HR Wallingford

PHYSICAL AND NUMERICAL MODELLING OF AERATORS FOR DAM SPILLWAYS

Contract Completion Report

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ABSTRACT

This report describes experimental and numerical studies on the performance of aerators for protecting chute spillways from cavitation damage. The work was funded by the Construction Industry Directorate of the Department of the Environment and by HR Wallingford.

The experiments were carried out in a 0.3m wide tilting flume which was uprated to allow flow velocities up to 15 m/s. In the first part, a systematic study involving 322 tests was made of the factors affecting the performance of ramp aerators : ramp height ; ramp angle ; flow depth ; flow velocity ; turbulence level ; and head-loss characteristics of the air-supply system. A best-fit formula for predicting the air demand ratio was obtained from an analysis of the test results.

The second part of the experimental study investigated the effect of scale on the amount of air entrained by ramp aerators. Three sizes of geometrically-similar ramp were tested giving scale ratios of 1:1, 1.5:1 and 2:1. The results showed that the air demand ratios scaled correctly provided : (1) the head-loss characteristics of the air supply were reproduced correctly ; and (2) the water velocity in the test exceeded about 5.2 m/s.

In the third part of the experimental work a study was made of alternative types of aerator that would remain efficient while causing less disturbance to high-velocity flows. A new design of three-dimensional wedge was developed which entrained 50% more air than an equivalent length of two-dimensional ramp. The design could be manufactured in steel and would be suitable for installation in both existing and new spillways.

To assist in the design of aeration systems a numerical model called CASCADE was developed. This interfaces with an existing model named SWAN that predicts the development of flow along a spillway channel and also estimates the amount of self-aeration at the free surface. If a risk of cavitation damage is identified, CASCADE is used to determine the size of aerator and supply system needed to provide a specified amount of additional air to the flow. The model offers the option of five different methods of predicting air demand, and also gives an approximate estimate of the spacing necessary between adjacent aerators.

A full description of the experimental and numerical studies is contained in HR Report SR 278.

CONTENTS

1 INTRODUCTION

Aerators are now often used to prevent cavitation damage in spillways and tunnels of high-head dams. Cavitation bubbles form within a liquid when the local static pressure falls close to the vapour pressure of the liquid (which for water is usually only slightly greater than zero pressure absolute). In civil engineering applications, this occurs most commonly in high-velocity flows and is the result of turbulence and flow separation at discontinuities in the boundaries. Damage to the perimeter of a channel is caused not by the formation of the cavitation bubbles but by their violent collapse when they enter regions of higher pressure. Damage therefore tends to be located downstream of the point at which the bubbles are generated.

Injection of air into water has been found to cushion the collapse of cavitation bubbles and, in sufficient concentration, to prevent damage ; note that the air does not itself prevent the formation of the bubbles. A spillway aerator consists of a ramp or offset (or combination of the two) that operates by creating a large air cavity within the water from which air can be entrained into the flow. The pressure within the air cavity is slightly below atmospheric pressure so that the air can be drawn in naturally via a system of ducts or wall slots without the need for injection pumps. It is important to distinguish between the cavitation bubbles, which are usually very small and filled mainly with water vapour at a pressure close to absolute zero, and the air cavity formed by the aerator, which is large and filled with air at a pressure only slightly less than atmospheric.

Research on aerators at HR Wallingford was started under a previous contract funded by the Construction

Industry Directorate of the Department of the Environment (DOE). The first stage consisted of a literature review on the general subject of cavitation and aeration in hydraulic structures ; the results were published in the form of a design manual in HR Report SR79 (see May (1987)). In the second stage, a high-velocity flume was specially built for the testing of spillway aerators. A systematic study of aeration ramps was carried out to investigate the relationship between air demand and the geometry of the ramp, the characteristics of the air-supply system and the flow conditions in the spillway channel. Results of these experiments were presented in HR Report SR 198 (see May and Deamer (1989)).

The present report describes two parts of a follow-on research study which was also funded by DOE. The first part was carried out using the high-velocity flume and extended the previous experimental work on aerators. Two aspects were studied : scale effects in model tests of ramp aerators and alternative configurations for new designs of aerator. The second part involved the development of a numerical model called CASCADE for designing aeration systems for spillways. The model uses as its starting point a computer program for self-aerated flows produced by Binnie and Partners. The model identifies the point on a spillway where cavitation damage becomes a danger, and enables the geometry of the required aerators and air-supply system to be determined.

2 SCOPE OF EXPERIMENTAL STUDIES

Model studies of spillway aerators are usually carried out with the same fluids (air and water) as in the prototype. Effects due to viscosity and surface tension therefore tend to be relatively too high in a model, and can cause it to underestimate the air demand that will occur in the prototype. Comparison of data from laboratory studies (see May (1987)) indicates that for a model of a spillway aerator the scale needs to be greater than approximately 1:15 if significant scale effects are to be avoided. A second requirement is that the velocity of the water in the model should be high enough to reproduce the air entrainment process correctly ; experiments suggest a minimum value of about 6-7m/s.

The tests on ramp aerators carried out at HR in the previous DOE contract (see May and Deamer (1989)) were limited to a maximum velocity of 6.8m/s by leakage problems in the flume. These were overcome at the start of the present contract by the construction of a new steel pressure box which enabled the flume to be operated at velocities up to 15m/s. The first stage of the present experimental work therefore extended the previous tests on ramp aerators to higher velocities and determined the extent of scale effects by means of comparative tests of different sizes of aerators having the same geometrical shape.

The second stage of the experiments investigated new designs of spillway aerator. Existing types appear to work effectively in preventing cavitation damage, but suffer from three main problems. Firstly, the ramps and offsets cause very major disturbances to the flow. The aim in a conventional dam spillway is usually to produce the smoothest possible flow profile. The provision of aerators creates a large amount of turbulence and bulking of the flow. The depth of the channel and the amount of freeboard therefore need to be increased, which can be expensive in terms of excavation and construction. Excessive spray from spillways is also undesirable and can cause erosion and slips in adjacent embankments. Secondly, aerators for wide spillways often require large ventilation shafts and ducts beneath the channel to supply air across the full width of the flow. These are costly and cannot easily be added as a remedial measure to an existing spillway which has suffered cavitation damage. Thirdly, large aerators are not a very efficient solution to the problem. A prototype study by Pinto (1986) of the spillway for the Foz do Areia dam showed that the turbulence created by the aerators entrained approximately three times as much air through the free surface as was entrained directly by the aerators. To prevent cavitation damage to the boundaries of a channel, the local air concentration needs to be above a certain minimum figure (often assumed to be about 7%, see May (1987)). The entrained air in the rest of the flow is not therefore effective as it tends to move upwards and away from the boundaries.

These factors suggest that a more efficient solution would involve the use of smaller aerators spaced more frequently along the spillway. These would create less disturbance to the flow and inject air close to the boundaries where it is required. The greater efficiency of the system would reduce the total amount of air added and thus cause less bulking of the flow. These benefits would allow the depth of the spillway channel to be reduced compared with that needed for a conventional aeration system. Smaller aerators could be prefabricated and would have the advantage of being easier to install on existing spillways where remedial measures are required. Preliminary experiments in the high-velocity flume were therefore carried out at a small scale on several alternative geometries. The selected design was then built to a larger scale and its performance compared with some of the conventional ramp aerators tested previously.

3 SCOPE OF NUMERICAL MODEL

CASCADE is a computer program developed by Hydraulics Research, Wallingford to assist in the design of aeration systems for preventing cavitation damage in chute spillways. CASCADE is an acronym for CAvitation Suppression on Chute spillways using Aeration DEvices.

The program is designed to:

- link with the computer program SWAN, developed by Binnie and Partners for the analysis of one-dimensional, steady state flow on a chute spillway. CASCADE is called into the main program when cavitation indicators show there to be a risk of cavitation damage.

- allow the operator to design an efficient aerator, to be installed at the point on the spillway where cavitation is predicted to be a problem.

- give the operator the option of specifying the air supply discharge, air duct geometry or ramp geometry.

- optimise the aerator geometry for specific flow criteria by equating the air demand (generated by the water flow over the aerator) with the rate of air supply (drawn from the atmosphere via a system of ducts).

Various researchers have investigated air entrainment at aerators and have described the phenomenon by equations of different form. The model gives the option of applying six alternative equations to determine the air demand. Some of these equations require an estimate of the length of the air cavity produced by the aerator. In the model this calculation is based on the work of Schwartz & Nutt (1963) on projected nappes but as modified by Rutschmann & Hager (1990).

The procedure to determine the distribution across the spillway of the pressure within the air cavity is based on that described by Rutschmann & Volkart (1988).

4 CONCLUSIONS

4.1 Experimental studies

(1) A systematic laboratory study has been made of the performance of two-dimensional ramp aerators for chute spillways. 322 tests were carried out to investigate the effect of the following factors on the amount of air entrainment : ramp height ; ramp angle ; flow velocity ; flow depth; head-loss characteristics of air supply system ; scale of model ; and level of turbulence in the flow.

(2) No air entrainment occurred below a minimum flow velocity V_o, which was found to be related to the height h_1 of the aerator by:

$$\frac{V_o}{(gh_1)^{1/2}} = F_* = 7.5$$

(3) Above this minimum velocity, the air demand per unit width q_a for a given aerator and water depth increased approximately linearly with the flow velocity V of the water.

(4) Increases in the following factors were found to increase the air demand q_a : height of aerator ; water velocity ; conveyance parameter M which is defined as

$$M = \frac{q_a}{h_1} \left(\frac{\rho_a}{\Delta p} \right)^{1/2}$$

where ρ_a is the density of air and Δp is the difference between atmospheric pressure and the pressure in the air cavity. Changing the angle of the ramp from 4.6° to 9.1° (while keeping its height constant) and varying the water depth d produced no overall change in the air demand.

(5) The following best-fit formula for predicting the amount of air entrained by ramp aerators was obtained from the test data.

$$\beta = 1.3 \; [1 - \exp(-2.5M)] \; [1 - (F_*/F)(h_1/d)^{1/2}] \; [h_1/d]$$

where β is the non-dimensional air demand ratio (air discharge/water discharge) and F is the Froude number $(V/(gd)^{1/2})$. This formula is valid for a flume slope of 15.5°, and has been tested over the following range of conditions: $0.1 \leq M \leq 1.4$; $5.7 \leq F \leq 15.1$; $2.9 \leq h_1/d \leq 9.5$.

(6) Comparative tests were carried out with geometrically similar aerators at three different scales to determine whether the air demand varied

with the size of the model. No consistent scale effect was found provided the water velocity in the test exceeded about 5.2m/s. Model tests must reproduce the head-loss characteristics of the air supply system correctly.

(7) Tests were made with three levels of turbulence in the water flow to investigate its effect on the air demand. Increasing the turbulence above the "normal" condition for the flume produced some increase in the amount of air entrainment. If the turbulence intensity T_i (root-mean-square velocity divided by local mean velocity at mid-depth) exceeds 5%, the predicted air demand ratio β obtained from the equation in (5) should therefore be divided by a factor

$$\Omega = 1 - 2.0\ (T_i - 0.05)$$

(8) Measurements also showed that the length of the air cavity was reduced significantly when the turbulence level was increased. This is believed to be the reason why turbulence has only a relatively small effect on the amount of air entrainment.

(9) A new design of three-dimensional wedge aerator was developed which is approximately 50% more efficient at entraining air than an equivalent two-dimensional ramp but causes less disturbance to the flow. The design could be manufactured in steel and would be suitable for installation in both existing and new chute spillways.

(10) Further development testing of the wedge aerator is recommended to optimise the transverse spacing and method of air supply.

4.2 Numerical model

(1) A numerical model named CASCADE has been developed to assist the hydraulic design of aerators for chute spillways.

(2) CASCADE interfaces with a model called SWAN (produced by Binnie & Partners) that predicts the development of flow down a spillway and the amount of self-aeration at the free surface. SWAN identifies the point along the spillway at which surface irregularities can first begin to cause cavitation damage. CASCADE is then used to design a suitable aeration system : the aerators itself and the air supply ducts.

(3) CASCADE offers the option of five different methods for estimating the air demand, some of which require the calculation of the length of the air cavity formed by the aerator. Head losses in the air supply system and the effect of the pressure drop in the air cavity are taken into account.

(4) The convection and dispersion of the entrained air downstream of the aerator is predicted in the combined SWAN/CASCADE model by a simplified input/output description of the process. This determines the next point along the spillway at which another aerator is needed to prevent cavitation damage. The development of a more detailed convection/diffusion model of the two-phase flow is needed to improve the estimates of the aerator spacing.

(5) The alternative methods of predicting air demand do not give consistent results, and testing of the model against available prototype and model

data is recommended to identify the most suitable equations.

Full details of the experimental and numerical work carried out in this study are given in May, Brown and Willoughby (1991).

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