

Inflatable weir used during construction of Mangla Dam

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I have read this paper with particular interest because of my direct involvement with the hydraulic model studies carried out at the Nandipur field laboratory of the Irrigation Research Institute. The analysis and conclusions presented by the Authors generally agree with my own observations on the model and on the damage to the bags after failure.

58. However, I disagree in one major respect, i.e. the statement in § 52 that there was no significant indication of longitudinal surging of the bags in the three-dimensional model. Significant surging was indeed observed on the 1:30 scale model at Nandipur.

59. It should first be emphasized, however, that the Consultants did not receive the information from the Nandipur model due to a sequence of unfortunate circumstances, including the armed conflict between Pakistan and India in 1965, leading amongst other problems to a breakdown in communications.

60. One of the many large-scale models of parts of the Mangla Dam structures at the field laboratory in Nandipur represented the inlet structures to the diversion tunnels, as well as the tunnel outlets, to a natural scale of 1:30.

61. The possibility of blow-outs at the tunnel exits with violent pressure surges and loud explosions of air, referred to in § 3, was in fact in the first instance realised when blow-outs actually occurred on the model during experiments on the tunnel inflow conditions. The significance of this event, when related to the tunnel lining failure in the Philippines and supported by calculations, led to the decision to install a water level control in the tunnel tailrace.

62. Following a failure to construct successful model bags from locally available rubber sheeting, an order was placed with the American manufacturers of the inflatable dams for the complete set of three model bags to 1:30 scale. The models were eventually delivered after a very long delay and the Consultants had in the meanwhile arranged the studies on two-dimensional models at the British Hydromechanics Research Association, the results of which were used for the final design and operation of the bags.

63. The model bags from the manufacturer were successfully employed at Nandipur, using water as the sole inflation medium. Vertical vibrations due to nappe instability were observed under certain conditions of flow over the bags. These vibrations could be reduced or even eliminated by increasing the pressure in the bags, as illustrated in Fig. 13.

64. When subsequently a request arrived at the Irrigation Research Institute to repeat the tests with a small amount of air in the bags in addition to the water fill, the communication difficulties, referred to above, had already arisen. This coincidence proved to be very unfortunate, as the air tests clearly showed the instability of the bags in the longitudinal directions, but only along the longitudinal axis of the bags. The 'snaking' of the prototype bags, as reported at Mangla during the period immediately prior to bag failure, did not occur on the model, probably because the model bags were relatively too stiff to reproduce the transverse motion on the model scale. Nevertheless, the observed behaviour was sufficiently alarming for the information to be relayed (unsuccessfully) to the Consultants in London.

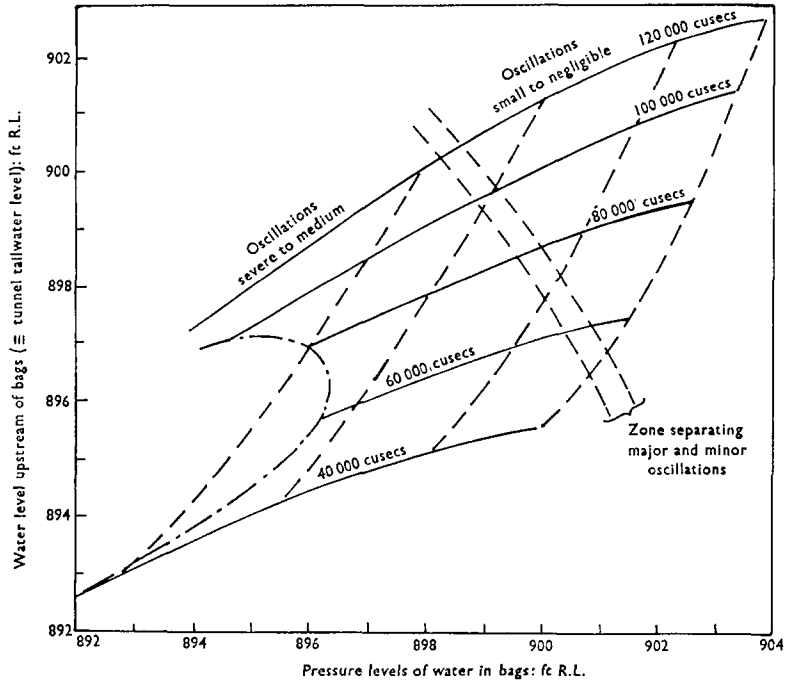


Fig. 13. Relationship between bag pressure and oscillations

65. The observed longitudinal surging of the model bags was in my opinion due to the introduction of air above a free water surface in the bags, in combination with a major difference of the actual shape of the bags at the pier connexions in comparison with the design. The bag crests, instead of continuing in the anticipated level line right up to the piers, showed a sharp dip at an appreciable distance short of the pier faces, leaving a deep V-notch in the partially inflated double sheet connexion to the piers. The fluctuating flow depths through the V-notches and over the adjoining tapering bag curves exerted fluctuating pressures on the water fill in the bags, where the free water surface permitted a surging action.

66. I believe that the failure of similar indications on the two-dimensional models at the BHRA was due to the constraints imposed on the movements of the bags by the vertical flume walls and the vertical rubber membranes across the end sections of the sectional model bags used. No longitudinal movement could occur under those conditions.

67. It was concluded by Dr Mushtag Ahmad, Director of the Irrigation Research Institute, and myself that the introduction of air in the inflatable dams contributed to the early failure of the bags at Mangla, but that collapse could also have occurred if air inflation had been omitted.

68. As a matter of general interest, air blow-out from the tunnel exits occurred on the prototype at Mangla on at least one occasion during a minor flood flow.

69. Another point of interest concerns the very brief reference to the construction of rock weirs in § 44. Immediately following the failure of the inflatable dams the

question of a substitute control structure was discussed and the need for another dam adopted. The Contractors could offer large sandstone blocks weighing in excess of 6 tons each and model studies were started immediately. A solution feasible in principle, using the large 'derrick' stones, was soon established, and work on the prototype commenced while the detailed studies continued. As a result of close co-ordination the site works and the studies were completed at approximately the same time, i.e. 3 weeks after the studies started during March 1966. Speed was essential in order to complete the works before the normal spring freshets arrived.

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The Authors have presented an informative Paper on the capabilities of an inflatable dam under severe overflow conditions. Several papers have been written on the analysis and/or behaviour of inflatable dams under static conditions, namely by Anwar,³ Harrison⁴ and Binnie.⁵ Anwar and Ogiwarra⁶ have also investigated dynamic behaviour. Other papers dealing with dynamic behaviour have been those on Fabridams in Queensland and New South Wales^{7, 8} and that by Baker² on the Mangla Dam model.

71. Of these papers it is interesting to note that the shape profile analysed according to the Anwar and Binnie methods contained minor miscloses under static conditions, whereas the Harrison computer-orientated method appears to be satisfactory. I have developed a simpler method of analysis by loaded string analogue, the results of which correspond closely to those of a model with regard to both shape and tension. From an associated model analysis a series of design graphs indicating optimum inflation pressures for various crest height and perimeter length ratios has been compiled. With respect to the dynamic case and pertaining to the Paper, a slow heave and a rolling and/or snaking action, were observed in the Koombooloomba model⁷ and in the Proston Weir respectively. A qualitative analysis into the dynamic overflow condition has also been conducted on two models using electric resistance strain gauges (capable of measuring up to 20% strain) to determine fluctuations in tension in the membrane and vibration frequency, and generally the findings support those of the Authors.

72. The two inflatable dam models studied were of the same material and of the same length but had different perimeters. When tested with the same inflating media under similar ratios of internal head to upstream head and under similar overflows, the smaller perimeter model developed longitudinal surging whereas the larger model did not. This would imply that the vibration mode is dependent on the length:diameter ratio of the dam, and in a sense a function of 'stiffness'. Stiffness here is applied in the same sense as in structural engineering where the stiffness of a beam, for example, determines the vibration mode. Reducing the length:diameter ratio has the additional advantage of improving the nappe aeration, thereby reducing the vertical or 'radial' vibrations.

73. Considering the nature of the surge and compression effect in the bags, it would appear that the perforated sheets would not be as useful as expected, unless they were made as stiff as the abutments. Without much success, efforts were made to prevent this surging effect by placing external transverse flow dividers, in the form of plastic hose, at intervals along the dam.

74. It was observed that the air- or part air-inflated cases exhibited a higher frequency of vibration than the water-inflated cases. In part air-inflated cases, under pressures of the same order as indicated by the Authors, there would be a tendency to increase the 'notching' effect, as well as the tension in the membrane.

75. From Fig. 12, it appears that the concrete eroded more in the vicinity of the fabric joint. This may be eliminated by using skewed joints, or by extending the rubber protection sheet downstream. Skewing the joints may have the additional advantage of strengthening the bag.

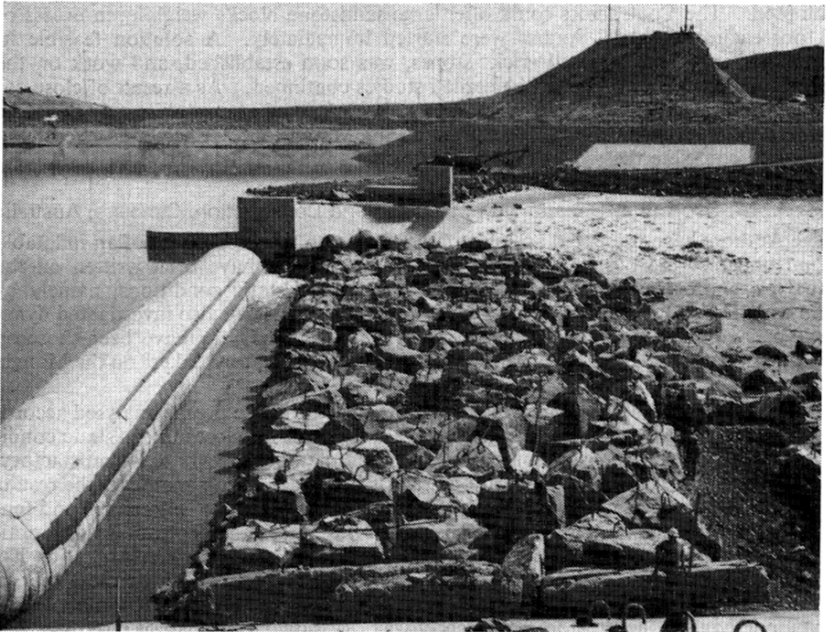


Fig. 14. Derrick stone armoring of right-hand rock weir



Fig. 15. Armoring downstream slope of left-hand rock weir. Note access over gabions, and end of bag in foreground ; also rocks washed over bag 3, centre left

76. Finally, in using strain gauges, I observed that the best place to glue them is on the inside, where they are protected from the effect of surface waves.

Messrs Binnie, Thomas and Gwyther

The comments of **Mr van Beesten** are of particular relevance because he was directly concerned with the model tests carried out in Pakistan at the Irrigation Research Institute. It is noted that longitudinal surging was observed in one of the models, though it seems that the model dam, while capable of vibrating transversely or longitudinally, was not flexible enough to vibrate in both modes simultaneously as occurred in the prototype.

78. It is possible that the introduction of air in large quantities would facilitate longitudinal surging but it is doubtful whether small amounts introduced to control transverse vibrations would have much effect unless it collected at one place—a reason for division of a long dam into compartments.

79. The construction of the rock weirs enabled control of the river to be successfully maintained until the end of the diversion period. They are briefly described in § 334 and illustrated in Fig. 90 (c) of the previous paper on Mangla.⁹

80. A fixed crest weir to provide the same range of tailwater control, i.e. down to 25 000 cusecs, would very probably have raised the tailrace above the power station cofferdam. Loss of control of hydraulic jumps at low flows was therefore accepted and it was estimated that control of jumps at the high, more damaging flows could probably be effected by a weir occupying about 70–80% of the vertical section of the fully inflated dam. The period in which low flows could be expected was in any event coming to an end with the approach of the monsoon.

81. Two rock weirs were provided, one from each bank, leaving a gap in the middle.

82. The right-hand weir was constructed 'in the dry' on the downstream side of bag 1 (Fig. 14). The left-hand weir was constructed 'in the wet' on the upstream side of the collapsed bag 3 in the lee of a rubble bund (Fig. 15).

83. The steel 'hairpins' set into each stone with hot sulphur for lifting purposes were, at the quarry master's suggestion, laced together with old steel wire rope. At least three stones were tied to each other and this undoubtedly contributed to the survival of these weirs, which are shown in Fig. 16, after being in service for about six months.



Fig. 16. Weirs after 6 months' service

DISCUSSION

84. It is of interest to note that Mr Stodulka observed a snaking motion in models of inflatable dams in Australia; also that the tensions in the membranes and vibration frequency were consistent with those observed in the Mangla models. The length and height of an inflatable dam would be expected to have opposite effects on frequency of longitudinal vibration as suggested by Mr Stodulka. Using a simple gravity wave analogy, the length:height ratio would perhaps be a better indication than length:diameter, but pressure must also be a factor. Long dams without any dividers or stabilizers to reduce longitudinal motion must be more vulnerable to longitudinal surge effects than relatively short dams, or dams divided into compartments, especially when a free water surface exists inside the envelope and the dam is partially deflated, and a partially deflated dam is doubtless more liable to 'notching', i.e. local depression.

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