Numerical Modelling of Aerated Flows Over Stepped Spillways

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Introduction

At high discharges the energy of flow over spillways can be extremely high. Spillways must dissipate large amounts of this energy to prevent scour at the toe of the dam, which can undermine the foundation and lead to failure.

As well as dissipating energy it is important that spillways aerate the flow to prevent cavitation or plucking damage. If cavitation or plucking occurs then backing material can be eroded and steel reinforcement can be corroded which can cause the spillway to fail. Seepage paths through the dam can also be formed which can lead to catastrophic failure of the dam.

Stepped spillways have been shown to be efficient energy dissipaters and entrain large volumes of air into the flow [6] [8] [9]. Reducing the required size of the stilling basin and negating the need for additional dissipaters or aerators.

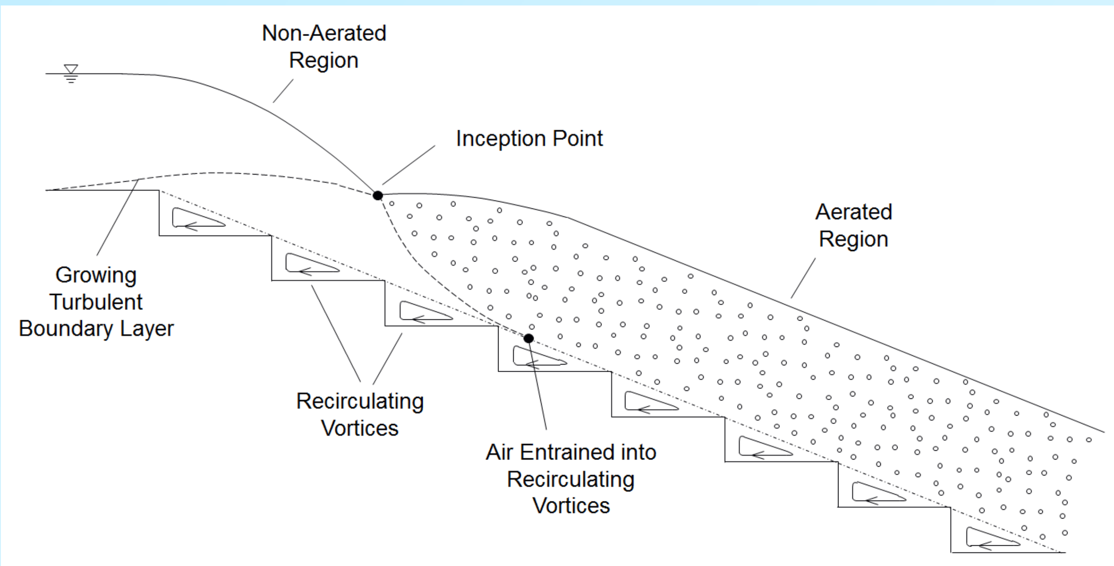
Masonry Stepped Spillway Failure Due to Plucking Damage

Flow characteristics over stepped spillways

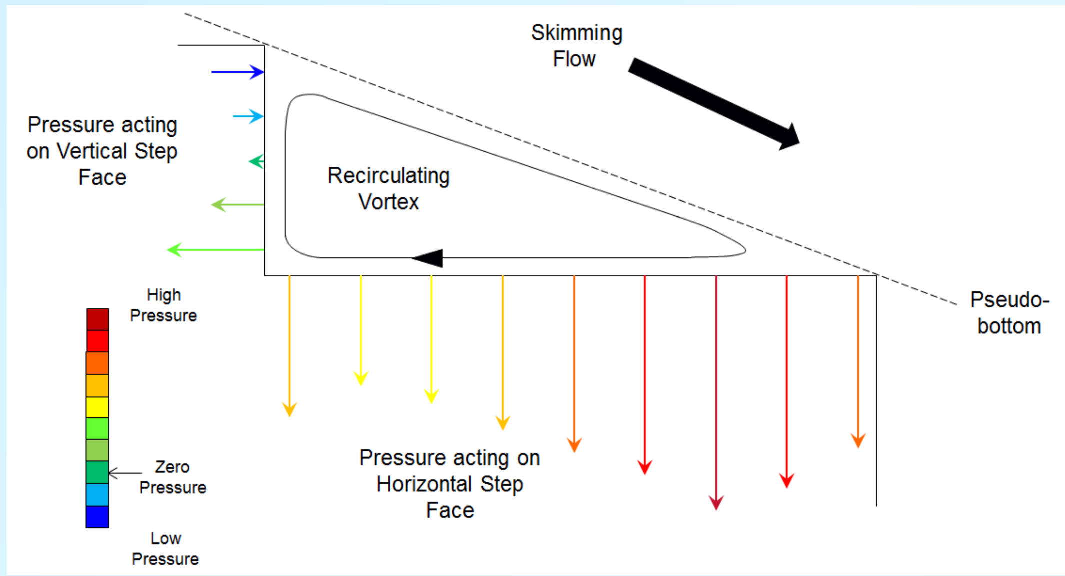
There are three distinct flow regimes which occur over stepped spillways: nappe, transitional and skimming flow. Skimming flow occurs at larger discharges and is therefore of most interest to reservoir engineers [3]. During the skimming flow regime most of the flow "skims" over the steps with recirculating vortices occurring in the spaces between the steps (Figure 2). The bulk flow and recirculating vortices are separated by a pseudo bottom formed by the step edges. At the crest of the spillway a turbulent boundary layer develops and increases in depth until it meets the free surface. This point is known as the inception point and is where air entrainment of the flow begins. The depth of this aerated region increases quickly until the entire flow is aerated and entrained air is transported into the recirculating vortices. Skimming flow is an efficient means of energy dissipation, with the primary dissipation mechanism being the transfer of shear stress from the bulk flow to maintain the recirculating vortices [3].Some energy is also dissipated through turbulence in the aerated region [2] [8].

High pressures occur at the downstream end of the horizontal step edge and at the bottom of the vertical step edges where the recirculating vortex impinges on the step. The top of the vertical step edge and upstream end of the horizontal step edge are subject to low pressures due to flow separation [5] [7].

Flow separation causes a significant drop in pressure, especially at high velocities. If the pressure falls below the vapour pressure then cavitation damage can occur. In masonry spillways low pressures can cause "plucking" where masonry blocks are removed from the spillway invert or side walls into the flow. Aeration of the flow has been shown to prevent cavitation and plucking damage by increasing pressures on the step edges [10].



Skimming flow over a stepped spillway



Pressure distributions on step edges

Multiphase Numerical Models

Volume of fluid (VOF) - Mesh based free-surface modelling technique. A single set of momentum equation is solved for each phase and the volume fraction in each cell is calculated. The volume fraction is used to track the free surface. The VOF model assumes that each phase is immiscible so does not model air entrainment.

Coupled Air Entrainment VOF Model (Implemented in Flow-3D) - An additional air entrainment model used in conjunction with the VOF model. The model is based on the competition between the stabilising and destabilising forces acting at the free surface. It includes a variable density formulation and flow bulking by the addition of air and buoyancy affects

Mixture Model - The mixture model solves a single momentum equation for all of the phases like the VOF model. In the mixture model, however, the phases can be interpenetrating and travel at different velocities through the use of a slip velocity function provided that the Stokes number is small.

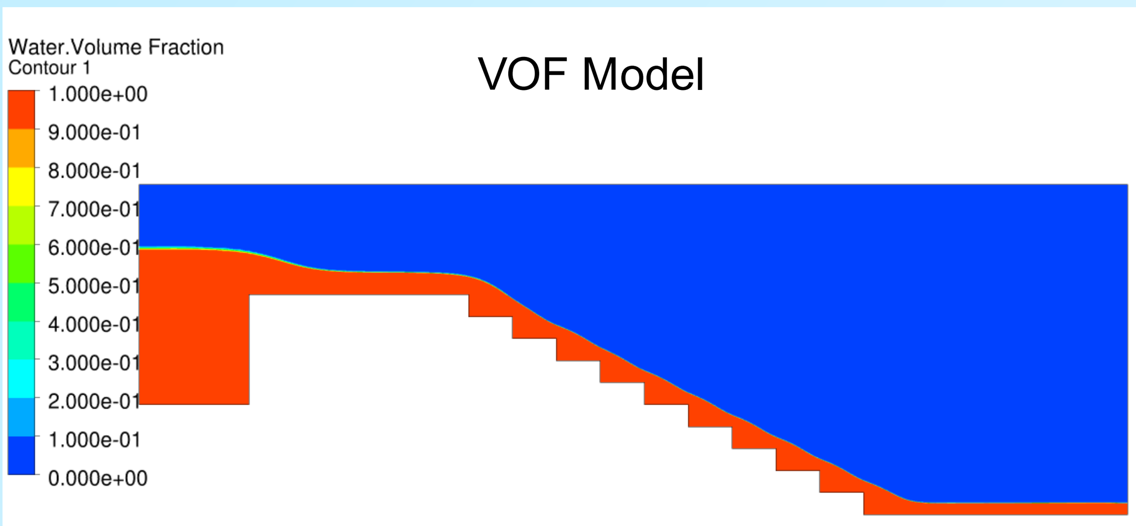
Eulerian-Eulerian - Can be used to model separate but interacting fluids by solving a momentum equation for each phase. This allows a greater range of Stokes numbers to be modelled but requires greater computation resources.

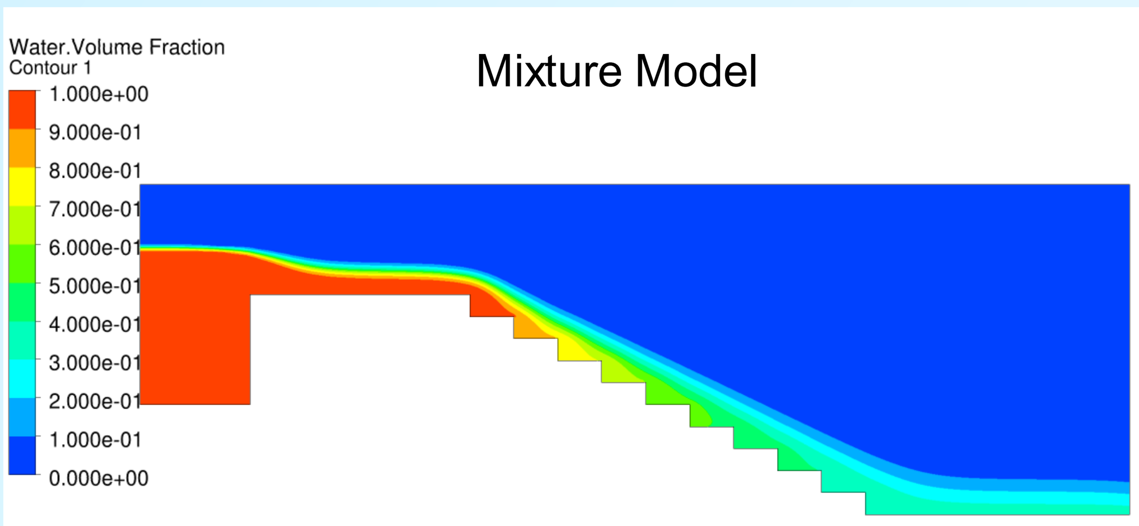
Smoothed Particle Hydrodynamics (SPH) - A mesh free numerical technique which models the fluid a set of discreet particles. A relatively new SPH model has been developed at the University of Innsbruck in Austria which models both air and water as distinct sets of particles. This technique is yet to be tested on open channel flow problems.

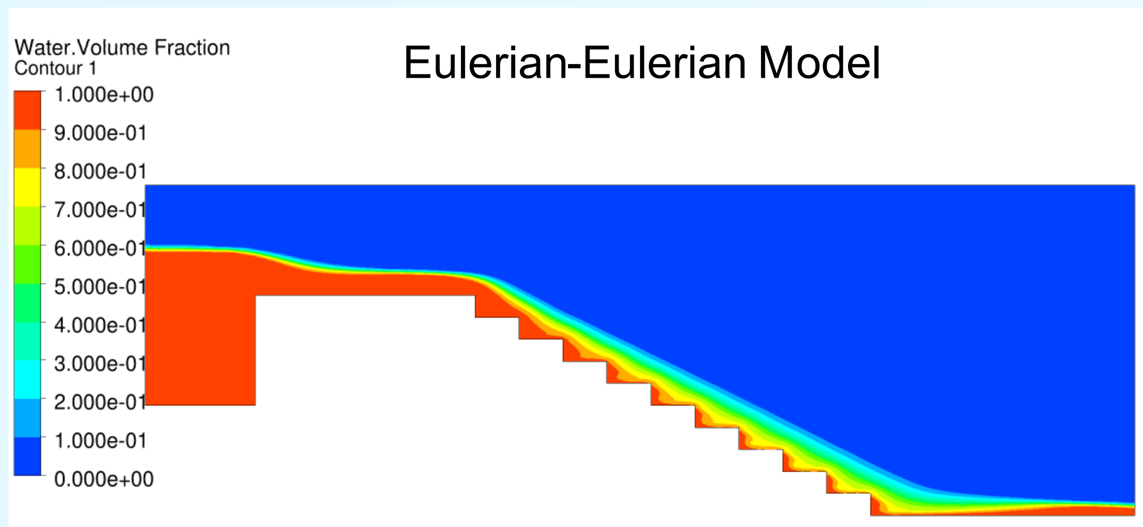
Cavitation damage on a smooth concrete spillway

Plucking Damage on a masonry stepped spillway

Preliminary Results







Project Aim

Current practice is to use physical scale models to predict flow characteristics over stepped spillways as these models are well understood by reservoir engineers. Physical models have limitations however, especially in predicting air entrainment [4]. Numerical modelling has the potential to predict flows over stepped spillways more accurately and at a lower cost than physical models. These models must be proven to be reliable, especially in high risk applications such as reservoir engineering, before they can be used with confidence.

This project will aim to evaluate performance of each of the numerical models described in predicting aerated flows over stepped spillways.

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