Proc. Instn Civ. Engrs, Part 1, 1981, **70**, Nov., 779–810

8382 DISCUSSION

Cavitation damage and the Tarbela Tunnel collapse of 1974

M. J. KENN & A. D. GARROD

Corrigendum

Table 1, 24 July: for 'T1G1 closed' read 'T1G2' closed.

Mr Kenn and Mr Garrod

The Authors believe that at the start of impounding the tunnels and gates were in good order and that all of the damage observed later can be accounted for by the subsequent flow conditions.

89. Once impounding had begun the tunnel gates and gate hoists became inaccessible. Consequently the gate positions could be estimated only to within about 1 ft and there was no direct evidence of either the water levels or the flow conditions inside the tunnels.

90. The tunnel outflow conditions and the air demand at the inlet ducts provided the indirect evidence at the time of the unknown flow conditions inside the tunnels. Piezometers were located at many places in the surrounding rock. Some of these indicated the groundwater pressures as these responded to both the reservoir water levels and to the break in the tunnel.

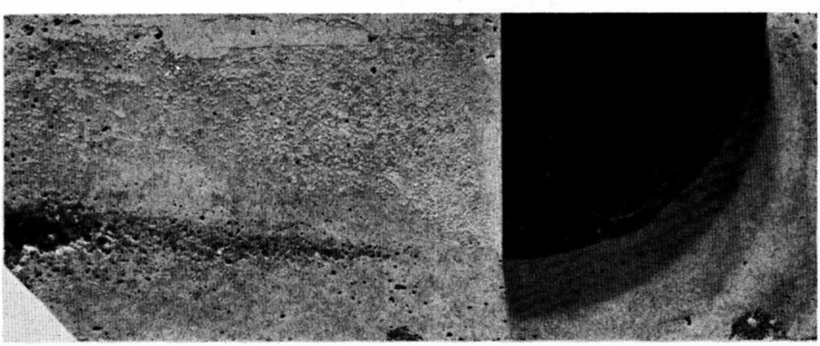


Fig. 17. Cavitation damage caused by the sheared flow of Fig. 4

Paper published: *Proc. Instn Civ. Engrs*, Part 1, 1981, **70**, Feb., 65–89.

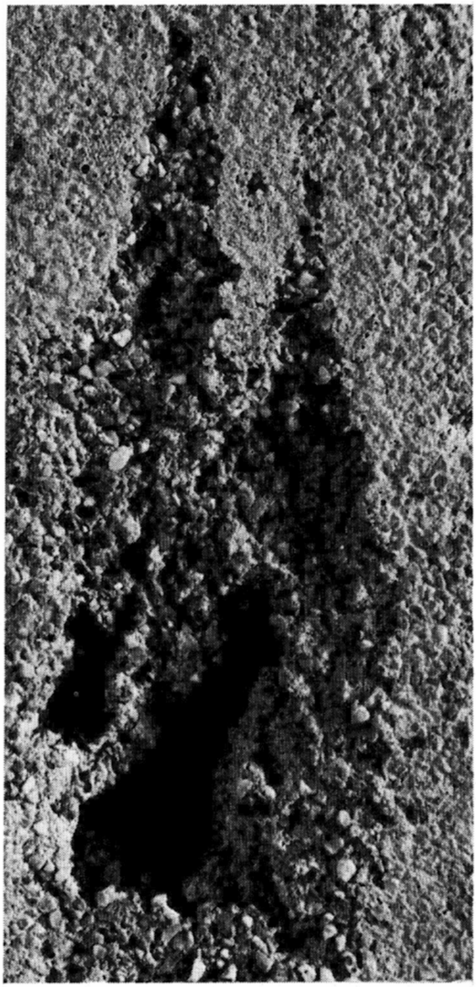


Fig. 18. Cavitation damage caused by the sheared flow of Fig. 5

91. Debris could be seen in the discharge from the tunnels and, if washed on to the side, could be identified either as concrete or fill material.

92. If simple Froude models are used to test high-velocity flow patterns, significant errors are necessarily introduced because of incorrect scaling of viscous forces, surface tension and other forces. A simple Froude model of Niagara Falls (with velocities almost comparable to those at Tarbela) would not, for example, correctly simulate the 'white water', the air entrainment, the induced winds, the spray, or the pall of mist and cloud (and other features) associated with the prototype.[41–44]

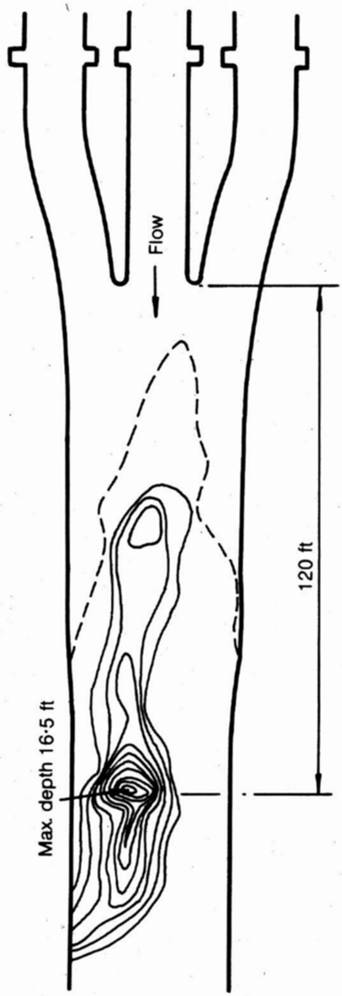


Fig. 19 (left). Cavitating eddies generated in the sheared flow downstream of a model intake structure, operating under full-scale head and with the centre gate wide open and both side gates shut (flow top to bottom); photo exposure $\sim 5 \times 10^{-6}$ s

Fig. 20 (right). Cavitation damage for the concrete invert of tunnel 2 at Tarbela associated with the conditions of Fig. 19

93. Even models tested with similar cavitation parameters, or particular forms of the Euler number, $\Delta p/(\rho v^2/2)$, are subject to errors (or 'scale effects') unless the tests are conducted at full scale, again because viscous forces, surface tension forces, elastic forces, turbulence levels, free-air contents etc. are necessarily incor-

rectly scaled. Nevertheless, a small-scale model, if tested in a water tunnel at full-scale heads and velocities, can usefully indicate likely patterns of cavitation and even of cavitation erosion for the elements of a large structure.

94. Figures 4 and 5 show conventional patterns of flow-induced cavitation in sheared flows; Figs 17 and 18 show the corresponding patterns of cavitation damage. These patterns of cavitation damage on weak 'concrete' specimens bear a very strong and indisputable resemblance to those observed in comparable flow situations in the field—at Tarbela, at Roseires, in Iran and elsewhere.

95. Figure 19 shows a simplified model of the Tarbela tunnel intake structure, operated under full-scale heads and with the centre gate wide open and both side gates shut. The associated cavitation damage for the actual invert of tunnel 2 is shown in Fig. 20.

Dr M. Baldassarrini, Tarbela Joint Venture

When these things happened in Tarbela, none of us seemed to know exactly what significance cavitation could have, otherwise different measures would probably have been taken. It was a miracle that the project was saved. If the lake had not been emptied as soon as it was clear that very important damage had occurred, and if there had not been co-ordination of effort by the Employer, the Engineer and the Contractor (who bore the brunt of doing the repair work), the damage would have been so terrible that the next flood would have rendered it irreparable.

97. I completely support the conclusions of the Paper that this phenomenon must be studied much more deeply, and its consequences must be communicated to everybody who has anything to do with water so that they know in advance what is at stake.

98. I arrived in Tarbela at about the end of July and was shown pieces of angular boulder gravel which had been ejected from the tunnel. They had been found on the deck of the adjacent gate structure of tunnel 3 on 29 or 30 July. So some puncturing had already occurred at that time.

99. The closure of the central gate of tunnel 2 was made in order to shut down the tunnel completely and allow the water to pass only through the irrigation tunnel.

Mr G. M. Binnie, past Vice President

In support of the hypothesis that the tunnels were destroyed by high velocity sheared flows, the Authors raise three quite significant points. First (§ 12) they say that, due to scale effect, an underestimating of prototype air demands and bulking could occur from model experiments. Secondly (§ 12) they say the collapse of tunnel 2 probably raised the tail water level in tunnel 1. Thirdly (§ 53) they talk about the asymmetrical damage in tunnel 2 being due to instability of jets.

101. Figures 21 and 22 show the Howell Bunger valves of the Dokan dam in Iraq which, except during the flood seasons, have been discharging continuously about 50–300 m^3/s during the last 25 years. They operate under a head varying between 70 m and 93 m. In Fig. 21 the irrigation outlet block can be seen on the right bank at the end of the weir. In Fig. 22 one can see the bulking which takes place. As anyone knows who has attempted to do so, it is quite impossible to reproduce this bulking effect in a model and it is an extreme example of how one needs to be wary about making deductions on two elements from experiments on only one of them.

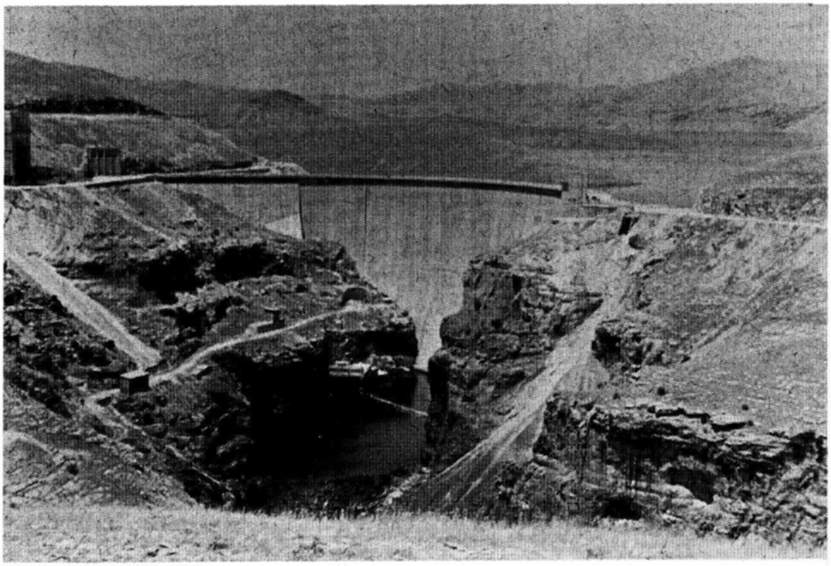


Fig. 21

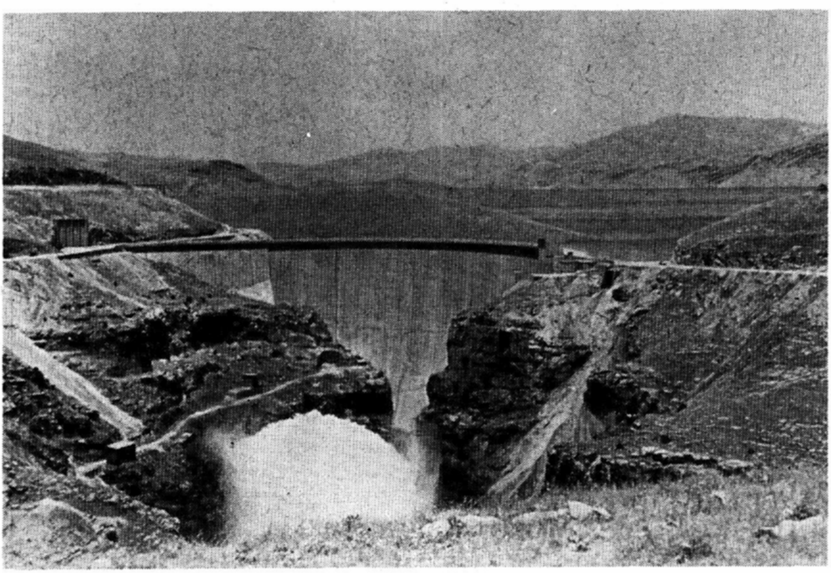


Fig. 22

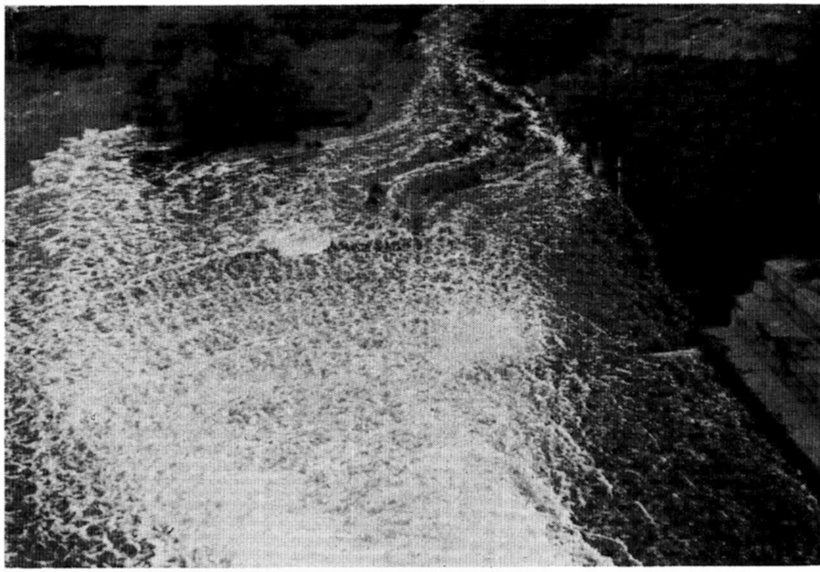


Fig. 23

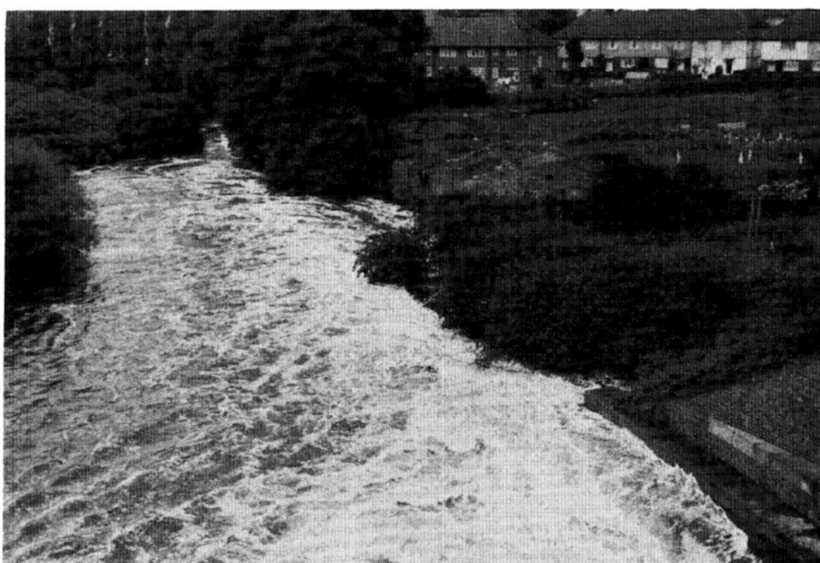


Fig. 24

102. As to the backing up effect, I think that probably the collapse of tunnel 2 raised the tailwater level in tunnel 1 but I wonder whether something else also happened which may have affected both tunnels. On the Jehlum river, a tributary of the Indus, we observed that during a major flood the river bed would be scoured quite low but it would extraordinarily quickly fill up again. This must have been due to bed load still being transported after the peak of the flood was over and I strongly suspect that the same applies to the Indus. Prior to impounding, the Indus at Tarbela was diverted through a channel on the right bank and, where it emerged, there may have been a check on the water velocity. Certainly there were changes in the directions of flow with possibly back currents generated by it. This went on for 3 years and it may have resulted in a significant amount of bed load imperceptible to the ordinary observer being deposited in the area downstream of the tunnels. This may have increased the tailwater levels in both tunnels above those that were anticipated and used in the model experiments.

103. An opportunity to observe the instability of jets occurred on the Brent reservoir which was built in north London about 125 years ago and incorporates a spillway consisting of a curved brick wall about 11 m high with two sluices at the bottom which discharge on to a flat apron at stream-bed level. About 10 years ago a test was carried out in which both sluices were opened fully, giving a discharge of about 34 m^3/s. The two sluices initially formed a single jet (Fig. 23) which appeared to be stable directly down the centre of the pool with strong reverse currents on both sides. However, after half an hour at full discharge, in a matter of seconds the jet suddenly changed direction and hugged the wall on the right bank (Fig. 24). This behaviour is very similar to that recorded by the Authors in their experiments (Fig. 5).

104. With true scientific detachment the Authors (§ 85) do not claim to have proved their theories but, in my opinion, the circumstantial evidence is very strong.

Mr J. S. Burgess, Hydraulics Research Station

Damage to the concrete floor and kicker block of the deep sluice stilling basin at the Roseires Dam on the Blue Nile is an example of the destructive forces which are brought into play when vapour-cored vortices collapse.

106. The Roseires Dam was commissioned in 1966 and the damage was discovered after the first operational season. Repairs were carried out but, following the next season's operation, it was found that damage to the apron and kicker block had again occurred. As a result, the Hydraulics Research Station was requested to investigate the hydraulic conditions in the basin to determine the cause of the damage.

107. The deep sluice structure contained five sluice-ways fitted with radial gates 10·5 m high by 6·0 m wide discharging into a short stilling basin incorporating a large kicker block at the downstream end. The overall head on the sluices reached a maximum of about 44 m resulting in a velocity of approximately 29 m/s at the gates.

108. A study of the prototype data, particularly the locations of the damaged areas, indicated that a possible explanation of the cause of the damage was the collapse of vapour-cored vortices generated in the regions of intense shear at the boundaries of the high-velocity jets issuing from the sluiceways.

109. A model of the deep sluice structure was constructed to a scale of 1 : 60 and pressure transducers were installed at strategic locations on the basin floor

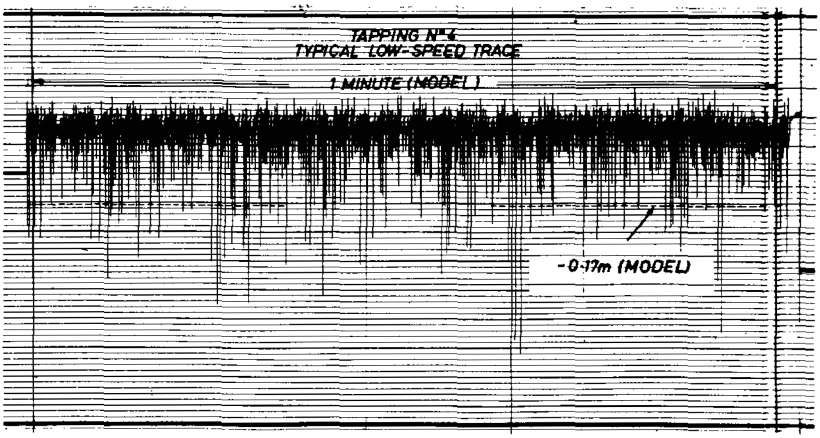


Fig. 25. Typical pressure changes with time recorded by transducer in the model

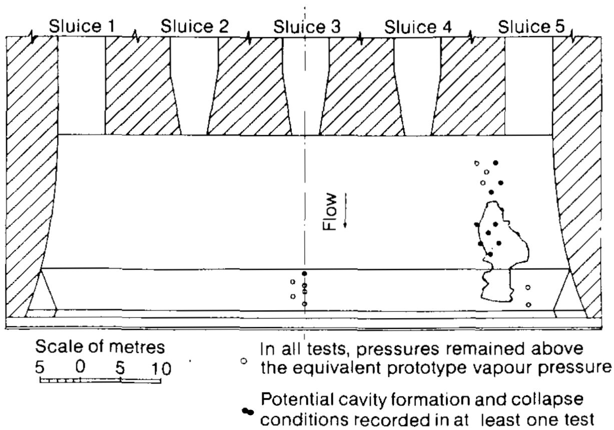


Fig. 26. Plan showing juxtaposition of damaged area (outlined downstream of sluice 5) with model recordings of potential formation and collapse of vapour-cored vortices

and on the kicker block, taking account of where damage had occurred and the regions of intense shear.

110. The trace shown in Fig. 25 was typical of the pressure head changes with time recorded from the transducers. Negative pressures below $-0{\cdot}17$ m represent potential cavity formation in the prototype, $-0{\cdot}17$ m being the model equivalent of vapour pressure.

111. Figure 26 shows the sluice exit channels, the basin and the kicker block in plan. The results of pressure observations at and near the shear boundary of the jet

from sluice 5 are illustrated in relation to the area of damage observed in the prototype. Potential cavity formation and collapse conditions occurred along the line of the intense-shear boundary, indicating that the mechanism producing vapour pockets in the prototype was that of vortex formation. The coincidence of the area of potential vapour pocket formation and collapse with the area of damage substantiated the contention that the cause of the damage was collapse of vapour-cored vortices.

Mr M. H. Palmer, BHRA Fluid Engineering

This is an interesting and informative paper. Let us hope that further papers will be forthcoming on this important topic.

113. The Authors' comments in §§ 10 and 11 suggest that there was insufficient air supply to the downstream side of the gates. This would cause sub-atmospheric pressures, resulting in a higher water level which could drown the jet downstream of the gate. I would be interested to know the Authors' estimate of the air flow and the pressure loss in the ventilation tunnels on this occasion.

114. In § 30 the Authors state that vapour cavities were generated in vertical shear zones downstream of the inner piers and that these cavities then collapsed downstream causing the extensive damage that they describe. It is clear, however, that when only one gate was open the flow velocity in the main tunnel was insufficient to provide positive pressure at the soffit of the tunnel downstream of the gates. Therefore pressures at this point were either atmospheric or below atmospheric if there was insufficient air supply. Calculations show that the cavitation parameter, as described by Ball *et al.*[38] was approximately 0·3, which is very much lower and therefore more serious than the critical value for step-, slot- or roughness-induced cavitation. Furthermore the position where the greatest damage occurred was just downstream of the transition between a horizontal and a circular tunnel invert. At this position the edges of the jet of water issuing from the gate channel were turned upwards, displacing the boundary layer so that part of the main body of water travelling at 38 m/s (125 ft/s) impinged directly on the concrete surface. This must have exacerbated the key problem of a critically low cavitation parameter.

115. I also feel that the statements in § 78 are not totally correct. With all three gates open, the velocities in the main tunnel would have been higher than in a single gate operation and water velocities in the gate channels would be reduced to 29 m/s (96 ft/s). The increased flow rate in the main tunnel would provide a static head in the area local to the gates of approximately 45 m (148 ft) at the tunnel soffit. This static pressure head and the slight reduction in flow rate through the gates would raise the cavitation parameter to nearly 1·10, which, although close to the critical value, would have been less likely to induce severe cavitation than single gate operations.

116. Model tests carried out in 1964 at Colorado State University on a preliminary design of tunnels 1 and 2 clearly showed that cavitation would occur if the bottom outlets were not operated with all three gates fully open.[45] This fact was emphasized in the model study report and acknowledged by Leonard A. Lovell of TAMS, in his foreword to the report.

117. The Authors state that the cavitation parameter and scale model test cannot fully predict the occurrence of cavitation or the extent of cavitation damage. This is true, but such calculations and studies have shown that cavitation

was highly probable if Tarbela's bottom outlet tunnels were not operated with all three gates fully open.

118. I therefore feel that the most important lesson to be learned from the tunnel failure is that the design engineer must ensure that owners and operators are aware of the potential dangers of incorrect operation of their designs.

Mr K. S. Smith, Sir Alexander Gibb and Partners

Part of the gate operation was forced on the Engineer by unforeseen circumstances. Moreover, the central piers for the service gates had not been constructed for the diversion stage through the tunnel in order to maintain full capacity: hence the three upstream gates. The original design basis for the intakes, tunnels and gates was that the three gates on each of tunnels 1 and 2 would be closed together to shut off the flow as soon as it was decided to discontinue diversion, and this is what was tested at Colorado State University. Later, to enable greater control of the reservoir filling rate to be achieved, it was determined by the Engineer (after additional studies, a review of the design and some modifications to the gates) that it would be safe to operate tunnel 1 or 2 with only the centre gate remaining open for a short period.

120. It was never intended that any gate would be held in a part-open position under any head. My view is that had it been possible to close the gate on 27 July when the reservoir was at an elevation of about 1340 ft, the erosion would have been small, and it would have caused no concern, as the area in which the bulk of the erosion occurred was due to be cut out anyway for the construction of the power elbow.

121. Referring to the air vents, my understanding was that their main purpose was to meet any air demand immediately downstream of the gates, particularly on their closure. Can the Authors explain more fully the high air demand through the air vent (§ 11) in the light of the assumption by the Authors that the tail water level in the intake passage downstream of the gates was at 1134·5 ft (the roof of the intake) and that this water was at near atmospheric pressure (§ 51).

122. Even allowing for the effect of bulking, I find it difficult to accept that the tunnel was flowing full with the single gate open, as the diameter of the tunnel downstream is about $2\frac{1}{2}$ times the area of one gate.

123. When I saw tunnel 1 and particularly the walls of T1G3, where the gate had been held approximately 24 h in each of two positions before being fully opened, I was particularly struck by the sharp edges of the erosion which coincided, as near as one could judge, with the bottom of the gate in the part-open position. It had cut very cleanly into the concrete to some depth. At the time I though it was due to vorticity-induced cavitation at the edge of a free-flowing jet. Would not the high silt content of the water have had a marked bearing on the extent and rate of erosion?

124. The presence of debris at the tunnel exit might give rise to suggestions this was bed load passing through the tunnel. However, recent surveys of the areas upstream of tunnels 1 and 2 show these to be still well below the inverts of the low level intakes.

Mr I. P. Haigh, Sir Alexander Gibb and Partners

For many years civil engineers have ignored the possibility of cavitation causing damage to concrete structures. It is both timely and worthwhile therefore that cavitation damage should now be the subject of a paper for discussion at a well attended ordinary meeting of the Institution.

126. Cavitation was studied in the 1890s by Thornycroft and Barnaby in connection with the development of a new type of warship, the torpedo boat destroyer. At the same time Parsons carried out some experiments on cavitation using water from which, for another reason, he was careful to extract the air, but incidentally perhaps in order to obtain reproducible results. He established the connection between a sudden drop in pressure and the vaporization of the water; this led to wide acceptance of the concept of the cavitation parameter.[46]

127. However, the water that civil engineers deal with, the real water in life, contains air and particles of solids in suspension. Some of these particles are colloidal and perhaps surface-active. The presence of air on these particles could produce cavitation at much lower velocities than are indicated by the cavitation parameter. A photograph taken from the deck of the research trawler of the University College of Swansea, when the ship was steaming at only $\frac{1}{2}$ knot, shows in the wake of the trawler ropes clearly visible plumes of cavitation bubbles. To a certain extent only the photograph is misleading because the ropes, being under tension and vibrating, actually possessed a greater velocity relative to the water than the speed of the ship. Nevertheless, observations of water flowing slowly in streams over boulder-strewn beds will also reveal milky cavitation occurring at points of separation from the solid boundaries.

128. In 1963 the British Hydromechanics Research Association published a translation of a Russian paper by Kozirev[47] which described cavitation tests observed by high speed photography and undertaken in water to which suspended solid particles had been added. The concept that cavitation damage is due to the shock waves set up by the microjets produced during the shearing of very small bubbles is now widely accepted. It follows that there is no reason for the pressure to drop to the level at which the water vaporizes for cavitation to occur; it will suffice if the pressure drops only sufficiently to enlarge and disturb the gas bubbles already attached to the crevices and asperities of the solid particles in suspension. Admittedly the cavitation damage to solid boundaries that will ensue will depend on the velocity of the water, faster-flowing water possessing more energy rapidly to shear the bubbles. It is doubtful therefore if there is a firm threshold velocity at which cavitation damage occurs.

129. Recently G. A. J. Young (BHRA) made unavailing enquiries in Russia about later work by Kozirev. It is evident therefore that hydraulic research in the UK should confirm the Russian results by repeating the tests and, if possible, extending Kozirev's conclusions, in particular as regards the rate of damage to structures.

130. There is a parallel to the possible influence of solid particles in suspension on cavitation. In the construction industry it is now common practice to remove mill-scale, rust and even paint by blasting the substrate with abrasives carried in a stream of air; undoubtedly impacts occur between the abrasives and the substrate. However, in the ship-repairing industry considerable use has been made of very high pressure jets of clean water, without abrasives, for the same purpose. The latest development, supported by CIRIA, is to use much lower water pressures, of the order of only 30–100 lbf/in^2, and abrasives; this development has been found to be very effective (more so in some respects), safer in use and much easier to operate; however, the theoretical aspect of whether wet blasting acts by means of cavitation, without the solid particles necessarily coming into direct contact with

the steel, or whether the abrasives literally erode the surface has not been established. It should be investigated—with the validation of the Kozirev results.

131. In § 22 the Authors state that, if the vorticity is sufficiently intense, cavitation bubbles can be sustained. How intense is the vorticity in turbulent flow? Research workers in hydraulics—and in aerodynamics—appear to have neglected this topic. This was understandable in the days when pressures had to be measured by slowly reacting and insensitive Pitot tubes, but this no longer holds today.

132. I would also question the extent to which vortex 'rollers' will extend into deeply eroded cavities in structures. Some years ago Mr Kenn showed me convincingly in the laboratory that flow patterns at corners in solid boundaries differ markedly from those to be visualized in two dimensions.

Mr W. D. C. Murray, Engineering & Power Development Consultants

The profession has a great deal yet to learn from the experience of Tarbela, and it is a useful look at the events described in the Paper in the context in which they occurred.

134. At Tarbela there are five tunnels and two spillways. Tunnels 1 and 2 in their permanent use carry water to the turbines, and tunnels 3, 4 and 5 carry irrigation water from the reservoir to the river channel downstream of the dam. The temporary intakes to tunnels 1 and 2 were close to river bed level, while the intakes to tunnels 3–5 are some 70 ft higher. During the later stage of dam construction tunnels 1 and 2 carried the river flow through their temporary intakes past the dam, and they were doing this immediately before the events described in the Paper took place.

135. The tunnel designs were fixed before the contract documents were issued in 1967. One can speculate that at that time a simple sequence of progressive closure was envisaged during reservoir filling. Because water was always required in the river, tunnel 1 or 2 would remain open until the water level reached the intakes to tunnels 3 and 4 or tunnel 5. Tunnels 1 and 2 would then be closed, and the required flow would be passed through tunnels 3–5 until the water level reached the spillways. In this procedure, the temporary gates of tunnels 1 and 2 would only be closed once, while the tunnels themselves either ran full or were completely closed.

136. In 1972 the planned filling procedure became more complex because it was decided to allow the reservoir to fill only to spillway crest level (about 60 ft below normal reservoir level). This partial filling was intended to test the efficacy of the seepage control arrangements.

137. To achieve the degree of control necessary to cope with all anticipated flood patterns, a procedure was developed that required the use of individual gates in tunnels 1 and 2. It also required, in certain circumstances, the centre gate in one of these tunnels to be open to a reservoir level corresponding to a head over the intake invert of 400 ft.

138. The gates and piers of the temporary intakes to tunnels 1 and 2 were intended for a short working life. Once closed they ceased to have any function, and the low level intake to the tunnels was to be plugged with concrete that formed the vertical bend to the higher level permanent intakes. In essence, all that was required was that the low level gates should close and the tunnel not leak.

139. No special measures were taken in the area of the temporary intakes or piers to protect them against damage from cavitation. The concrete, formwork and

finishes were all as for normal large section concrete elsewhere on the project. There was no steel lining.

140. All this suggests that when the intakes were designed they were not expected to be exposed to high velocity water and, later (when the reservoir filling requirements became more demanding), the use of the centre gate alone under high heads was not expected to produce unacceptable damage in works that were for temporary use only.

141. I find it difficult to believe that no consideration was given to possible damage from cavitation; it seems far more likely that the scale of the damage that could result was simply not appreciated.

142. The outlet of tunnel 5 also suffered from cavitation damage. It was on the left bank, and it discharged into the channel that carried spillway flows back to the river. When the reservoir was drawn down after the first filling, and the walls of the tunnel 5 outlet were found to have suffered cavitation damage, the Nespak engineers responsible for the design decided on two modifications. First, effective width of the discharge chute was reduced by adding a 2 ft thickness of concrete to the inside of each of the side walls. Secondly, air was introduced into the jet via 6 in dia. vertical holes drilled in the walls at each side of each outlet just upstream of the point at which the jet emerged into the air, and a series of smaller holes drilled to connect the vertical hole to the water passage. These measures appeared to prevent cavitation—but the jet from the tunnel undermined a construction camp on the opposite bank, and quite a lot of it fell into the river.

143. Perhaps the general lesson of Tarbela is that the damage that can be done by water is much greater than seems possible until it actually happens.

Mr P. H. D. Hancock, George Wimpey Ltd

My question arises from the demonstration that water hammer simulates the effect in a main when a pump stops. When I was on a hydro job operating a large temporary pumping installation of twenty-four 12 in pumps, problems with water hammer were cured by the introduction of a small percentage of air into the lines. This obviously turned the water into a compressible fluid and quite altered its properties. Is this something one would consider at the design stage in marginal cases of cavitation?

Mr P. Ackers, Binnie & Partners

My comments really are an attempt to get some clarification of the Authors' views on the advantages and disadvantages of operating high-head gates well drowned. It seems that their study of the Tarbela case led them to conclude that

- (*a*) free, unsubmerged flow from the gates would have entailed low risk of cavitation damage;
- (*b*) flow just submerged (including submergence from the side as well as from above) gives a high risk of cavitation because of the setting-up of vortices in shear zones;
- (*c*) greater submergence would not have reduced the problem significantly.

I agree fully with (*b*) but I am far less clear about (*a*) and (*c*).

146. Let us consider the effect of the number of gates open and the degree of opening. If only one gate in three is open, the tunnel friction is relatively small, little if any backpressure is generated, the full reservoir head therefore applies

across the gate, and the maximum potential velocity is achieved. If all the gates are fully open, the tunnel friction increases considerably to develop a backpressure beyond the gates, reducing the head and hence velocity, as well as increasing the mean ambient pressure. Do the Authors not agree that three gates fully open would be a safer operating condition than one gate open, or safer than almost any partial opening? They appear (§ 78) to discount any benefit from backpressure: if this is indeed their view, it is unconventional.

147. Having the three gates fully open would appear to me to be the normal basis of hydraulic design for this type of high-head low-level outlet. The part-open condition would be acknowledged as highly risky from the point of view of cavitation and thus identified as a transient condition to be passed through quickly. The question in my mind is whether the actual mode of operation of the gates was in accordance with, or in direct contravention of, the assumptions made in the hydraulic design. I think this has a considerable bearing on our understanding of why this particular trouble arose. This is perhaps the major lesson to be learned. When operational decisions were made, were the views and wishes of the hydraulic designers given less credence than they deserved? If so, how did this come about?

148. Concerning ventilation, descriptions of the ferocity with which air entered the ventilating system suggest that it may have reached sonic velocity. This implies a pressure drop of about half an atmosphere at least, and thus the ambient pressure in any air space behind the gates would have been about 15 ft below atmospheric. The air vent referred to in § 10 and shown in Fig. 6 was, I think, intended for local ventilation of the gate slots. It seems rather small to have been able to provide the full air demand of the tunnel at partial gate opening with only a small pressure drop. Under those conditions there would have been confused free surface flow in the transition, providing an extremely effective air-entrainment mechanism involving very high volumetric demand. I would be interested to hear the Authors' views on the functioning of the vents and the extent to which sub-atmospheric pressures might have contributed to the severity of the cavitation and the consequential damage.

Dr C. Jaeger, Member

Information reaching London at an early stage of Tarbela's tunnel disaster suggested that a rock weakness had possibly triggered off the rupture of the tunnel.[48] On the site, there was no evidence of any rock movement. Inspection of the tunnel with some senior staff of Engineering and Power Development Consultants showed typical cavitation damage.

150. Two aspects of the Tarbela disaster should be investigated: the type and extent of cavitation, and some basic aspects of hydro-power designs.

151. The excellent Paper by Kenn and Garrod convincingly describes the type of sheared flow cavitation which occurred in the immediate vicinity of the intake structures of tunnels 1 and 2. An alternative interpretation of the damage to the tunnel suggests that the 'sheared flow cavitation' in the vicinity of the intakes is only one aspect of a more general and more severe cavitation condition reaching down the tunnel. The aspect of the cavitation damage in the tunnel differs considerably from what was observed near the intakes. Tests have been carried out at Colorado State University Hydraulic Laboratory on a model of Tarbela tunnel.[49] Local pressures corresponding to severe cavitation on the prototype were measured. But in the chapter on conclusions and recommendations the CSU report, the

word cavitation is not mentioned, in spite of the low pressures measured. Negative pressures (vacuum pressures) are the condition for cavitation to occur and to be maintained. The requirement for simultaneous high velocities and for low pressures is not clearly analysed in Kenn and Garrod's Paper, which limits the validity of some of its conclusions.

152. Too many important details of the flow at Tarbela are not explained by Kenn and Garrod's theory. Difficult additional model testing, including the controversial aeration duct, would be required to give a more convincing image of the cavitation conditions in the area downstream of the intake structure.

153. The story of Tarbela revealed other weak points on the gates, on the gate rails and at the tunnel outlet. The design of Tarbela is inspired by known solutions which have been successfully used elsewhere on other power plants, for other conditions of pressure and water velocity and rock conditions. In particular the design of the intake is suitable for a power tunnel running under pressure and feeding turbines, but it was proved to be not acceptable for a tunnel discharging under free surface flow conditions at high velocities.

154. When is extrapolation of a known design to other hydraulic conditions acceptable?

155. Another example illustrates the danger of using a system of conduits designed to run under pressure for other flow conditions. The Campbell River power station on Vancouver Island consists of a rockfill dam and a short pressure conduit leading to the turbines. The pressure conduit has two sharp bends. The lower section of the conduit was a concrete pipe, 6·70 m in diameter, with a steel lining. The design was inspired by similar successful designs. Under emergency conditions, during dam construction, it was decided to use the conduit under free surface flow conditions for the discharge of floods.[50,51] High turbulence developed in the sharp bends of the conduit, vibration of the steel plate (and locally poor concrete) caused fatigue and a very small fatigue crack in the steel. Water penetrated behind the plate and full 'Pitot pressure' caused a spectacular rupture of the whole lining. The whole process of rupture was reproduced on several hydraulic models.

156. Any new hydro-power design is supposed to be inspired by accumulated knowledge and previous successful designs. But any new design should be re-thought for all the possible situations which may occur during construction and/or under running conditions.

Mr D. S. Miller, BHRA Fluid Engineering

The Authors are to be congratulated on making available details of the failures caused by cavitation in the tunnel at Tarbela.

158. The Paper does not bring out the fact that no hydraulic designer would willingly have an intake structure operated under the conditions that occurred at Tarbela. Since the early part of this century it has been accepted that it is impractical to design a gated inlet structure to operate under high heads when the inlet gates are controlling the flow.

159. The failure of the Tarbela tunnel is a classic example of the most prevalent cause of engineering failure, namely communications failure. A system designed to meet a specific duty was operated well outside that duty. Although not of concern to the Paper, the failure raises the question of what responsibilities lie with a designer who is aware of the conditions that can cause failure (in this case that the

reservoir level would greatly exceed that necessary to cause failure), but who has to design on the basis that the system will not be operated under failure conditions. Since history shows that, if it can be operated, it will be operated, the engineering profession must seek ways of improving communications between designers and operators.

160. As the structures at Tarbela were not designed for the high velocities to which they were subjected, studying how they failed is only useful if it provides insight into cavitation mechanisms and/or damage rates. Undoubtedly useful information can be extracted using the known operating conditions and details of the damage contained in the Paper. Contrary to the Author's views on model studies, my own opinion is that much more information could be extracted if model studies were carried out reproducing the failure flow conditions at Tarbela.

161. The approach adopted by the Authors is to concentrate their attention on cavitation and not on the fluid dynamics of the flow causing cavitation. This is a dangerous approach and, in my opinion, it has led the Authors to misunderstand the failure mechanism.

162. Studying processes within fluid flows is extremely difficult and usually involves sophisticated instrumentation and flow visualization techniques. Cavitation, however, involves a change of phase and, as a result, is visible. The fact that one can see cavitation can seduce one into believing that one can understand it. In reality, the important aspects of cavitation are not those to which the eye is drawn. Intense cavitation damage requires vapour bubbles to grow and almost immediately collapse, within a bubble diameter of the surface, in a steep pressure gradient. This usually requires that processes are occurring which cause the displacement of boundary layer material in order to bring high velocity flow with vapour bubbles on to a surface. An example is secondary flows in the wake of a cavitating object, which can cause rapid erosion in the zone where secondary flows sweep over the surface.

163. Because of the difficulties of making measurements in cavitating flows, it is often more appropriate, once the pattern of cavitation erosion is known, to make measurements in non-cavitating flows, in order to establish the mechanism driving the erosion process.

164. Cavitation of the form shown in Figs 4 and 5 occurs frequently in many flow situations. It is the least damaging form of cavitation. It arises in zones of high energy dissipation, which means that energy is not available to force vapour bubbles on to a surface and to collapse the bubbles rapidly. Because shear-induced cavitation is convected with the flow, there is adequate time for dissolved and free gas to collect in the bubbles and to cushion any subsequent collapse.

165. If shear cavitation exists, the potential also exists, if the high velocity flow is in contact with surfaces, for much more damaging forms of cavitation. In the intake structures at Tarbela conditions were ideal for intense cavitation damage to be caused by a number of mechanisms much more likely to cause damage than shear-induced cavitation. Using readily available data on pressure losses and conditions necessary for cavitation (e.g., Miller[52]) one can conclude that cavitation was inevitable in the flow passages.

166. The surface finish required to prevent cavitation just would not have been achieved in a tunnel the size of Tarbela, constructed for flows which were assumed to have no cavitation potential. The tunnel had been used for diversion flows, so it could have been expected to be rough in a cavitation sense. Parts of the gate passages acted as diffusers under some conditions and would have operated with

intense cavitation. Secondary flows were present in the gate passages and on the floor of the tunnel when only one gate was open. On the tunnel floor the secondary flows would have increased the cavitation susceptibility at a time when the static pressure was low due to the sudden expansion in flow area from one gate passage up to the full tunnel area.

167. Based on the above brief comments, and on other fluid dynamic reasoning, one can re-interpret nearly all the Authors' conclusions as regards failure mechanisms. I would like to ask the Authors to have faith in model studies; the failure at Tarbela confirmed the findings of the original model studies of the intake structures. Our understanding of fluid dynamics, which includes cavitation, comes from model studies.

Professor R. E. A. Arndt, St Anthony Falls Hydraulic Laboratory, University of Minnesota

This work clearly illustrates the extreme practical importance of cavitation in turbulent shear flows. Unfortunately, this is a relatively unexplored area of research.[53] Just as the Authors trace the problems in the Tarbela project to cavitation in turbulent mixing layers, there are many other problems associated with this phenomenon involving valves, energy dissipators, and separated flow in pumps and turbines. We have a basic lack of understanding and this is compounded by the fact that small-scale models often fail to predict the extent of the problem.

169. The physical processes involved in cavitation inception have been studied for many years.[54,55] Much of this research has been directed toward an understanding of the dynamics of bubble growth and the determination of the sources of cavitation nuclei and their size and number in a given flow situation. This research has led to a general understanding of some of the environmental factors involved in scaling experimental results from model to prototype. More recently, considerable attention has been paid to the details of the boundary layer flow over streamlined bodies and the role of viscous effects in the cavitation process. This research has shown that viscous effects such as laminar separation and transition to turbulence can have a major impact on the inception process and that there can be considerable variation in the critical conditions for cavitation between model and prototype.

170. In the absence of viscous effects, the scaling problem reduces to an understanding of the size distribution of nuclei and the temporal response of these nuclei to pressure variations as viewed in a Lagrangian frame of reference. This was first treated in detail by Plesset.[56] As already mentioned, consideration of viscous effects shows that the cavitation inception process can be considerably altered by either laminar separation or transition to turbulent flow. Obviously these phenomena are interrelated and are strongly dependent on Reynolds number. The recognition of the importance of these factors has had considerable impact on the direction of cavitation research in recent years. Several recent papers deal directly with this aspect of the cavitation scaling problem (e.g. Arakeri and Acosta[57]).

171. It is reasonably well understood that intense pressure fluctuations, either at the trailing edge of a laminar separation bubble or in the transition region, can have a major effect on the inception process on streamlined bodies. This research is vital to the interpretation of laboratory experiments *vis-à-vis* the prototype situation, since many model studies are performed at Reynolds numbers that are low

enough for these viscous effects to dominate, whereas the Reynolds number in many prototype situations is high enough for the flow to be fully turbulent, with viscous effects playing a relatively minor role in the cavitation process.

172. Obviously the effort expended on cavitation scale effects for streamlined bodies has been worthwhile. However, if one looks at the magnitude of the scale effect, it has fairly well defined limits. For example, the observed variation in the critical cavitation index in the ITTC round-robin tests with a body having a minimum pressure coefficient of about −0·6 ranged from nearly 0·3 to about unity.[58] On the other hand, if one looks at cavitation in free shear flows, the variation is much more extreme. For example, the observed incipient cavitation index for submerged jets varies by a factor of 10 for jet diameters ranging from 0·05 in to 2 in.[59] Similarly, experiments with a sharp-edged disc[60] show a variation in the inception index of 0·75 to 3 in the Reynolds number range $0{\cdot}8 \times 10^5$ to 15×10^5. Arndt and Keller[61] also observed much broader variations in the incipient cavitation index of a disc when the flow was supersaturated (as high a value as 7). In addition, there is some evidence that the intensity of the pressure fluctuations that induce cavitation in the disc wake is related to the development of the boundary layer on the disc face.[62] Of even more concern is the fact that in many cases the upper limit on the cavitation index has not been defined by the experimental work published to date. It is evident that the state of knowledge in this area is poor, yet very little experimentation has been done where cavitation phenomena have been correlated with important flow features (in this case turbulence). An exception to this statement is the classical work of Rouse,[4] who correlated observations of cavitation in a submerged water jet with measurements of pressure fluctuations in an air jet. This point is underscored by the recent findings that jet turbulence at moderately high Reynolds numbers can have 'memory' and be strongly coupled to the initial growth of shear layer instabilities originating at the nozzle lip. In fact, the experimental evidence strongly indicates that the character of jet turbulence varies substantially in the Reynolds number range 5×10^4 to 2×10^5. Above about $(Re) = 2 \times 10^5$ turbulent jets appear to behave in a 'classical' manner.[63–65] This is an important factor since the available data on cavitation inception in shear flows have been obtained at moderate Reynolds numbers. Related to this is the observation of large-scale coherent structures in turbulent flows. These structures are now readily observable but contain less than 20% of the turbulent energy. Their influence on the turbulent pressure field is not clearly understood. This point is illustrated in Fig. 27 which compares the observed cavitation in Fig. 4 with observations of coherent structure by Brown and Roshko.[66] The cavitation acts to visualize the coherent structure in much the same manner as the shadowgraphs of Brown and Roshko. It is not clear whether cavitation is occurring as a result of this wave-like structure or whether bubbles from the cavitation process are merely entrained in the large eddies, producing a picture that would be similar to that obtained with dye injection.

173. There are a myriad of factors that enter into the inception process in turbulent shear flows. As a minimum, we need information on the turbulent pressure field, such as spectra and probability density. We require an understanding of the diffusion of nuclei within the flow, and we need to know how these nuclei respond to temporal fluctuations in pressure. In taking into account the bubble dynamics inherent in the problem, consideration must also be given to gas in solution which can have an influence on both bubble growth and collapse. This leads to the conclusion that any research programme must be carefully designed to

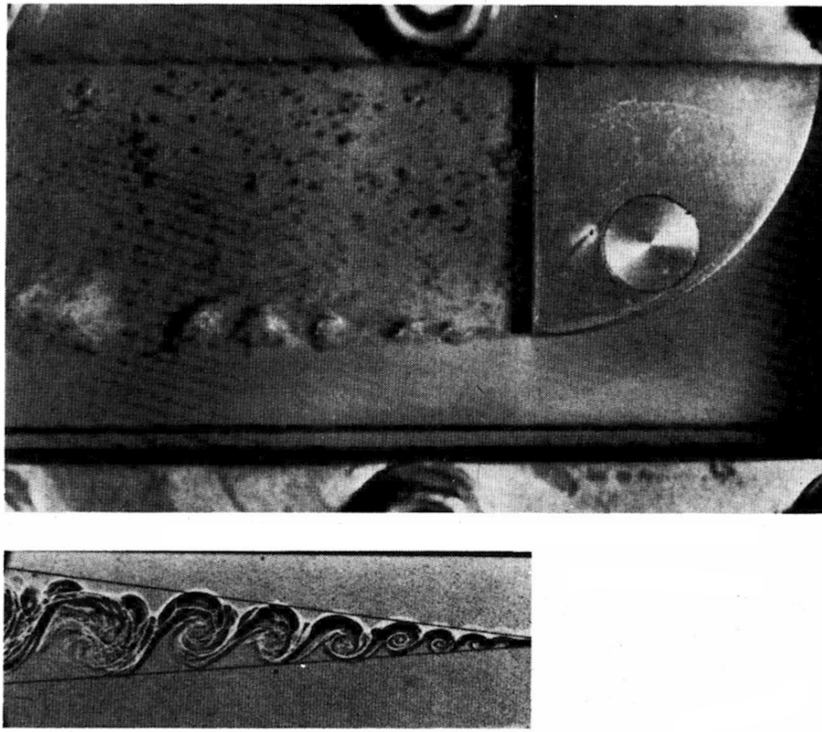


Fig. 27. Cavitation (upper photo) and observed coherent structures (lower photo) in a mixing layer (flow right to left); adapted from Fig. 4 and Brown and Roshko[66]

address these issues. To the best of my knowledge, no such comprehensive experiments have been carried out. The hydraulic engineer should be continuously cognizant of recent developments in aeronautics. In this particular case the recent interest in jet noise and its mitigation has led to a considerable research effort in the area of turbulence in shear flows. Much of this work is applicable to the problem at hand, as outlined by Arndt and George.[53]

174. I want to thank the Authors for bringing into sharp focus the interrelationship between important design problems and the need for fundamental research.

Mr J. Lowe, Partner-in-charge, Tarbela Dam Project, Tippets–Abbett–McCarthy–Stratton, New York

It is necessary to put into perspective the cavitation/erosion damage and Tarbela tunnel 2 collapse of 1974 described in the Paper. In the original design, tunnels 1 and 2 were to be used first for diversion and afterwards converted to power use. The tunnels were to be closed when the closure section of the main embankment dam reached sufficient height that it would be safe against overtopping under the most adverse flow conditions during the months remaining before its completion to full height. The three fixed wheel intake gates of each tunnel were to be closed simultaneously. The gates of tunnel 2 were scheduled to be closed first and some time afterwards those of tunnel 1. Later this sequence was reversed to improve flow conditions downstream.

175. At one of the Board of Consultants' meetings held during construction, it was decided that the rate of rise of the reservoir level during first filling of the reservoir should be slower than would result from successively closing each tunnel completely. After considerable study, it was agreed that it would be permissible to close progressively first the side gates of tunnels 1 and 2, and later the centre gates. This procedure would permit a slower rise of the reservoir. If all had gone well in summer 1974, it would have involved operating tunnel 1 with centre gate open for about 11 days at reservoir elevations not exceeding El. 1314 ft, and the tunnel 2 centre gate open for 15 days at reservoir levels not exceeding El. 1339 ft.

176. By 27 July the side gates of both tunnels had been closed and also the centre gate, G2, of tunnel 1. During the attempt on 27 July to close the centre gate of tunnel 2, the last of the six gates to be closed, the gate became stuck in the 28 ft open position (45 ft equals full open). Repeated attempts to close this gate over a period of 17 days were unsuccessful and tunnel 2 collapsed on 13 August at reservoir level El. 1461 ft. Later when the reservoir was empty, it was found that the rails on which the wheels of the gate rode were missing in the lower portion of the gate slot and were the cause of sticking of the gate.

177. In order to empty the reservoir the gates of tunnel 1 were reopened insofar as possible, keeping the gate openings reasonably similar. Under high head gates G2 and G3 stuck in part-open position due to loss of rails. Later, under low head, it was possible for the gates to be opened fully.

178. Ultra-conservative design against cavitation damage was not considered necessary because of the one-time short period of the expected use with only one gate open. If the last gate had been closed when intended, cavitation/erosion damage would have been minor, if it occurred at all, and entirely acceptable.

179. The cavitation experience on the invert of the Roseires stilling basin, to which the Authors refer, is not relevant to the cavitation/erosion which occurred on the side walls of the passageways immediately downstream of the stuck gates in tunnels 1 and 2, nor for that which occurred on the side wall of tunnel 2 in the collapse section.

180. The Paper is concerned with the mechanisms of cavitation/erosion for a condition of inadvertent use of tunnels 1 and 2, which was drastically different from the proposed condition of use. Even so, the mechanisms which the Authors propose could not have occurred since backwater was swept out of the area where they propose that horizontal and vertical shear occur. Further, the area where the postulated mechanisms occur is 200–250 ft upstream of the collapsed section of tunnel 2.

181. Irrespective of how cavitation/erosion occurred on the right side wall in the collapsed section, collapse would not have occurred if it had been possible to close the centre gate of tunnel 2 when first attempted.

Mr P. C. Chao (Chief Project Engineer, Tarbela Dam Project) and **Mr A. R. Luecker** (Head Civil Hydraulic Engineer, Water Resources Division), Tippetts–Abbett–McCarthy–Stratton, New York

Tunnels 1 and 2 served as river diversion tunnels prior to and during the initial filling of Tarbela reservoir in 1974. Cavitation was a factor leading to the collapse of tunnel 2 in August 1974. The flow situation that led to cavitation in tunnel 2 was brought about by operation of the centre gate (one of three), which inadvertently stuck at part-gate-opening at heads that steadily increased up to a maximum of 350 ft. In tunnel 1, damage occurred when each of the three gates could be opened only partly during emergency drawdown of the reservoir.

182. The part-gate operation was the result of accidental jamming of the gates due solely to structural failures in the gate track systems and was forced by circumstances that could not be foreseen. It was never intended that any gate would be held in a part-open position. The original design basis for the intakes, tunnels and gates was that the gates be used only to shut off the flow completely when the time came to discontinue diversion through the tunnels. Later, after additional studies, design review and some modifications, a determination was made that it would be safe to operate tunnel 1 or 2 for a short period with only the centre gate remaining open (fully open), if such operation should be required to achieve the desired reservoir filling rate.

183. The Authors' description of the events and conditions leading to the failure in tunnel 2 is essentially correct, but their analysis of the hydraulics has fundamental flaws. They base their thesis on the assumed occurrence of vertical planes of severely sheared water flows leaving the inner walls of adjacent piers, and horizontal layers of highly sheared flow stemming from the submerged lips of partially open gates. They offer explanations for all concrete erosions in tunnels 1 and 2 intake areas as results of cavitation originating from these shear planes, acknowledging with properly qualified language that their conclusions are speculative. Gate slots, wall curvature, and other surface discontinuities are mentioned (§§ 67 and 68) and dismissed as possible factors. The possibility of vortices formed at the corners of the gate openings is acknowledged but not considered significant. The Authors state (§ 58) that the water levels downstream of the partly open gates must have been above the corresponding gate lip level. They admit that jet submergence was not proved, but insist that it must be regarded as likely (§ 85); the principal justification given for this conclusion is that if it were not true their theory would not apply. They cite the extent of damage to the right wall of tunnel 1 as indicating that the tunnel was flowing full at that location (§ 60), while actually the upper limit of the damaged area indicated on Figs 13 and 14 correlates well with the free-surface-jet profile for the prevailing gate operation.

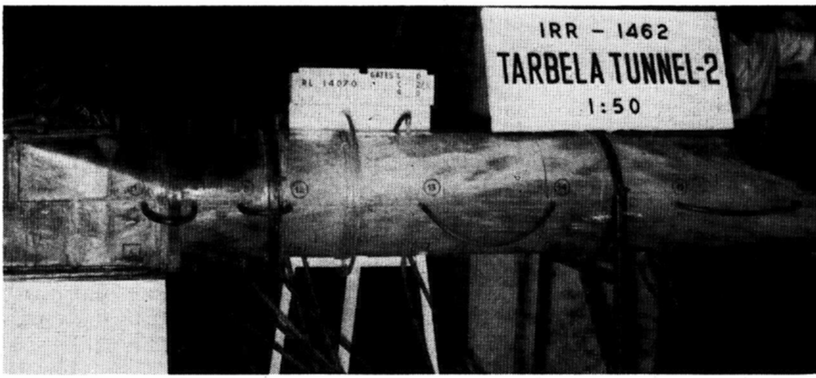
184. One need not assume that the full extent of the damage was a result solely of cavitation. Once the concrete was eroded (whether by cavitation or by abrasion) and reinforcing bars were loosened or broken, jarring and tearing would extend the damage beyond the areas of direct action by the water.

185. When one examines the overall hydraulics of the outlet tunnels, including intakes and gates, it becomes apparent that the Authors' explanations are inadequate. The three gate openings were 13·5 ft wide by 45 ft high with areas totalling 1822 ft^2. The controlling area downstream was 1486 ft^2, in the 43·5 ft dia. tunnel beginning downstream from the service gate shaft. Whenever the combined opening of the three gates was less than 70% of their combined full-open area, water was swept out of the gate passages and tunnel, and a flow regime with a free water surface was established throughout. This was demonstrated in design computations and in model tests.

186. The gate operations chart, Fig. 3, shows no operation of either tunnel at any time approaching the 70–100% range where gate lip submergence was possible. In model tests when a gate remained closed while a neighbouring gate was

open or part open, the transparent model showed the passage downstream from the closed gate nearly dry or partly filled with turbulent, highly aerated water. During operation of the prototype prior to the failure, flow characteristics insofar as they could be observed were consistent with the model and analytical results. The reasoning (§ 11) by which the Authors conclude that the high air demand is an indication of a drowned jet is not convincing. On the contrary, a high air demand is generally recognized as proof that the jet is flowing with a free surface and entraining large quantities of air.

187. Had the Authors been able to witness conditions at the tunnel outlets after 21 August, they would not have speculated as to possible backwater effects arising from the substantial discharge from tunnels 2, 3 and 4 (§ 12). Tail water was completely swept out and the channel bed was actually exposed in a zone between the jets from tunnels 1 and 2.



(a)

(b)

Fig. 28. Tarbela tunnel 2 model at the Lahore laboratory of the Irrigation Research Institute of the Punjab; photo covers chainage 524 to 790, approx.; photo by IRI: (a) centre gate open 27 ft, side gates closed, reservoir at elevation 1407 ft; (b) centre gate open 45 ft, side gates closed, reservoir at elevation 1426·5 ft

188. With a free water surface springing from the gate lip and continuing past the ends of the gate piers whenever a gate was part-open, the zones of horizontally sheared flow could not have existed. Erosion attributed by the Authors to cavitation induced by the assumed horizontally sheared flow was obviously due to other factors. The following are the most likely initial cavitation causes, in our opinion:

(*a*) vortices arising in the flow at the upper corners of the gate opening during part-gate operation;
(*b* high-velocity flow past small irregularities in formed concrete surfaces and at monolith joints;
(*c*) pressure reduction where the jet springs free at the rounded pier noses.

189. Figure 28 shows flow conditions downstream from the piers when the outlet operates with the centre gate open 27 ft and with it wide open. The pier ends are just outside the photo field at the left; the tunnel reach affected by the collapse begins just to the right of the structural support below the large placard. The situation appears to be that of a free jet emerging from the confinement of the walls and mixing with aerated quieter water some distance downstream. The flow is so complex that no isolated vortex source can be cited as the principal cause. Free water surface can be clearly seen even with heavy spray on the top of the circular tunnel section.

190. If there were two vertical shearing planes beyond the ends of the piers, the erosion of the invert of the tunnel would be approximately symmetrical. Fig. 8 indicates the contrary.

191. Justification for the Authors' statement (§ 37), that much of the erosion on the lower part of the right wall of tunnel 1 occurred during a 24 h period when this gate was open 8 ft, is not apparent. The pattern in general suggests that most of the erosion here occurred while the right gate was open approximately 38 ft for 5 days, 23–28 August, and that the convexity of the wall may have been a factor. The left wall is a mirror image of the right wall and was subjected to similar treatment for a much longer period (gate open 7 ft from 23 August to 4 September). Yet erosion pattern on this wall has little in common with that on the right wall (both are shown in Fig. 14).

192. The Authors state that tailwater levels immediately downstream from the gates must have been high when cavitation damage occurred in those regions (§ 51). As demonstrated earlier in this discussion, the condition downstream of the gates was that of a free, unsubmerged jet whenever either tunnel operated with less than two gates wide open. The Authors are correct in their surmise that they may have understated the velocities, but the difference has no practical importance in this context.

193. The Authors conclude that 'the patterns of invert damage described in the Paper are very similar to patterns observed at Roseires and both situations are entirely consistent with the hypothesis for sheared-flow cavitation' (§ 84). Roseires buttress dam has five sluiceways controlled by radial gates. The waterways are convergent, separated by square-ended buttresses and discharging into a short stilling basin with a large kicker block (a baffle block and energy dissipator) at the downstream end. As with many stilling basins throughout the world, this one suffered damage to its floor and kicker block.The HRS report[1] does not show any damage on the sluiceway walls. This outlet structure seems to have little in common with the Tarbela tunnel intake structure.

Mr Kenn and Mr Garrod

The Authors are delighted that the Paper has provoked so much useful discussion.

194. They are especially grateful to **Dr Baldassarrini**, and to **Mr Binnie** for his continued personal interest. Mr Binnie's present observations are of great relevance.

195. The Authors are indebted to **Mr Lowe**, **Dr Jaeger**, **Mr Murray** and **Mr Palmer** for their balanced overall views of the many problems at Tarbela. It is quite clear that if the intake gates could have all been closed at an early stage the sheared flows at high velocity would not have persisted and much less cavitation damage would have been caused to the tunnel intake structures.

196. Dr Jaeger, Mr Palmer and **Mr Miller** comment on the effects of boundary layers and surface defects. The Authors have recognized these influences,[67,68] and indeed the influence of the boundary transition from rectangular to circular tunnel cross-section is shown clearly (for tunnel 1) in Fig. 14. The upstream limit of erosion in the conduit section forms a straight line at the commencement of the conduit section (except for a small upstream projection of the erosion, probably caused by a local surface discontinuity). However, the field and laboratory evidence (Figs 5, 8, 18–20) suggests that the primary cause of the failure of tunnel 2 stemmed from the cavitation damage generated by the vertically sheared flows from gate 2 shown in plan in Figs 5 and 19. The cavitating eddies and the cavitation damage begin on the shear planes defined by the downstream edges of the pier walls of gate 2. Moving downstream the mists of cavities in the cavitating eddies grow in intensity, as does the damage intensity, and the greatest depth of invert erosion, 16·5 ft, occurred 120 ft downstream of the pier tails (after a time interval of about 1 s), presumably where the intensity of cavity collapse was greatest.

197. Even the asymmetry of the invert erosion in tunnel 2 (Figs 8 and 20), commented on by **Mr Chao** and **Mr Luecker**, is reproduced by the simplified model (Fig. 18). Mr Kenn's simplified models, tested under full-scale heads and velocities, also faithfully reproduced the deflected, vertically oriented, cavitating shear layers generated by the jet (shown in plan, Figs 5 and 19). Mr Kenn has also found, on another model, that whether the jet clings to the right or left wall is dependent merely on the sequence of closure of gates 1 and 3.

198. In general, cavitation damage arising from submerged, vertically sheared flows will occur on horizontal surfaces and vice versa. At Tarbela, however, the tunnel floor and walls merged into common curves after the transition region. Thus in tunnel 2 the cavitation damage (stemming essentially from the vertically sheared flows of the deflected jet leaving the pier inner walls) necessarily occurred downstream not only on the tunnel invert (Fig. 8) but also on the merging right wall (Fig. 7).

199. The Authors suggest the possibility that if the models at Lahore (Fig. 28) had been viewed from underneath, with dye injected upstream, the diffusing jet from gate 2 might have been seen when gates 1 and 3 were closed. Even with the relatively small-scale, low-velocity, Froude models tested at Lahore, some water and spray appear to reach the tunnel soffit (Fig. 28).

200. In retrospect, it would of course now be interesting to mount pressure-transducers appropriately on the Tarbela model invert, at Lahore, to try to detect the transitory low-pressure eddies of the diffusing jet, as described by Mr Burgess for his Roseires model.[1]

201. **Mr Burgess**'s test results (Fig. 26), and Mr Kenn's simplified model (Figs 4

and 17) tested at full-scale head and velocity, clearly account for the erosion pattern on the apron floor at Roseires. This was produced by the collapsing cavities in the vertically sheared flow leaving the right wall of the most used sluice, number 5. The mechanism of cavitation generation in a sheared flow is the same, in similar circumstances, regardless of its location or orientation.[2]

202. **Mr Smith** comments on the sharp edges of the erosion which coincided with the gate openings in tunnel 1 at Tarbela. This is typical of cavitation damage stemming from sheared flows and can also be clearly seen on the invert of tunnel 2, in line with the pier walls of gate 2 (Fig. 9). It has also been reproduced by the cavitating eddies generated in the sheared flows associated with Figs 17, 18 and 29(b). This type of damage is not produced at an air–water interface, which is why

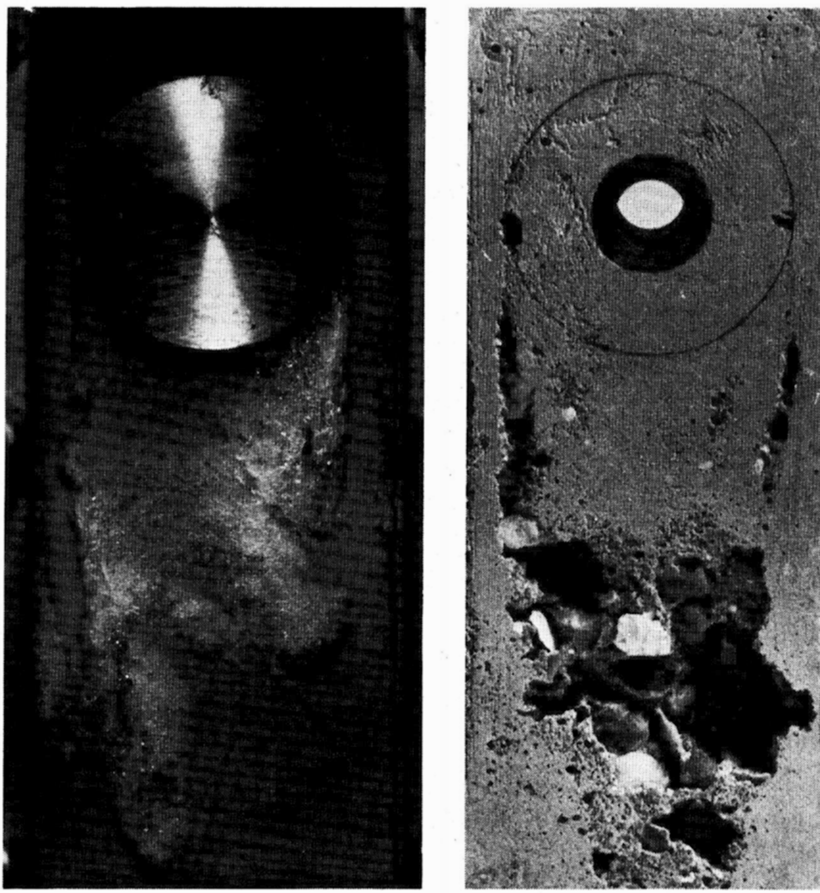


Fig. 29. (a) Cavitating eddies generated in the sheared flows downstream of a cylindrical pier; (b) associated cavitation damage to the concrete invert

(as **Mr Chao** and **Mr Luecker** note) no damage occurred to the sluiceway walls at Roseires,[1] where the jets emerging from the partly opened gates were flowing free to the atmosphere (until they reached the hydraulic jump located in the stilling basin).

203. At Tarbela, the presence of the cavitation damage on the pier walls downstream of the partly opened gates suggests to the Authors that the emerging jets were at least partially submerged in these regions when the cavitation damage occurred.

204. The mechanism is shown in elevation in Fig. 4 and the pattern of damage has been reproduced by the Authors (at full-scale head and velocity) in Fig. 17.

205. Damage to the apron floor and kicker block of the Roseirés deep-sluice structure stemmed from the cavitating eddies generated in the vertically sheared flow of the high-velocity jet leaving the pier of sluice 5. The type of flow pattern is clearly shown in plan in Fig. 4 and the mechanism has been confirmed by the tests of the Hydraulics Research Station at Wallingford and is outlined by **Mr Burgess**.

206. The vertically sheared flows in tunnel 2 at Tarbela (as portrayed, in plan, in Figs 5 and 19) behaved similarly (except for the anticipated deflexion) to the vertically sheared flow leaving the right pier of the most used sluice, number 5, at Roseires (as portrayed, in plan, in Fig. 4).

207. **Professor Arndt**'s considered comments on the present limited knowledge of the behaviour of cavitation in severely sheared flows at high velocities are very apt and are much appreciated. **Mr Miller** is surely wrong in saying that the prediction of cavitation damage is a simple matter or that the mechanics of sheared flows at high velocities have yet been fully described.[54] There is considerable difference between the behaviour of cavitating eddies generated in the severely sheared flows downstream of a solid object (such as a pier, butterfly valve, or partly opened gate) and that of the cavitating eddies generated within a boundary layer.[3–5,38,69] The contrast is shown clearly in Fig. 29 with high-velocity water flowing past a cylindrical pier. Cavitating eddies in the well co-ordinated alternating shear layers downstream of the cylinder produce particularly severe damage to the concrete invert. In contrast, the minute cavitating eddies generated in the boundary layers adjacent to the tunnel side walls occur away from these walls and cause almost insignificant damage.[2,9,67] Cavitation damage from boundary-layer influences appears to have been of minor significance in the Tarbela tunnels. Laboratory evidence has shown that cavitation damage can be particularly intense when it stems from severely sheared flows, and a smooth concrete finish provides little defence against this form of attack. Laboratory and field evidence do not appear to support the notion that air coming out of solution will cushion the cavitation collapse.

208. The Authors agree that further studies are needed concerning cavitation generated by vorticity in sheared flows. Professor Arndt's contribution confirms these views.

209. Mr Miller's faith in model testing perhaps needs to be tempered by the reservation that a universally constant force scale cannot strictly be achieved in any hydraulic model unless the model is built to full scale.[41–44,70–72]

210. **Mr Ackers** and **Mr Smith** draw attention to the possible inadequacy of the tunnel air vents. Inadequate ventilation would probably not have greatly influenced the cavitation damage to tunnel 2 stemming from the vertically sheared flows, except perhaps marginally to alter the location of the eroded holes. However, inadequate ventilation could well have contributed to the unexpectedly high

water levels and consequent submergence of the water jets emerging from the partially opened gates in tunnels 1 and 2.

211. A high air demand through the air vents, downstream of the intake gates, was presumably expected.[42,44,73,74] Water levels in the tunnels immediately downstream of the gates were never measured and they remain unknown. A water level of 1134·5 ft was assumed by the Authors only for determining a conservative estimate of flow velocities at the gates (§ 51). The Authors have not suggested that the tunnels were flowing entirely full, but have inferred that the jets from partly opened gates were submerged and that cavitation damage was caused to the piers and walls by the horizontally sheared flows.

212. The Authors agree with **Mr Hancock** that entrained air, if well dispersed and present in sufficient quantities in the right places, can markedly influence the effects of cavitation. Mr Kenn has successfully used this technique for suppressing cavitation, water hammer, and the associated resonant vibrations of the dam at Bolarque.[75] Other corresponding uses of entrained air have been recently and usefully reviewed by Quintela.[76] **Mr Murray** also refers to the use of air for this purpose.

213. **Mr Ackers**' queries and **Dr Jaeger**'s reservations concerning the influence of downstream pressures, together with **Mr Haigh**'s query concerning the influence of water velocity, may perhaps be answered best by contemplating the application, at full scale, of a conventional cavitation parameter (or particular form of Euler number), K, where $K = (H_D - H_{VP})/(H_u - H_D)$ (or, approximately, $K = H_D/(v^2/2g)$), where H_u is upstream total head, H_D is downstream pressure head, and H_{VP} is effective vapour pressure head. The denominator, $H_u - H_D$, represents the head available to generate cavitation; the numerator, $H_D - H_{VP}$, represents the head available to cause the cavities to collapse and hence cause damage.[20,29,38] Restriction of use of the parameter to full scale helps to avoid 'scale effects' otherwise introduced by the incorrect scaling of the other fluid-dynamic forces (including those due to viscosity, surface tension, elasticity etc.).

214. For similar downstream conditions or values of $H_D - H_{VP}$, the cavitation parameter (or Euler number) will have similar values in differing field situations for

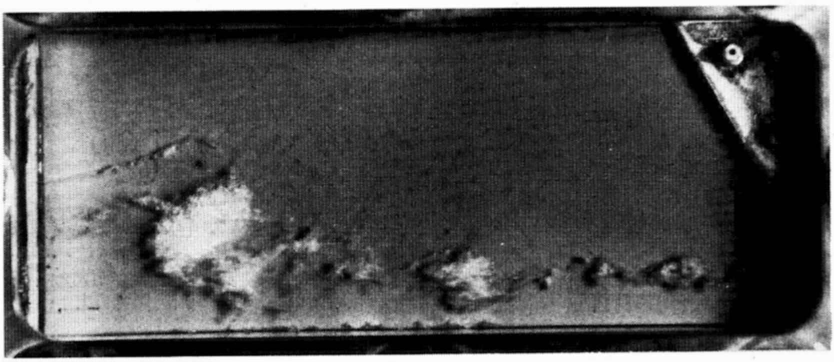


Fig. 30. Cavitating eddies in the sheared flow downstream of a gate lip: upstream head 242 ft; downstream head ostensibly at atmospheric pressure (flow right to left); photo exposure $\sim 5 \times 10^{-6}$ s

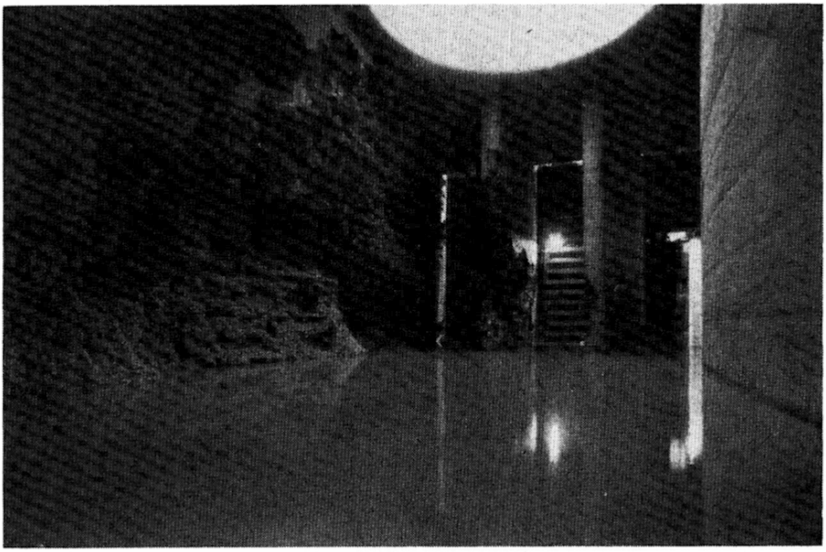


Fig. 31. Damaged intake piers and right wall of tunnel 1, viewed from downstream (courtesy Tarbela Joint Venture)

similar values of $H_u - H_D$, or velocity head, and therefore velocity. Accordingly the onset of cavitation damage to concrete, arising from cavitating eddies generated in severely sheared flows, ostensibly at near-atmospheric pressures (free-surface conditions), has occurred at corresponding sheared-flow velocities of about 100 ft/s at, for example, Roseires,[1,2,77] Tarbela, and various Electricité de France sites.[26] If the gate is more deeply submerged additional upstream head will be required in order to generate cavitation. However, the subsequent collapse of the cavities will be correspondingly more severe because of the increased value of $H_D - H_{VP}$. For interest, cavitating eddies in the sheared flow downstream of a gate-lip are shown in Fig. 30. With an unsubmerged gate-lip a horizontal shear layer would not be generated and cavitation damage would not be expected on the pier walls. This latter condition was exemplified at Roseires and is commented on by **Mr Chao** and **Mr Luecker**.

215. In tunnel 1 at Tarbela, the damage of the left-hand wall, at low elevations, would not necessarily be expected to correspond to that of the right-hand wall. Unlike gate 3, gate 1 had been cracked open for the 6 days prior to 22 August and it is believed that much of the invert damage, to a maximum depth of 11·4 ft just downstream of T1G1 (Fig. 14), was caused during this period. This deeply eroded hole would have influenced the flow patterns at the subsequent gate openings. The pattern of erosion on the right wall of tunnel 1 (seen in elevation in Figs 14 and 31) in fact resembles the pattern of erosion on the apron floor at Roseires, shown in plan in Fig. 26.

216. The Authors agree with Mr Chao and Mr Luecker that the downstream convexity of the wall probably aggravated the damage caused by cavitation to the right-hand wall in tunnel 1 (Figs 14 and 31).

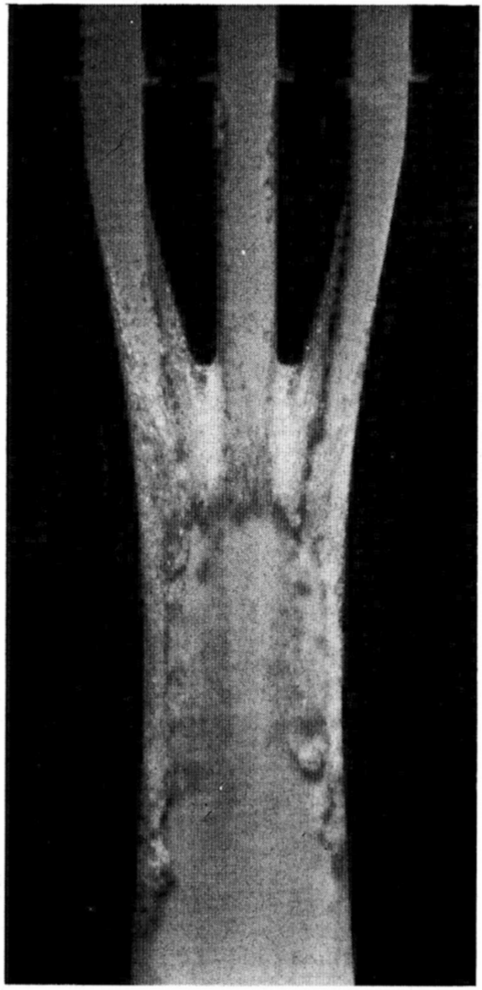


Fig. 32. Model intake structure operating under full-scale head and with all three gates wide open: severe cavitation may be generated by the sheared flows leaving the pier sides (flow top to bottom)

217. The Authors also agree with **Mr Ackers** and **Mr Palmer** that cavitation damage from vertically sheared flows would have been less severe with all three gates wide open. A probable pattern of flow is shown in Fig. 32.

218. The lesson drawn by Mr Ackers and Mr Palmer, that structures should be operated as intended by the designers, is perhaps a truism, which might hardly

justify this Paper. However, in the summer of 1974, although it was the unconnected accident of the gates jamming which extended the cavitation damage to disastrous proportions, the constraints on operation applied by the designers at the time of impounding did not preclude sheared high-velocity flows, whose relevance they apparently still do not accept. The Authors suggest that the essential lesson to be learned from the collapse of tunnel 2 is the destructive power of cavitation induced by high-velocity sheared flows.

219. The Authors believe that **Mr Haigh** must have observed air bubbles entrained behind his slowly trailed rope. Cavitation is a process of 'high-speed distillation' and is rather more difficult to induce.

220. In answer to Mr Haigh's other conjectures: it is clear from the evidence of sand-blasting in air that abrasion can occur in the absence of cavitation; conversely, when testing inert materials in clean water, cavitation damage can occur in the absence of abrasion.

221. Silt does not appear to have been a factor concerning the damage sustained by tunnels 1 and 2 at Tarbela. However, when using a silt-laden water it is conceivable that any cavitation damage may be modified by the silt presence. Kozirev's tests were not framed to establish this matter[2,10] and more recent tests by Du-Tong[78] were also inconclusive because of the test conditions.

222. Mr Kenn has observed cavitating vortices penetrating deeply into eroded holes and disappearing around and behind large pieces of aggregate. This behaviour may account in part for the characteristically rough appearance of cavitation damage.

223. The corner vortices referred to by Mr Haigh would not account for the damage patterns at Tarbela or Roseires. Downstream of sluice 5 at Roseires, intense cavitation was apparently generated in the vertically sheared flow leaving the right pier. Upon collapsing in the higher-pressure region downstream, the cavities caused cavitation damage to the apron floor and kicker block. In contrast little damage was apparent to the apron floor adjacent to the left wall, which implies that the influence of corner vortices was small.

224. The Authors wish to emphasize that the distribution of cavitation damage at Tarbela strongly suggests that it mostly occurred along the boundaries of the high-velocity jets emerging from below the gates or between the piers. If, in these areas, the jets were bounded by zones of comparatively still water, then the damaged areas corresponded to the regions in which sheared flow would have occurred, and this provided a mechanism which not only accounted for the damage but enabled it to be reproduced in a cavitating model.

225. Conversely, if the jets were bounded by air then the damage which occurred along these zones still awaits a plausible explanation. At Roseires the high-velocity jets between the piers were free to the atmosphere and damage was not caused to the pier walls. In contrast the apron floor *was* damaged by the vertically sheared flows of the jets leaving the pier walls.

226. In the Paper the Authors have endeavoured to use the available field data and to supplement their deductions with experimental evidence. By such means it was hoped that progress could be made. The many questions which have been raised in the discussion have added to the Paper and the Authors are much indebted to the contributors.

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Conversion factors

1 in	25·4 mm
1 ft	0·305 m
1 ft^2	0·0929 m^2
1 ft/s	0·305 m/s
1 knot	0·51 m/s
1 lbf/in^2	$6{\cdot}89 \times 10^3$ Pa