ENERGY DISSIPATION OF FREE FALLING JETS
LITERATURE REVIEW

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ABSTRACT

The provision of means of spilling excess water from behind dams has long been a problem for design engineers. The difficulty lies in conveying the flow to the downstream river bed in such a way that excessive scour is prevented. Of the methods available the use of free falling jets is becoming more common due to the simplicity and economy of the structures required.

Various methods of dissipating the energy of free falling jets are reviewed. These include the forced disintegration of a jet by devices on the dam face, increased air resistance due to jet trajectory consideration, and at the base of the dam energy dissipation in an increased tailwater or plunge pool.

The author highlights areas of the subject which have a definite influence on the behaviour of a falling jet yet have been given little consideration in published investigations.

INTRODUCTION

Many modern dams are of thin concrete arch construction. This design of dam is not normally compatible with hydraulic jump basins for flood energy dissipation and the usual methods used are ski-jump outlets or chutes, and vertical drops from the crest of the dam. The latter method is attractive because the structure is compact and means can readily be incorporated to break up the jet and dissipate substantial amounts of energy by air resistance. However, a negative feature of this method of energy dissipation is that it takes place close to the dam and it is essential to provide a protective apron under the jet. Existing dams using this method may or may not have water pools on the apron; there has been little information available as to the benefits of either approach. This review seeks out the available information on this subject and proposes steps to be taken to augment it.

SCOPE OF REVIEW

The range of information related to jets falling on fixed surfaces, and the influence of tailwater pool depth on the forces generated, is rather small. There is however, a wider range of information on the scour developed by falling jets on erodible surfaces. There are features that are common to both situations and information gained on one has relevance to the other. Papers on the development of scour under falling jets are therefore included. Also included in the bibliography are a number of papers not specific to the topic under review but of background interest.

HIGH LEVEL JETS

The heading refers to the jet from overflow crests or outlets high in a dam and therefore not under high pressure. The throw is relatively short and the jet on impact with the ground or apron below the dam will have a vertical or near vertical trajectory.

The principle papers that refer to these conditions are those by Ishikawa and Hausler and Hartung.

Ishikawa (1) addresses the question of forces on a fixed surface beneath a steeply falling jet directly and identifies two types of flow. Type A occurs when downstream tailwater depth is less than sequent depth and downstream flow is therefore supercritical. Upstream flow is submerged and creates a pool behind the jet. This implies a sheet jet and two dimensional flow with very little space around the sides of the jet. Type B flow occurs when downstream depth is greater than sequent depth and downstream flow is therefore submerged. The author makes assumptions on energy conservation and momentum balance to derive an equation for dynamic pressure on the fixed bed. Theory is compared with model tests and gives good agreement. The English version of this paper gives only a contracted form of the theory and no details of the model tests. A translation of the longer original version of the paper in Japanese is not yet available.

Hausler (2) (also Hausler and Hartung (3)) is mainly concerned with scour under a jet but deals with the form of a water jet in water as an analogy to the theory of free jet turbulence founded by Prandtl and tested in air. The author's conclusion is that dispersion is almost completely linear and that a core is formed that has the same velocity as the entry velocity to the tailwater. The boundaries of the core are also linear and converge with a half angle between 4 and 6 degrees depending on Reynolds No (4). Hausler assumes that the tangent of the half angle can be taken to be 0.1 (5.7 degrees) and that the core length is therefore 5 x diameter or width of the entering jet. He further states that at this depth in the tailwater 20 per cent of a rectangular jet's energy will have been dissipated and 30 per cent of the energy of a circular jet. Since jet theory would only predict total dissipation at infinite depth, the author carried out experiments and predicted that in practice a circular jet would have almost completely dispersed at a water depth of 20 x diameter of jet on entry to tailwater. Model studies by Cola (5) predicted a similar level of dispersion for rectangular jets at a depth of 40 x width of jet. It is not clear in references to rectangular jets which width dimension is being referred to but reasoning suggests it would be the smaller.

Hansler equates the length of a jet in unlimited water to the potential depth of scour under a jet and therefore to the depth of tailwater for zero pressure on the bed. For lower depths he states that if the bed is within range of the jet core (depth less than 5 x jet diameter) the peak pressure will equal the entering velocity head and the distribution will be Gaussian to a distance of one third of the water depth either side of the centre.

SCOUR UNDER JETS

Many equations have been proposed to calculate the depth of scour that will occur under the impact of a jet. A comprehensive review and assessment of these equations has been made by Mason and Arumugam (7). The scour depth in most of the formulae is the depth from the water surface, on the assumption that total water depth is the criterion for energy dissipation. Only one or two formulae assume that the proportion of total water depth that is above bed level i.e. the tailwater depth will influence the total water depth. The authors showed that the various formulae gave widely different results when tested against a wider variety of data than that used in the original development of a particular formula. Mason therefore proposed a formula in the form that had showed to be the most satisfactory.

This was :

$$D = K\, q^{x}\, H^{y}\, h^{0.15}/g^{0.3}d^{0.1}$$

where D = depth of scour

q = unit discharge

H = height from tailwater to reservoir level

h = tailwater depth

g = acceleration due to gravity

d = characteristic particle size (models)

= 0.25m (prototypes)

$K = 6.42 - 3.1H^{0.1}$

$x = 0.6 - H/300$

$y = 0.15 - H/200$

This equation does not relate directly to the problem of pressures on a fixed bed but is an alternative way of estimating depth of tailwater for hydrostatic pressure.

AERATION

All the foregoing papers on pressures on an apron, dispersion of a jet and scour under a jet assume no significant aeration of the jet. Ishikawa assumes the velocity and dimensions of the jet at entry to the tailwater. Hausler suggests ignoring air entrainment in order to make the results conservative or to assume a small dispersion in air and slightly reduced core size on entry to the tailwater. He does not, however, give positive guidance on this point.

On the other hand there is a body of evidence to suggest that deliberate introduction of air into a falling jet can substantially reduce pressures/scour on impact.

Johnson (8) experimented with a vertical nozzle discharging onto a gravel bed. The nozzle was slightly below water level to exclude all uncontrolled air entrainment.

A measured amount of air was introduced to the jet such that the jet contained 50 per cent air at atmospheric pressure. When the unaerated jet was giving maximum scour depth, the aerated jet under the same tailwater conditions was scouring to only half the depth. A further test is also of interest. The unaerated jet was split into 32 fine jets of the same total area. The jets were parallel but the separation between the jets doubled the overall impact area. This had virtually no effect on the scour depth compared with the single jet.

A number of model tests of specific projects (e.g. 9 and 10) have shown that, despite the inability of models to entrain air on the scale of a prototype, marked gains in energy dissipation have resulted from the deliberate break up of the jet from an overspill crest. Although the details may differ, the principle normally used is that developed by Roberts (11) using splitters on the crest. McKeogh and Elsawy (12) showed that the turbulence intensity of a jet as it leaves a nozzle has a pronounced effect on the behaviour of the jet. Using small circular nozzles the authors investigated the 'disintegration length' of a vertical falling jet and showed that the jet broke up into spray in as little as half the distance when flow in the nozzle was deliberately made turbulent. It may be therefore that the beneficial effect of splitters on the crest is due to an increase in turbulent intensity rather than the entrainment of air. When Roberts type splitters are operating at low discharge it is usually seen that they divide the flow into individual jets without promoting a high degree of turbulence. Under these circumstances the energy dissipation is not notably higher than for a single jet. This is in line with both the observations of Johnson and of McKeogh and Elsawy.

Whether the effect of splitters is to break up the jet through turbulence or introduce air that is carried down the water column the effect is to carry entrained air into the downstream pool. Volkart (13) showed that falling droplets entrain air on impact with a pool in a study of air bubble entrainment in self-aerated flows using stroboscopic techniques.

It has been shown experimentally (Homma (14)) that when air is entrained in a jet, the jet disperses on entering a pool in a shorter distance than a non-aerated jet.

It is apparent that aeration of a jet both above and in the tailwater pool can potentially reduce the pressures on the bed of the pool by such an extent that to ignore aeration in order to provide a safety margin could lead to excessive overdesign or to the rejection of a viable design option.

CONCLUSIONS

It is essential to model test falling jet energy dissipators to ensure that flow conditions are satisfactory in every respect. The tested design will be the outcome of preliminary desk studies and given the cost of model studies and the time taken to execute them, radical variations are unlikely to be made unless the initial design is totally unacceptable.

It is therefore of great advantage if initial design options can be compared on a basis of sound knowledge of the behaviour of falling jets from outlet to tailwater pool to pool bed.

At present the information available is more qualitative than quantitative. Only one study has been found that specifically attempts to determine the focus on a concrete apron under a falling jet by theoretical means. The theory assumes that the velocity of the jet on entry to the pool is known and that the jet is coherent and not aerated. The effect of natural or deliberate dispersion or aeration of the jet cannot therefore be assessed. The remainder of the available information consists of isolated studies of individual aspects of jet behaviour.

There is a need to draw together these various aspects and relate them to the practical problem of designing effective and safe falling-jet energy dissipators. Implicit in this is the need to relate, as accurately as possible, model performance to prototype performance.

Particular questions to be answered are :

a) The behaviour of rectangular or sheet jets in a tailwater pool. Most work has been done so far with circular jets. Occasional references to rectangular jets suggest that their behaviour may be quite different and this is the form most often occurring in practice.

b) The characteristics of jets in pools with finite boundaries. Most work on jets relates to pools of unlimited extent.

c) The effect of air entrained in the jet or by the jet on the dispersion within the tailwater pool.

d) Characteristics of the jet on entry to the tailwater pool in terms of discharge, dimensions of jet at its origin and the height of fall. McKeogh and Elsawy related length of fall before jet broke up from natural instability to total discharge for circular jets. Horeni formed a similar relationship, using unit discharge, for a rectangular jet.

e) The effect of turbulence on the break up of the jet.

f) The effect of the introduction of air near the origin of the jet on the break-up of the jet.

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