. Bull. No. 7*. Natural Rubber Producers' Research Association, London, 1962.
4. MINISTRY OF TRANSPORT. Provisional rules for the use of rubber bearings on highway bridges. *Memorandum No. 802*. H.M.S.O., London, 1962.
5. GENT A. N. and LINDLEY P. B. The compression of bonded rubber blocks. *Proc. Instn mech. Engrs*, 1959, **173** (3) 111–122.
6. LINDLEY P. B. Engineering design with natural rubber. *Tech. Bull. No. 8*. Natural Rubber Producers' Research Association, London, 1964.
7. LINDLEY P. B. Compression characteristics of laterally-unrestrained rubber 'O' rings. In the press.
8. SMEE A. R. Century old rubber joint rings exposed at West Ham. *Rubber Developments*, 1963, **16** (4) 115–118.