Seismic activity at man-made reservoirs

R. G. T. LANE

Mr Lane

From engineering and other points of view, seismicity at a dam site can be very important. To quote an example, the design of a large embankment dam at a difficult site near zones of earthquake activity is now under review. The difference in cost between making provision for moderate seismicity at the dam site, or, alternatively, the effects of an event of magnitude between 6 and 7 with epicentre near the site, is estimated to be of the order of £1 million sterling.

41. A special feature of the seismicity which sometimes follows the impounding of a large reservoir, is that the centres of disturbances are located at or near the reservoir. Events greater than magnitude 6 have been recorded so far, and it must be appreciated that the energy released increases a thousand fold for each increase of 2 in magnitude. If earthquakes occur following impounding, and damage results, to what extent is the owner of the reservoir responsible?

42. On the other hand, recent investigations at several existing reservoirs in the USA have indicated that in some cases the dam construction and reservoir impounding may lessen earthquake activity at the site, which is consistent with the views put forward in the Paper.

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From § 2, I agree it is important to establish the reasons and mechanisms which lead to the seismic activity at man-made reservoirs.

44. From studies in several disciplines, it is thought that earthquakes in the earth's crust are caused by the sudden release of strain energy produced by slip along existing faults or by fracture. Consider a rock specimen at some stage of testing in the laboratory, or the rock masses around a tunnel or a portion of the earth's crust. These masses have had a complicated stress history and apart from the strain energy they may contain because of gravity and tectonic forces, they may also contain some due to residual stresses. Further increase in stress or decrease in strength in some part of the mass may bring about instability and local failure of the material. Consequently part of the stored energy will be released and will radiate in the form of seismic waves.

45. Thus the generation of an earthquake will require slip or fracture in the earth's crust, and this may be brought about by a stress increase or, equally well, by a strength decrease. A stress increase can be brought about naturally or by human intervention by deep excavations, rapid accumulation of deposits, tunnelling and mining works, reservoir impounding, and also by rapid barometric changes, tide loading as well as by extra-terrestrial forces. Tectonic forces and rock expansion caused by alteration may also cause stress changes. On the other hand, a decrease in strength may be caused by changes in the effective stresses, weathering and alteration.[8]

46. Where there is such an instability, strain energy will be released, but whether this energy will be converted into seismic waves will depend on the speed with which the slip or rupture will occur. The velocity of the slip-propagation is the single, most important factor in the production of an earthquake. If the velocity is slow and the slip takes place rather slowly, all the strain energy will be spent on friction on the fault and there will be no seismic energy radiation and consequently no earthquake. If the velocity of slip or rupture propagation is infinitely large and the stress release takes place instantaneously over the entire failure plane, then most of the energy will be converted into seismic energy and the ground motion near the rupture will become catastrophic with maximum particle velocities of about 4 ft/sec.[9] Factors controlling

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the slip velocity (0·8–4·5 km/sec) control the destructiveness of the associated earthquake, e.g. as in reference 10.

47. If progress is to be made towards a secure prediction theory, first the state of stress and also the available strength of the rock masses before impounding must be predicted (at depths ranging from 5 to 50 km) as well as the velocity of rupture propagation in the event of rapid dislocation.

48. The Author unfortunately follows Hast's ideas[7] about the state of stress in the earth's crust and his theories for a shrinking earth. There are many more authoritative works on the state of stress in the earth's crust and plate tectonics (a model which, incidentally, says nothing about shrinking or expansion of the earth). But even if Hast's ideas about the state of stress of the rocks at depths of one kilometre or so were correct, they are irrelevant to what happens 5–50 km in the crust where most of the earthquakes triggered by reservoir impounding have their origin.

49. A recent instrumental study of the Koyna earthquake shows a long and narrow fault, extending from the surface down to 80 km into the lower crust,[11] and long period spectra are consistent with a focal depth of 55 km.[10] Moreover, aftershocks extended to a depth of 40 km.[12, 13] A re-evaluation of the Kremasta earthquake shows that the shock originated 25 km in the crust and that aftershocks were located between 15 and 40 km.[14]

50. It is unnecessary to show further that Hast's values are irrelevant and that deeper processes in the earth's crust cannot and should not be interpreted in terms of what is known about the rock properties in the upper kilometre or so.

51. More controversial is the crucial assumption that Mr Lane makes about the permeability of a fault zone at depths all the way to the focus. He assumes that reservoir water has access to a faulted zone extending to a great depth. There will be some who say it is not possible to have a continuous open crack or porous zone leading from the surface to depths of say 5–40 km. There is evidence to show that mylonitized fault zones under intermediate to high pressures corresponding to depths of 3–20 km may be equally or more impervious than the surrounding rock. Also cracks, isolated or continuous, cannot remain open beyond a certain effective stress.

52. Finally, referring to the general effect on seismicity of reservoir loading, I find it logical to assume that stress or strength changes in the earth's crust may delay or even prevent an earthquake from happening. Not only cases of increased activity after impounding are known, which have naturally attracted most attention, but also cases of decreased activity.[15, 16]

53. An extensive study of the San Luis Reservoir in California shows little or no indication that reservoir loadings cause an increase in local seismicity. The San Luis Reservoir is in an area which has been subjected to intense seismic activity. A major fault extends beneath the lake area, and the San Andreas Fault passes within 30 km of this location.[17] At the Kurobe reservoir in central Japan, recent studies show that the observed seismicity after impounding is not related to the filling of the reservoir but it is a continuation of the local activity which otherwise is quite high.[18] The filling of the Kastraki reservoir in Greece, a major reservoir adjacent to that of Kremasta, has caused so far absolutely no change in the seismic activity.

54. The most pertinent parts of the Paper are those in which the need for more fact finding and research and their relevance is discussed. There is still much to learn about man-made earthquakes from field observations and seismological studies. However, generalizations and deductions from a dozen case histories are hazardous.

55. In parallel with the investigations suggested by Mr Lane, the engineer must decide at an early stage whether he should design his structures to resist a nominal earthquake, independent of the results of the investigation suggesting seismic risk. Monitoring of seismic events during and after construction of a dam and impounding will provide information too late for economic corrective measures to be taken. Seismic effects should be extended to include the design of new structures nearby, the stability of artificial slopes not directly associated with the reservoir, the stability of

nearby masonry and hydraulic fill dams, downstream flooding due to overtopping or breaching of the dam, the provisions for reservoir draw-down, and the adequacy of station operation manuals in the event of seismic activity. This is only acceptable until solution of the earthquake prediction problem and methods must be used which appear to be adequate.

56. In conclusion, in the assessment of the seismic risk involved in a site, not only the state of stress in the earth's crust is a major contributing factor, but also the available strength of the rock masses before impounding, as well as the velocity with which the rupture will propagate if stress or strength changes bring about failure. But with real crustal masses, 5–40 km thick, it is difficult at present levels of science to determine, or even assess for a particular site, how large or how small an induced stress or strength change would be necessary to bring about a damaging earthquake, and it is almost impossible to predict the speed with which failure will occur. Modern ideas of the behaviour of the earth's crust, such as plate tectonics, are invaluable but the engineer must understand the advantages and limitations of such ideas before he can define precisely or establish reasons and mechanisms; it is more than mere awareness and it requires high scientific knowledge.

57. Since present advancements in seismology allow a far from adequate knowledge of the generic causes of earthquakes and observational data are so meagre and so little understood, proposals for diagnostic investigations can only be tentative, and it is well to remember the stricture that for any given hypothesis one can find self-consistent data.[19]

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It is not sufficient to be complacent about these problems on the grounds that there is uncertainty about mechanism. Rather, it should be considered what can be done at present. The various projects must be so instrumented that data become available, which in the long term will allow the mechanism to be determined, while in the short term will allow some elementary predictions of behaviour to be made. I suggest there should be a basic theory, which will generate some constructive form of experiment to describe the behaviour of particular sites.

59. The Author mentions the theory of plate tectonics, and says incorrectly that this leads to expansion. The point of plate theory is to recognize that the upper 60 km of the earth's surface is a set of solid, rigid plates capable of sustaining stress. Lithosphere is formed at mid-ocean ridges, spread out laterally and old lithosphere is absorbed along the island arcs. The boundaries of the plates are regions of maximum stress, and are delineated by the principal zones of earthquake activity.

60. Earthquakes are possible as a direct result of pouring liquid into the ground. Thus it is possible by pumping liquid at strategic points within a plate to release some of the latent strain energy of that plate. Within a plate there are regions of weakness which are faults, and these faults if 'lubricated' may slip, although they would not slip at all under normal surface loading. Thus it is likely that impounding will result in the release of some of the latent plate strain, accompanied by a readjustment of the strain pattern over the plate as a whole.

61. Fault slip not only leads to earthquakes, but also to displacements. These displacements would be in such a direction to minimize the strain on the plate as a whole. It is likely that some motion will occur at a site which bears no relation to the way in which a site is loaded. Instead it bears a relation to the stress pattern existing over the plate prior to construction.

62. There should be an adequate array of seismometers at every site to enable the fault structures, their activity and their magnitude–probability curves to be seen in three dimensions. Also measurements of displacements should be made. These may be seen on the ground if the activity is sufficiently intense. It is then relatively simple to obtain a prediction theory sufficient to say whether displacements are likely to occur in a particular direction at a particular fault.

63. Adequate instrumentation is needed. First, a ground fault survey by a geologist is required. A seismic array of suitable dimensions and number of instruments may then be designed to make adequate observations of events over these faults. There are sophisticated processing techniques which are available to assist in the general seismic techniques, and full use should be made of these. Recordings should be made on magnetic tape and processed using modern digital techniques (such as are available in the processing laboratory at Durham) to extract the maximum amount of data to the highest accuracy. The whole of this data should be used to build a theory of the behaviour of a site before construction, on which predictions may be based. A lot can be found out provided the right instrumentation is on site at the correct time and the records are satisfactorily processed.

Mr J. C. W. Fowler, Sir Alexander Gibb & Partners

Out of the several thousand large dams which have been constructed, there are about twenty examples where an apparent increase in local seismicity has been reported to be associated with reservoir impounding, and one where a decrease is said to have occurred. Of these, probably the best documented are those listed by the Author. In addition, there are a few cases where instrumentation has been installed, but no change in seismicity has been recorded on loading. In most cases, the filling of reservoirs has not been accompanied by significant changes in local seismicity, and consequently special geological or hydraulic conditions have to be postulated for such occurrences. In order to specify what these conditions are it may be informative to look at the characteristics of the particular cases which have been reported.

65. First, the seismic history of the reservoir region does not appear to have any particular bearing on whether or not impounding leads to changes in seismicity. Characteristic examples are associated not only with areas of recent tectonics and high seismicity, e.g. Grancarevo and Kremasta, but also with more stable masses with an old orogeny, e.g. Koyna and Kariba. The distribution in time of any change in seismic activity differs markedly in the various cases studied.

66. The filling of the Contra Dam in Switzerland was accompanied by continuous small tremors. At Kremasta a strong earthquake occurred during filling, preceded by many foreshocks, but at Koyna the strong shock happened after several years' operation of the reservoir. As far as focal depth is concerned, it ranges from less than a kilometre in the case of Camarillas in Spain to many tens of kilometres in the case of Kremasta.

67. The depth of water in the reservoir does not appear to be more important than total water load. Whatever the mechanism, the changes involved will be dependent on the total depth of water, which may be greater than the apparent depth of the reservoir. However, the extent of the reservoir is important in that it influences the probability of occurrence of a seismic event through its effect on the volume of rock subjected to a given stress change.

68. On impounding a reservoir additional stress changes are superimposed on those changes which are already occurring in the lithosphere. In some instances it is probable that a natural process of strain accumulation is accelerated. If the crust were already near the point of rupture, additional load caused by the weight of the reservoir or an increase in interstitial water pressures might produce either a redistribution of internal stresses by fault movement in the form of creep, or a more rapid movement leading to a seism, or even fracture of the rocks.

69. The Author has demonstrated one possible mechanism applicable in the case of very shallow earthquakes. At greater depths where even the secondary permeability will be zero because of the lack of continuity of fissures, some sort of mechanism related directly to the applied stress has to be postulated. The stress distribution beneath the load will differ markedly from that predicted by Boussinesq because of inhomogeneities and anisotropy in the rock, and the maximum shear stress may be several times greater than that quoted for Kariba.

70. The lack of fit which usually occurs between geodetic observations and predicted deflexions serves to confirm the inhomogeneous, anisotropic, inelastic and discontinuous nature of the material of the lithosphere. Several mathematical and mechanical models have been developed as a better approximation to real behaviour than the elastic theories.

71. The Author mentions the importance of establishing the reasons and mechanisms which lead to these phenomena. Engineers must be careful not to become too involved in attempting to draw conclusions regarding the causes or mechanisms of seismic activity in any particular case, or in the risky business of earthquake prediction. An understanding of man-made seisms must await a better understanding of natural earthquakes. Well documented case histories including geological and seismological data must be studied and any common factors from what appear to be special cases must be found, so that an empirical approach can be adopted when implementing reservoir schemes. Such case histories are only of significance when based on readily comparable quantitative data obtained from suitably instrumented dams and reservoirs. The engineer is still left with the task of recognizing whether or not he has a potential problem.

72. One approach he might adopt would be to incorporate at the feasibility stage: (*a*) a study of the seismicity of the reservoir region (including both instrumental and historical data, if available); (*b*) a geological survey of the reservoir and its adjacent area aimed at pinpointing any active features; (*c*) a temporary seismograph network to sample seismic conditions before impounding. On the basis of the information gathered, the engineer must then conclude whether to go ahead and implement: (*d*) a more detailed geological and tectonic study of the reservoir and its adjacent area; (*e*) the installation of permanent seismological instruments; (*f*) a programme of precise levelling; (*g*) the installation of fault instrumentation.

73. Thus, the realization that changes in seismicity can be induced by reservoir impounding adds to the factors which the engineer is required to assess during the study and implementation of reservoir projects.

Mr A. C. Allen, Allen, Gordon & Company

In Scotland the occurrence of natural earthquakes of low or medium intensity is of relatively high frequency compared with England and Wales.

75. The situations described in the Paper are unlikely to happen in Britain, where the highest dams and largest reservoirs are at the low ends of the ranges of size given in columns 4 and 6 of Table 1, and it seems likely that they will continue to be so, because of the topography and needs. Records of seismic activity in Britain, chronicled to some extent over hundreds of years, continue to rely heavily on non-instrumental information. From this kind of evidence and the instrumental data now becoming available, there is nothing to indicate any change in seismic activity in consequence of the making in Britain of many reservoirs, albeit of moderate size by world standards. Such changes may have happened, but they have not been on a noticeable scale.

76. In Britain, at present in the unfinished Quaternary Ice Age, the land was for 2 million years, until as recently as 10 000 years ago, subjected to successive glaciations in which the ice over it built up to thicknesses of thousands of feet. Such ice loads far exceeded any forces which might be imposed by the construction of reservoirs. It could be that the tremors, which are of relatively shallow origin and are experienced occasionally, originate from the earth's crust continuing to relieve itself from the effects of the extra gravitational pressures imposed by the ice loads, in addition to any continuing contraction or expansion as referred to in the Paper. These considerations similarly apply to Canada, Scandinavia and Russia in the northern hemisphere.

77. I suggest to the Author that he should consider: (*a*) clarifying the meanings of 'man-made reservoirs' and large 'man-made lakes'; (*b*) adding a qualification to the

Paper to indicate the extent to which he considers it should have world-wide application, with particular reference to Britain.

78. It would be useful if the criteria for selecting the 17 reservoirs included in Table 1 could be given, and if references could be quoted to facilitate individual cases being studied in more detail. The extent to which the Paper is based on Kariba could then be determined. An eighth column in the table indicating seismicity before construction would be valuable. It seems that where reservoirs are formed in remote parts of the world, e.g. Mangla, records of previous seismic activity are likely to be sparse. This may account for eleven of the dams being in either European countries or North America, and the remaining six being distributed elsewhere in the world, with the exception of Russia, South America, the Middle East and Britain.

79. The comment in § 9 should not be surprising because of the many other variables in each case, particularly the state of the earth's crust before impounding.

80. Referring to §§ 31–36, the scale indicated for the initial investigation and exploratory work is out of proportion for British conditions. The area within which a reservoir is to be formed should be studied by a geologist. From seismic and other considerations this assumes extreme importance if there are or may be any underground mineral workings in the vicinity. Britain is fortunate as most areas are reasonably mapped geologically. Instrumentation of dams is vital in ensuring their safety and I would recommend that in an area of known seismic activity, one or more of the modern, convenient to use, instantaneous or continuous recording seismometers should be installed as early as possible in the locality of the reservoir.

81. Lednock Dam and Loch Turret, which has been greatly enlarged by the construction of a new dam, are close to the Highland Border, or Boundary, Fault in Scotland. Comrie has the reputation of being the earthquake centre of Scotland, and from 1839–1848 experienced 320 shocks, two of them reaching an intensity of 8 on the Rossi-Forel scale. There has been a marked migration of activity in recent years from the vicinity of Comr ie eastwards to nearer Perth, through a distance of 20 miles or so.

82. This is relevant to § 32, referring to records over a period of six months possibly giving an assessment of the future probability of occurrence of seisms of various magnitudes. On account of the adjustments and migrations at faults actively producing tremors, a record of less than many years is of no value in providing such an assessment for a reasonable future period, even after allowing for statistical analysis.

83. Referring to § 34, such activities, as they grow, must be carried out not simply for research in isolation, but so as to be of maximum practical application. Moreover as civil engineers direct, on an ever increasing scale, the great sources of power in nature for the use and convenience of man, to some extent they will still need to make progress by faith.

Mr D. A. Howells, Howard Humphreys & Sons

An engineer who has to advise the promoter of a project for a large reservoir, having a greatest depth in excess of, say, 80 m, will be aware that there is some risk of causing earthquakes within a few years of the first impounding. Unfortunately it is not possible at present to say that certain sites have a higher risk than others, which are probably the majority. The Author's recommendations for investigations at sites of future reservoirs are welcomed, and it is hoped they will give an insight into the general nature of the problem as well as the assessment of the risk at a particular site.

85. A proper investigation of earthquake risk cannot be made by a relatively small extension of the investigations usually done for a large reservoir site corresponding to those outlined in § 31. It would constitute an extensive and expensive programme. The depth of the initiation of earthquakes which have occurred is not known, but may be conjectured to be about five kilometres or more. Boreholes to this depth correspond in cost to the deeper oil exploration boreholes and are probably prohibitively expensive. At Denver the log of the injection well contributed to the interpre-

tation of the geological structure. A procedure of investigation is needed and it must be realized that a high degree of certainty cannot be attached to the interpretation of the results.

86. The investigation of the existing state of stress in the rock at depth is similarly a considerable and expensive undertaking. The Author refers to the figures reported by Hast,[7] which related to a particular geological region and were carried to a maximum depth of one kilometre. Jaeger and Cook[20] discuss these and other figures including a measurement at 1·5 km and one at 2·5 km. These figures may be sensitive to the choice of suitable stress concentration factors and the published results show wide scatter. So extrapolation from the depths at which results have been obtained so far to 5 km cannot be considered reliable. An additional result from a depth of 1·35 km in the Mont Blanc tunnel has been quoted by Oberti *et al.*[21] In some cases the observed vertical component of stress differs quite widely from the overburden pressure.

87. Referring to § 32, in the case of the Denver earthquakes Healy *et al.*[22] describe the network set up to study that phenomenon. Eight small arrays of slightly modified explosion seismology equipment were used. Each array consisted of six vertical seismometers at half kilometre spacing set in an L-shaped pattern with two horizontal seismometers at one of the vertical seismometer positions. A survey of the seismic velocities of the rocks penetrated by the disposal well and a nearby seismic refraction profile were used to determine a local velocity depth function. With this they estimated that well recorded earthquakes could be located with a precision of 0·3 km horizontally and 0·5 km vertically.

88. At present, there is no way of avoiding this high cost, and the only way it can be reduced is by a rapid build-up of general information, particularly in identifying those regions which are usually stable but have tectonic stresses large enough to produce earthquakes. Work of this sort needs to be co-ordinated internationally, and a UNESCO working party has sent out a recommendation inviting member States to take part in the work. I understand that the Geophysics Committee of the Royal Society is following this up.

89. It is generally agreed that two factors are involved in causing earthquakes near large reservoirs—a pre-existing state of stress in the rock close to a fracture, which can be changed to one of fracture by a small modification, and a trigger mechanism to make this modification. For the Denver earthquakes, the injected fluids were probably the trigger and since the depth of 3·7 km was known and the quantities and later the pressures were recorded this could be confirmed. There could be the same trigger mechanism for a reservoir, but the relationship is more conjectural. The ability of surface water to penetrate through rock fissures to great depth was noted in the Mont Blanc Tunnel by Oulianoff.[23] He found the fissures caused by orogenic forces were still unclosed in spite of the millions of years that have passed after their formation, and that none of the processes which might be expected to seal them had taken place. The considerable quantities of water were much cooler than the surrounding rock, suggesting their recent arrival from the surface. These observations were made in a tunnel 50% of whose length was between 1·7 and 2·5 km below the surface, so that it is speculative to assume that similar open rock fissures can be expected at the depths of superficial earthquakes such as the man-made ones. Though it is deep, the tunnel is quite high above sea level, so that it is possible for this water to appear at the surface and take part in the hydrologic cycle, while any fissure water that may be the cause of earthquakes is perhaps permanently withdrawn from circulation.

90. The state of stress in the rock at the depth of such earthquakes needs to be carefully defined if the existence of a network of fissures is assumed whose spacing is relatively wide in relation to possible measuring instruments. I wonder whether it is significant that the average state of stress to be expected at the depths of such earthquakes appears to be close to the transition between ductile and brittle behaviour, so that rock, which might deform in a ductile manner under overstress in the natural

state, is placed in a state of brittle fracture by the hypothetical increase in fissure water pressure.

Dr P. L. Willmore, Institute of Geological Sciences Edinburgh

Filling a dam can either increase or reduce the probability of earthquakes, and the prediction problem cannot be solved until the pre-existing strength and stresses and the extent to which these stresses can be modified by a dam are known.

92. Experimental networks now look more practical than they did a few years ago, and the unattended running time is being extended to an extent which makes such systems much less costly to operate. Conventional seismographs run for 24 hours and a man has to change the recording sheets daily. Modern tape recording equipment can run for at least two weeks, and equipment which can run for a year is under development.

93. In the areas in which there are no local records, knowledge of earthquakes of magnitude 6 and over goes back 50 years, and knowledge of earthquakes of magnitude 4·5 goes back about 10 years. Now earthquakes of about magnitude 1 are being observed by local networks. In terms of frequency of events it means that 50 years ago, over the world, 50–100 events were known to take place each year from long range observation. Now there are about 20 000 events known from long range observation, and if micro-tremors were recorded there would be a data flow of millions of events a year. So the time scale is enormously contracting. This does not necessarily help as much as might be hoped, because there is also a problem of intermittent activity in faults, and a short sample is not necessarily representative of long-term hazard.

94. It would now be interesting to consider the proposition that the magnitude of triggered earthquakes should always be within the range of magnitudes to be expected in the absence of triggering, because triggering usually seems to work by reducing the strength of bedrock thereby bringing about the release of strain energy which would otherwise build up to a higher level. If this proposition were true, the dam which caused a quiet period when filling would be the more dangerous one in the long run.

95. A second hypothesis worthy of investigation is that the timing of large earthquakes is less susceptible to triggering influences than that of small earthquakes, because the energy sources of the former must be larger, and must therefore reside at greater depths in the earth.

96. Lastly, considering the strategy of instrument deployment, a micrometer network can now be installed in a month or so, and installation would be easier if the equipment went back to an area which had been prepared in a previous period of occupation.

97. Therefore a number of dam sites could be kept under observation by moving a single body of instrumentation from one site to another, returning repeatedly to see if the pattern of activity was consistent. Total instrumentation might therefore be used several times over any number of sites, and there would be a greater chance of finding long-term patterns.

Mr I. P. Haigh, Consultant, Sir Alexander Gibb & Partners

The paper by Hast[7] is of such importance in drawing attention to widespread horizontal stresses in the crust that little purpose was served in quoting the speculation about possible changes in the size of the earth as Mr Lane has done in § 20.

99. Civil engineers ought now to take a keener interest in plate tectonics.

100. Although scientists are not fully satisfied with the theory, civil engineers, accustomed to rely on less than perfect data, could be prepared to accept the idea of convection cells in the mantle dragging the extensive areas of new crust under the oceans against the continental masses. High horizontal stresses would then be exerted and maintained on these masses, irrespective of whether a trench is present or absent.

101. Bott has reviewed the present state of geophysical knowledge in relation to plate tectonics[24] but his chapter on the mechanism of plate movements lacked the discipline that civil engineers might have contributed to it from their training in the strength of materials. Collaboration between geophysicists and engineers, using the data already acquired by geophysicists and the technique of finite elements, could yield results of value to geophysicists, as well as to engineers concerned with the construction of tunnels and other underground works. Analyses involving large non-linear displacements are difficult, but assistance might be found from previous work in the hot rolling of ingots, the cold rolling of sheet metal, the moulding of plastics, and creep in asphalt pavings.

Dr R. J. Maddrell, Sir William Halcrow & Partners

The possibility of identifying areas where man-made earthquakes will not occur arises as a result of work done in Ecuador. If the distribution of earthquakes is plotted as a section across a country, a pattern of earthquakes results, showing plate tectonics suggesting a continental drift of the Andes in a westward direction, with the zone of earthquake centres sloping down beneath the Andes. The area where the work was done on the dam was from 70–100 km below the dam site. There are other earthquake centres, the shallowest being in the region of 30 km. I wonder if in an area like the Andes, where the surface rocks are of such thickness to have depressed the rocks beneath them and the earthquake centres are so deep, that to build a dam and fill it will have little effect on the area which is producing the earthquakes.

103. I am not familiar with all the cases cited in the Paper, but perhaps in some of these dam sites there are older crustal rocks which are close to the surface. In a case such as this a dam will have an effect, and could bring about earthquakes, but in an area such as Ecuador or the Andes where the crust is depressed, and the main area of seismic activity is 100 km below the site, this does not seem possible. I also wonder whether, in a zone such as South America which is seismically active, the seismicity which is going on at depth has an effect on the stress of the rocks above, and whether it could alleviate earthquakes or stresses and strains building up in the rocks above these levels. Earthquakes at depth could release these pressures, and it would mean that earthquakes would not be expected at the upper part of the crust in these areas.

Mr M. M. Ghadery, Imperial College of Science and Technology

The recommended investigations and action in §§ 31–36 should not be overlooked and should be considered with caution, especially by a developing country in a seismic region which is in the process of building a man-made reservoir.

105. The question of whether a man-made reservoir can cause seismic activity can be considered as one of the many important parameters. The suggested reason for seismic activity as a result of an increase in the impounded level of the reservoir is an over-simplification. On the basis of the available information, an increased pore pressure due to impounding has not been traced at a depth of more than 1·5–2·0 km below the geoide, so the suggested conclusion seems to be a gross extrapolation from surface evidence.

106. The examples given in Figs 3 and 4 are not comprehensive and are very much idealized.

107. Considering the financial limitations imposed by the authorities in charge of the constructions of a reservoir in a seismic area, is it not better to concentrate on the seismic design of the dam on the basis of data which has been developed by the scientists on seismicity, and data on the nature of ground motions, rather than by using results from the expensive instrumentation that is suggested. Moreover, if the infor-

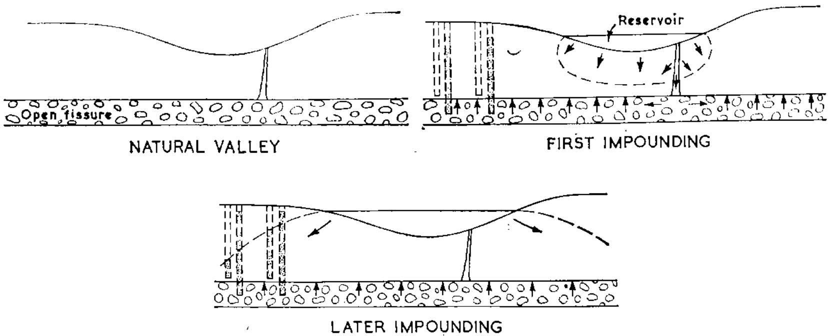

Fig. 5

mation obtained through this type of instrumentation becomes available, how is it to be used to prevent future damage to the reservoir?

108. What the Author suggests is the use of the dam as a guinea pig.

Mr E. T. Haws, Director, ERCON

In supporting the Author's conclusions in §§ 19–22, Fig. 5 shows the probable mechanism in a different way. For simplicity the existing water table is not included in the diagrams, and it is the differentials or increase in the water table which are significant. The higher permeability foundation layer is assumed connected to the reservoir at some point, the location and manner of the connexion not being important. However, immediately the reservoir starts filling, water virtually at full reservoir pressure is assumed to permeate the permeable layer, exerting uplift pressures equivalent to full reservoir head. In the area of the reservoir these uplift pressures are balanced by the deadweight of the superimposed water-load resulting in zero change of effective stress. However, outside the reservoir area the rock at the upper surface of the permeable layer is subjected to full uplift pressure with no compensating increase in vertical load. As Mr Lane says, the result is a decrease in effective stress with a consequent loss of shear resistance which may result in local failure and seismic movement. The pressure conditions are probably accompanied by softening of fault breccia or other cohesive materials which accentuates the effect. During the early stages of impounding the unbalanced uplift pressures will probably be greater than when the foundation mass is becoming more fully permeated with water related to the higher reservoir condition.

110. For the purpose of the diagram it has been assumed that there is a virtually impermeable layer at the top of the permeable zone. This is not essential to the argument and in nature a variety of conditions at this interface will exist. The proportional reduction in effective stress will be much greater where the natural ground topography is comparatively level and this is perhaps an aspect which requires more emphasis.

111. From Table 1, at Kariba the reservoir raised the water level from about 1300 ft to about 1600 ft and the reservoir with a huge water spread is bounded by a plateau area which only rises an additional 1600 ft in a distance of 150 miles from the lake perimeter. Thus, in the circumstances of any geological conditions similar to those of the diagrams, percentage changes of effective stress at depth would be appreciable and could explain seismicity.

112. Also from Table 1, at Koyna in India, the dam raised the water level from approximately 580 to 665 m and a saddle across the continental divide to the west is of virtually no higher topography. The foundations consist largely of basalt, but

there are horizontal layers of tuff breccia which conform closely to the diagrammatic area of the sketches. The area is aseismic naturally, but the situation described appears ideal for development of seismicity upon impounding, as did occur.

113. Again from Table 1, at Kremasta in Greece, the water level was raised by 145 m to a maximum pool level of 284 m, and there are some seven or eight saddles around the reservoir rim at levels from 500 to 1000 m. However, if the topography appears less favourable to the mechanisms described, the geology is of the type which might give problems, consisting of sedimentary deposits of siltstone, sandstone and conglomerates said to contain permeable zones in the banks. Also, the area is active seismically in nature. Thus, conditions at three dams which have shown strong seismicity show the characteristics required by the probable mode of action because of reduced effective stress.

114. Seismologists have emphasized the depth of focal points for some of the seismicity associated with reservoir impounding, but surely the mode of action suggested by Mr Lane and supported here could result in the release of sufficient energy to trigger off more deep seated seismicity.

115. Extended site investigations are essential whenever the impounded level is to approach substantial surrounding saddles or when the area is one of natural seismicity.

Mr P. Lancaster-Jones, Cementation Ground Engineering Limited

I shall confine my remarks to a description of some emergency remedial works at dams whose partial failure was due to earthquakes (or believed to be so) without commenting on the origin of the tremors.

117. In § 16 Mr Lane refers to Koyna Dam in India as one of those affected. The main shock occurred on 11 December, 1967, and largely destroyed the construction camp with the loss of about sixty lives. Damage to the main body of the dam was limited to the appearance of horizontal cracks in the concrete on both upstream and downstream faces. Emergency repairs required before the onset of the monsoon included stressed cables extending from the crest to below the crack zone, drainage holes, and injection of the cracks with epoxy resin to restore bond strength.

118. The cracks generally ranged from 50 to 300 μm but in places reached 3 mm. To inject, say, a 100 μm crack with a grout having a viscosity of 1000 cP, means an injection rate of only 5×10^{-4} grouts/min, and the time to penetrate to a 5 ft radius is $1\frac{1}{2}$ hours. Therefore the viscosity of the grout, its pot life and the availability of suitable plant is important. After extensive research the chosen grout was Dobeckot 505, with Hardener 770, manufactured by Beck. Although intended for moulding work, this resin was immediately available from Poona. The hardener is a polyamide, and thus more suitable for wet conditions than a polyamine. The reaction is exothermal, and careful cooling had to be arranged to ensure that the viscosity and pot life were not adversely affected by a rise in temperature above about 30°C. At this temperature, even with a diluent, the viscosity approached 800–1000 cP.

119. Approximately $3\frac{1}{2}$ tons of grout were injected in 8600 ft of drilling, the maximum quantity in any hole being 30 lb. Some less viscous polyester resin grout was injected into the thin cracks observed in the dam gallery. This work was completed in two months, before the onset of the monsoon. A more detailed report on the effects of the quake, and other remedial measures will be found in reference 25.

120. About 180 miles north of Koyna is Bhandardara (formerly Wilson) Dam—a masonry gravity structure completed about 1920. The crest length is 1500 ft with maximum height 270 ft. In September 1969 heavy leakage developed suddenly at the downstream toe, and cracks were seen in the outlet structure. Subsequent drilling from the crest showed that a crack had developed about 140 ft below the crest on the upstream face. The crack extended laterally over the entire 400 ft wide section of the dam across the gorge, and penetrated horizontally about halfway through the dam before inclining downwards to the toe. It was apparent that the upper part of the dam

had moved downstream about 2 cm before arch action temporaily restrained it. During the 1968 and 1969 monsoons maximum flood levels had occurred, overtopping the dam, and one theory is that these aggravated a crack initiated by the Koyna earthquake in masonry bonded with lime mortar which is always liable to slow deterioration.

121. A crash programme of remedial work was initiated in January 1970 and completed in June. The upstream third of the dam was grouted first through holes drilled from the crest, followed by the installation of 108 cables, each anchored to bedrock and stressed to 270 tons. Further consolidation grouting of the main body of the dam was followed by a pattern of drainage holes drilled from the downstream face. Altogether some 150 000 ft of drilling were done and about 600 tons of cement were injected, at a total cost—including anchors—of more than £½ million.

122. Both dams have subsequently been modified by additional concrete or masonry on their downstream faces, and additional spillway capacity has been provided at Bhandardara.

Mr L. Armstrong, Commissioner, Bureau of Reclamation, Washington, D.C.

The Bureau of Reclamation began investigating the effects of reservoirs on the stability of the earth's crust during the design studies for Hoover Dam.[26] Subsequently, as part of this work the Bureau cooperated with the Coast and Geodetic Survey (now National Ocean Survey) in obtaining settlement and seismic measurements near Lake Mead, the reservoir impounded by this dam. Settlement data were acquired by making first order level observations before and during filling of the lake.[27]

124. However, seismic measurements were not begun until 12 February, 1938, when the lake contained $16{\cdot}0\times10^9$ m^3 of storage. At that time, these data were recorded on a short period seismograph located in Boulder City, Nevada. Since the records from this seismograph only furnish sufficient information for estimating epicentral distances from the recording station, two more seismographs were installed in 1941 so that the locations of earthquake epicentres could be determined. These additional seismographs were located about 40 miles apart and about 40 miles from Boulder City. This tripartite seismic facility was put into operation when the surface of Lake Mead reached an elevation of nine feet below the maximum water surface. Storage at that time was about 34×10^9 m^3. After being operated for more than ten years, two of the tripartite stations were closed down during the last six months of 1952. The third station, at Boulder City, is still active.

125. During the 33 year period seismic measurements were made near Lake Mead, many local earthquakes were observed. At least three of these were rated MM 6 on the intensity scale. It is possible that some of the seismic disturbances which have occurred near Lake Mead could have been triggered in some manner by the reservoir. However, any logical explanation for such an assumption should include a comparison of the seismic activity near Lake Mead before, during, and after filling the reservoir. As previously indicated, no seismic measurements were made before impounding water behind the dam. Even if an earthquake had occurred near or within the reservoir site during preconstruction times, there were few people in the area during that period to report such an event.[28] Since data are not available to make the requisite comparison, little evidence exists to substantiate the conclusion that Lake Mead has in some way triggered local earthquakes which have occurred since the completion of Hoover Dam.

126. In addition to the Hoover Dam seismic investigations, similar studies have also been made by the Bureau at Shasta ($5{\cdot}55\times10^9$ m^3), Hungry Horse ($4{\cdot}28\times10^9$ m^3), Glen Canyon ($33{\cdot}3\times10^9$ m^3), Flaming Gorge ($4{\cdot}67\times10^9$ m^3), and San Luis ($2{\cdot}52\times10^9$ m^3) dams. The numbers in parentheses are the total capacities of the reservoirs impounded by the dams named. The seismograph at each of these dams was installed several years before completion of the structure. The seismic data recorded at all five dams mentioned indicate no apparent change in local seismic activity before,

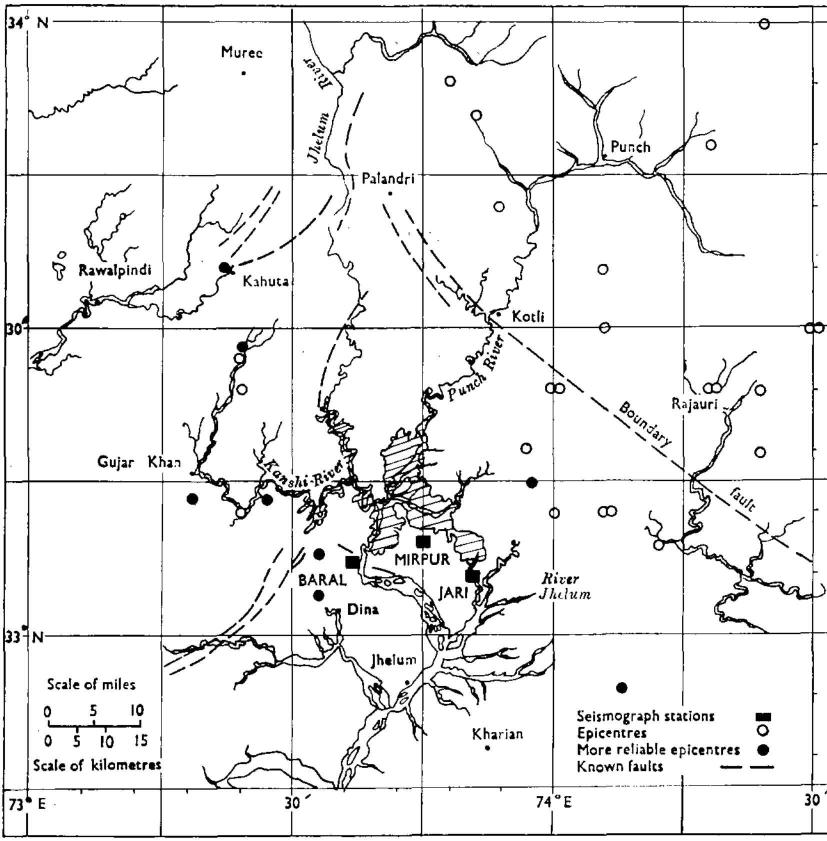

Fig.. 6. Mangla region showing seismograph stations, located earthquakes and known faults (after Adams and Ahmed[32])

during, and after reservoir filling. The study for San Luis Reservoir was of particular interest to Bureau engineers since this body of water is located in California in a seismically active area at a distance of about 20 miles from the San Andreas Fault.[29] In addition, another fault, the Ortigalita, extends through the reservoir site.

127. By February 1972, the Bureau will have completed a seismograph installation near Auburn Dam site in northern California. The dam, which will be 685 ft in height, will impound a $3{\cdot}08 \times 10^9$ m^3 reservoir. Since, according to present schedules, the reservoir will not be filled for at least ten years, ample information will be available on the local seismicity of the area before it is subjected to superimposed crustal loadings produced by the impounded water.

Mr A. L. Little, Binnie & Partners

In Table 1 Mr Lane refers to several reservoirs, including Mangla, where the post impounding activity was slight. Although Mangla is in a seismically active region, there is no record of severe earthquakes in the area. However, the dam is within 32 miles of the Himalayan boundary fault along which severe shocks have been recorded

(Fig. 6), e.g. 160 miles away at Kangra in 1905 there occurred one of the strongest earthquakes ever recorded (magnitude $\simeq 8{\cdot}6$). Accordingly, with the assistance of Professor Skempton and Dr Ambraseys, Mangla Dam was designed to resist a similar earthquake having its epicentre at the nearest point on the boundary fault to Mangla. This resulted in the imposition of an equivalent average horizontal acceleration of $0{\cdot}11\ g$ on the fill and $0{\cdot}15\,g$ for the top 130 ft of the embankment.[30]

129. As a part of the observation of seismicity at Mangla to assist in the design of the dams and to assess subsequent behaviour, seismic stations were set up at Mirpur, Baral and Jari (Fig. 6). These stations were also used to monitor shocks during and after impounding.

130. Changes in seismic activity as a result of impounding in reservoirs must be regarded as well established and Mr Lane gives a number of examples including Kariba. Perhaps the earliest case on record is that at Marathon[31] where shocks following impounding in 1929, resulted in an earthquake of magnitude 6 on 20 July, 1938.

131. In 1969, Adams and Ahmed[32] showed that, following impounding at Mangla, the number of small earthquakes and the energy released had both increased. They concluded that there did seem to be some relationship between seismic activity and changes in reservoir level. The shocks were small, the largest being only magnitude 3·6, while most were magnitude 1 or 2. The number of detected earthquakes rose from 1·6 per month for 14 months before impounding to 4·1 in the 21 months after impounding—a factor of 2·5, but this result must be considered in its context. The Mirpur station was re-equipped in 1965 and the other two stations did not start recording until impounding. Considering events recorded by the Mirpur station alone, the increase in the number of shocks was only 30% to 2·1 per month—by no means significant.

132. The data have been extended to autumn 1970 (Fig. 7). In these further 22 months, 48 shocks were recorded, or 2·2 per month at all three stations, the magnitude remaining small, not exceeding 3·6. Thus, there has been a decline in the number of earthquakes, the overall monthly average recorded by all three stations since impounding now being 3·1.

133. Dr Adams[33] noted that, apart from impounding, other causes of triggering earthquakes were known. He gave as examples a connexion between tides and the Alaskan earthquake of 1964 and a relationship between Ganges basin floods and local seismicity. A similar tendency has been noted in the Mississippi valley.[34]

134. Authenticated cases of reservoir filling unaccompanied by seismic phenomena complicate matters. Table 1 gives two examples, to which may be added Benmore near a seismically active region in New Zealand.[33]

135. The problem for engineers remains one of forecasting likely seismic activity connected with impounding. With the several known cases now on record caution must be taken but, because there are so many examples of perfectly safe impounding, unnecessary alarm must be avoided.

136. Perhaps the best indication of impending trouble is a significant increase in the number of appreciable (felt) shocks. After impounding at Cremasta, the number of recorded shocks rose steeply in the fortnight before the principal shock of 5 February, 1966. Well before this, local inhabitants became alarmed at the frequent tremors and pressed the Electric Power Corporation of Greece to write to the Seismological Institute at Athens asking for an investigation, which it did on 21 January, 1966. Because of its early date, the pre-earthquake behaviour at Marathon is less well recorded but there also seem to have been premonitory tremors there. If such patterns of behaviour are observed during impounding, special precautions should be taken. Although Mr Lane's proposals seem to be the minimum which an engineer constructing a dam of appreciable height (say, exceeding 200 ft) should observe, the cost may be a formidable proportion of the total. Short-term seismic observations do not remove the need to allow for the overall seismicity of the region, deduced from pre-existing records.

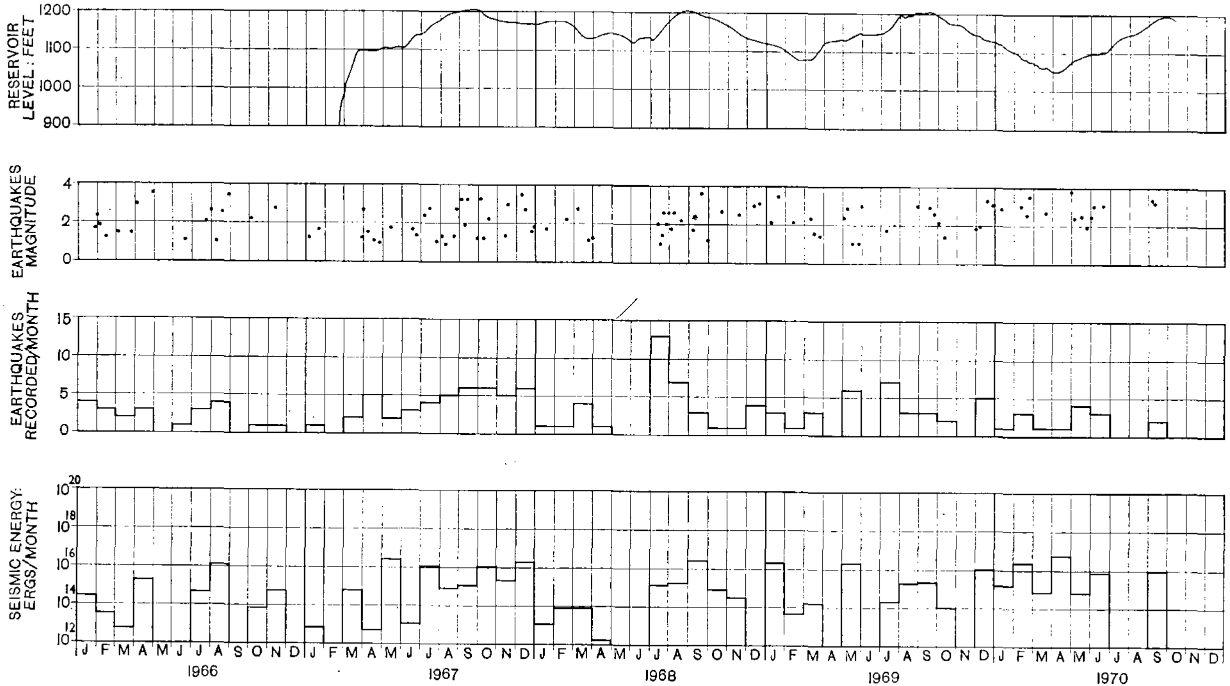

Fig. 7. Earthquake record at Mangla

Mr Lane

This discussion is a significant contribution to knowledge on the subject of seismic activity at man-made reservoirs, and the Author wishes to thank all who have contributed.

138. **Dr Ambraseys** has added some interesting data which are relevant to the overall subject of earthquakes; the Paper had been intentionally confined to the narrower limits set by the title. As all the contributors to the discussion realized, this is a problem where neither the engineer nor the seismologist yet knows all the answers, and no data must be discarded at this stage. The fieldwork of Hast[7] provides important data. Has Dr Ambraseys any evidence to justify his suggestion that Hast's figures might not be correct? Dr Ambrasseys' final statement in § 48 is not understood. It is established that reservoir loading initiates earthquakes with centres at depth. The only communication is by change of stress in the rock, which must originate at the reservoir and reach to the focus.

139. Assuming a modest sized permeable (faulted) zone, say 25 km long and only 2 km deep, in which the water pressure is increased by 100 m, then the bursting force on the rock is 5000×10^6t—which compared with the weights of water stored in man-made reservoirs, would make it one of the world's largest. If the same change of pressure were to occur only in the upper, say, 25% of a fault, the size of the one which Dr Ambraseys quotes for Koyna, the bursting force would be far greater. However, what matters is the effect of this bursting force, which depends on the existing state of stress in the rock at the level where this force is applied. Perhaps it is easier to think of the problem in two parts: (*a*) the new forces due to the reservoir which are active at or near the surface and which have to be added to the existing forces; (*b*) the effect of these forces, which is related to both stress and strength, and which may be felt at depth, and perhaps remote from the reservoir.

140. Dr Ambraseys' recommendation that seismic forces should be accounted for in the design of the structures is appreciated by the engineer, but seismic factors for design have to be estimated. It is interesting to refer to **Mr Little**'s contribution concerning Mangla Dam, which shows the kind of rather arbitrary decision which has to be made at present. Such a decision is as logical as the known conditions allow, but has inadequate scientific or factual backing.

141. **Dr Long**'s comments are helpful and show that the best possible use should be made of the research and instrumentation which the seismologist can now provide. The facilities available at Durham University are unique in England.

142. **Mr Fowler**'s comments are interesting, but as mentioned in § 138, the seismic events are not assumed to occur at the shallow depth where the operative forces are applied.

143. **Mr Allen** poses some difficult questions. The dividing line below which seismic effects due to impounding are negligible can at present only be defined on two considerations (neither of which is theoretically a perfect answer)

(*a*) statistical evidence in regard to the smallest capacity reservoirs, and lowest depths of impounding which have caused seismic effects

(*b*) the evidence that earthquakes of magnitudes up to about 6 occurring at about 20 km from the site, have not caused significant damage to structures built to modern standards of design and control.

144. The list of reservoirs selected for Table 1 was made up of ten cases known to be well documented, plus the seven largest of the world's completed dams, and additional references are given.[29, 35–37]

145. **Mr Howells**' comments, and the data he gives, are helpful. He also answers the questions posed by Dr Ambraseys in §§ 48 and 51. It was not the Author's intention to recommend deep holes to the level of possible seismic hypocentres, but to ascertain the probable limits of effective loading from the impounded water.

146. **Dr Willmore**'s information regarding the level of seismic investigation, and his proposal to adopt moveable instrumentation are most helpful. His proposition that the absence of triggering on filling could be more dangerous in the long run requires careful consideration in relation to further investigations.

147. I agree with **Mr Haigh**'s comments which are useful.

148. **Dr Maddrell**'s suggestion that earthquakes due to filling might be less severe in areas of high seismicity also requires further study, and appears to be supported by some of the available data.

149. **Mr Haws**' illustrations of the alternative ways by which impounding may exert loads within the rock mass are interesting, and emphasize the Author's comment that load at or near the surface can result in the release of energy at depth.

150. **Dr Lancaster-Jones**' account of repairs done at the Koyna and Bhandardara Dams indicates the costs that can arise due to earthquake considerations. Perhaps the cost would have been even more (or perhaps less) if greater seismic factors had been accounted for in the original design, and maybe such design could have averted the damage, as referred to in § 140.

151. The information provided by **Mr Armstrong** about the dams and research done by the Bureau of Reclamation is most helpful, and the results of the studies at Auburn Dam will be interesting.

152. Mr Little has provided some useful data, and the Author agrees with his comments regarding the action which the engineer must take.

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Conversion factors

Imperial units	*SI units*
1 lb	0·4536 kg
1 ton	1·016 t
1 ft	0·3048 m
1 mile	1·609 km