Model Studies Of The Aeration Device Of The Clyde Dam Spillway

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Abstract

On large spillways, cavitation damage to spillway surfaces may be prevented by installing aeration devices to introduce air in the layers close to the channel bottom. Four model studies of the aeration device of the Clyde Dam spillway were carried out. The main results are summarized and compared with other data. The main conclusion is that similitude of the air entrainment mechanisms occurring above an aerator is not possible, but model studies are very useful in understanding the air entrainment processes and the interactions between these processes.

1. Introduction

1.1 Presentation

When water flows over a spillway there is a region of clear water with a growing boundary layer. When this boundary layer reaches the free surface the turbulence in the layer can initiate natural air entrainment. When the air-water region reaches the spillway surface, this surface is protected from cavitation damage. With an increase in the height of dams and greater spillway discharges per unit width, the air from the free surface does not reach the spillway surface. If the velocities are high enough cavitation bubbles will form and the bubble collapses will give rise to high pressures and possible cavitation damage (QUINTELA 1980).

Experimental investigations show that the damage can start at clear water velocities of between 10 to 15 m/s (FALVEY 1990) and at up to 20 m/s it may be possible to protect the surface by streamlining, improving the surface finishes or using resistant materials (MAY 1987). If the tolerances of surface finish required to avoid cavitation are too severe (ie. V>30 m/s) or if there is no free surface aeration (e.g. downstream of a gate), air must be artificially introduced by devices called aerators located on the spillway floor and, sometimes, on the side walls .

The Clyde Dam spillway (New Zealand) has a 70 metre long spillway followed by a stilling basin (50 metre long) with a 8: 1 reverse slope which ends at a flip bucket (Fig. 1). The

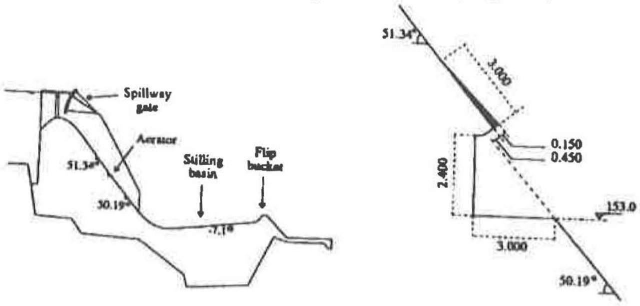

Fig 1 - Clyde Dam spillway (New Zealand)

spillway was sized to pass 4100 m^3/s and it was considered prudent to install a bottom aerator (HATTON et al. 1987). From 1983 to 1988 four model studies were carried out on a 1:15 scale model of the Clyde Dam spillway (Table 1). The main results obtained from these four studies are presented, and several lessons for the design of aeration devices are deduced. Further, a comparison with model experiments performed in China for the Feng Jia Shan project (PAN et al. 1980, SHI et al. 1983, CUI 1985) is presented .

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1.2 Effect of Air on Cavitation Damage

In presence of gas content, flows may cavitate at higher static pressures (HOLL 1960). MOUSSON (1937) and RASMUSSEN (1956) showed that substantial quantities of air produce a large reduction in damage rate. RUSSELL and SHEEHAN (1974) suggested that entrained air is effective because:

(i) The presence of air in the vapour cavities will cushion the cavity collapse and reduce the resulting water hammer pressure (HICKLING and PLESSET 1964), and

(ii) The presence of air will reduce the shock wave celerity and the magnitude of the shock waves on the material surface.

Several experiments were performed with concrete specimens in Venturi test sections, cavitation tunnels and chute spillways (Table 2). In Venturi test facilities and cavitation tunnels, 5 to 10% of air was required to protect concrete specimens of 10 to 20 MPa compressive strength. Lower air content is required with higher strength concrete.

Reference (1)	Slope deg. (2)	Offset height t_s(m) (3)	Ramp height t_r(m) (4)	Ramp angle deg. (5)	d_o m (6)	Fr (7)	P_N (8)
Clyde Dam model TAN (1984)	51.30	0.030	0.0	0.0	0.05 / 0.09 / 0.1 / 0.15	2.8 to 15.4	0.003 to 1.52
			0.023	4.4	0.05 / 0.09 / 0.1 / 0.15	3.8 to 15.4	0.002 to 0.69
LOW (1986)	51.30	0.030	0.023	4.4	0.050	6.4 to 15.4	0.003 to 0.60
			0.030	5.7	0.050	6.4 to 15.4	0.003 to 0.60
CHANSON (1988)	52.33	0.030	0.0	0.0	0.023 / 0.03 /0.035 / 0.05 / 0.065 /0.08 / 0.11	5.4 to 23.6	-0.03 to Subm.
			0.030	5.7	0.023 / 0.03 /0.035 / 0.05 / 0.065 / 0.08 / 0.11	3.4 to 23.4	-0.08 to Subm.
RUTSCHMANN (1988a)	51.30	0/0.015 /0.03	0.023	4.4	0.05	6 to 14	0.001 to 0.6
		0/0.015 /0.03	0.030	5.7	0.05	4.9 to 13.4	0.002 to 0.42
		0/0.015 /0.03	0.039	7.4	0.05	4.4 to 12.7	0.03 to 0.22
FengJiaShan model PAN et al. (1980)	0.0 10.0 30.0 49.0	0.0	0.01/ 0.015	5.7	0.1 to 0.2	2.0 to 19.2	
SHI et al (1983)	49.0	0.0	0.015	5.7	0.058	18.6	
CUI (1985)	0.0 30.0 49.0	0.0	0.015	5.7	0.120 0.150 0.120	8.9 6.0 7.5	

β^{inlet} : range of dimensionless air discharge

P_N : range of pressure gradient numbers

Fr : range of Froude numbers

Subm. : submergence of the aerator

TABLE 1
SPILLWAY MODEL CONFIGURATIONS

On large chute spillways in China, several experiments were performed on concrete blocks. At Wujiangdu, 4% air concentration prevented erosion for velocities up to 44 m/s and roughness height less than 60 mm (DENG 1988). On the Fengman spillway, concrete blocks of 10-15 MPa compressive strength were used with, and without, air entrainment and velocities of 34 m/s. No cavitation damage was observed with 5% air concentration next to the spillway floor (ZHOU and WANG 1988). Also on the Wujiangdu spillway, artificial irregularities of 20 to 100 mm were tested at velocities up to 42 m/s for 50 to 170 hours and flow depths in the range 3 to 3.6 m (ZHANG 1991). The amount of air required to prevent cavitation damage decreased as the flow depth increased. Indeed the cavitation index increases with the pressure and the risk of cavitation diminishes (FALVEY 1990).

In summary: For chute spillways it is believed that the presence of 4 to 8 % of air, in the flow layers close to the spillway bottom, will prevent cavitation damage for velocities up to 45 m/s.

Ref	U_w	σc	C	Test duration	d	Remarks
	m/s	MPa	%		m	
[1]	30.5	17.0	7.4	2 hours		Venturi test section
[2]	46.0	13.0	5.5	2 hours		Venturi test section
	46.0	15.3	4.1	2 hours		
	46.0	16.0	5.5	2 hours		
	46.0	18.8	5.5	2 hours		
	46.0	43.0	1.5	8 hours		
[3]	13.5	29.2	0			Cavitation tunnel
	17.0	32.6	0			
	17.8	34.8	0			
	18.9	38.3	0			
	18.9	41.3	0			
	22.0	48.7	0			
	21.9	34.0	4.0			
	21.9	16.9	8.0			
[4]	22.0	9.8	9.7			Cavitation tunnel
	22.0	14.7	8.0			
	22.0	19.6	6.8			
	22.0	24.5	5.7			
	22.0	29.4	4.7			
	22.0	34.3	4.0			
	22.0	39.2	3.0			
[5]	36.6		1.0			Chute Spillway : Wujiangdu
	37.3		1.5			k_s < 60mm
	41.2		2.4			
	44.2		4.1			
[6]	42.0		2.8	50 to 170 hours	3.6	artificial roughness 30 to 100mm
	42.0		4.1		3.2	artificial roughness 30 to 100mm
	42.0		8.1		3.0	artificial roughness 30 to 100mm
[7]	34.0	10.0 to 15.0	5.0			Chute spillway : Fengman

[1] PETERKA (1953)
[2] RUSSELL & SHEEHAN (1974)
[3] GAL'PERIN et al. (1974)
[4] SEMENKOV & LENTYAEV (1973)
[5] DENG (1988)
[6] ZHANG (1991)
[7] ZHOU & WANG (1988)

U_w : flow velocity σc : compressive strength C : air concentration d : flow depth

TABLE 2

REQUIRED AIR CONCENTRATION TO PREVENT CAVITATION EROSION ON CONCRETE SPECIMEN AS A FUNCTION OF THE FLOW VELOCITY AND COMPRESSIVE STRENGTH

1.3 Aeration devices

If the air entrained at the free surface (ie. self-aeration) is not enough to protect the spillway surface, air must be introduced artificially through aeration devices located on the spillway bottom and sometimes on the side walls, (Fig. 2), With supercritical flows a small deflection in a chute structure (eg. ramp, offset) tends to deflect the high velocity flow away from the chute surface. In the cavity formed below the nappe, a local subpressure (ΔP) is produced by which air is sucked into the flow (Q_{air}^{inlet}). The three basic shapes of a bottom aerator are a ramp (also called a deflector), an offset and a groove.

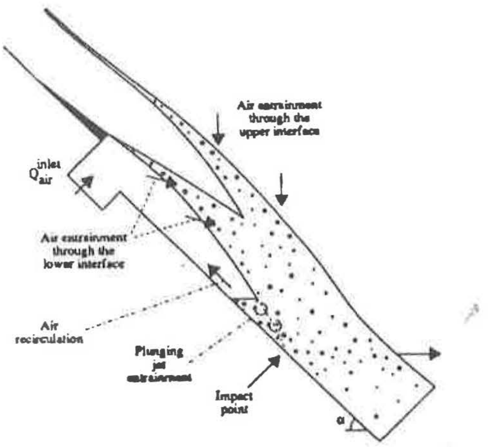

Fig 2 - Air entrainnment above an aeration device (CHANSON 1989a)

A ramp is most effective in causing large air entrainment for small discharges and is used as a remedial measure on existing spillways. The main disadvantages of a deflector are:

(i) The production of shock waves in the rapid flow,
(ii) The difficulty to obtain an optimum air amount for a wide range of discharges, and
(iii) The risk of submergence at high discharges when the ramp ceases to draw air into the flow.

An offset is simpler in design and produces less disturbances (shock-waves) than a ramp. Also an offset enlarges the jet trajectory for high discharges but it does not always provide enough air for small water discharges .

VISCHER et al. (1982) and VOLKART and CHERVET (1983) have analyzed the behaviour of a large range of aerators. Usually a combination of the three types provides the best design: the ramp dominates operation at small discharges while the groove provides space for the air supply and the offset enlarges the jet trajectory at higher discharges.

2. Air Entrainment and Aeration Devices

2.1 Flow Regions on a Spillway with an Aeration Device

The flow regions above an aerator are defined as: the approach flow region, the transition region, the aeration region, and the impact point region. Downstream of the aeration device the regions are: the gradually varied flow region and the uniform flow region (Fig. 3).

The approach flow conditions characterize the initial flow conditions above an aerator. The flow may be aerated.

The transition region coincides with the length of the deflector. A ramp increases the shear stress on the spillway bottom and the local pressure in the flow rises above hydrostatic.

In the aeration region the flow is a two-dimensional jet subject to a negative pressure gradient and, for high Froude numbers, large quantities of air are entrained through both the upper and lower free surfaces. If the jet is long enough, a fully aerated jet region starts developing downstream of the point where the central part of the jet becomes aerated (Fig. 2).

The impact point region extends from the point where the nappe re-attaches to the bottom of the chute down to the beginning of the downstream flow region. The flow is highly turbulent, a high energy loss and a strong de-aeration process occur.

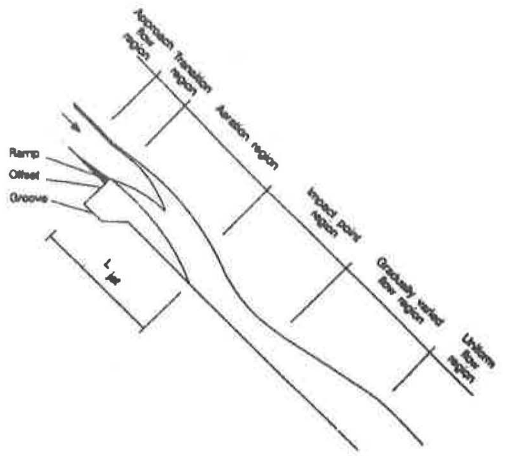

Fig 3 - Flow regions above a spillway with aeration device

In the gradually varied flow region a slow air concentration and velocity redistribution occurs. On a long spillway this ends when the air concentration and velocity distributions reach equilibrium in the uniform flow region far downstream.

2.2 Mechanisms of Air Entrainment Above an Aerator

In the aeration region air entrainment is characterized by:

(i) Nappe entrainment through the upper and lower free surfaces of the jet,
(ii) Plunging jet entrainment at the intersection of the water jet and the pool formed at the end of the cavity,
(iii) Air recirculation in the cavity below the jet and
(iv) A strong de-aeration occurring at the free surface, near the impact of the jet with the spillway surface (Fig. 2).

A simple analysis of the continuity equation for air above an aerator (CHANSON 1989a) indicates that the quantity of air entrained within the flow at the end of the jet (q_{air}^{max}) is:

$$q_{air}^{max} = (q_{air}^{upper} + q_{air}^{inlet}) + q_{air}^{o} \qquad \text{.........(1)}$$

where q_{air}^{upper} is the net entrainment at the upper free surface, q_{air}^{inlet} the air discharge supplied by the air inlets and q_{air}^{o} the quantity of air entrained at the end of the deflector. The equation (1) indicates that air entrainment above an aerator is a function of the air discharge supplied by the air ducts and the upper nappe entrainment.

2.3 Dimensionless Parameters

The relevant parameters for a model study of spillway aerator come from the following groups:

- the fluid properties,
- the spillway and aerator geometry,
- the geometry of the air inlets,
- the flow properties (in the approach flow region),
- the undernappe cavity properties, and
- the downstream flow properties.

The parameters required to design an aeration device are the air discharge supplied by the inlets, the pressure difference (ΔP), the water jet length (L_{jet}), the flow depth along the spillway (d) and the air concentration near the floor downstream of the aerator (C_b).

Studies are performed usually on geometrical models and it is convenient to use a slice model. If the effects of the side wall boundary layers are assumed small the analysis becomes a two-dimensional study. Further, the nappe subpressure is usually controlled by valves on the air inlet system and this enables the underpressure to be treated as an independent parameter. For a constant density ratio, a given aerator configuration and an initial flow depth (d_o), the dimensionless relationship between the design parameters and the independent parameters becomes:

$$\beta \text{inlet}, \quad \frac{L_{jet}}{d_o}, \frac{d}{d_o}, C_b = f(Re, Fr, We, Tu, P_N)$$

where:

β^{inlet} is the dimensionless air discharge :

$$\beta^{inlet} = q_{air}^{inlet}/qw,$$

Re is the Reynolds number,
Fr is the Froude number,
We is the Weber number,
Tu is the turbulent intensity, and
P_N is the pressure gradient number:

$$P_N = \frac{\Delta P}{\rho_w * g * d_o}.$$

Any combination of these numbers may be used to replace one of the combinations. WOOD (1991) showed that the Reynolds number may be replaced by the Morton number:

$$Z = \frac{g * \mu^4}{\rho_w * \sigma^3}.$$

If the fluids are the same on model and prototype (i.e. Z = constant) the above equation becomes:

$$\beta^{inlet}, \frac{L_{jet}}{d_o}, \frac{d}{d_o}, C_b = f_1 \text{ (Fr, We, Tu, } P_N) \qquad \text{........(2)}$$

3. Study of the Aeration Region

3.1 Air Demand

The air demand of an aerator is defined as the relationship between the air discharge provided by the air supply system, the subpressure in the cavity and its distribution along the nappe, and the flow characteristics. TAN (1984) and RUTSCHMANN (1988a and 1988b) expressed the air demand relationship as proposed by PAN et al. (1980) and PINTO et al . (1982):

$$\beta^{inlet} = K' * \frac{L_{jet}}{d_o}$$

but this equation does not take into account the air recirculation and the plunging jet entrainment. The air entrainment above an aerator occurs by different processes and each of these processes yields a different nondimensional equation (CHANSON 1991). LOW (1986) and CHANSON (1988, 1990) studied the air demand as:

$$\beta^{inlet} = f_2 \text{ (Fr,} P_N) \qquad \text{........(3)}$$

although this type of relation is incomplete and does not characterize any single physical process. For the Clyde Dam spillway model typical air demand characteristic curves are presented for various flow conditions (Fig. 4).

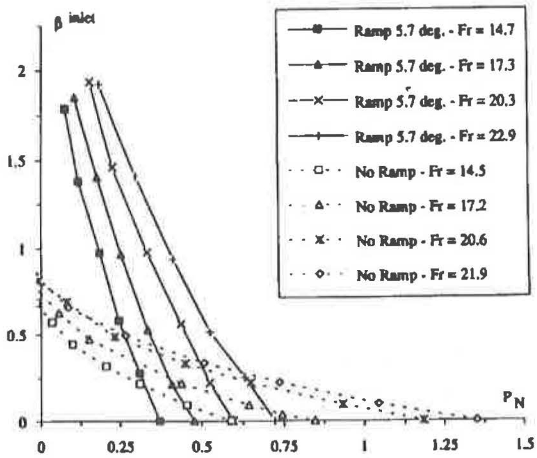

Fig 4 - Air demand characteristic curves - CHANSON (1988)

The operating point (ie. β^{inlet}, P_N) is obtained by combining the pressure drop curves of the air inlets with the air demand characteristic curves (LOW 1986, RUTSCHMANN et al. 1986). These calculations fix the underpressure in the cavity beneath the jet and hence the jet trajectory and the cavity geometry.

Under high subpressures the aeration device may be drowned out at low Froude numbers and this is called the submergence of the aerator. Experimental results obtained by TAN (1984) and CHANSON (1988) indicate that the aeration device becomes drowned out for (CHANSON 1992):

$$\frac{d_o}{t_s} < 0.6$$

aerator without ramp ....*(4a)*

$$Fr_o < 2.77 + 0.94 * \frac{d_o}{t_s}$$

aerator with a 5.7 degree ramp ....*(4b)*

3.2 Jet Trajectory

Jet trajectories may be obtained by a model of such a scale that there is little air entrainment, an analytic method (SCHWARTZ and NUTT 1963, PAN et al. 1980, LAALI 1980, GLAZOV 1984, CHANSON 1988), numerical methods (YEN et al. 1984, YUAN 1990) or the finite element method (WEI and DE FAZIO 1982). For engineering applications TAN (1984) developed a simple and accurate method .

The jet trajectory calculations provide the jet length, the cavity geometry, the geometry of the jet including the position of the impact of the lower interface and the angle of the water jet with the spillway floor.

3.3 Nappe Entrainment

From the edge of the deflector the pressure gradient across the flow changes rapidly from a quasi-hydrostatic distribution to a negative pressure gradient. The bubble rise velocity becomes a fall velocity (CHANSON 1989a) and in the aeration region air is entrained by a combination of the buoyancy force and the action of turbulent eddies close to the surface.

The diffusion equation applied to air bubbles at the free surface provides an analytical solution for the upper nappe entrainment (CHANSON 1991):

$$\frac{q_{air}^{upper}}{q_w} = K_o * \left[\frac{L}{d_o} * \tan\psi^U - 2*\beta^o*LN \left[1+½ * \frac{\tan\psi^U}{\beta^o} * \frac{L}{d_o}\right]\right] - 0.90 * \frac{L}{d_o} * \frac{u_r}{U_w} * \cos\alpha \qquad ....(5)$$

where $K_0 = \frac{1}{\sqrt{2*\pi}} * e^{-0.5*(1.2817)^2}$

L	is the distance from the end of the deflector,
u_r,	is the rise velocity of air bubbles subject to a negative pressure gradient P_N
U_w	is the flow velocity,
α	is the spillway slope, and
ψ^U	is the lateral spread of the jet.

On the Clyde Dam model the spread angle of the jet may be estimated as: $\psi^U = 0.75$ degrees for low pressure gradient. For high pressure gradient the spread angle and the fall velocity (u_r), increases and CHANSON (1988) reported a substantial increase of the quantity of air entrained at the upper free surface that is consistent with the equation (5). On Figure 5 the quantity of air entrained within the upper flow region: $\beta^{up} = \beta^{upper} + \beta^o$, computed using the equation (5), is compared with experimental data.

It must be emphasized that the equation (5) was developed in the region where the inner core of the jet is un-aerated. On most of the prototypes the jet length is not long enough for the development of an aerated jet core.

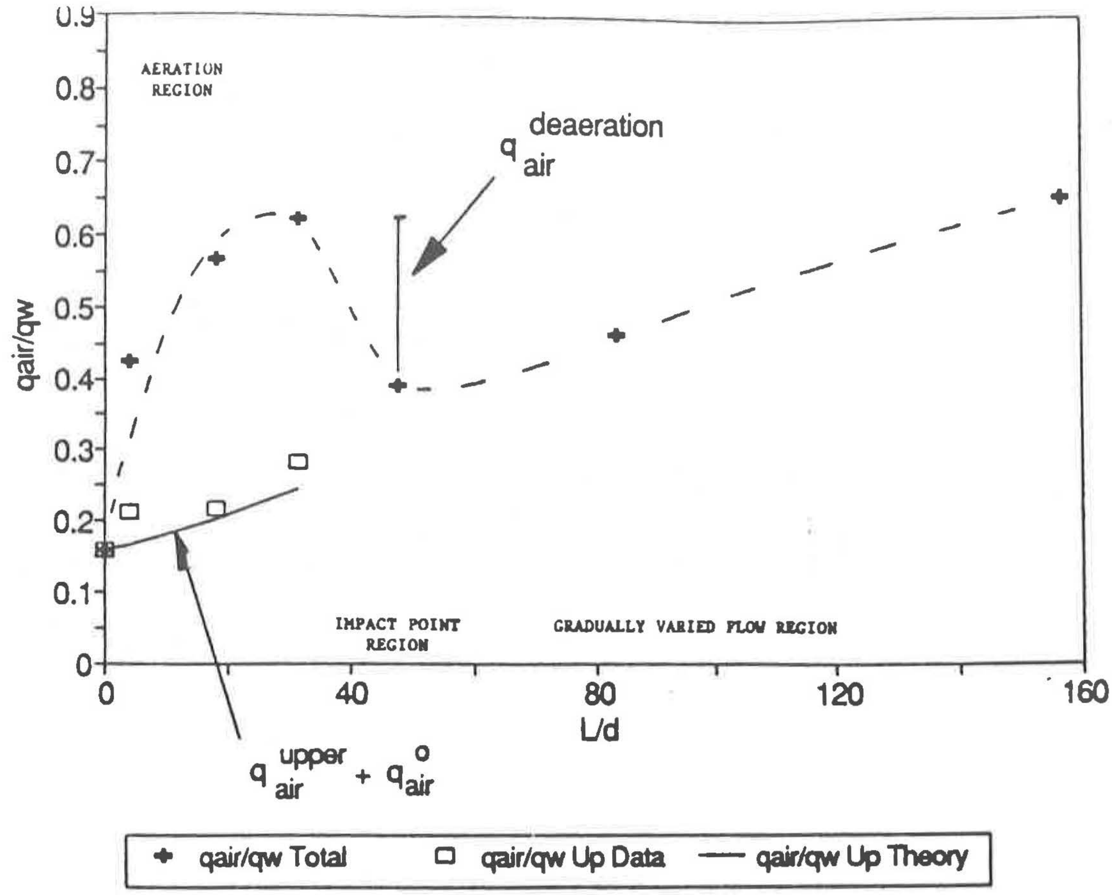

Fig. 5A - $\beta^{inlet} = 0.679$ - $P_N = 0.011$

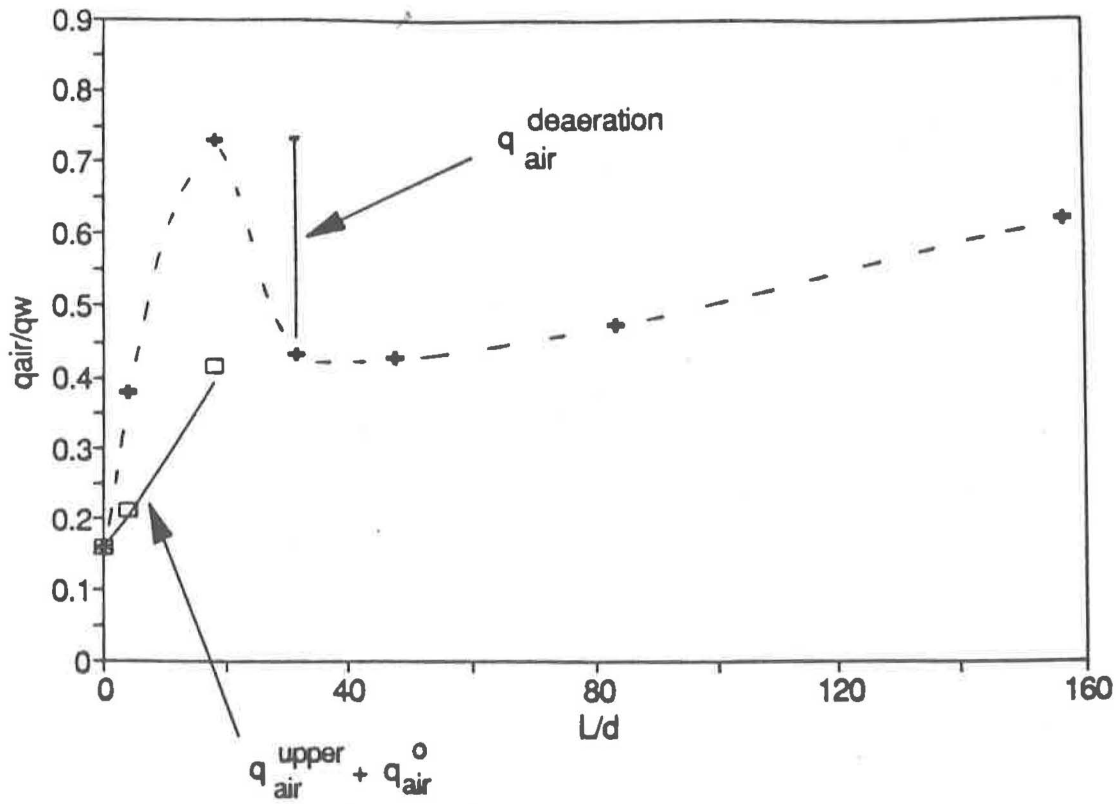

Fig. 5B - $\beta^{inlet} = 0.0$ - $P_N = 0.742$

Fig. 5 - Quantity of air entrained above an aeration device - CHANSON (1988)
No ramp - Offset height : 30 mm - Fr = 19.5 - d_o = 22.9 mm

The knowledge of the air discharge supplied by the inlets, the cavity subpressure, the jet length and the upper nappe entrainment enables the estimation of the quantity of air entrained at the end of the jet (eq. (1)).

4. The Impact Region

In the impact point region the flow is subject to a rapid change of pressure distribution from a negative pressure gradient above the

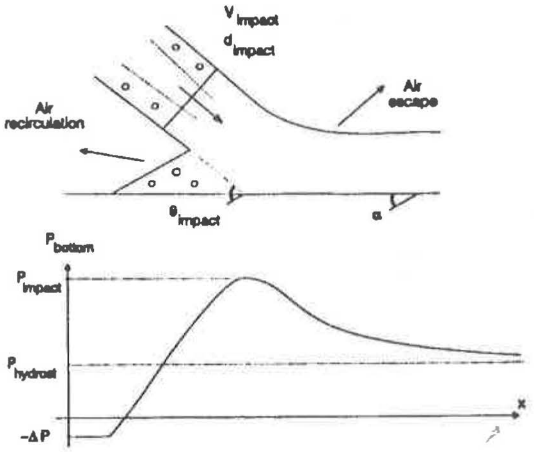

Fig 6 - Impact point region

nappe to a maximum pressure gradient at the impact point (TAN 1984, RUTSCHMANN 1988a) (Fig. 6). Experimental results obtained by LOW (1986) and CHANSON (1988) show clearly a strong de-aeration process occurring in that region (Fig. 5). The quantity of air escaping in the impact point region is a function of the jet velocity at the impact (V_{impact}) the jet thickness at the impact (d_{impact}) the gravity, the angle of the water jet with the spillway floor at the impact (θ_{impact} - α), the channel slope (α) and the quantity of air entrained at the end of the jet (q_{air}^{max}). Dimensional analysis yields:

$$\frac{q_{air}^{deaeration}}{q_{air}^{max}} = F\left[\frac{V_{impact}}{\sqrt{g * d_{impact}}} ; \theta_{impact} - \alpha ; \alpha\right]$$

The data of LOW (1986) and CHANSON (1988) were compared with the experiments of SHI et al. (1983) and CUI (1985) (Table 1). The results suggest that the de-aeration process is primarily a function of the impact angle (θ_{impact} - α). For these experimental data the above equation may be written as:

$$\frac{q_{air}^{deaeration}}{q_{air}^{max}} = 0.0762 * (\theta_{impact} - \alpha) \quad ....(6)$$

where the angles θ_{impact} and α, defined on the Figure 6, are in degrees. The equation (6) is compared with the experimental data on the Figure 7 where the impact angle (θ_{impact} -α) was computed from the jet trajectory calculations using TAN's (1984) method. It must be noted that, for the experiments of SHI et al. (1983) and CUI (1985), the subpressure in the cavity beneath the nappe was deduced from the work of PAN et al. (1980) on the same spillway model. The air concentration at the end of the impact region C* is then deduced:

$$C^* = \frac{q_{air}^{max} - q_{air}^{deaeration}}{q_w + q_{air}^{max} - q_{air}^{deaeration}}$$

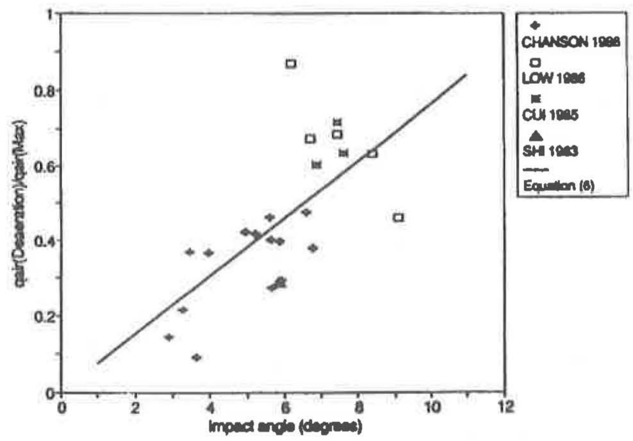

Fig 7 - Detrainment in the impact region $\frac{q_{air}^{deaeration}}{q_{air}^{max}}$ as a funtion of the impact angle (θ_{impact} -α) - SHI et al. (1983) - CUI(1985) - LOW(1986) - CHANSON (1988)

In the impact region high momentum losses occur. The data of SHI et al. (1983), CUI (1985), LOW (1986) and CHANSON (1988) suggest that the flow depth at the end of the impact region (d*) may be estimated as:

$$\frac{d^*}{d_{impact}} = 1.92 - 0.135 * (\theta_{impact} - \alpha)$$

where θ_{impact} and α are in degrees. The equation (7) is compared with the experimental data on Figure 8.

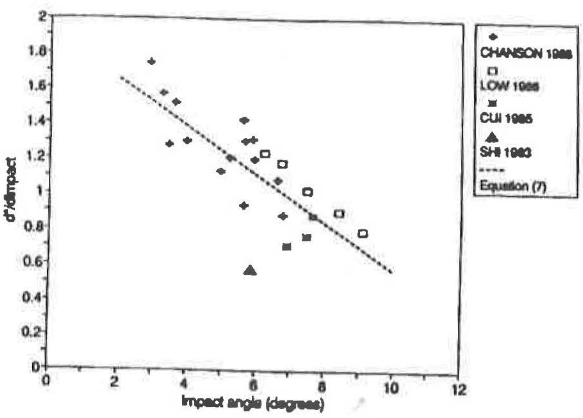

Fig 8 - Flow depth at the end of the impact point region as a function of the impact angle (θ_{impact} -α) - SHI et al. (1983) - CUI(1985) - LOW(1986) - CHANSON (1988)

It must be emphasized that, in despite of the strong de-aeration occurring in the impact point region, bottom aerators are very efficient devices for introducing large quantities of air over a short distance.

5. Downstream Flow Region

The studies of both LOW's (1986) and the author's data suggest that the downstream gradually varied flow region starts at a distance:

$$L^* = 1.3 \text{ to } 1.5 * L_{jet}$$

from the end of the deflector. The author developed a complete analogy between the flow downstream of an aerator and self-aerated flows (CHANSON 1989b). The classical analysis by WOOD (1985) and extended by the author (CHANSON 1989b, 1992) shows that the continuity equation for air and the energy equation provide two simultaneous differential equations in terms of the flow depth (d) and the average air concentration (C_{mean}). If the air concentration (C*) and flow depth (d*) at the start of the downstream flow region are known (equations 6 and 7), the continuity and energy equations can be solved by a finite difference method. The knowledge of d and C_{mean} at any position on the spillway leads to the calculations of the air concentration and velocity distributions at any point.

6. Discussion

6.1 Design of Aeration Devices

The results obtained by the author suggest that the quantity of air supplied by the air ducts is not always an important design parameter in terms of the aerator efficiency. In fact on a steep spillway the total quantity of air entrained above an aerator increases with the cavity subpressure (Fig. 5) and the largest quantities of air entrained are obtained with air inlets sealed (CHANSON 1989a).

In any case it must be emphasized that the designers of aerators must avoid the aerator submergence (eq. (4)), limit the cavity subpressure to reasonable values and limit the air velocities in the air inlets. FALVEY (1990) suggested that the cavity subpressure should be less than one tenth of the critical pressure ratio for sonic velocity, to prevent excessive noise. To avoid the effect of compressibility PRUSZA et al. (1983) indicated that the air velocities in the vents should be less that 100 to 120 m/s, or the Mach number must be smaller than 0.30

(McGEE 1988). All together these considerations may be more important when designing an aeration device than the maximisation of the quantity of air supplied by the air ducts.

6.2 Scale Effects

Usually it is not possible to reproduce on model the same flow properties as on prototype. Although the model is geometrically reproduced it is not possible to model correctly the velocity distribution and the velocity gradient next to the spillway floor. Further it is difficult to scale the roughness, and hence the local turbulence and the turbulence distribution. LAALI and MICHEL (1984) and PINTO (1984) showed that the roughness height affects the onset of the instabilities on the lower free surface and has a marked effect on the air entrainment. Also ERVINE and FALVEY (1987) showed that nappe entrainment depends critically upon the turbulence intensity.

PINTO et al. (1982) performed experiments on a series of hydraulic models whose scales varied from 1:8 through to 1:50 and were able to show that the model reproduced the prototype air demand for all water discharges for scales larger than 1:15. For scales 1:30 and 1:50 the correct air demand was only reproduced for the larger discharges.

It is also certain that the bubble sizes and their distribution across the flow are not correctly scaled above the aerator and downstream of the aerator. On prototype CAIN (1978) observed bubble sizes from 5 to 20 mm but on the model the author recorded bubble diameters in the range 0.3 to 4 mm (for C<50%). This affects the estimate of the bubble velocity (u_r) and the air entrainment calculations.

Downstream of the aerator the author showed also the presence of an air concentration boundary layer (CHANSON 1989b). It is suggested that the model reproduces the prototype air concentration distributions for scales such that the effects of the air concentration boundary layer are small.

7. Conclusion

The complete results of the studies on the Clyde Dam spillway model are summarized on the Table 3. The study of a spillway aerator is complex and should include:

(i) An analysis of the aeration region with the study of air demand, the jet trajectory calculations and the study of the upper free surface aeration,
(ii) The study of the impact region and
(iii) The analysis of the downstream flow region.

The air demand is studied on models. The cavity subpressure is deduced by combining the relationship, $\beta^{inlet} = f(Fr, P_N)$ with the pressure drop curves of the air ducts. The jet trajectory calculations define the geometry of the aeration region and the impact region, and the upper nappe entrainment may be computed in the free surface aeration region (eq. (5)). In the impact point region the flow is highly turbulent and little information is available on the processes occurring near the impact point. In the downstream flow region the author developed a complete analysis that provides the air concentration and velocity distributions at any point along the spillway and hence the local air concentration (C_b) next to the spillway bottom (CHANSON 1989b, 1992).

These studies highlighted that it is not possible to reproduce the initial flow properties on model as on prototype and that the air bubble sizes are usually not correctly scaled. Although a complete similitude of the air entrainment mechanisms is not possible, model studies are very useful to quantify the air demand characteristics curves and the upper nappe entrainment, and to understand the interactions between the air entrainment processes.

Calculations (1)	Analytical Method (2)	Experimental data (3)
Air demand	LOW (1986) (air duct calculation)	TAN (1984), LOW (1986), CHANSON (1988), RUTSCHMANN (1988)
Jet trajectory	SCHWARTZ and NUTT (1963), WEI and DE FAZIO (1982), TAN (1984), CHANSON (1988)	TAN (1984) CHANSON (1988).
Air concentration distribution	CHANSON (1988, 1989a, 1989b)	LOW (1986) CHANSON (1988)
Velocity distribution		CHANSON (1988)
Nappe entrainment	CHANSON (1991)	LOW (1986) CHANSON 1988)
Impact region		LOW (1986) CHANSON (1988)
Downstream flow	WOOD (1985), CHANSON (1988)	CHANSON (1988)

TABLE 3
STUDY OF THE CLYDE DAM SPILLWAY AERATOR: THEORY AND EXPERIMENTS

APPENDIX 1.
Clyde Dam Spillway Model

From 1983 to 1988 four model studies were performed on a 1:15 scale model of the Clyde Dam spillway at the University of Canterbury, New Zealand. The experimental configurations are described below and the complete set of experimental data were reported by TAN (1984), LOW (1986), CHANSON (1988) and RUTSCHMANN (1988a).

On the Clyde Dam spillway, the aeration device is located at the change of slope in the spillway from 51.34 to 50.19 degrees at the end of the extension piers. The aerator is positioned 39 m below the reservoir flood level and 28 m above the stilling basin (Fig. 1). It includes a 3.0 m long and 0.15 m high ramp (i.e. ϕ = 2.86 degrees), an offset height of 0.45 m and a triangular groove of 3.6 m^2 cross-section area. The air intakes have been sized with two 2.4 * 2.4m^2 openings in the spillway sidewalls and three 2.4 * 1 m^2 openings through the top of the spillway pier extensions

Characteristics	TAN	LOW	CHANSON	RUTSCHMANN	Clyde Dam
Channel					
Slope (deg)	51.3	51.3	52.33	51.3	51.34 / 50.19
Width (m)	0.25	0.25	0.25	0.25	4 * 10
Length (m)	3.60	3.60	3.60	3.60	70
Aerator					
Ramp angle (deg)	0 / 4.4	4.4 / 5.7	0 / 5.7	4.4 / 5.7 / 7.4	2.86
Ramp height (m)	0 / 0.023	0.023 / 0.03	0 / 0.03	0.023 / 0.03 / 0.039	0.15
Offset height (m)	0.03	0.03	0.03	0 / 0.015 / 0.03	0.45
Groove area (m^2)	0.057	0.057	0.057	0.057	3.6
Flow conditions					
Discharge (m^3/s)	0.145 to 0.91	0.21 to 0.54	0.16 to 0.84	0.17 to 0.49	4100
Flow depth (m)	0.05 to 0.150	0.05	0.020 to 0.120	0.05	
Froude number	3.8 to 15.5	6.4 to 15.4	3 to 25	4.9 to 14	
Air inlets					
Cross section area (m^2)	0.02	0.02	0.025	0.02	18.7 for the 4 spillways
Maximum air discharge (m^3/s)	0.140	0.162	0.18	0.104	

TABLE 4
CLYDE DAM SPILLWAY MODEL CONFIGURATIONS

Notation

The following symbols are used in this report:

C	air concentration defined as the volume of air per unit volume;
C_b	air concentration next to the spillway bottom;
C_{mean}	depth averaged air concentration defined as: $(1 - Y_{90}) * C_{mean} = d$;
C^*	mean air concentration at the start of the gradually varied flow region;
d	characteristic depth (m) defined as: $d = \int_{y=0}^{y=Y_{90}} (1-C) * dy$
d_{impact}	flow depth (m) at the end of the jet, near the impact of the jet with the spillway bottom;
d_o	characteristic depth at the end of the approach flow region (m);
d^*	characteristic depth (m) at the start of the gradually varied flow region;
Fr	Froude number defined as: $Fr = \frac{q_w}{\sqrt{g * d^3}}$
Fr_o	Froude number in the approach flow region defined as: $Fr = \frac{q_w}{\sqrt{g * d_o^3}}$
Fr_{impact}	Froude number near the impact of the jet: $Fr = \frac{q_w}{\sqrt{g * d_{impact}^3}}$
g	gravity constant (m/s^2)
H_R	vertical extent of the roller (m);
L	distance from the end of the deflector (m);
L_{jet}	jet length (m);
P_N	pressure gradient number defined as: $P_N = \frac{\Delta P}{\rho_w * g * d}$
$P_{N_{impact}}$	pressure gradient number at the end of the jet: $P_{N_{impact}} = \frac{\Delta P}{\rho_w * g * d_{impact}}$
P_{N_o}	pressure gradient number defined as : $P_N = \frac{\Delta P}{\rho_w * g * d_o}$
Q	discharge (m^3/s);
q	discharge per unit width (m^2/s);
$q_{air}^{deaeration}$	de-entrainment in the impact region (m^2/s);
q_{air}^{inlet}	air discharge (m^2/s) supplied by the air inlets;
q_{air}^{max}	quantity of air entrained within the jet at the end of the aeration region, (i.e. end of the jet length) (m^2/s): $q_{air}^{max} = q_{air}^{inlet} + q_{air}^{upper} + q_{air}^{o}$
q_{air}^{up}	quantity of air entrained (m^2/s) within the upper flow region of the water jet: $q_{air}^{up} = q_{air}^{upper} + q_{air}^{o}$
q_{air}^{upper}	air entrainment (m^2/s) through the upper interface of the water jet;
q_{air}^{o}	quantity of air entrained at the end of the deflector (m^2/s)

Re	Reynolds number defined as: $Re = \rho w * \frac{U_w * d}{\mu_w}$
t_r	ramp height (m);
t_s	offset height (m);
U_w	flow velocity (m/s): $U_w = q_w/d$
u_r	bubble rise velocity (m/s)
u'	root mean square of longitudinal component of turbulent velocity (m/s);
V	velocity (m/s);
V_{impact}	water jet velocity (m/s) near the impact of the jet;
W	channel width (m);
We	Weber number;
Y_{90}	characteristic depth (m) where the air concentration is 90%;
y	distance from the bottom measured perpendicular to the spillway surface (m);
α	spillway slope;
β	(i) dimensionless air discharge: $\beta = q_{air} / q_w$' (ii) dimensionless quantity of air entrained within the jet;
ΔP	difference between the pressure above the flow and the air pressure beneath the nappe (Pa);
ϕ	ramp angle;
μ	dynamic viscosity (N.s/m^2);
θ	angle between the water jet and the horizontal;
θ_{impact}	angle between the water jet and the horizontal at the impact of the jet with the spillway bottom;
ρ	density (kg/m^3);
σ	surface tension between air and water (N/m);
σ_c	compressive strength (Pa);
ψ^U	lateral spread angle at the upper free surface computed between Y_{90} and Y_{10}: $\tan\psi^U = (Y_{90} - Y_{10})/L$

Subscript

air	air flow;
impact	flow at the end of the jet, near the impact of the jet with the spillway bottom;
o	flow at the end of the approach flow region;
w	water flow

Superscript

inlet	air flow supplied by the air inlet;
upper	upper nappe entrainment.

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