Dam disasters

by

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The Author, in introducing his Paper, said that he greatly appreciated the honour of being allowed to present his Paper on 'Dam disasters' to the members of the Institution. It was particularly gratifying to him that this opportunity should arise during the Presidency of Mr Mountain whom he had the pleasure of meeting about twelve years ago in connexion with some overseas work on which they were then collaborating.

62. The Author was particularly interested in Mr Mountain's Presidential address on the future of electricity supply, and he felt that the President's quotation from the late Sir Alexander Kennedy's Presidential address in 1906 might well serve as an introduction to his own Paper.

63. Sir Alexander pointed out '... that our modes of thought and action inevitably affect art, interfere with nature and even react on philosophy'.

64. Before going further, the Author would like to acknowledge the help which he had received from Mr Kenneth Hunter who lent his profound knowledge of the English language when revising the manuscript.

65. The failure of dams had, in recent years, been the subject of a number of technical papers and even symposia. It was the information provided by these papers, combined with occasional visits to the sites of past disasters, which led the Author to search for a better understanding of such failures.

66. A study of published information suggested that the failure of dams constructed in modern times might be attributed to either human error or to *force majeure*, while the failures of antiquity might, in general, be attributed to the inadequate engineering knowledge of the day.

67. Before continuing, the Author would like to make clear that in his Paper he had made no attempt to describe specific dam disasters. Where references were made to actual instances, this was done so only to illustrate the Author's general arguments and to provide a basis for discussion.

68. The earliest record of a dam failure was to be found in Sura 34 of the Koran which stated '... so we sent upon them the flood of Irem'.

69. The scene of this disaster was first visited by a Frenchman in 1843. It lay in the Yemen, 200 miles north of Aden, and concerned the Mareb Dam. The dam was built about 1700 B.C., and according to the records which had been handed down, it was breached about 100 A.D. The dam was two miles long and had a height of about 120 ft—a considerable structure even today.

70. Much further back, before recorded history, a study of geology provided evidence of the failure of natural dams formed of ice or rock. The bursting of such barriers was the consequence of a natural trend towards a state of equilibrium. Water especially possessed the ability to break out of any confining barriers, and when stored above sea level, there existed an ever present potential danger.

71. In recent years mankind had achieved some success in banishing many of the hazards to which human existence had always been subject. Among such ancient hazards were famine, disease, and, at least to some degree, war. But while science had secured notable successes in reducing those ancient risks, the progress of civilization had given rise to new ones. Today, human settlements, and the industries on which they depended, often lay within the flood route of great reservoirs. Should such reservoirs break out, it was very unlikely that those who might be legally responsible would find it possible to pay adequate compensation for the damage done. Such disasters might, indeed, be on so great a scale as to affect an entire nation and might require international aid.

72. Under the old League of Nations an attempt was made to provide a fund out of which compensation could be paid to those who might suffer from such calamities. More recently, a proposal had been put forward for an international insurance scheme based upon the principle that the more wealthy members should bear a greater portion of the burden than the poorer members. The scheme was similar to those which had been suggested to cover the risks arising from the peaceful use of nuclear energy.

73. The damage which might be caused by the sudden failure of a dam should be considered in relation to the benefits attributable to the reservoir. Where the benefits took the form of potable water supplies or irrigation, it was usually a fairly easy matter to determine their value. It was less easy, however, where a reservoir served a hydro-electric undertaking. This was especially so in the case of complex inter-connecting systems where dams built originally to provide storage might be subsequently used to provide a constant head. Another complicating factor arose from the loss of storage capacity due to silting.

74. In general, the highest values per unit of water stored could be attached to those reservoirs which served pumped storage schemes.

75. The works of civilization inevitably involved risks to the societies which they served. The invention of the ploughshare, which enabled early man to cultivate the soil, provided him, at the same time, with a lethal weapon. Wherever engineering structures were built to serve mankind, it must be accepted that in spite of every care taken in their construction there always existed the possibility of a disaster.

76. In dealing with dams it must not be forgotten that all calculations were necessarily approximate. The calculated factor of safety might appear liberal, but changes in the assumptions on which the calculations were based might result in a fatal reduction of the factor of safety. Over the years, the size of dams had steadily increased until now they were comparable with the hills and mountains among which they were constructed, and their behaviour was subject to the same basic laws which governed the rocks on which they rested.

77. The failure of a dam was followed by such dire consequences to human life that it became an inescapable duty to probe its causes and to present to the engineering profession the results of such an investigation.

78. The engineer could not divest himself of the responsibility for the dam which he had constructed, and he should never forget that however great his skill, all man-made works carried within them the seeds of their own eventual decay and destruction.

Mr J. A. Banks (Vice-President, and of Babbie, Shaw & Morton) congratulated the Author on the concise manner in which he had presented a subject of such great importance, not only to engineers, but to the world at large. The Author concluded that every dam which impounded water presented a potential danger, and the risk of sudden disaster was for ever inescapable. That was, indeed, a powerful statement, and it would seem to be supported by some of the records which were given in the Paper, particularly in §§ 7 and 8.

80. It was staggering to note that of 1764 dams listed in the United States about 2% failed, and of 1620 dams mentioned in the Spanish publication *Revista de Obras Publicas*, no less than 19% had been the subject of serious accidents. The engineer

concerned in the design and construction of dams could approach his problems calmly and in the light of the ever-increasing knowledge that was internationally available through the International Commission on Large Dams and other commissions and societies; but to ordinary people living in valleys with impounding reservoirs upstream, figures such as those which had been quoted could be very disturbing.

81. Under the aegis of the International Commission on Large Dams, a world register of dams was in course of preparation and Mr J. Guthrie Brown, a member of the Institution, was chairman of the sub-committee dealing with the matter. The register, which it was hoped would be published before the next International Congress on Large Dams to be held in Edinburgh in May 1964, would record particulars of dams exceeding 50 ft in height. The British returns which had been made revealed that in the United Kingdom there were 421 such dams. In view of the remarks which had been made about dam failures in other countries, it was pertinent to observe that, as far as Mr Banks knew, there was no record of any of those dams having failed, certainly not disastrously. Mr Banks did not intend to suggest that British engineers had been superior to others in their approach to the design and construction of dams, and there were not in this country risks such as glacial outbursts, but the figures were significant and perhaps reassuring.

82. There were, however, many smaller dams under 50 ft in height, and the effects of the bursting of such dams could be very serious. There were two on record and it was following the failure of these that the Reservoirs (Safety Provisions) Act, 1930, was passed. One, namely, the Eigiau Dam in North Wales had been referred to in the Paper. The other, which was not mentioned, was a small dam—Skelmorlie Reservoir—in south-west Scotland. It was significant that the latter reservoir had a catchment area of only 33 acres and a storage capacity of 5½ million gallons. Nevertheless, when, in April 1925, the dam burst (and it was not far from the sea), several people lost their lives. The cause of the disaster was of some interest. There was a quarry with a drainage culvert to the reservoir and this culvert had become choked with debris. During a period of heavy rainfall the quarry filled with water, and when it had developed adequate head, it burst through the choke in the culvert and the whole contents discharged into the reservoir. The flood could not be dealt with by the overflow which was simply a pipe through the embankment. The latter was overtopped and disaster followed. This emphasized that the failure of even small dams could have disastrous results, and it was a matter of gratification that in Britain there was the Reservoirs (Safety Provisions) Act which required dams exceeding 5 million gallons capacity to be inspected at least once in ten years and so ensured a periodic check on the adequacy of the design and a reasonable safeguard against deterioration.

83. The Author pointed out in the Paper that 'in the majority of cases failure occurred because the knowledge available at the time of the event proved to be incomplete'. The knowledge which had been acquired concerning soil mechanics in recent years, together with the knowledge that it was hoped to acquire in respect of rock mechanics, also the increasing reliance on model tests, all tended towards safety in the design and construction of dams. Incidentally, the very acquisition of knowledge had led engineers to construct very high dams on sites which, up to a few years ago, would have been regarded as quite unsuitable for dams at all. But uncertainties would always be present. There were imponderables such as the degree of uplift, what the rock conditions might be, and so forth, and it finally rested with the engineer responsible for the construction of the dam to see that the foundation was satisfactory. Probably no other branch of civil engineering work was more dependent on the practical experience and judgement of the engineer. Guided as he would be by technical knowledge, the engineer must in the end exercise his practical judgement. He must do so even if it meant departing from what academic findings might indicate. He should not hesitate to overrule any academic calculations, however

positive they might seem to be, if in his practical judgement there was any element of doubt about the safety of the reservoir.

Mr J. Kennard (Edward Sandeman, Kennard & Partners) said he desired in the first place to refer to the Reservoirs (Safety Provisions) Act, 1930, which the Author mentioned in his Paper, and to which Mr Banks referred, as it might be of some interest to know that Act was conceived.

85. Following the failure of the Dolgarrog Dam, his late partner, Mr Edward Sandeman, wrote a letter* to *The Times* (in 1925) drawing attention not only to Dolgarrog, but to defects which he had discovered from time to time during his inspections of numerous dams in many parts of the country. That letter evidently stirred the Government into action, with the result that soon afterwards the Reservoirs (Safety Provisions) Act was passed in 1930. It was gratifying to note that this country was the first to take steps to ensure the safety of existing and future reservoirs. It was true to say that since the Act became law, no dams forming reservoirs had failed in this country, although there had been partial failures during construction of three or four of them. It was worth noting that in the case of a large open storage reservoir, built in about 1870, it failed in 1951, notwithstanding that it had been twice inspected under the Act.

86. Generally speaking, the Act worked fairly well, although there were certain shortcomings. There were, however, at the present time many old dams which had never been inspected, and only last year he was asked to inspect three such dams, although the Act was passed over thirty years ago.

87. So far as new dams were concerned, the large majority in this country were designed by consultants specializing in that work; others by qualified engineers employed by water undertakings, often with the help and guidance of consultants. The Author had rightly and forcibly drawn attention to the many complex problems associated with the design of dams, and referred to the need for geological advice. He would no doubt readily agree that it was generally necessary to consult geophysicists and soil mechanics experts in the case of earth dams, and sometimes even chemists.

88. It was difficult enough for an engineer practising as a reservoir consultant, day in and day out for forty years or more, to keep abreast with new developments and modern techniques and to build dams on increasingly difficult sites at twice the speed to which his predecessor was accustomed. But when it came to the periodical examination of dams to ensure that decay and deterioration had not set in, and that the structures were properly maintained and safe, what did one find?

89. Mr Kennard said it struck him as very odd that a human being, individually, in his right senses, when concerned with his health and condition and in need of a check-up, would not dream of consulting a retired medical practitioner who was no longer up-to-date in his particular field or perhaps did not have access to the special equipment required to conduct the necessary examination and tests. Yet those very persons, collectively as a water authority, would often entrust the examination of a reservoir to a retired engineer who might have ceased to practise for anything up to twenty years, and in fact might not have been actively associated with the construction of a dam for perhaps a longer period. As the years went by, those inspections should be more and more thorough, and should not be confined to a superficial look at the embankment or a walk along the dam. In certain cases a soil mechanics investigation would be justified. In recent years it had become the practice to install piezometers and settlement gauges in earth dams, and uplift and deflexion gauges in concrete dams. Yet when the consultant had handed over the structure and the resident engineer had left the site, quite often the existence of those instruments was ignored and no further records were kept.

* For the text of the letter, see the Appendix at p. 369.

90. That attitude was wrong, and there was room for improvement along those lines in connexion with the records which had to be kept under the 1930 Act. It was no exaggeration to say that more attention was often paid to the cutting of the grass banks and the painting of the railings, and to the maintenance of the authorities' motor vehicles, costing, say, £1000 or £2000 each, than to a reservoir costing over £1 million.

91. It was interesting to read in a paper presented by Terzaghi and Leps¹⁷ some four years or so ago, dealing with the Vermilion Dam, California, in a remote area where access in winter had to be made by helicopter, that the authority there spent about \$10 000 per annum in carrying out an observation programme to read and analyse the piezometers, seepage flows, settlement and alignment gauges.

92. Turning to § 28 of the Paper, Mr Kennard said he confessed that he was somewhat sceptical about the reliability of providing a 'fuse plug' spillway. It seemed that to cause erosion of the plug an appreciable head would probably be required and there was no guarantee that the fuse would blow as designed. The proof of the pudding was in the eating, and one wondered whether the Author knew of any such fuse plug spillway that had been successfully used. There was a reference in the technical press recently of a model test carried out for a rock-fill plug for the Oxbow Dam for the Idaho Power Company, and it seemed that there was always the possibility of a rock-fill bank becoming more resistant to erosion in the course of time due to settlement and vegetation, and it would then possibly require a greater head to cause a breach.

93. The Author referred to the Oros Dam in § 17. From an account which Mr Kennard read at the time, it appeared that about 15 ft of uncompacted fill was placed on the embankment in three days. On the next day the fill was breached, but not before a depth of 2½ ft of water was overflowing over the whole length of the embankment. From that, it showed that even loose fill could be resistant to overflowing water and also some rock-fill dams had been specially designed to be overtopped during construction.

Mr R. H. Macdonald (Sir M. Macdonald & Partners) said that as he had had the privilege of knowing Mr Gruner for some forty years, he was very glad to have been given the opportunity of joining in thanking him for his Paper, and congratulating him on so ably giving it in a foreign tongue.

95. Mr Gruner's firm had been established in the field of dam construction for over 100 years, so it must be acknowledged that his experience well qualified him to give a Paper on dams of the past, though, by luck and by good Swiss design, none of the dams he had dealt with in the Paper was his own firm's, which was a splendid record.

96. The Author must be congratulated not only in coming here to give his Paper, but on being bold enough to deal with a subject which most people keep firmly at the back of their minds. Perhaps if the Paper had been entitled 'Lessons to be learned from dam failures of the past', it might have been less alarming and yet served a useful purpose.

97. A review was given by the Author in which foundation weakness was given as 40%, while floods accounted for 23% of dam failures; but most of the former probably also collapsed during severe floods. But if the floods had been miscalculated, failure of the dam should not necessarily be inevitable, as could be seen from the Author's example of the Rincon de Bonete Dam, which took an enormous excess over the predicted floods. Furthermore, the Kariba Dam, under construction, also took twice the estimated maximum flood without irreparable damage.

98. The fewness of dams collapsing due to earthquakes was remarkable. In Japan there were now some 200 large dams, yet in that country there were constant earth tremors and frequent disastrous earthquakes.

99. There should be little excuse nowadays for poor construction which accounted

for 12% of the failures. One wondered whether the fault lay with the constructor or with the supervisor. Perhaps an important lesson could be learned there, especially by private clients who might not be aware of the real necessity for strict supervision.

100. Could the Author give any example of 'incorrect operation' which seemed a curious reason for a dam collapsing? Further, it would be interesting to know whether ice pressure had ever caused a dam failure.

101. Mr Gruner gave defective materials as the cause of only 2% of the failures as against 12% due to poor construction. That spoke well of the choice of materials exercised by the designers. There was a hazard which might affect the older concrete dams, besides attacks by weathering or acid water; there might be a risk of deterioration of the concrete by some as yet unknown features of its constitution. Time alone would show.

102. One never seemed to hear of water seals at construction joints as giving irreparable trouble by faulty construction. It had been alleged that asphaltic or bituminous seals, which could be reheated, eventually hardened by slow evaporation of their volatile oils, when the plastic property on which the seal depended would be lost. It would be of interest to learn whether the Author had heard of instances where there had been real trouble due to seal failure.

103. One feature seemed to be common to all dams. The type of design made them critical to instantaneous collapse. No one yet seemed to have been able to invent a design for a dam which would show clear signs of pending collapse in the way that an elastic structure would do. In that respect a prestressed dam might well have an advantage over other types, even though the use of the steel introduced the additional hazard of deterioration of the metal.

104. Reference was made to the failure of the original Delta Barrage before it could be used. That led to an interesting adjunct to 'dam disasters', namely, that of 'dam failures to achieve purpose', either by recognition early enough of the inadequacy of the design, so that additional strengthening had to be done before filling, or by sheer inability to fill the reservoir due to excessive seepage, either through the dam and its foundations, or through the ground surrounding the reservoir.

105. It would be recalled that a year or two ago a lecture was given at the Institution by an Egyptian engineer who was bold enough to predict that fate for the proposed new Aswan High Dam. Most people probably thought him pessimistic; but the possibility was not unreal, for Mr Macdonald knew of a dam 300 ft high in Southern Spain which had never held water due to seepage into limestone caverns, and it would be interesting to learn of any others.

106. Several dams had been strengthened after construction. The original Aswan Dam was one, having to have downstream protective aprons constructed a very few years after the dam was put into use to obviate erosion at the toe, which, if not checked, would undoubtedly have led to its collapse. One of the abutments at Kariba had recently been strengthened, and both abutments of the 900-ft-high Vajont Dam had also been recently strengthened by prestressing, the reservoir being kept empty in the meantime.

107. The Glen Devon Dam had had to be emptied and regouted to prevent heavy initial leakage. The existing Aswan Dam had also been recently grouted up after many years of active use, apparently so as to be able to raise the permissible maximum water level by 1 m. It was understood that some grouting of the rock surrounding the Dokan Dam was being done. There were probably scores of instances of 'post-filling' strengthening of dams throughout the world.

108. The Author's allusion to the El Habra Dam failing due to the high specific gravity of the water load charged with silt was interesting. Although probably hundreds of dams had silted up in past ages, one did not seem to have heard of one failing by being converted into a retaining wall by the accumulation of silt. Perhaps the Author knew of some instances. Loss of usefulness by silting was important in

small dams, but seemed to be much less so in large dams. If given long enough, however, all reservoirs would eventually silt up.

109. High dams which had lost their usefulness by silting were all very old dams; and it was understood that there were many such ancient dams in Arabia. The dams were still there, but had now been by-passed by the river which had scoured its way past one of the abutments leaving the dams high, dry and useless.

110. To return to the Author's suggestion as to safety precautions for dams, it was doubtful whether his suggestion for a flood-warning system for those living below high dams would be very welcome in this country, where it would be interpreted as either a clear warning that the dam was really unsafe or, at best, as an infringement of the rights of those likely to be affected, for which there was no warrant. It would not be possible to get dams built in this country at all if the public were needlessly alarmed about their safety.

111. There had been a suggestion recently—it was thought to emanate from Russia—that the design of dams should be codified, and that the construction materials such as concrete, etc., for the dams should also be codified. That might well be useful, but Mr Macdonald for one felt that human ingenuity being what it was, someone was bound to stretch up to, if not beyond, the borders of existing knowledge in the quest for novel designs, and for novel materials; but the quest might be well worth the risk, and codifying the design would do a real disservice if it stifled initiative.

112. In conclusion one might suggest as a safety precaution that engineers licensed to design and inspect dams, and contractors allowed to build dams, be made to read, and even memorize, a representative list of failures of the past. In fact, the Paper might well be proposed as 'required reading' for dam designers, and would then perform a useful function in its own right in ensuring future safety.

Mr J. K. Hunter (Sir Alexander Gibb & Partners) said he was glad to avail himself of the opportunity to take part in the discussion of Mr Gruner's Paper, particularly as he found himself so much in sympathy with its basic philosophy. He did not intend to offer any comment on matters of detail, but merely to deal in rather general terms with some of the more salient points which had struck him.

114. The Author had given several impressive examples of dam failures which had occurred over the past 100 years, starting with the collapse of the Mohammed Ali Barrage on the Nile in 1867 and ending with the destruction of the Oros Dam in Brazil in 1960. The uninitiated might suppose that as more became known about the building of dams, failures would become less frequent. But that was not supported by the available statistics, and the Author had prefaced his Paper by referring to no less than three important failures which had occurred in 1961.

115. Such disasters inevitably involved heavy loss of life, and it was not an exaggeration to claim that in no field of engineering endeavour were the responsibilities to the public so great or so exacting as in the design and the supervision of dams to impound large bodies of water. Moreover, in no type of engineering work were the stakes, in terms of human life, so high.

116. The Author referred to the setting up in 1929 of the International Commission on Large Dams which had since provided a permanent world organization for the advancement of the science of dam building. During the past thirty years it was undoubtedly true that much progress had been made, and yet it might be questioned whether that progress could be compared with that achieved in other fields such as medicine, agriculture and physics. It would seem, indeed, that it was only in the field of soil mechanics that any really significant progress had been made.

117. In spite of the knowledge gathered over the years there remained today a wide diversity of opinion among engineers on a number of matters of vital importance to the construction and safety of dams.

118. In reviewing the papers submitted to the Large Dams Conference held in

Paris in 1955, the General Reporter drew attention to several aspects of dam design which were still the subject of diverse, and, indeed, opposing, views. Among them, he mentioned uplift, the choice of type of dam best suited to the prevailing foundation conditions, and the effect of earthquakes on the choice of type.

119. The construction of a dam inevitably created a hazard for those who inhabited the valley which lay downstream and it was, therefore, the duty of the engineer to ensure that the dam for which he was responsible was and should remain as safe as it was humanly possible to make it.

120. As the Author had already pointed out, safety was a comparative term, for there could be no such thing as absolute safety. Moreover, the real factor of safety of a dam—a term which was itself difficult to define—could never, as the Author had indicated, be known with certainty. It could only be estimated by making several assumptions, some of which were not subject to proof. It must be accepted that the real factor of safety might sometimes be quite different from that assumed—a consequence which became tragically apparent when a disaster occurred.

121. Over the past thirty or forty years experience of dam failures had led in the majority of highly-developed countries to the introduction of legislation to control the construction of dams in the interests of public safety. In Great Britain such legislation was introduced in 1930 as a result of the Dolgarrog disaster. Briefly, the purpose of the Act was to ensure a periodic review by a competent engineer of the safety aspects of every significant reservoir in the country, and to provide that no new reservoirs would be created except under proper supervision. But Mr Kennard had pointed out that, although more than thirty years had passed, there were still several reservoirs which had to be given their first inspection.

122. The Author had given an example in his Paper of the financial consequences which might follow in the wake of a bursting dam, and a moment's thought would make it clear that calamities as those had often been in the past, they were insignificant compared with what could conceivably occur. Without doubt, the British Act of 1930 had not only made the owners of reservoirs conscious of their responsibilities towards the public, but, by bringing reservoirs under continual review, had greatly reduced the risk of disaster arising from neglect.

123. As the Author had pointed out, the responsibility under common law for the consequences of a dam failure lay on the owner, which meant that those who suffered financial loss must look to him for compensation. It seemed clear, however, that except possibly in the case of the large nationalized boards, which might reasonably be supposed to be supported by the resources of the State, claims for compensation might well be on such a scale as to be beyond the capacity of the owner.

124. That raised the question of some form of compulsory insurance to protect the public. The need for such protection had already been recognized by Parliament in the case of the hazard created by nuclear reactors. Under the Act of 1959 the owner of a reactor was required to cover himself by insurance up to a limit of £5 million. Beyond that figure Parliament would provide compensation. But who was prepared to say whether a nuclear reactor represented a greater risk than a reservoir?

125. Not all reservoirs were owned by national boards, and, in these days of the Welfare State, the desirability of reviewing the provisions of the 1930 Act was worthy of consideration by members of the Institution. As the Act stood at present the financial penalties for non-compliance were wholly inadequate. The maximum penalty which could be inflicted by the courts upon an owner for refusing to comply was a fine of £500. It seemed that the time had arrived when the whole question of protection of the public against financial loss should be reviewed.

126. Many countries with a greater awareness of the importance of the public safety aspect possessed powers to require the owner of a reservoir which was deemed to be unsafe to dismantle the dam in such a way that it could no longer constitute a

potential danger. Such powers provided an effective means of protecting the public interest.

Dr Charles Jaeger (English Electric Co. Ltd) said that to the lists of dam disasters mentioned by the Author it was worth while adding a list of 42 earth dam failures published in 1951 by Messrs Charles Mallet and J. Pacquant, with short comments on each case. Those concerned must be struck by the number of dam failures, some of them causing hundreds of deaths.

128. Concentrating on what happened in very recent years, it was known that there were, in addition to the tragedies of Vega de Tera, in Spain, and Malpasset, in France, over half-a-dozen dams where either substantial reinforcements of the rock abutments or of the dam itself had to be carried out in the past few years, or where the reservoir was still maintained well below its foreseen normal level because of doubts about the dam safety when possible reinforcements were still being considered. In a few of those cases, partial or ample information was available. In most cases, however, information was kept as a closely-guarded secret and none was volunteered. Even when all the facts about difficult designs or difficult dam foundations were carefully analysed, as for the Malpasset Dam disaster, understanding of what were the causes of the trouble was often only partial. Further advance in the technique of dam design could be achieved only by systematic and free discussions, not of one isolated case but of all the cases with all their particular characteristics. If those two points were accepted, the conclusion was that detailed reports were needed, as well as analysis of all the dams where difficulties occurred either with the dam itself or with its foundation.

129. To illustrate the first point, the case of the Malpasset disaster could be quoted. A full technical report with 41 bulky appendices was available. The information volunteered comprised the geology of the whole area, the dam design itself, and the checking of the strains and stresses in the dam; the analysis of the physical properties of the rock, and a detailed description, backed by measurements and calculations, of the two principal phases of the dam failure.

130. The cause of the failure was said to be weakness of the rock, but when it came to give a coherent physical description of what was meant by 'rock weakness', the opinions of the commentators diverged. Rock weakness at Malpasset could be an undetected weak rock layer, as suggested by Terzaghi, or a local low value of the modulus of elasticity, or uplift pressures in micro-fissures of the rock, or any combination of those causes. Present knowledge of the physical properties of rock and of the statics of rock abutments was not sufficient for determining with absolute certainty the real causes of the failure.

131. The second point followed then immediately. In order to widen present knowledge of rock mechanics for dam foundations, more cases of difficult dam conditions must be analysed and a considerable amount of additional research work and testing had to be done in the research laboratories and in the field.

132. One of the most urgent aims of rock mechanics was to devise a series of typical rock tests and to produce an elementary classification of rocks for the purpose of guiding the civil engineers in charge of dam designs. That required a considerable effort.

133. That classification would benefit from whatever correlations could be established between the different properties of rock tested in the laboratory and rock tested in situ. An example of correlation of great importance, well worth further consideration, was that shown to exist between the index of rock alteration as defined by Serafim of Portugal and the crushing strength and modulus of elasticity of the rock. Other types of correlations still not exhaustively analysed were correlations between the different moduli of elasticity, static, dynamic, plastic and elastic, and the rock strength.

Mr R. C. S. Walters (Herbert Lapworth Partners) said that in § 42 of the Paper the Author referred to periodical inspection of reservoirs, which apparently in Switzerland was not carried out after the first inspection. If the Author expected Mr Walters to give an account of the dam disasters for which he had been responsible, he would be disappointed! The nearest Mr Walters had got was to note suspicious circumstances in many old earth embankments of no great height, but, as previous speakers had pointed out, no less dangerous, such as dishing crests, decrepid tunnels, defective overflows, no means of emptying, trees, and cloudy water coming from leaking tunnels, and generally what he liked to call 'suspicious old dams' for want of a shorter term! Such dams should be inspected regularly.

135. In §§ 27–32 the Author referred to spillway capacity. In England it was a difficult problem to keep to a reasonable minimum cost of a spillway according to the size of gathering ground and assessment of the catastrophic flood. Although perhaps, compared with continental conditions, it was not quite so important, because spillways might not be quite so expensive, however large one made them. A site on which it was necessary to confine the supply of water between two dams, one upstream and one downstream, meant dealing with flood water, either by pumping or by a tunnel going under the reservoir. Such tunnels, perhaps 4 ft 6 in. in diameter, were not pleasant places to walk through nowadays; for example, one of them had sagged some 18 in. in the middle, and could be dangerous.

136. English practice in water supply did not provide for any particular form of gate overflow, possibly because of a suspicion of mechanical contrivances. The water supply people in this country did not have the facilities for operating press-button controls for emergency gates. There was some nervousness about our dense population. Sites were isolated, and there was a reluctance to empty reservoirs for water supply, because of a risk of a shortage of supply following a drought or a dry summer.

137. In § 9 the Author showed that the percentage of failures, according to the Spanish list, through spillway inadequacy and foundation failure amounted to 63%. The estimate given was about right for English conditions, but three or four reservoirs in this country had recently caused some trouble because of slipping owing to excessive pore pressures.

138. That led to § 48 in which the Author said that deterioration of a dam was a slow process. Most of the disasters had occurred fairly quickly after construction, and one wondered whether the embankments, after they had got rid of pore pressure, were in one respect stronger. They might have sagged, but if additional material were put on them and crests were brought up to their original level, they should be all right; the earthen part had probably got rid of pore pressure and was relatively stronger.

139. In § 35 the Author referred to the collaboration between the engineer and the geologist. In some cases they seemed to work in separate spheres, not as a team, and did not quite appreciate each other's points of view. The geological formation meant a great deal to the geologist, whereas it might not mean so much to the engineer. In France the engineer responsible for a scheme did not appear to assume any geological responsibility whatever.

140. The Author also referred to 'political masters', and it was not absolutely clear what he meant by 'political masters'. If he meant his employers, there might be a good deal of discussion on the matter which might perhaps be better left unsaid in the Institution! Dam building was the only form of engineering which was the subject of an Act of Parliament in this country, and, for that matter, most other countries, and the engineer should not be fettered, particularly in the matter of finance, by his employers who, in many cases, consisted of Boards composed of laymen whose only object, quite rightly from their point of view, was to cut down expenditure. The engineer's mind must not be clouded, when engaged in constructing a dam, by the question of expenditure.

Mr T. N. W. Akroyd (Consulting Engineer) said it was clear that when considering damage on a large scale, the apportionment of responsibility and liability for the damage was important. There appeared to be a theme running through the Paper that most catastrophic failures were due to gaps in the state of knowledge at the time of construction of the dam. For example, it was now known that pore pressure could cause porous rocks to behave under stress like a material which possessed no internal friction, and it could cause a fundamental change in their behaviour from that when partly saturated.

142. On the other hand, as in the case of the Rio Negro, it might be impossible to estimate the extent of possible rain storms, and the design might have incorporated in it, all unbeknown to the designer, the seeds of an inevitable accident—a catastrophic rain storm termed an ‘Act of God’. This was an unhappy irreligious expression, but one which meant an operation of nature so unexpected that no human skill or foresight could anticipate it. In those circumstances, assuming that neither the engineer nor the contractor nor the owner of the dam had been negligent in its construction, then no one would be liable for the damage caused.

143. Mr Akroyd pointed this out, in order to draw attention to §§ 52 and 53 of the Paper. No one could, of course, take exception to § 52, but in § 53 the Author mentioned the case of *Rylands v. Fletcher*, where the water from a reservoir did serious damage to an adjacent mine. But in that disaster there was an element of negligence on the part of the contractor. The Author quoted from the case, but had unfortunately omitted part of the judgment (§ 52); this should continue: ‘... and, if he does not do so, is *prima facie* answerable for all the damage which is the natural consequences of its escape. He can excuse himself by showing that the escape was owing to the plaintiff’s default; or perhaps that the escape was the consequence of *vis major*, or the Act of God. . . .’

144. Following the *Rylands v. Fletcher* case, there was another case involving an artificial lake. The lake had been constructed by damming up a stream, and during a very heavy rain storm the lake burst its banks and carried away four county bridges! The heavy storm was held to be an Act of God and the lady who owned the lake was not liable for damage caused. That case (*Nichols v. Marsland* (1876) followed the *Rylands v. Fletcher* case; the cause of the failure was held to be an Act of God, and that there was no liability on the owner of the dam. That was a startling result when one bore in mind the emphasis which had been laid upon the liability of the engineer. In addition, there was evidence to suggest *Rylands v. Fletcher* might not apply to local authorities or to statutory authorities; these of course included most owners of large dams. It seemed, therefore, that there was a gap in the chain of responsibility. If, as the Author suggested, catastrophic failures were due to gaps in the state of knowledge at the time of construction of the dam, then there would be no responsibility, under *Rylands v. Fletcher*, for any consequent damage due to the failure of the dam.

Mr E. M. Gosschalk (Senior Engineer, Sir William Halcrow & Partners) said the Author had pointed out the crux of the matter. It was impossible for a designer to ensure with absolute certainty that any dam would not at some time fail. In present circumstances it was left to the judgement and conscience of responsible individuals to decide with what degree of security a given design should be imbued. The failure of a dam was in many ways unique among failures of civil engineering structures in the form and calibre of disaster which it might bring, and individuals should not be expected to carry such invidious responsibility in peace time. If, from discussions such as the present one between engineers, an internationally-accepted code of practice for safety in the design of dams could be evolved, the result would be of great value in fortifying not only the engineers concerned, but also those who might be affected by disaster.

146. Perhaps the greatest uncertainty for the designer of a dam was the probability to be chosen that the designed capacity for flood discharge past the dam might prove

inadequate during the foreseen life of the structure, say, 100 years. Accepting that it would almost always be uneconomic, if not entirely impracticable, to provide sufficient capacity for the most improbable flood which might yet however be conceivable, no doubt the probability of inadequacy to be accepted need not be so exacting when the reservoir was to contain only, say, 50 acre-ft and was never likely to threaten more than a scattered population, as it must be near the other extreme when the reservoir was to contain perhaps 100 million acre-ft and would dominate a large city. Even in the former case, however, the choice might involve the lives of persons not consulted, and presumably any foreseeable chance that the spillway capacity might be disastrously inadequate for a flood during the life of the structure should be remote to some degree.

147. The matter might be rationalized if it were made obligatory to take out comprehensive insurance for all dams. The cost of the premium would be expected to vary with the degree of security of the design, and would become a factor to be reckoned in the economics of the design. Unfortunately, in the present state of knowledge the risks were very difficult to assess, even by experienced engineers. The matter was further complicated in a multi-stage development, because the failure of one dam was likely to threaten any others downstream of it.

148. To give an illustration of the present difficulties, in the case of one important rock-fill dam, Sir William Halcrow & Partners concluded that the reservoir should be designed in probability not to exceed a certain static level with an expectancy more often than about 1 in 10 000 years, and in view of the vast capacity of the reservoir, and the magnitude of the disaster should the dam fail, the full requirement for free-board was met in fixing the crest of the dam at 10 ft above the designed static water level. In a changed economic climate the same problem was presented to an American firm of engineers who also adopted the same crest level and concluded that the frequency of the worst flood to be considered should be about 1 in 10 000, but with that flood they accepted a water level lapping the crest of the dam, while maintaining water levels 10 ft lower for floods with a frequency of more than 1 in 100 years. Both those assessments were no doubt valid in their own contexts, but the differences between them, which might appear subtle, were in fact very real. In practice the former could deal with a much larger flood without disaster than could the latter, and the effects on the land and inhabitants on the fringe of the reservoir between crest level and 10 ft below that level in the two schemes were significantly different. It might be difficult to credit alternative schemes with the value of such relative security, but the cost of providing the two different degrees of security was no doubt quite tangible. The difference between, say, 1 in 1000 and 1 in 10 000 might seem academic unless it became the difference between disaster and safety in a specific year.

149. It should be mentioned that the concept of frequency and probability in relation to large floods was almost inescapable, but its application must remain restricted until all the factors affecting the occurrences of such floods were better understood.

150. Mr Gosschalk suggested that foundation failure, although the most frequent cause of the failure of dams (apart, questionably, from old age), did not offer the same dilemma to the designer as did the selection of the design flood. Having decided upon a degree of flood which he must accept could cause failure of the structure, the designer had a mandate to take every precaution which he could foresee might be necessary to ensure that the foundation would be secure at least unless the design flood were exceeded. Since foundation conditions were invariably uncertain, that required the application of a factor of safety to the foundation design under disastrous flood conditions. It was apparent from all those considerations that a realistic assessment of the degree of security of a dam required the investigation of both ultimate and working conditions.

151. The effect of the type of spillway on the security of the dam as a whole had to be considered. Clearly an uncontrolled spillway was more reliable than a spillway

controlled by gates which for some reason might not operate when required. The probability that such gates would not operate must be considered, and it was a practice of Sir William Halcrow & Partners to ensure that the structure itself would not be endangered, even if all control gates should remain closed during exceptional flood conditions.

Dr M. F. Kaplan (Director, Civil Engineering Research Council) said that members of the Institution would know of the formation towards the end of 1958 of a committee to study critically the methods of designing arch dams. The work of that committee was initiated by the Institution and was now being supported by the Civil Engineering Research Council.

153. In § 7 of the Paper the Author referred to a list, prepared in the United States, of 1764 dams which had been built up to the year 1959. In the 40 years between 1918 and 1958 there were 33 failures, 10% of which were multiple arch dams, whereas less than 1% were failures of concrete arch dams. On the other hand, the information in § 8 seemed to give a different picture. The Author referred to 1620 dams built up to 1961, and stated that some 308 of those dams had been the subject of serious accidents. Of these dams, seven were multiple arch dams, whereas 70 were concrete gravity dams. In other words, the failures of concrete gravity dams in that list were ten times greater than those in multiple arch dams. In the list given in § 7 it was the other way round. Perhaps the Author could explain the difference.

154. Referring to § 9 in connexion with the causes of failure of dams, it would be interesting to know from the Author whether in the Table which appeared in that paragraph he was referring to the list in § 7 or that in § 8.

155. It was recorded that 40% of the failures were due to foundations. There was also the heading 'uneven settlement' which gave a figure of 10%. Perhaps the Author could say whether uneven settlement was in any way related to foundation failures. If so, it would appear that approximately 50% of the failures recorded were due to the foundations. It would be interesting to know what proportion of the arch dam failures had been found to be due to foundation failures; similarly, for gravity dams.

156. At the end of 1960 the United States Bureau of Reclamation sent a team of three to Europe to study European practice in the design and construction of dams. It was interesting to note that they reported that the most basic and comprehensive study of arch dams was being made in Great Britain, and they referred specifically to the research which had been initiated by the Institution and which was now being financed by funds from the Civil Engineering Council.

Mr A. C. Twort (Binnie & Partners) stated that he had been present at a dam failure. But he hastened to reiterate that it had been a failure and not a disaster and that he himself had been the occasion rather than the cause of it. This failure occurred to a 50 ft high, 100-year-old earth dam in Staffordshire while it was being prepared for the construction of a new dam alongside. Full particulars of the event would be available in due course; for the moment he wished to deal only with the errors of thinking which permitted the failure to occur.

158. The first error he wished to speak about was one which was extremely difficult to avoid, and it was likely that such errors would occur again in the future. Several borings had been sunk through the old dam and a trial pit had been excavated. From the results of these and the related soil tests, it was very well known that the dam was in a weak condition. Even so it failed because its condition proved to be much worse than anyone had expected. The reasons for this were later to be revealed, the principal one being that the dam appeared to have failed in that section some 80 or 90 years before. This fact was not, of course, known before the recent attempt to raise the dam. The particular point of note here was that it was extremely

difficult, even when one knew that something was bad, to get hold of the idea that the situation was, in fact, a great deal worse than one had allowed for already. One could not, by thinking alone, obtain different thoughts from the ones one already had.

159. The second error was this. The dam was known to be in poor condition; the results of all the boring tests had been very carefully inspected in the light of present day knowledge. In effect what had been done there was to use the knowledge of today in trying to interpret work carried out in a by-gone age. This led to errors in assumptions. Thus, to take an instance, the original borings had revealed rock in some parts of the dam and this had led to the belief that in those areas the dam should prove to be more stable than elsewhere. In fact, the contrary was the case; because this rock was later revealed to comprise purpose-made rock-fill drains to take away leakage from the disrupted portion of the dam resulting from the earlier failure.

160. On a third point he was particularly sensitive. This was the idea (previously mentioned in discussion and often quoted elsewhere) that a dam which had stood for any length of time would be likely to have gained strength from natural consolidation. As far as Mr Twort's experience indicated, that might not be the case and a dam which had stood for a century might still fall down tomorrow. The same kind of error of thought was likely to arise when using a term such as 'a 1000-year flood'. That description did not imply that the event would not happen tomorrow. Hence he agreed most strongly with Mr Gruner's statement that the primary cause of failures was lack of knowledge at the time; but to this he felt should be added an equally potent cause, namely, *unawareness* of ignorance.

161. In a supplementary letter Mr Twort wrote that he wished to clarify his remarks which had been made extempore. On reflexion, he thought that use of the phrase 'error of thought' was itself in error. More precisely, it was a gap, or lacuna, in the process of thinking—a thought which it would have been extremely useful to have enter one's head, but which did not. He wished also to make it clear that all these 'gaps' in thinking mentioned, he had himself committed, since he had probably spent more time thinking over the puzzling features of the old dam than anyone. It was always easy to be 'wise after the event', but exceedingly difficult to be wise before. One only had to ask oneself the chastening question: 'What errors am I committing now that I do not know about?' to realize the difficulty of finding the right answer to that question.

162. He would like also to draw attention to the great difference that existed between the 'factor of safety' for a dam and that for a framed building, for instance. For a building the actual factor of safety applying could be split into two parts: (i) the degree to which the actual loading approached the design loading, and (ii) the degree to which the actual strength of the structure approached the assumed strength. This latter portion usually formed the quoted safety factor, and was often of the order of 2 for framed buildings.

163. For many such buildings, however, the median value of the actual loading was well below the design load. To cause an approach to the latter, there might have to be an event whose probability of occurrence was small; and to cause an approach to 200% the design load (thus nullifying the strength safety factor), there might have to be an 'extreme' occurrence of great rarity. Similarly, failure by lack of strength had a statistical nature to it, since catastrophic failure of a building usually required the occurrence of sub-standard strength in several parts of the structure at once.

164. For a dam, however, there was no chance nature about the load. It started at 99% or maybe 99.9% of the design load and stayed at that. The quoted strength factor was often a good deal less than 2.0, and there was a much greater variance in the actual strength factor than for a building because our knowledge of foundations and soils was not so precise and well attested as our knowledge of steel and reinforced

concrete. Furthermore, in the case of a dam, the time factor could reduce strength, for, if a weakness existed, it could be magnified with time.

165. The rarity of building failures (relative to the number erected) stemmed from the low probability of the design load being approached or exceeded, combined with a strength safety factor having a relatively low variance. But dam failures, as Mr Gruner had noted, were frequent and this arose because full loading was almost a certainty and there was a large variance attached to the strength. The only practicable way to build dams 'as safe as houses' was to reduce the variance of the strength safety factor by extending our knowledge of foundations and the behaviour of soils.

The following contributions were received in writing:

Mr A. H. Clark (Senior Engineer, Sir William Halcrow & Partners) wrote that the Author made the following remark in the concluding paragraph of his Paper: 'Every dam which impounds water presents a potential danger which should neither be under-nor over-estimated.'

167. No one would deny the truth of it. It underlined the position in which an engineer was placed when he undertook a commission to design a dam. In this country, the Reservoirs (Safety Provisions) Act of 1930 placed the responsibility for the safety of a dam on an individual. Admittedly, that individual had to have sufficient experience of the right kind to satisfy the President of this Institution to enable him to advise the Home Secretary that the particular individual was competent to undertake the work. The duty imposed on the President was without doubt most carefully and conscientiously carried out and was, in itself, an exacting one, but not, perhaps, quite so onerous a responsibility as rested upon the engineer for a dam. It was known that, not infrequently, an engineer did consult another engineer, or a panel of engineers, over the design of a dam, particularly if the structure was large or important. Such consultation, though highly desirable, might in most cases be voluntary and analogous to the medical consultant taking a second opinion over a diagnosis. It was suggested that there might be merit, in the knowledge of the great responsibility resting at present on a single engineer, of it being made obligatory for a design to be vouched for by at least one other engineer, i.e. certificates required under the Reservoirs Act would bear two signatures instead of one. Sharing of responsibility in that way might, it was felt, be welcomed by most engineers and if any lessening of the risk of failure were achieved by so doing, it would appear to be well worth while.

Mr P. Baumann (Consulting Civil and Structural Engineer, Sierra Madre, California) wrote that in an impressive yet fascinating manner the Author combined statistics with words of caution that should be heeded by all engineers who were or might be concerned with the design, analysis and construction of dams. Of particular significance was the Author's reference to the so-called factor of ignorance. Technical advances notwithstanding, this factor was still, and probably always would be, a part of the 'equation'.

169. The trend toward higher dams of all types which had been extant for some time should call for sober reckoning and scrupulous weighing of the relative importance in regard to safety in light of known, little known or (as yet) unknown factors. The influence of temperature and especially intense sun exposure of the downstream face of a thin concrete dam, opposed by cold-water exposure on the upstream face, probably fell within the 'little known' category, whereas the behaviour of foundations over a period of perhaps 100 years, as often used as the amortization period of such dams, might well be placed in the 'unknown' category. The latter mainly because of the circumstances that the longer a dam had been in operation, the greater the expectation became of the occurrence of major natural or man-made disturbances. Among the natural disturbances should be mentioned not only those of seismic

origin but also such phenomena as 'growing' mountains, often observed in the Alps, and the tremendous forces thereby mobilized.

170. The Paper could not help but strengthen contention that, as an engineering structure, a major dam on a natural stream was in a class of its own. Once constructed, it must be maintained and kept in the best of repairs lest an asset became a liability. Even minor dams should be treated as if they were larger, so as to avoid by all reasonable means their failure. For any dam failure would eagerly be exploited by the Press in view of it being sensational and would, so far as public sentiment was concerned, be a black eye to the engineering profession.

171. He could never forget the wise remark by the late Professor Narutowics of the Swiss Federal Institute of Technology (which was also the Author's Alma Mater) in regard to dams. He said: 'If in your engineering career you should be faced with the design of a dam, always remember that after its construction you still have to sleep!'

Mr V. J. Sevia (Baghdad, Iraq) wrote that the Author deserved congratulations for his contribution to a subject presenting growing interest when needs and control of water resources all over the world necessitated construction of dams. Adoption of new techniques to dams built on sites of multiform geological formation, improved workmanship and materials, etc., reduced hazards on dam disasters. These however were handicapped, since long-term hydrological forecast on extreme flood flows remained in many instances uncertain and the life of man-made structures was somehow limited.

173. There, in ancient Mesopotamia, the country of Biblical tradition of the floods, direct factors had caused through the ages a succession of devastating floods of the Mesopotamian plain. Perhaps judiciously-sited and well-manned capacious reservoirs—if such techniques were known in earlier periods—would have eliminated a great many of the calamities or at least restricted flood risks to habitually-known dam disasters.

174. As to floods caused by 'landslides' (§ 4), Mr Sevia referred to Sir A. T. Wilson who quoted¹⁸ from Capt. B. Dickson's *Journeys in Kurdistan*¹⁹ that 'a landslide in one or more of the narrow gorges through which the Little and Great Zab and the Khabur debouch on the Mesopotamian plain would hold up and suddenly release, when it collapses, an immense volume of water'. Sir A. T. Wilson added that 'such landslips are well known in the upper reaches of the Indus, and great precautions are taken to cope with them'.

175. A check to flood risks was also obtained—physical conditions of the country allowing—either by diverting flood flows into nearby depressions and/or by-passing them around sites to be protected. Under such conditions, water diversional works presented less hazards of calamity through collapse than high dams. But water was precious; its conservation necessitated storages and avoidance of its dissipation. Consequently, the addition of water diversional works, whenever possible, and acting as 'safety valves', the controlled by-passing of excess floodwater through flood plains, and the adequate drawdown programme of reservoirs would mitigate, but not remove, dam disasters and their consequences.

176. As the Author concluded, correctly: 'The risk of sudden disaster is for ever inescapable, and while knowledge and vigilance may reduce such a risk, it can never be entirely banished'.

Mr H. F. Wilmot (retired) wrote that big dam disasters were virtually unknown until the increasing demands for domestic and industrial supply created a demand for water which only higher and still higher dams could satisfy, due to the ever-growing world's population and increased standards of living. (The population of England and Wales in the early nineteenth century was only 9 million approximately.) The lack of dams over a 100 years old could, therefore, be easily accounted for, with

extensive use of wells in this country. To what extent the growth in the present trends must be limited—especially in the United Kingdom with the ever-continuing diminutions in suitable sites—was a matter for grave consideration and some form of metering would ultimately be imperative (Fig. 1).

178. The Author dwelt on lack of maintenance as one of the causes for scarcity of old dams. Silt had been and would continue to be one of the main difficulties, as the U.S.A. was realizing to its cost. The elaborate irrigation system of the past in Iraq—the layout of which could be clearly discerned from the air—was ultimately completely throttled from this cause, possibly commencing in the initial stages with a war which stopped all clearances.

179. The insurance against disaster for all those living downstream of a dam could not possibly be met by private means, and the assessment of risk, i.e. the factor of safety of a dam, was one which even a much-experienced engineer could only make provisionally, for all the care and thoroughness of maintenance.

FIG. 1: APPROXIMATE RELATIONSHIP BETWEEN NUMBERS OF MAJOR DAMS AND POPULATION GROWTH IN GREAT BRITAIN

180. Differences in sites might involve vast differences in the insurance concerned. Cynically speaking, those who lost their lives at Val Gleno (500–600) or Vega de Tera (100–200) would not require any compensation, whereas survivors in Egypt, who would lose their all should the new dam now being built at Aswan fail, would probably be the majority of its seething population (say 20 million), assuming they would be warned in time to get to the higher escarpment on their flanks; no government could hope to cope with such a situation.

181. There were two aspects of design which Mr Wilmot would like to touch on—(a) the downstream drainage, and (b) the design of barrages on sand and silt foundations.

182. Downstream drainage, with the advent of soil mechanics, resulting in the prevention of a build up of pressure upstream causing uplift was of vital importance for all types of dams, and careful watch on the flow of outlets downstream could give

ready warning of any deterioration in conditions upstream, but remedial measures to reduce any increase in flow could be both slow and difficult.

183. The design of barrages on permeable foundations was first put on a sound theoretical basis of design by what had been described as Bligh's 'creep theory' which related the safe permissible head on such a structure to the length over which under-flow or percolation must take place; it required masonry aprons both upstream and downstream of the main structure, and of sufficient mass downstream to overcome any tendency to uplift, that at the downstream limit being assumed nil.

184. This theory, since more accurately assessed by soil mechanics' principles, laid down safe heads varying from $1/24$ to $1/12$ of the apron length, depending on the nature of the foundation soil. In India prior to this, several weir failures had occurred downstream, e.g. the Narora Weir, but the adoption of Bligh's rule led to safe design both there and on the Nile in Egypt.

185. The practice in both those countries had been to make the upstream apron short and that downstream long; this had involved very heavy downstream construction, but it had the advantage that any incipient failure under head could be readily detected, and repairs carried out without undue difficulty.

186. In Russia, the above technique had been applied to many of their high earthen structures across rivers, relying on a thin upstream anti-seepage apron constituted by a continuous bitumen filament both upstream of, and under, the dam. Repairs to such an apron when the dam was full would be well nigh impossible. Such dams would seem to be vulnerable without additional precautions. The permanence of these structures, requiring large *intact and continuous* areas for their filament, appeared to be very questionable, and especially so with any possibility of uneven settlement taking place, the risks being commensurate with the total area involved.

187. The Author's reference to the failure of ice barriers brought to mind the continual recurrent threat to the Punjab, at intervals of several years, from the ever-forming ice dams located at Shiyok in the Himalayas which could reach a height of 80 ft. Steps had to be taken to blast this obstruction before it became too dangerous, and the resulting large flood had to be carefully routed for hundreds of miles downstream along the Indus and ultimately through the Sukkur Barrage.

188. Regarding extreme examples of thin arches given in § 37, their completion dates had significance, namely 1955 and 1961. Those outstanding earlier examples of Zola (1843) and the Bear Valley (1912) had proved their reliability over a long period, and deserved mention.

189. The interesting percentages of failures given in § 9 would seem misleading in some respects. Rates of 19% failures over 145 years, or 13% every 100 years would seem a reasonable deduction for those listed in § 8. The American list (§ 9) gave 1.87% in 40 years, or 4.7% every 100 years as the present rate. The important figures were clearly those related to each *type* of dam, thus the arch type would appear safest to date (§ 7), with gravity a close second. The present popularity of earth and rock-fill dams was partly due to soil mechanics and partly (though not wholly justified) to freedom from major disasters, even in earthquake areas.

190. Mr Wilmot would be grateful for confirmation or otherwise that the original design of the Grande Dixence Dam was altered during construction from buttress to mass gravity by the State for strategic reasons.

Mr A. K. Biswas (Research Fellow in Civil Engineering, Loughborough College of Technology) wrote that it was difficult to ascertain the cause or causes of the majority of dam disasters, since very little proof was left in the wake of the calamity. However, the reasons could be surmised with a high degree of accuracy.

192. It was not possible to predict the maximum flood that a dam had to withstand in its estimated economic life. If the stream-flow records were known for a considerable number of years, then, from the frequency analysis, a 100-year flood

could be defined. It could be said that, on an average, it would occur ten times in 1000 years, but it was quite possible that it could occur every year for the first ten years and never in the next 990 years (though the probability of such an occurrence was remote). Again, one could not say definitely that the maximum flood in 50 years was the 50-year flood. It was quite possible that the flood observed was a 1000-year flood. In 1935, the Republican River flood exceeded the maximum flood record available for a period of 40 years by nearly 250%. Therefore, if there was a possibility of expecting a flood much higher than the spillway design flood, which, when incorporated, would render the scheme uneconomic, an emergency auxiliary spillway might be provided. This could carry a discharge as high as 80% of the design flood. Before the dam was overtopped, the auxiliary spillway would go into action and pass the extra discharge at a substantial damage to it. This would not only save the dam from the impending disaster but would also impart a much-needed extra factor of safety to the scheme.

193. A certain amount of risk might be justified in fixing the spillway design flood, but under-estimating it would result in a disaster. An appreciation of this point could be best shown by the Perregaux Dam in Algeria. In 1872, a flood of 25 000 cusecs washed away 165 ft of the spillway section; in 1881, nearly 410 ft of the dam was washed away by a flood of 30 000 cusecs (in both instances the cause of failure was attributed to insufficient foundation) and finally a storm of nearly 141 000 cusecs practically washed away most of the dam in 1927. A more recent example was the Kaddam Dam of India. Only a year after the completion of the dam, August 31, 1958, the dam was overtopped by 1.5 ft and consequently there was a breach of 450 ft wide on the left composite dam and two more breaches on the right composite dam. The causes attributed were either insufficient spillway capacity or incorrect operation of the gates, or both.

194. Another interesting dam failure was that of the 208-ft high, semi-hydraulic fill Saluda Dam of Columbia, S. Carolina. It failed in 1932 because of the lack of proper drainage on the downstream side.

195. So far as deliberate enemy action was concerned, perhaps the buttressed dams were more vulnerable to destruction because of their thin sections. But an inherent resistance to earthquake forces was provided by the articulated buttressed dams. The best examples being the Stony Gorge Dam, and the Rodriguez Dam of Mexico, both of which were built across a fault and were still standing.

Dr Serge Leliavsky (Consultant) wrote that he believed the historical approach was particularly valuable in technological science when it was allowed to depict and analyse the gradual development of the various branches of this science. Thus in the case of science and art of dam construction, the historical failures of some famous dams, as they occurred in the past, were particularly noteworthy and especially interesting to the profession, in so far as they contributed to the development of the art of dam building, and to the theory of dam stresses.

197. It was, therefore, rather surprising to observe that the two main dam failures, which had broadened the outlook on the dam theory in general, were not mentioned at all in an otherwise excellent Paper.

198. The two dams in question were the Puentes Dam, in Spain, and the Bouzey Dam, in France.

199. The failure of the Puentes Dam was a rather 'long' story. After having first failed in the eighteenth century, it was rebuilt many years later according to new plans, and stood now in excellent condition.

200. But what interested Dr Leliavsky now, in particular, was the earliest part of its history, dating back to the eighteenth century (1785–1802), as described by Aynard in his *Irrigation du Midi de l'Espagne*.

201. The section of the dam at that time was fully adequate, the base-width being about 145 ft for a height of about 164 ft, which yielded a maximum compression

stress of about 16 lb/sq. ft. But the striking point of that design, which distinguished it entirely from modern masonry dams of the same type, was that it was founded on piles 22 ft long, driven into a bed of sand and gravel at least 25 ft deep.

202. It was true that the original design contemplated reaching solid rock, but that was not realized in practice.

203. The piling and a slab of masonry 7.4 ft thick were continued 131 ft below the dam, thus forming an impermeable coating 283 ft in breadth.

204. For eleven years the level never rose more than 82 ft above that apron, but, in 1802, as the water rose to full supply level, it was seen to boil on the downstream side of the dam, and, half an hour later, the boiling increased to an enormous quantity of water.

205. That failure marked a milestone in the history of masonry dam construction, because, since then, it had been standard practice that such dams should be built on rock and never founded on alluvial deposits.

206. Curiously enough, whilst the central part of the foundation was washed away during the first failure, the main part of the masonry remained standing for many years and was used by the inhabitants as a bridge spanning the valley until the whole work was reconstructed.

207. The Bouzey Dam marked a development no less significant than the Puentes Dam. In order to realize its importance, it should be remembered that, as late as about 1895, the principle of 'no tension stresses in gravity dams', and Rankine's Middle Third Rule, derived from it, were by no means a generally accepted practice.

208. In looking through the books on dam design dating back to this period, it might be found that some of them recommended carrying out actual experiments on blocks of masonry of the same consistency as those proposed to be used in the project, and, then calculating the profile in such a way that the tensile and compressive stresses should not exceed those found in these experiments.

209. That explained that some such dams were narrower than what would have been considered safe, according to present-day standards.

210. One among such dams was the Bouzey Dam.¹⁰ From the various reports on the subject, it appeared that the designers assumed that the stresses should be limited to 3075 and 20 500 lb/sq. ft, respectively, in tension and compression. The law of the 'middle third' appeared to have been altogether unknown to the designers.

211. It was, therefore, not surprising that, in 1884, when the water level was still 2.70 m below the designed maximum, the dam cracked, moving bodily downward in some places.

212. The gravity of the situation did not appear to have been fully realized, but the reservoir was emptied, and an extensive programme of repair work was carried out; but looking at the general arrangement, it seemed that the first objective was to stop percolation along the foundation and to prevent the dam from sliding downstream. Nothing, however, was done at, or above, the level at which the highest tensile stresses (about 3 lb/sq. ft) occurred.

213. The reservoir was filled again, and the dam stood, without much trouble, except for some leaks, until 27 April, 1895, when water rose to the originally-designed maximum (371.5 m), and the dam cracked horizontally between levels 358 m and 361.5 m. The cracked portion, about 600 ft in length, was bodily swept away, causing an enormous death roll and producing an unprecedented calamity.

214. It was generally said at the time that the numerous articles written on the subject were comparable to a sea of ink, but the effort was fully justified, for the 'middle third rule' became, henceforth, a generally-accepted design principle, and no gravity dam with tensile stresses had since been allowed to be built.

215. From the numerous publications relating to that failure, Dr Leliavsky mentioned, first, Maurice Levy's 'Communication to the French Academy of Sciences', dated 5 August, 1895 (i.e. four months after the failure). In that paper Levy gave his famous rule, which dominated dam design for over two decades; namely,

that the compressive stress in the material of the dam at the upstream face must be greater than the water pressure at the corresponding depth in the reservoir. The reason usually given for that rule was that, under such conditions, water was not supposed to be able to penetrate into the dam, and that consequently percolation would be absent.

216. It was rather curious to observe that a misunderstanding appeared to have taken place in connexion with that rule and the Ministry circular of 15 June, 1897, which the French Government was forced to issue under the pressure of public indignation following the Bouzey disaster.

217. According to that circular, Maurice Levy's rule was prescribed *manu militaire* for all dams built in France, but the whole point of the matter was that the prescription did not refer to the rule which Dr Leliavsky had just outlined, but to another question altogether, which had also been dealt with by Levy, namely, the calculation of the maximum compressive stress on oblique joints. Whereas, in the case of uplift, the 1897 circular prescribed merely to reduce by 100 kg/cu. m the specific weight of the material of the dam. Thus, if that weight was found by field experiment to be 2400 kg/cu. m, the designer must assume it to be only 2300 kg/cu. m in his calculation of stability. That was, indeed, the official French method, which remained in force until the publication some twenty years later of a new circular.

218. But the majority of designers, believing that Levy's rule, quoted in the old circular, was his principle as applied to the prevention of uplift, designed their dams accordingly, and the result was that many French dams of the period were particularly wide.²¹

219. To be nearer to actual facts, the wording of § 13 might possibly be somewhat adjusted, because the French Ministry of Agriculture never prescribed a 0.2 ton/cu. m reduction in the assumed weight of the material of the dam. The prescribed reduction was 0.1 ton/cu. m, but even that was according to the circular of 1897, which ceased to be valid at the time of the El Habra failure. Also, by this time, Maurice Levy was long since dead, but a most interesting discussion took place in the pages of the 'Proceedings' of the French Academy of Sciences, and of the magazine *Genie Civil*, between M. Baticle, M. Pigeaud, and M. Jacques Menager. But that was another story!

Mr A. C. Allen (Managing Engineer for Scotland, Sir M. MacDonald & Partners) wrote that from the Author's reply to the oral discussion, he understood it to be the Author's view that he considered it to be a merit of the Reservoirs (Safety Provisions) Act, 1930, that an engineer appointed to inspect a reservoir required to be independent of the owners of the reservoir.

221. Although 'independent' was defined in s. 2(10) of the Act as meaning 'not in the employment of the undertakers otherwise than in a consultant capacity and not the engineer responsible for the design or construction of the reservoir', the proviso of s. 2(5) of the Act was that 'where there is in the employment of the undertakers a qualified civil engineer within the meaning of this Act who is responsible to the undertakers for the maintenance of the reservoir, the undertakers may appoint that engineer to make any such inspection and report'.

222. An engineer responsible for the design or construction of a reservoir was not permitted to make a statutory inspection of it, although an employee or associate of his, or any other engineer not excluded by s. 2(10), so long as he remained 'qualified' as defined by the Act, might make unlimited successive inspections.

223. Although it was not suggested that there had been any loss to the safety of the public in the past, it would seem to be worth while considering if it could ever not be in the best interests of safety that a statutory inspection of a reservoir might be made by an engineer who had been connected with an engineer responsible for its design or construction. Also whether there could be advantages in not permitting consecutive inspections by one engineer and in permitting an engineer responsible for

the design or construction of a reservoir to make occasional inspections excluding the first one.

224. It would be useful if the Author would say whether in his study of the regulations of other countries he had found any provisions corresponding to those suggested in the last paragraph. Any comments he would care to make on the suggestions would be appreciated.

Dr A. A. Ahmed (retired) wrote that in his concluding remarks, in § 60, the Author had said that our knowledge of the forces which led to the deterioration of the dams was incomplete and much help could be obtained by making a close study of dam failures when they occurred.

226. The analysis which the Author had made of the causes which brought about the failure of the dams discussed in the Paper was, therefore, a valuable addition to our knowledge of the subject.

227. It might be added, however, that since those forces might vary widely in magnitude and character under different structural, geological and other local conditions, there would always be room for fresh experience in this field.

228. With the results obtained from a sufficient number of cases, we could formulate general rules which were applicable to certain classes into which dams might be divided according to their structure, type of foundation and other characteristics. The experience gained in this way would enable us to predict what was likely to happen in certain classes of dams, and, eventually, to select the appropriate class to meet given technical and economic conditions by striking a balance between cost and possible damage in case of failure. It might so happen, however, that the damage arising from failure would be so overwhelming that it must be avoided at all costs.

229. For instance, the Aswan High Dam, on which the future of Egypt, for good or ill, depended, was to be built as rock-fill on sand and other erosion products 200 m deep below bed level.

230. In a paper he gave in 1960 Mr Ahmed questioned the safety of the High Dam and mentioned, in § 103, that the failure of rock-fill dams was not uncommon.

231. It was interesting to note that Mr Gruner had quoted, in § 8, that out of 1630 dams built between 1799 and 1944 there were altogether 308 failures, of which 163, or more than half, were classed as earth embankments, and 70 only were concrete gravity dams.

232. The sandy foundation and the difficulties associated with its grouting and compaction over that great depth, had been dealt with in § 706 *et seq.* of the discussion of his paper,²³ where it was shown that building the dam on this precarious foundation was extremely hazardous.

233. Referring to dam foundation, the Author had stated, in § 9, that faulty foundation was responsible for most dam failures, being 40% of all the causes listed in § 9.

Mr L. Sancha (Chief Engineer, Sir William Halcrow & Partners, Buenos Aires, Argentina) wrote that the very interesting Paper by Mr Gruner on dam disasters, including the analysis prepared by the *Revista de Obras Publicas* of Spain, of 308 dam failures, was a most important contribution to the subject.

235. If one added to foundation failures those due to uneven settlement which were, strictly speaking, foundation failures, this cause accounted for 50% of all dam failures. Together with failures due to inadequate spillway that accounted for 23%, these two causes alone were responsible for three quarters of all failures.

236. Generally, foundation failures were due to inadequate site investigation, inadequate attention to the construction of the foundations, or to false economies in design or construction.

237. An omission in Mr Gruner's Paper was any comment on the Malpasset Dam

disaster, the most important in recent times, and his views would be of the greatest interest.

238. Professor Terzaghi's views of the disaster, as reported in Dr Charles Jaeger's article, published in *Water Power*²¹ of last February, were that 'the left abutment of the dam appeared to have failed by sliding along a continuous seam of weak material covering a large area'. If Professor Terzaghi's views were correct, it would appear that the disaster might have been avoided if a more comprehensive site investigation had been undertaken, when the danger would have been exposed and remedial action taken or a different site selected.

239. The best method of avoiding dam disasters was, undoubtedly, the thorough investigation and study of those that had occurred. Engineers, like doctors, were reluctant to admit their own failures or to comment on those of their colleagues. However, there was a strong case for an agreement to be reached by all members of the 'Commission on Large Dams of the World Power Conference' to exchange full information on the subject without maintaining the present secrecy which was so damaging to the engineering profession and the general public as a whole.

240. The second main cause of dam failures was the inadequate provision of spillways which accounted for 23% of the total; to these should be added a proportion of cases when an inadequate spillway did not result in a disaster, as was the case with the 'Rincón del Bonete' power project on the Rio Negro, in Uruguay—the power-house was flooded in April 1959, when the reservoir level overtopped the dam, but there was no danger to the structure itself.

241. The cases of inadequate spillways resulted from under-estimates of the probable maximum flood to be expected. Often this was due to the fact that insufficient data was available, but, in general, it could be said that the forecast of the maximum flood for a given catchment was entirely empirical as a result of the very rudimentary stage of meteorology.

242. The theory that had been expounded relating maximum floods to sun spot activity appeared to be confirmed by the experience during 1957–59 when the maximum floods ever recorded occurred in widely distant areas. This was the case in Venezuela, Uruguay and Rhodesia when the following maximum floods recorded occurred.

<i>Date</i>	<i>River</i>	<i>Catchment, sq. km</i>	<i>Average flow, cu. m/sec</i>	<i>Estimated maximum flood recorded, cu. m/sec</i>
Aug. 1957	River Caroní, Venezuela	95 000	5 300	17 000
Feb./Mar. 1958	River Zambezi (Kariba) Rhodesia	640 000	1 200	16 000
Apr. 1959	Rio Negro, Uruguay	40 000	525	16 000
Apr. 1959	Rio Uruguay, Argentine/ Uruguay	240 000	4 600	37 500

243. An instance that illustrated the very low standard of present-day knowledge of weather forecasting was that no indication was given by any weather office of the impending very long and exceptionally severe winter which occurred in the Northern hemisphere this year. It was interesting to read from Buenos Aires in the *Observer* of 23 December last that a 'crisp sunny Christmas in parts of England and Wales' could be expected, but no indication whatsoever was given of the beginning of a long Arctic spell, the most severe for a century. However, in the *Observer* of 25 November it was stated that 'if berries on the trees are the weather guide, some believe we shall need very warm shoes this winter!'—a very accurate forecast! It would appear

that the state of weather forecasting, which was of such importance to engineering and so many other activities, was still no further advanced than it was centuries ago, but if sufficient funds could be provided for the study of this very important subject by the U.N. or other agencies, it could be turned into a science.

Mr J. Guthrie Brown (Partner, Sir Alexander Gibb & Partners) wrote that the Author had referred to the Reservoirs (Safety Provisions) Act, 1930, which in this country provided, in the public interest, a measure of control over the design, construction and use of reservoirs. As he had explained, it was the Dolgarrog Disaster in North Wales on the evening of 2 November, 1925, which led to the passing of the Act. Since no complete account of the disaster had previously been published in the *Institution Proceedings*, the present Paper afforded a suitable occasion for recording the basic facts.

FIG. 2: RELATIVE LOCATION OF BOTH DAMS

245. Fig. 2 showed the relative location of the two dams which were involved. The upper and older dam at Eigiau had been constructed in 1908 on behalf of the Aluminium Corporation Ltd by Bott & Stannings to the designs of Harper Bros. Three years later the dam was raised by the Corporation, an operation which involved constructing a long low wall across the width of the valley. This additional work was carried out by direct labour and resulted in a concrete dam with a total length of 3253 ft and a maximum height above stream bed of 35 ft providing 160 million cu. ft of storage.

246. The second dam involved in the disaster was at Coedty about $2\frac{1}{2}$ miles downstream of the Eigiau Dam.

247. The Coedty Dam was completed in 1924 and consisted of an embankment built from the local moraine material with a central core wall of reinforced concrete. It had a maximum height above river bed of approximately 36 ft and was 800 ft long, forming a reservoir with a capacity of 11 million cu. ft from which the Dolgarrog power station was supplied.

248. The spillway consisted of a side channel projecting in a downstream direction from the right flank of the dam.

249. The flood which overwhelmed the village of Dolgarrog, about 1 mile downstream of the dam, arose from two quite distinct events. The first was the local under-mining or blow-out which occurred beneath the base of the Eigiau Dam, while the second and major incident was the consequential failure of the embankment dam at Coedty.

250. The discharge of water released by the breach in the Eigiau Dam was much in excess of the capacity of the Coedty spillway. In consequence, the dam was overtopped, washing away the material from the downstream side of the core wall which then collapsed. The breach formed was about 220 ft wide at the top and 60 ft at the

bottom. There was little doubt that the failure of the Coedty Dam, by releasing all its contents very rapidly through the breach and almost without restraint, created a peak discharge far in excess of that issuing from the breach in the Eigiau Dam; it was this peak flow from Coedty which was mainly responsible for the loss of life in the valley below.

251. Following these events, Mr Guthrie Brown's firm, Sir Alexander Gibb & Partners, was instructed by the owners, the Aluminium Corporation Ltd, to examine the causes of the disaster and report on all the dams belonging to the Corporation.

252. Site investigations made it clear that the base of the Eigiau Dam had throughout been founded on the blue glacial clay which covered the whole width of the valley to a considerable depth; the base of the dam had only been taken a few feet below the ground surface, in some places only a few inches into the clay (see Fig. 3). No attempt had been made to carry the foundations down to solid rock. Moreover, the concrete of which the dam had been constructed was of very poor quality.

FIG. 3: CROSS-SECTION OF DAM NEAR BREACH

253. Over the section of the dam where the blow-out occurred the concrete base had been carried less than 2 ft into the blue clay, the upper part of which was soft and porous. The dam had been in use without incident for nearly fifteen years, but the situation might well have been aggravated by the partial drying out of the clay during the preceding dry summer when the lake bed was exposed.

254. Whatever the reason, however, it was evident that under the initial head of 18 ft, which existed at the place in question, leakage under the foundation had resulted in a blow-out. The blow-out rapidly scoured a channel to a width of 70 ft and to a depth of 10 ft below original ground level. It was estimated that the breach thus formed was capable of discharging about 50 million cu. ft of water in an hour (14 000 cusecs)—equivalent to lowering the lake level by about 5 ft.

255. It was perhaps worth while quoting an account of that fateful night as subsequently recorded by an eye-witness, Mr G. Gerard, who was a member of the power station staff.*

* Extract from 'Hydro-Electric Engineering' by G. Gerard, F.R.S.E., A.M.I.E.E., Pitmans, London, 1949, p. 150.

'The disaster occurred in the evening about 9.15 p.m. Providentially, however, it was the one evening of the week when a film show was held in the Assembly Hall. This place was situated on high ground, away from the flooded area. The cinema was well-attended at the time of the disaster and the audience was unharmed by the flood. If the dam had burst an hour earlier or later, there would have been heavy casualties,* because the people would have been in their homes.

When the dam burst, the water washed away the communication circuit from the reservoir to the power station. It was impossible for the reservoir attendant to race the flood, and so no warning of the approaching danger could be given. The shift engineer on duty in the power station was about to read the instruments for the 9.30 p.m. log when the water entered the power station. The operating staff stuck to their posts and succeeded in getting the plant shut down, and then managed to escape from the building. Happily, the lights in the station did not fail, because they were supplied from a small Pelton-driven generator above flood level.'

256. In conclusion, it should be recorded that although plans for the reconstruction of the Eigiau Dam were prepared shortly after the disaster, they were not proceeded with. Instead, the Eigiau Dam was abandoned for storage purposes and now served merely as a diversion weir. The Coedty Dam, however, was reconstructed and still served as a headpond for the Dolgarrog power station.

Mr J. K. Hunter (Consulting Engineer) wrote, as a supplement to Mr J. Guthrie Brown's discussion, that over the past 150 years *The Times* recorded the failure of sixteen dams in Great Britain. Of these the two best known were those at Bradfield in 1864, and at Dolgarrog in 1925, both involving considerable loss of life.

258. More recently, there was the failure in 1937 of the Chingford Reservoir embankment while under construction, and there had no doubt been several partial failures of an unspectacular nature which were not reported in the national press.

259. The circumstances surrounding the Dolgarrog disaster had been described by another contributor to the discussion on Mr Gruner's Paper, but it might not be generally known that some months before that event took place, a partial failure occurred to another dam in an adjacent valley. That was the Cowlyd Dam which, like the two which failed later, belonged† to the Aluminium Corporation and was used jointly for the production of power and potable supplies to the surrounding district. Like the Coedty Dam at Dolgarrog it was an earth embankment constructed from the local moraine material and was provided with a lightly-reinforced concrete core wall.

260. Within two years of its completion, the Cowlyd Dam nearly met with disaster as the result of overtopping during a storm on New Year's Eve, 1924. Over a considerable length the embankment fill was washed out down to stream bed level. Complete destruction of the dam was prevented by the core wall which mercifully remained intact and retained the upstream part of the embankment while frantic efforts were made to replace the fill on the downstream side. Had the dam collapsed, the consequences would, without doubt, have been far more calamitous than those which followed the Dolgarrog failure ten months later.

261. After the downstream fill had been restored, steps were taken to increase the freeboard of the dam by lowering the spillway, and, in addition, the height of the wave wall was raised. The dam had since been in continuous service.

* Owing to these circumstances, the loss of life was limited to sixteen.

† The agreement under which the dam was constructed provided that ownership should be vested in the local Water Board while responsibility for maintenance should remain with the Corporation.

APPENDIX

MR E. SANDEMAN'S LETTER TO 'THE TIMES' IN DECEMBER 1925

262. Sir,—In view of the loss of life following upon the failure of the dams of reservoirs in Scotland and North Wales recently, I beg to call your attention to the report made by the Select Committee on the Waterworks Bill, 1865 (Sessional Paper 401), after they had considered the evidence as to the failure of the earth embankment of the Bradfield Reservoir on March 11, 1864, when 245 lives were lost. Shortly, this Committee recommended (*inter alia*) that:—

1. Plans of proposed large reservoirs should be submitted to the Home Office or Board of Trade, together with a description of the mode of construction.
2. The plans should be reported upon by a competent person, and the report submitted to any Select Committee appointed by Parliament to consider the Bill by which powers were to be obtained to construct the works.
3. The works should be inspected, to ascertain if they complied with the rules laid down by any Private Act authorizing them.
4. As large reservoirs have been allowed to decay and to become dangerous, periodical inspection should be made of them.

263. It is unfortunate that some such control as was then suggested has not been brought into effect. Those of us who are engaged in work connected with the water supply of our towns are not infrequently impressed by the fact that there is vital need for an examination and inquiry into the present condition of the reservoirs of the country, from the point of view not only of their sufficiency to withstand the pressures to which they are subjected, but also to ascertain whether, in view of the exceptionally heavy rainstorms which have occurred locally in the last 10 or 15 years, they are provided with overflows of a capacity requisite to deal with the floods following upon similar rainstorms.

264. Three of these cases of heavy rainfall occurred in areas of low annual rainfall in the counties of Norfolk, Somerset and Lincoln, when 6 in. to 9 in. fell in short spaces of time: had one of these occurred upon a watershed draining to a reservoir deficient in respect of overflow capacity in one of the thickly-populated valleys in the northern part of England, the loss of life might conceivably exceed anything previously experienced in this country.

265. Within my own experience (and probably other engineers will be able to give similar instances) I have within the last five years warned two water authorities that the earth embankments of their impounding reservoirs—made forty or fifty years ago—had sunk in the centre so as to be dangerous. Both these cases have now been rectified. In other instances I have found the overflows—which are the safety valves of reservoirs—interfered with and altered to a dangerous extent. These instances alone are sufficient to show that inspection of existing reservoirs is necessary. In the interests of the public safety it is of importance that the matter should receive attention without delay.

I am, Sir,
Yours faithfully,
'Civil Engineer'.

The Author, at the end of the discussion, thanked all those who had taken part.

267. Mr Banks had remarked that Britain was among the first to introduce legislation to control in the public interest the construction and use of reservoirs, and the Act of 1930 seemed to have served its purpose well. Legislation in other countries tended to be on somewhat different lines. For instance, the regulations in force in California stipulated that if any dam became dangerous, steps must be taken to dismantle it to such an extent that the river could pass freely.

268. In Britain it might not be easy to find people with the necessary qualifications required under the Act. In the first place, the engineer must not only be experienced but he must be thoroughly familiar with present day developments in the design and construction of dams. In addition, he must be completely independent of the owner of the dam.

269. Mr Kennard had mentioned the 'fuse plug'. The application of such devices

to reservoirs was of fairly recent origin. They were first developed in the United States where it was found that they were both more economical and more reliable than a great number of standby flood gates. If the embankment used as a fuse plug should settle in course of time or become resistant to erosion, it could, in an emergency, be removed by explosives. The effectiveness of a fuse plug would always be limited by the extent to which the embankment was bounded by non-erodable concrete or rock.

270. Mr MacDonald had referred to the Author's suggestion that an accident might arise as the result of incorrect operation. An example of this had recently come to the Author's notice in connexion with an accident to an arch dam in southern Peru. In this case it was claimed that vibration set up in the penstocks had caused cracks in the body of the dam. When the damage was observed, the town of Arequipa was evacuated and the reservoir emptied through the bottom outlets. It was an unfortunate fact that the knowledge of such incidents tended to be suppressed and the lessons to be learnt from them were very often lost to the engineering profession.

271. During the course of discussion, it had been observed that in spite of its somewhat sensational title, the Paper presented little that was not already known. The Author agreed that this was a valid comment, and he wished to make it clear that in preparing the Paper, it had never been his object to present any fresh advance in the science of dam construction.

272. It was as a result of his consideration of the Rio Negro flood in Uruguay which had occurred in April 1959, that the Author had asked himself these questions:

- (a) What could be learned from either partial or complete dam failures?
- (b) How, and by whom, were dams inspected?
- (c) Who compensated those who suffered loss as the result of such calamities?

273. The Author believed that such questions were better answered by a penetrating study of the considerable mass of information available concerning accidents to dams, rather than by examining the often incomplete reports on a few spectacular failures. As Dr Leliavsky had observed, general discussion of such problems among engineers often led to important contributions to the science of dam building.

274. Mr Banks had suggested that engineers and laymen might tend to put different interpretations upon the statistics of dam failures given in the Paper, and it must be admitted that, in the absence of a full knowledge of the facts, it was easy to draw erroneous conclusions. The Author would commend to every engineer the opinion expressed by Mr Banks that experience and judgement supported by profound technical knowledge should have priority over purely academic considerations.

275. The evolution of each type of dam was accompanied by changes in its inherent safety factor. In the case of a novel design, the trial and error aspect was inevitably prominent. With increasing knowledge and experience it was possible to achieve economies, and this might in time tend either to routine design procedures or to undue boldness in design which might ultimately end in disaster.

276. It was natural that the attention devoted to the maintenance of a dam would depend to some extent on its size and importance. Inevitably, a small reservoir hidden away from the public was more likely to be neglected than would be a large and important structure.

277. Mr Kennard had spoken of the difficulties inherent in the application of the British Reservoirs Act. At present, the responsibility for declaring that a dam was no longer serviceable fell upon the engineer entrusted with its inspection. The factor of safety of a dam might be calculated during the design stage, but there was no generally accepted standard as to what the figure should be.

278. The fuse plug concept could be looked upon as an extension of the normal spillway to deal with floods of exceptional magnitude. The Idaho Power Company

had carried out model tests in order to study the behaviour of a fuse plug embankment. The tests had shown that breaching could be initiated by a pilot channel provided its action was maintained. An important aspect of the fuse plug was the provision of a permanent sill to limit the flood discharge to a value which could be accepted by the valley downstream of the dam. The Rio Negro flood already referred to had endangered the Rincon de Bonete Dam, but its destruction was prevented by the use of explosives to remove an auxiliary embankment constructed upon rock. It might be questioned whether emergency flood gates would be better maintained than an erodable embankment.

279. The Author was responsible for the incorporation of a fuse plug embankment in the design of the Mehardeh Dam on the Orontes in Syria. Should it ever be brought into use and should it appear that the erosion taking place was not likely to suffice, it would always be possible to enlarge the breach by dropping explosives from the bridge carrying the service road.

280. Mr MacDonald had suggested that an appropriate sub-title to the Paper would be 'Lessons to be learned from dam failures', and the importance of such lessons was recognized by Mr Sancha who had proposed that the maintenance of dams would be a proper subject for discussion at a future meeting of the International Commission on Large Dams. The Author appreciated Mr MacDonald's suggestion that his Paper should be treated as 'required reading' by dam designers, and he would like to add that it should be complemented by those who have practical experience of the maintenance of dams.

281. The Author thought it was improbable that ice pressure alone could endanger a dam, but he felt, nevertheless, that ice might be linked with dam failures. Near the Grande Dixence Dam there was an artificial lake which was used for storing irrigation water. In the summer of 1963 a cascade of ice from the Prafleuri Glacier created a wave which swept away part of this dam. Again, the Mattmark Dam stood partly on the moraine of the Allaline glacier: if this glacier should expand as the result of a series of abnormally cold years, it was possible that the ice might exert pressure on the toe of the dam. The pneumatic effect of an avalanche or the mechanic effect of a mountain slide might cause a fatal wave. The mountain slides of Yellowstone Park and of Valdivia were after-effects of seismic tremors; neither fell in a reservoir but they gave rise to reservoirs which were dangerous.

282. The necessity for grouting at the existing Aswan Dam was an example of the constant maintenance which such works required. As a result of horizontal cracks through the dam, leakage had occurred near the left abutment. It was not always realized that such a structure never acted truly as a monolith.

283. It was perhaps worth mentioning that the fate which had been predicted by an eminent Egyptian engineer for the reservoir to be created by the new Aswan High Dam had, on a smaller scale, already overtaken the Resia reservoir in the Alto Adige in Italy. In the latter, water was lost through seepage. On the Nile, piping underneath the dam might become fatal.

284. Mr Hunter had pointed out that there could be no such thing as absolute safety, and it was probably true that most dam failures occurred as the result of an incomplete appreciation of all the factors which had a bearing on safety. This was particularly true of spillway capacity and foundation conditions. The verdict of the official enquiry into the Ribadelago disaster in Spain was particularly instructive in this connexion.

285. The failure of the Ribadelago Dam on a tributary of the River Duero, resulted in the loss of 144 lives. In the opinion of Count de Torroja, its failure could be attributed to the differences which were subsequently found to exist between the moduli of elasticity of the masonry and the concrete used in its construction. Because of this it was recognized by the Public Prosecutor that nobody could be held responsible. The Hidroelectrica Moncabril S.A., the owners of the dam, prior to the opening of the legal proceedings, had provided compensation to those who had suffered

loss and this action had resulted in the withdrawal of accusations against the company itself. There remained, however, the formal charges levelled by the Public Prosecutor against a group of ten people whose negligence it was alleged had contributed to the disaster. The defendants pleaded not guilty and the court found that the basic cause of the failure could be attributed to the differences already referred to in the moduli of elasticity.

286. In the case of four of the accused, however, the charges of negligence were upheld and they were condemned to one year's conditional imprisonment. In addition, they were dismissed from their employment, their public rights were suspended, and they were ordered to pay a fine. The results of the court proceedings were published on 4th April, 1963, in an illustrated Spanish weekly *La Actualidad Espanola*, no. 587.

287. It might be noted that the number of victims claimed by the Ribadelago disaster was on the same scale as that of a major air crash. The quality of the risks involved in the two cases was, however, quite different. The people living in the village of Vega de Tera were entirely ignorant of their danger, whereas an air passenger was always aware of the risk he assumed and could, if he wished, cover himself by insurance. The victims of a dam disaster, on the other hand, should be compensated by those who owned and profited by the works concerned.

288. Dr Jaeger had referred to our inadequate knowledge of rock mechanics, and it must be admitted that this particular branch of science had become more important with the continued growth in the size of dams. A small dam could be looked upon as a plug inserted into a natural gorge, but as the size of the plug was increased, the abutments and the dam became increasingly inter-dependent. Since most natural valleys followed tectonic features, particularly geological faults, it was reasonable to assume that any differential movements between the rock masses must lead to stresses and strains in any artificial monoliths which might be used to bridge them. For this reason joints in a dam should be placed wherever a discontinuity occurred in the geological structure of the site.

289. The late Professor Lugeon of Lausanne University, an eminent authority on engineering geology, said in one of his lectures that knowledge of the foundations on which a dam had to be constructed should extend to a depth at least as great as the height of the proposed structure.

290. Dr Jaeger had concluded from his study of the reports available on the Malpasset disaster that the precise cause could not be determined with complete confidence. The dam failed, as had several others in the past, following the first filling of the reservoir, which in this case took place rapidly as the result of a storm. It had been accepted that the design of the dam itself was sound and that it was well constructed. The question might therefore be asked whether the dam would have failed if, as the result of slow and controlled filling of the reservoir, the abutments had had time to adjust themselves to the load. It seemed clear that if the initial filling of a reservoir was carried out slowly and under expert supervision, the risks of a sudden foundation failure should be reduced.

291. The Author felt that Mr Walters's misgivings concerning the use of mechanical contrivances to control spillways was justified. In the cold winter of 1927, it was anticipated that ice might cause trouble with the flood gates on the Rhine barrages and that floating ice might endanger some of the works. At Laufenburg the precaution was taken of moving the gates periodically until the chains broke due to their becoming frozen in their guides, and it was feared that a serious situation might arise. Fortunately, the ice melted as the result of the flow of water through the reservoir, and since that time the gates on the Rhine barrages had been equipped with electric heating.

292. The Author's reference to the engineer's political masters was meant to draw attention to the fact that the final decision with regard to important engineering projects often lay with non-technical people such as politicians, financiers, or even the

general public. Mr Banks's observation on the importance of sound practical judgement might be amplified by saying that engineers should never allow non-technical people to influence their professional opinions.

293. The Author agreed with Mr Akroyd's comment that every new engineering development involved risk and that the gaps in our knowledge could only be filled in by a process of trial and error.

294. Mr Gosschalk had referred to the possibility of having a code of practice relating to the safety aspects of dams which would be internationally accepted. The Author did not feel that this was practicable since there was no way of ensuring uniformity in the attitude of people towards what could be considered an acceptable risk. Strictly speaking, absolute safety was an abstract concept which could often only be closely approached at prohibitive cost. It was important to realize that the factor of safety of a particular dam was likely to change in the course of time. Because of this the Author felt that the safety of a dam should be re-examined from time to time, both in the light of its actual physical condition and of the latest advances in engineering knowledge. Among the aspects which should be examined were uplift pressures, the crushing strength and other physical properties of the materials used, and especially the effect of deterioration with age. The effect of cracks and seepage especially required close scrutiny.

295. Dr Kaplan drew attention to the discrepancies to be found in the two lists of dams, the one American and the other Spanish, which had been referred to in the Paper. The Author wished to explain that he had intentionally made use of the information available from these two sources to demonstrate its inadequacy as a means of definitely determining the causes of past disasters. A full appreciation of the factors which had given rise to a particular failure could only be obtained if the available records were both complete and reliable. The Author thought that the best way of ensuring the reliability of such records was to be sought under the auspices of the International Commission on Large Dams.

296. Mr Twort had given an interesting account of the partial failure of an old dam with which he had been personally concerned, and perhaps it was worth observing that, as had happened in this instance, successive failures tended to take place in the same section of a work.

297. Mr Twort had referred to the risks inherent in an engineer's unawareness of the limitations of his own knowledge. Once a dam had been completed, it was commonly the case that the engineer who had been responsible for its design and construction ceased to have any further connexion with it, and the responsibility for its maintenance fell upon others. Because of this, the detailed knowledge acquired during the course of construction tended to become lost.

298. Mr Kennard had pointed out that inspections made under the present Reservoirs (Safety Provisions) Act were left very much to the discretion of the engineer concerned. The Author thought that such inspections should sometimes be accompanied by a review of the general design of the dam in the light of present day knowledge.

299. Mr Clark had made the suggestion that the responsibilities of an engineer making an inspection of a dam under the Safety of Reservoirs Act should be shared by consultation with another engineer. While the Author did not feel able to comment on this aspect of the British Act, he did, nevertheless, feel that the interests of the public would be better served if the responsibility for the safety of a dam lay squarely upon the shoulders of one man. If it became difficult to obtain the services of an experienced inspecting engineer, then it might become necessary to transfer the inspection to a government department.

300. Mr Baumann referred to the phenomena of 'growing mountains' and their effect on dams. It was not only in the Himalayas and in the Sierra Nevada of the Pacific coast of America that such slow tectonic movements were experienced. Wherever they occurred, faults and joint systems tended to give rise to movements

between adjacent mountain masses. It was recognized that the deadweight of water stored in a reservoir caused a local depression of the ground surface and led inevitably to a slow movement of the dam in a downstream direction. It was not yet established whether such movements were the result of differential stresses in the geological strata or were caused by minor recrystallization within the foundation rocks and the materials of which the dam was built. The Author was inclined to think that the latter was the more likely explanation.

301. Mr Sevan had referred to the succession of devastating floods which had occurred in the Mesopotamian Plain since biblical times, and it was indeed rather surprising that in spite of such recurring floods, the inhabitants still persisted in settling on land which was known to be subject to occasional inundation.

302. A point which should not be overlooked was the effect of intense agricultural development on the flood retention capacity of the land. Moreover, should the peaks of the floods discharged by the various tributaries of the Tigris coincide, the results were liable to be catastrophic. The disastrous effect of such coinciding peaks could, of course, be deliberately brought about by so timing the destruction of a series of dams as to cause the maximum devastation. The Mesopotamian Plain was so vast that it was possible to re-route floods around densely populated areas and to store water in natural depressions. From the calculated value of anticipated floods, it was possible to obtain a fairly accurate estimate of the probable inundation.

303. Mr Wilmot had enquired about the official attitude in Switzerland towards the adoption of buttress dams. Following the bombing of the Ruhr Dams during the war, the Swiss authorities made a study of the vulnerability of their own reservoirs. From these studies it was concluded that a conventional high explosive bomb dropped between the buttresses of a dam would cause the collapse of a number of buttresses, while a similar bomb, if dropped on a mass concrete gravity dam, would only result in breaching the crest within a few metres' radius of the point of impact. In 1948 there were five buttress dams in Switzerland and, following the enquiry into their vulnerability, the gaps between alternate pairs of buttresses were filled with concrete in the case of the St Bartholomey, Cleuson, and Salanfe Dams. Similar action in the case of the Lucendo Dam was deferred for administrative reasons. The fifth buttress dam was that at Dixence. This was now completely submerged in the new reservoir created by the recently completed Grande Dixence Dam which was a mass gravity structure.

304. Since 1948 all new dams had incorporated a reinforced crest in order to increase their resistance to hostile action. Earth dams were now provided with caps of coarse rock fill, while concrete dams, whether of the mass gravity or arch type, incorporated a reinforced section covering the upper 16 m. The cost of such measures was considerable, and as an alternative to reinforcement, it was considered that the safety aspects could be sufficiently covered provided the owner installed outlet valves which would permit the reservoir to be drawn down to a prescribed level within a period of three days.

305. The Author supported Mr Biswas's suggestion that the inherent resistance of dams to earthquakes should be the subject of further study.

306. Dr Leliavsky referred to the historical approach to the solution of technical problems. This was important because it was too easily forgotten that the successful development of a new technical conception, and especially the problems associated with increasing scale, required just as much perseverance and ingenuity as the original tentative steps. Progress in research into the deterioration of dams presented somewhat different problems. It would usually be fairly easy to determine the cause of failure of an old dam of simple construction, whereas the more sophisticated dams of the present day might well present a picture which could only be unravelled with difficulty.

307. The Author believed that a better understanding of the mechanisms involved in the failure of dams could be found by studying defects which had not as yet

culminated in complete disaster. In this belief he had deliberately omitted reference to some of the classical failures of the past, and he hoped that this policy might lead to the submission by other engineers of information relating to dam failures which had hitherto not been made public. He did agree, however, that the references made by several contributors to the discussion to the notable failures of the Puentes Dam in Spain and the Bouzey Dam in France were valuable additions to the Paper.

308. Mr Allen had enquired whether the statutory regulations obtaining in countries other than Britain permitted the inspection of dams by an engineer who was either responsible for its original design or was in the employ of the owner. The Author was not able from his own knowledge to answer these questions. He did, however, suggest that as an intimate knowledge of a dam could only be acquired gradually, there were obvious advantages in employing the same engineer to make successive inspections. In the case of dams of unusual size or complexity of design, it was obviously desirable that the engineer originally responsible should remain associated with the work for as long as possible. Reports on the state of a dam and recommendations for its maintenance should be made to an authority which had the necessary power to ensure that any measures necessary for public safety were, in fact, carried out.

309. The Author felt that there were advantages in entrusting to a government department possessing its own staff of qualified engineers the responsibility for making periodic inspections. The duty of keeping records should lie with the owner of a dam, who should provide copies to the official inspectorate. Regular inspections should, of course, be compulsory, and the duties and powers exercised by the inspectorate would follow similar lines to those possessed by a public authority responsible for fire prevention and other safety measures.

310. Dr Ahmed had suggested that a close study of the forces which caused dams to fail would make it possible to formulate general rules governing specific types. The Author agreed that this was logical and felt that such a study would reveal that the main risks arising from a dam built on difficult foundations would, even in those cases where the most advanced techniques had been used, be found to reside in the foundations themselves.

311. Because of the exceptionally unfavourable foundation conditions associated with the Aswan High Dam, the Author believed that the execution of this bold project was fraught with a good deal of hazard, and he could not help observing that to tie the very existence of a densely populated country to such an enormous and, in many ways, novel project was, to say the least, imprudent.

312. The calamities which befell the Puentes Dam in Spain and the Bouzey Dam in France were examples of what might occur when an engineering work was carried out beyond the safe limits set by the technological science of the day. If it were possible to capitalize the risks involved in such hazardous enterprises as the Aswan High Dam and to add the sum so obtained to the actual construction costs, it would often be found that the ultimate objectives could be achieved by adopting quite different solutions and with greater advantage to the public welfare.

313. Mr Sancha had drawn attention to the Author's omission of any reference to the Malpasset disaster. The omission was, of course, deliberate since the available technical literature contained a mass of information relating to specific dam failures of the past. It had been the Author's intention in preparing his Paper to remind those who were concerned with dams that much could be learned from a study of the forces which led to their deterioration, and that the knowledge to be gained in this way was perhaps even more important than that obtained from a consideration of complete failures.

314. The Rio Negro flood of April 1959, and the consequent inundation of Rincon de Bonete power station, had a double lesson for engineers. It was only after the occurrence of this near catastrophe that calculations were made, on the basis of meteorological data, of the maximum possible theoretical flood which could occur.

The calculation showed that the cost of providing a spillway to deal with such a theoretical flood would have been quite prohibitive. When the dam was overtopped and the powerhouse was flooded, ultimate disaster was avoided by the courage of those who stuck to their posts and took emergency measures to mitigate the situation, including the use of explosives to breach a subsidiary dam. While the fortunate outcome of these critical events might be regarded as a matter for congratulation, it should not be forgotten that although the Rincon de Bonete Dam remained intact, the narrowness of the margin by which the ultimate catastrophe was avoided must remain a matter of conjecture.

315. In concluding his reply to the discussion, the Author would like to emphasize that one of his main objects in writing his Paper was to demonstrate that dams, in common with all man-made works, were subject to a life cycle and he was happy to think that his philosophy had been found acceptable by so many engineers.

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