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Air Entrainment Devices (Air Slots)

Peter Volkart
Peter Rutschmann

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Preface

Air entrainment devices are installed in steep channels of large spillways to prevent cavitation erosion. Their design has not yet found its standard solution; some important questions still remain unanswered. It is therefore useful to provide scientists and engineers with the state of the art.

The following communication of our institute is intended to be a contribution. It was conceived during the preparation of the laboratory's contribution to the monograph "Air Entrainment and De-aeration", which has been planned by the International Association for Hydraulic Research (IAHR) under the guidance of Professor Ian R. Wood, New Zealand. To him we would like to express gratitude for reviewing the outline. The content of our communication is mainly based on our former communication no. 66 "Air Slots for Flow Aeration", some further tests performed in our laboratory for large prototype applications and on the literature.

Prof. Dr. D. Vischer

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1. INTRODUCTION

Over the past decade the increase in height of dams and the increase in discharge/unit width has meant that air entrained at the free surface of the flow does not reach the concrete spillway surface. At high velocities and without the protection of the air bubbles there is a large increase in bottom cavitation erosion. Experimental investigations have shown that erosion damage may already occur at mean clear water velocities greater than 12 to 15 m/s. Erosion cavities in the concrete surface can reach a depth of several meters within a relatively short time. At velocities greater than about 20 m/s, protection of the bottom by means of streamlining the boundaries, lining critical areas with steel plates, using other improved surface finishes and/or cavitation erosion resistant materials, is neither economical nor completely successful.

At these high velocities the cavitation parameter k is computed using

$$k = (p - p_v)/\rho u^2/2 \qquad (1)$$

where

- p = reference pressure, average value
- p_v = vapour pressure of fluid
- ρ = water density
- u = mean velocity

with h = flow depth normal to surface

α = angle between bottom and the horizontal

r = radius of curvature of the boundary

and $$p = \rho g \ (h \cos \alpha \pm (h/g) \cdot (u^2/r)) \qquad (2)$$

+ for concave boundary curvature

- for convex boundary curvature.

k is normally determined by laboratory tests involving simplified spillway surface irregularities. Unfortunately, the real flow induced wall pressure fluctuations in critical low pressure zones of the channel cannot be predicted exactly and the resulting prognosis for the behaviour of prototype spillway chutes is therefore uncertain.

For the above reasons it has become usual to protect the spillway surface from cavitation by increasing the compressibility of the fluid near the surface through the introduction of air at the chute bottom. This is done by means of air entraining devices called air slots.

2. CAVITATION EROSION

Cavitation requires the formation of vapour or gas filled hollow spaces (cavitation bubbles) which result when tensile stresses in the interior of a fluid become too high. In water this normally occurs where pressures become sufficiently low to approximately equal vapour pressure p_V. Cavitation is a reversible process. In contrast, cavitation erosion is a non reversible process, and starts at the moment that cavitation bubbles move into a flow region of increasing pressure. Then the cavitation bubbles collapse over a very short time period and cause pressure shocks of high intensity and frequency close to the walls and channel bottoms. Cavitation erosion therefore is produced by alternating stresses on the micro structure of the concrete at high flow velocities. Because of the short collapsing time special attention must be paid to flow induced pressure fluctuations which normally are of longer duration but which yield ideal conditions for the described cavitation erosion process. Under these conditions, cavitation erosion may occur at mean pressures p which are higher than vapour pressure p_v.

Fig. 1. shows schematically some frequent reasons for cavitation erosion on spillway chutes. The most important hydraulic parameters to be considered are the flow velocity u, the pressure p and the amplitudes of pressure fluctuation; a possible protective measure for the channel concrete at moderate flow velocities is a smooth surface with a high degree of hardness.

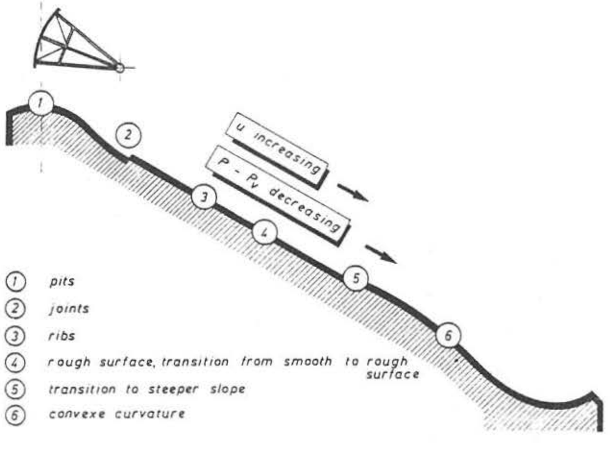


Fig. 1. Possibilities for cavitation erosion on an open chute spillway.

3. AIR SLOTS FOR PREVENTING CAVITATION EROSION

Principle of operation

The aim of bottom aeration devices is to produce a local pressure drop so that air is sucked into the flow. The increased compressibility of the air-water mixture protects the surface concrete from cavitation erosion by markedly reducing the intensity of the collapsing process by absorbing the impact of collapsing cavitation bubbles. As an approximation, 0.1 per cent by volume of air bubbles in water (the bubbles having a larger diameter than cavitation bubbles) increases the mean compressibility by a factor of 10.

The air entraining mechanism at the channel bottom is shown in fig. 2. : In the approach zone the rapid flow is characterized by the usual velocity profiles and a surface layer that may contain air bubbles entrained by self-aeration at the free surface.

The transition zone is defined by the length of a bottom ramp of flatter slope. The pressure at the ramp increases above hydrostatic pressure. The actual aeration zone may be divided into a shear zone, a spray zone and a mixing zone.

As presented by Pinto, Neidert and Ota, 1981, the fluid leaves the ramp at the beginning of the shear zone; hence, there is no longer a shear stress acting on the lower streamlines and the fluid in this region is accelerated. This fact together with the no slip condition implies that movement of the air under the nappe will occur. Consequently instabilities develop at the air-water interface. The length of the shear zone probably depends on the geometry and surface finish of the ramp (i.e. deflector).

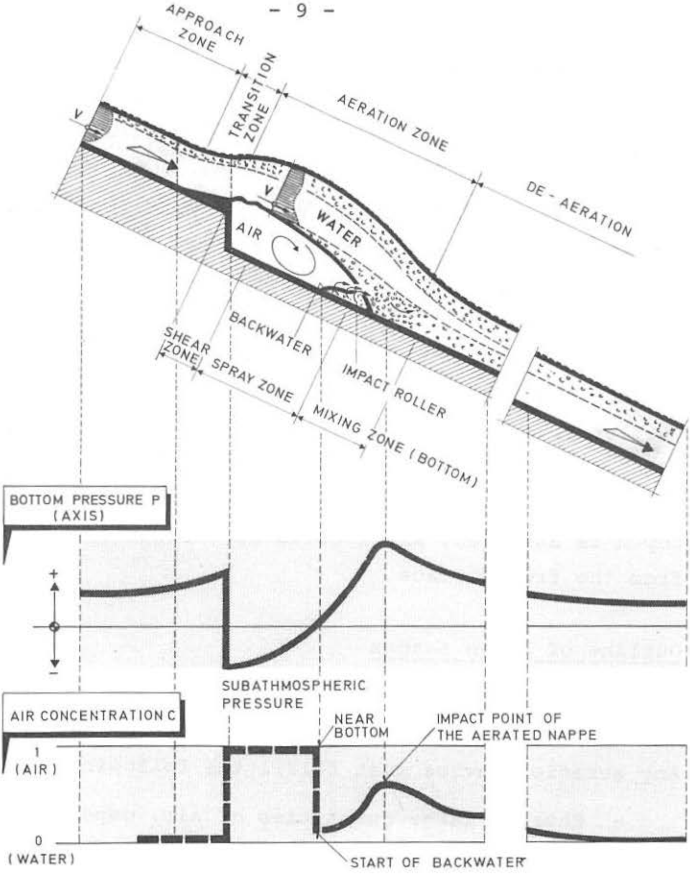


Fig. 2. Air entraining mechanism by an air slot. (Principle of air slot operation).

Once surface tension effects are overcome, water at the air-water interface changes into spray (spray zone), which has a high efficiency in terms of entraining air. The continuity of the process requires, of course, a continuous air supply to the space under the nappe. In that region, pressures will be sub-atmospheric due to the velocity of the air flow and to head losses through the supply system. This pressure difference will cause a deflection of the jet trajectory in relation to that of the normal free jet.

In the mixing zone, when the nappe hits the bottom of the chute the flow will have entrained a certain volume of air. Sometimes, with relatively steep angles between spray jet and channel bottom, water rollers may entrain an additional quantity of air but this is not of great importance. Air concentration and bottom pressure near the floor reach their maximum at the impact point of the jet.

As the water-air mixture moves downstream (de-aeration zone) the air concentration next to the floor reduces as air bubbles rise. When this has reached an unacceptable level another, second, aeration device must be constructed. This is normally before an equilibrium condition of the mixture depth is attained, which could be influenced by air entrained from the free surface.

Outline of known shapes

The need for a practical aeration device is a very restrictive criterion and only a small number of shapes are feasible. Any aeration device must fulfil the following conditions:

- Entrain large quantities of air, especially so that air concentration is high at the most endangered surfaces
- have a simple and economic design and yet prevent any erosion damage of the device itself.

These conditions have resulted in only a few main shapes being used, such as deflectors, offsets, grooves, and combinations of these types (see. fig. 3.).

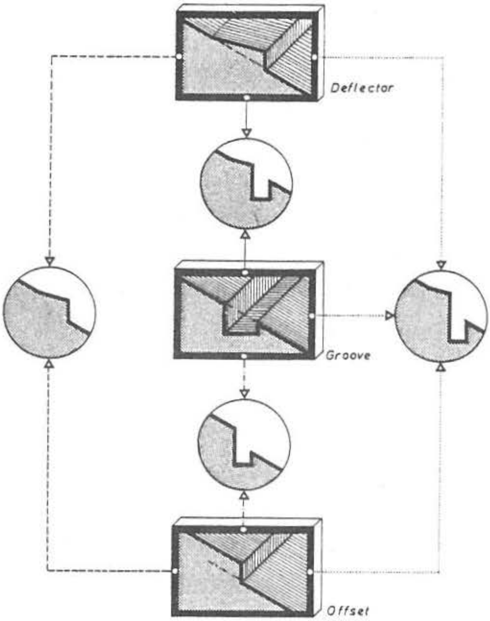


Fig. 3. Main aeration devices and their combinations.

These elements are usually placed at the bottom of the spillway. However, when additionally installed at the side walls of the chute they also can replace a special aeration system by creating space for air supply to the bottom cavity. The three air slot types, namely deflectors, offsets and grooves all work according to the operating principles presented in fig. 2. However, due to the special geometry of each device, dimensions of the shear zone, spray zone and mixing zone may differ. Therefore the three air slot types also possess differing air entrainment characteristics. The main characteristics and optimum operating conditions can be summarized as follows:

Initially the deflector was prefabricated from steel and has been used as a remedial measure on existing spillways. Its height usually ranges from 0.10 to 1.00 m. An advantage of this air entraining device is that even with small deflector heights an underjet space of considerable length is created, and the increased velocities in the boundary layer due to the ski jump effect results in increased aeration intensity. The main disadvantages of this type are the high shock wave production, and the small range of discharges with optimum air demand. However, a deflector usually is combined with another device to achieve a wider operational range.

If aeration is anticipated at the outset of the design stage, offsets may be incorporated in the design. These have the advantage of minor shock wave disturbance, an enlarged jet trajectory at higher discharges and enough space for air supply. Because the air demand of the offset is poor at small and more frequent discharges it is often combined with a small deflector (see fig. 3.), thus guaranteeing optimum aeration.

Grooves, which are often used in tunnels or after gates, have the advantage of ease of air supply. This supply comes either from special air vents or a free air space produced by the arrangement of aeration devices on the spillway side walls. Grooves are usually 1.00 to 2.50 m deep. The main disadvantage is their small air demand due to the small exposure of the nappe to the air. Most grooves are therefore combined with either a deflector or an offset.

Recent experience has tended to favour a combination of offset and deflector as the most practical aeration device, while shunning grooves.

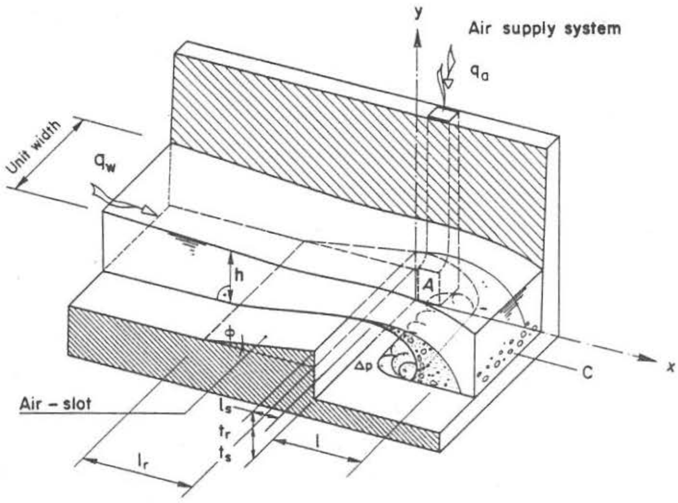


Fig. 4. Nomenclature for aerator.

Main parameters

Referring to fig. 4. , it is possible to define the following main variables to be considered in the study of aerator geometry and the air entrainment phenomenon:

A	m^2	sectional area of air jet at exit of supply system
B	m	chute width
C	%	air concentration: $100 \cdot$ air volume / (air volume + water volume)
E	-	Euler number $= u / (\Delta p/\rho)^{1/2}$
F	-	Froude number $= u / (gh)^{1/2}$
K	-	constant
R	-	Reynolds number $= \rho_W \, u \, h / \mu$
W	-	Weber number $= u / (\sigma/\rho_W \, h)^{1/2}$
g	m/s^2	acceleration due to gravity

h	m	flow depth normal to the bottom
l	m	water jet length (distance from $x = 0$ to the impact point of the spray jet)
l_r	m	ramp length
l_s	m	shear length
q	m^3/ms	specific discharge
t_r	m	ramp height, deflector height
t_s	m	step height, offset height
x	m	coordinate in flow direction
y	m	coordinate normal to the flow direction
u	m/s	flow velocity
$tg\,\alpha$	-	channel slope
β	-	aeration coefficient
Δp	N/m^2	air pressure difference to atmospheric pressure under the nappe
$tg\,\phi$	-	inclination of the ramp (deflector) with reference to the channel bottom
μ	$N\,s/m^2$	dynamic viscosity of water
ρ	kg/m^3	density
σ	N/m	water surface tension coefficient

special indices: a: air w: water

The water jet length

As shown in fig. 2. , the aeration zone can be subdivided into a shear zone, a spray zone and a mixing zone. Air entrainment takes place mainly in the spray zone, but the entraining process probably is not completely independent of the flow processes in the two other zones. Consequently, the water jet length l (which is characteristic for the geometry of the cavity under the nappe) seems to be a dominant parameter for computing the specific air discharge q_a. But take note that because of the physical reasons mentioned above this represents only an approximation.

Nevertheless, the calculation of the jet's trajectory is of interest and has already been performed by several authors over the past decades.

For a reasonable approximation the solution of Schwartz and Nutt, 1963, can be used; this considers the equations of motion and continuity as well as the relative underpressure beneath the nappe. Above all the authors have been able to show that a relatively small transverse pressure can appreciably alter the profile of the nappe.

In order to obtain a general solution surface tension effects were assumed to be negligible. The resulting inaccuracy is negligible unless the nappe is extremely thin. The formulae of Schwartz and Nutt can be written as follows:

$$\frac{y'}{h_o} = \frac{F_o^2 \sin \theta_o}{a \sin \gamma} \left[\cos \gamma - \cos \left(\frac{u_o\, a\, t}{F_o^2\, h_o} + \gamma \right) \right] \qquad (3)$$

$$\frac{x'}{h_o} = -\frac{u_o t}{a h_o} + \frac{F_o^2 \sin \theta_o}{a \sin \gamma} \left[\sin \left(\frac{u_o\, a\, t}{F_o^2\, h_o} + \gamma \right) - \sin \gamma \right] \qquad (4)$$

with a>0.

The following additional symbols and abbreviations are used (see also fig. 5.):

F_o	-	Froude number at the ramp
h_o	m	initial flow depth at the ramp
t	s	time
u_o	m/s	initial velocity at the ramp
x'	m	coordinate in horizontal direction
y'	m	coordinate in vertical direction
θ_o	-	initial angle of the trajectory = $\alpha - \phi$

a - $= \frac{\Delta p}{\rho\, g\, h_o}$

γ - $= \arctan\left(\frac{a \sin\theta_o}{a \cos\theta_o + 1}\right)$

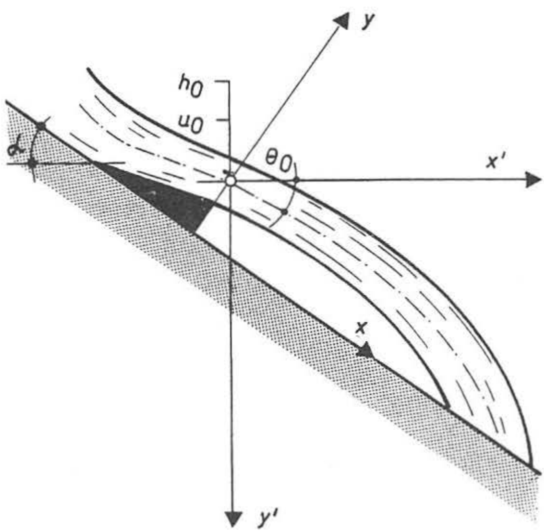


Fig. 5. Definition of coordinates x' and y'.

From equations (3) and (4) the water jet length l can be determined from the trajectory of the nappe described by $\frac{y'}{h_o}(t)$ and $\frac{x'}{h_o}(t)$. A systematic comparison with other known formulae that give the length l directly shows that for vanishing pressure difference Δp most computed trajectories are more or less identical. But for relative subpressures $|\Delta p| > 0$ (as expected for aerators) the equations given above enable a sufficiently accurate estimation of l.

The entrainment coefficient

The phenomenon of air entrainment on the underside of the nappe may be described by the following function:

$$f(q_a, u, h, l_s, l_r, t_r, t_s, \alpha, \phi, l, \Delta p, g, \rho_w, \mu, \sigma) = 0 \quad (5)$$

or with dimensionless groups:

$$f'(E, F, R, W, \frac{q_a}{u\,l}, l/h, t_r/h, t_s/h, l_r/h, (g\,l_s/u^2), \rho_a/\rho_w, \mathrm{tg}\,\alpha, \mathrm{tg}\,\phi) = 0 \quad (6)$$

Pinto et al.,1981, proposed the simplified equations (7) and (8.)

$$Q_a = q_a \cdot B = \text{constant} \cdot A\ (\Delta p/\rho_a)^{1/2} \quad (7)$$

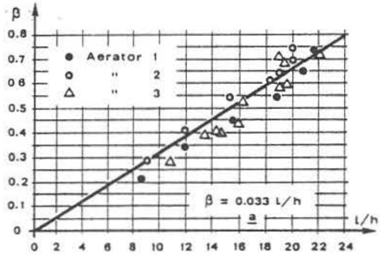
and $q_a/q_w = K\,\frac{l}{h} = \beta$; or $K = q_a/u \cdot l$ (8)

This allows an initial estimation of q_a, assuming that the jet length l is the most important parameter of the air entraining process. Obviously, the jet length l itself depends mainly on the flow velocity u and the aerator geometry. Thus the quantity of entrained air along the water-air interface on the underside of the nappe may be determined roughly by equation (8)

Values for β were plotted by Pinto et al., 1981, and Wei and de Fazio, 1982, and are shown in fig. 8. for various shapes of aerators.

The following assumptions underlying equation (8) should be noted:

- The effects of Reynolds number R and Weber number W may be disregarded for the size of hydraulic structure being considered,



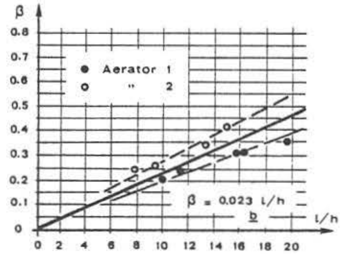


Fig. 6. $\beta = f(l/h)$ as estimated from prototype results.

- On normal spillways only small variations in ramp geometry are possible and deflectors with curved shape are excluded,
- the shear length l_s does not depend on ramp geometry and concrete roughness, and is assumed to be short,
- the mean flow velocity u is a sufficient representation of the velocity distribution at $x = 0$,
- the pressure distribution of the air in the space under the nappe is sufficiently characterized by the parameter Δp,
- impact rollers are able to be neglected, and
- the flow always remains 2-dimensional (constant chute cross section, no side deflectors and no particle activities transverse to the x-y-plane).

Supply Systems

As shown above, spillway aeration is achieved with two devices, the air slot and a connecting air supply system.

The action of these can be compared to a water jet aspirator consisting of a pumping device (the so called ejector) and an air approach duct respectively. The ejector behaviour depends on its geometry and discharge, while the behaviour of the air approach duct only depends on its geometry (see fig. 7).

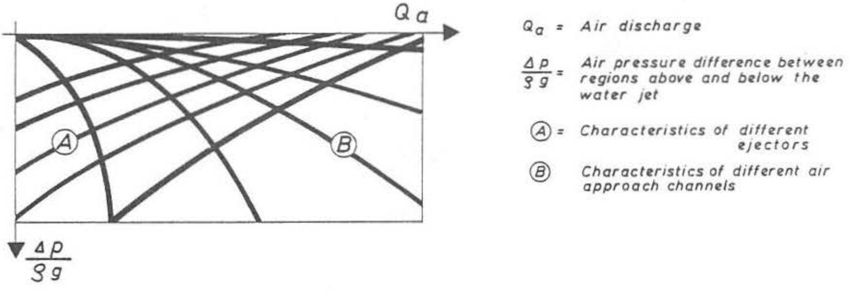


Fig. 7. Characteristics of a water jet aspirator (principle)

Fig. 7. shows that specific air entrainment could be improved by either changing the deflector or the approach duct geometry. Of importance in fig. 7. is that the air approach characteristic curve intersects the curve characterizing the ejector at a relatively flat segment. This means that only a small change in the supply system effects a considerable change in the specific air discharge. This must be considered in designing and constructing air slots.

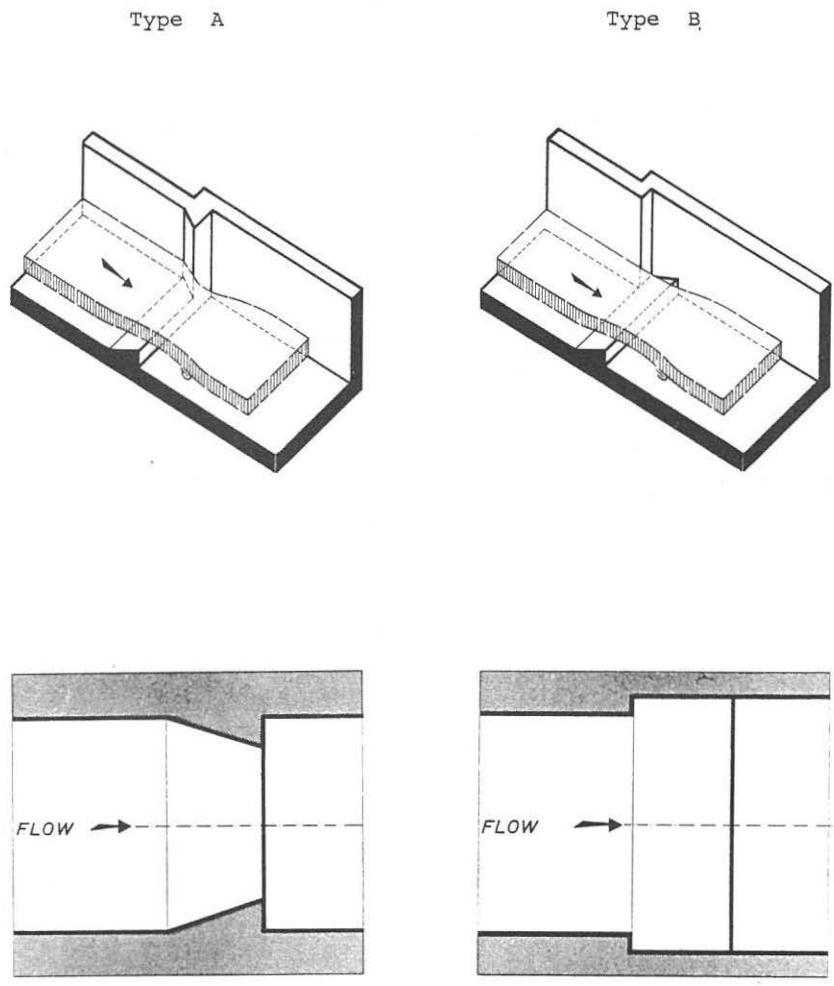


Fig. 8. Examples of air supply systems.

Type A: Air supply with lateral deflector
Type B: Air supply with lateral offset

Type C Type D

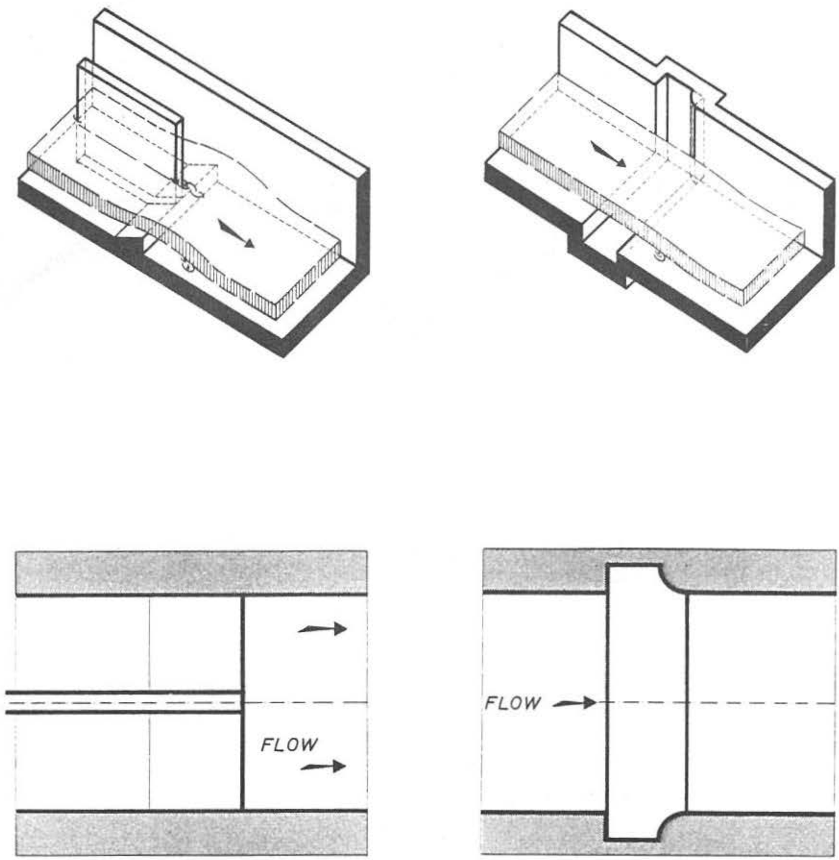


Fig. 9. Examples of air supply systems.

Type C: Air supply behind pier
Type D: Air supply by lateral grooves

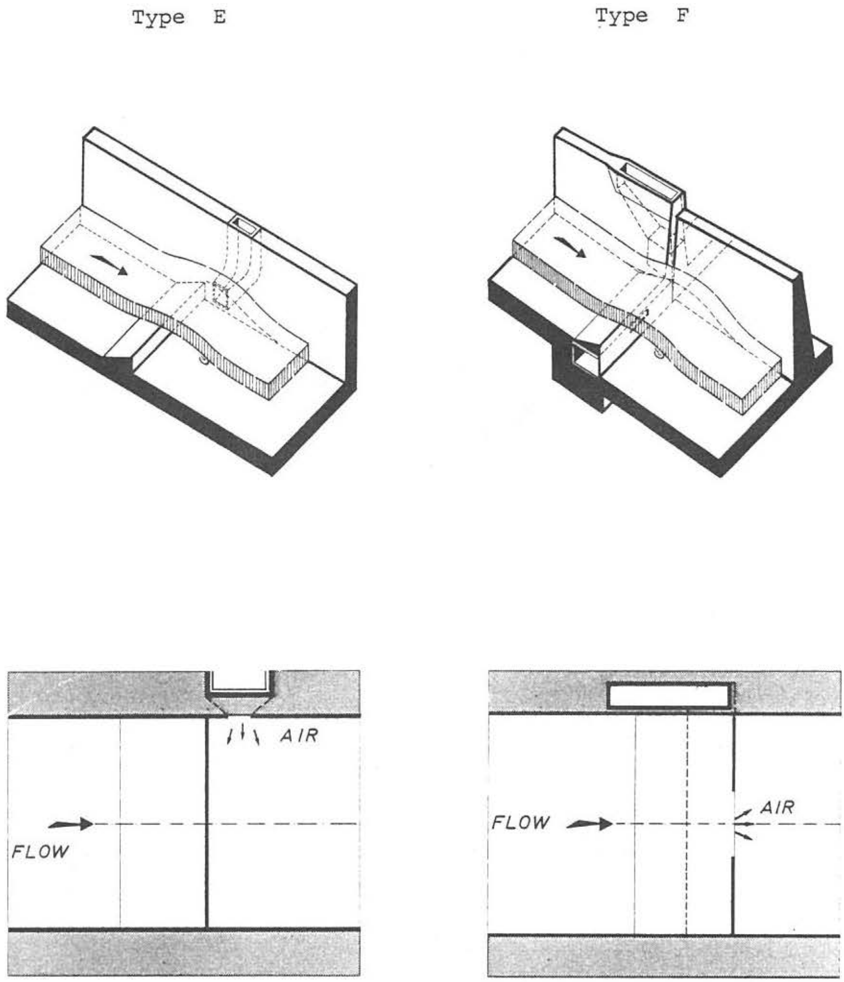


Fig. 10. Examples of air supply systems.
Type E: Air supply by special air ducts below water jet
Type F: Special aeration system

A large number of the known supply systems work either with a lateral geometric discontinuity creating a cavity between the water body and concrete surface, or with special air shafts or conduits (see fig. 8 to 10). The latter solution has the advantage of not additionally disturbing flow conditions because shock waves are suppressed.

Assuming symmetrical air supply, pressure differences between regions above and below the water jet diminish toward the axis of the spillway chute. Measurements made by Pinto,1979, at Foz do Areia are presented in fig. 11. Considering the change in pressure across the chute as implied by fig. 11, from fig. 7 it seems obvious that air entrainment across the chute will be non-uniform in this case. Conditions for systems of type F are somewhat different in that the pressure distribution across the spillway chute can be influenced by the arrangement of the air outlets. Best conditions were achieved with air entrainment across the chute either uniform or slightly favouring the axis to allow for the higher velocity close to the center line.

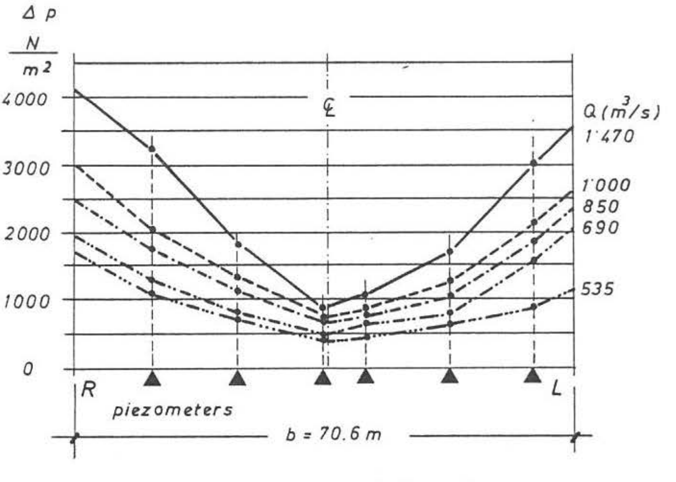


Fig. 11. Pressure distribution below the water jet. Symmetrical air flow conditions.

4. CRITERION AGAINST CAVITATION EROSION

The criterion for preventing cavitation erosion by aeration is based on the results of Peterka, 1953. Tests of concrete specimens were performed in a cavitation apparatus. The test period was 2 hours and the velocity was up to 35 m/s. The weight losses of the specimens were plotted against the air concentration (see fig.12).

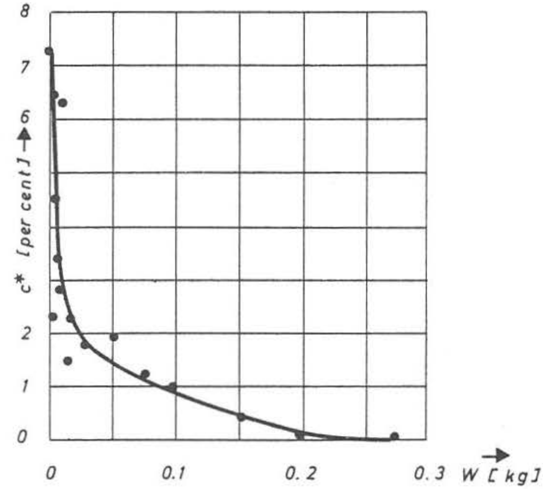


Fig. 12. Air content versus cavitation weight loss of concrete specimens (according to Peterka A.J., 1953).

An important result from fig.12. is that a small air bubble content C* of about 1 to 2 % already reduces cavitation erosion markedly. For almost complete protection of the surface concrete an air concentration near the bottom of the flow of 6 to 8 % is currently used ('near the bottom' implies up to 20 cm above the floor of the chute.) It should be noted that the required air concentration may exceed these values for flow velocities greater than 35 m/s.

Additional investigations by Galperin et al, 1981, show that the required air concentration also depends on concrete strength and flow velocity (see fig. 13). Further, Ball, 1976, shows that the maximum allowable velocity of cavitation erosion free flow depends on the size and shape of surface irregularities, although the influence of surface roughness nearly vanishes when the bottom layer is aerated.

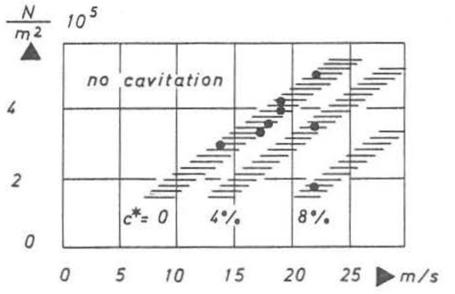


Fig. 13. Relation between allowable velocities of a cavitation flow, the concrete strength and the air content C* (according to Galperin, R.S. et al 1971). C*=100·air volume/water volume.

5. AIR CONCENTRATION DOWNSTREAM OF AN AIR SLOT AND AIR SLOT SPACING

Air concentration downstream of an air slot and near the channel bottom is of primary importance for cavitation erosion protection. It can generally be said that at the point of impact of the unaerated jet the bottom air concentration is very low. But at the position where the aerated nappe reaches the bottom, and also just downstream of the mixing zone, concentration rises to a maximum value of more than 50 %. Beyond this air concentration decreases continuously as shown before.

Figures 11 and 12 show typical air concentration profiles: The first cross section is positioned just downstream of the point of jet impact. The nappe is aerated from beneath and above, so there are two maximums in the concentration profiles with the overall concentration being between 50 % and 100 %. However, because of the non-uniformity of aeration, there is still a core of almost pure water. At the bottom there could be a roller upstream of the point of impact which causes the concentration to decrease to zero near the bottom.

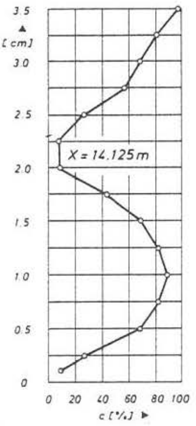


Fig. 14. Example of air concentration profile for $tg\,\alpha = 1:4$, $q_W = 40\ m^3/ms$, $t_r = 0.50$ m, $t_s = 0.75$ m. (according to Vischer, Volkart, Siegenthaler, 1981).

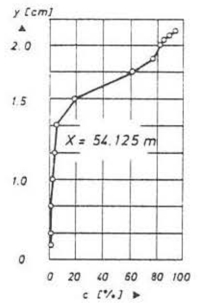


Fig. 15. Profile a considerable distance downstream of the air slot (with the same parameters as in fig. 4.)

As a result of turbulence effects, air concentration in the direction of flow initially decreases at the bottom of the flow. The surplus air in the lower layer rises because of buoyancy, and the lower maximum in the concentration profile disappears. Farther downstream the aerated layer near the surfaces decreases in extent, but even at considerable distances from the air slot there is still more air in the flow than without an aerator. However, at usual dam spillway chutes, air bubbles entrained by self-aeration at the free surface (i.e. without air slots) normally do not reach the channel bottom and thus do not aid in protecting the concrete surface against cavitation erosion. Flows with very small specific discharges q_w and flow depths h are exceptions to this situation, as the point of intersection of the turbulent sublayer with the free surface is reached at a rather short distance downstream of the dam crest.

Figures 16 and 17 show examples of concentration distributions along the channel bottom. For low Froude numbers the concentration profiles at the walls are approximately the same as that along the chute axis. Because of drag at the side wall, and resultant lower velocities, the jet first reaches the bottom near the wall. Therefore the point of impact and the maximum air concentration (after mixing) are a little nearer to the air slot than they are on the channel axis. For higher Froude numbers the nappe

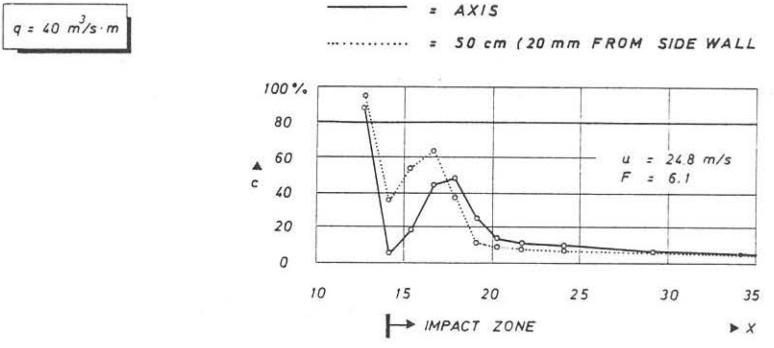


Fig. 16. Air concentration distribution along channel bottom. (10 cm above the bottom).

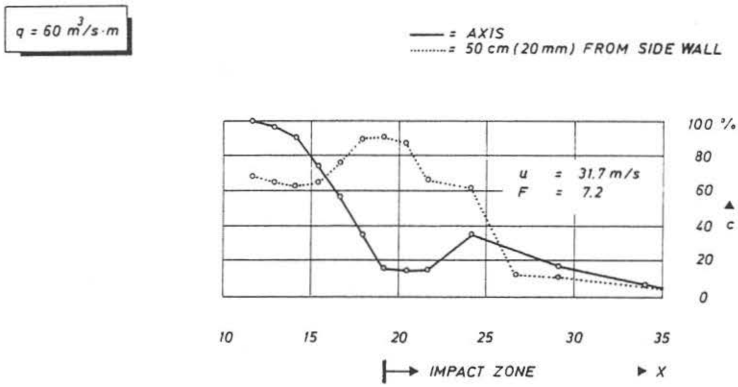


Fig. 17. Air concentration distribution along channel bottom.

may separate from the side walls due to shock waves from the deflector. Consequently the air concentration is initially very high because the nappe is aerated from the sides also.

To protect long open chutes the installation of a succession of slots is appropriate. The first should be installed at the beginning of the cavitation erosion risk zone and the subsequent ones where the air concentration near the bottom decreases below a certain value, for instance 8 %. In order to have a maximum length of protected zone beyond each air slot, a mean air concentration between about 20 % (Pinto, Neidert, Ota, 1981) and 30 % (Oskolov, Semenkov, 1979) should be generated. Semenkov and Lantyaev, 1973, found (as a rough approximation) the specific air loss downstream of an air slot to be close to a value of 0.5 to 0.8 % per m, and 1.2 to 1.5 % per m for a channel with concave curvature. Now, the distance between two air slots depends directly on the flow velocity u, and very little on the specific discharge q_w. After deciding the maximum allowable velocity without aeration (which depends on concrete strength and surface irregularities) the distance between air slots has to be estimated with the help of model tests and in comparison with working prototype spillways. Normally, distances are between 30 and 100 m.

A guide is given in tables (page 31), the information having been compiled from known prototype experiences. Caution must be employed, however, as few examples covered the highest predicted spillway discharges. On the other hand, distances between air slots that are too short will result in non-effective aeration as the water-air interface beneath the nappe will still be partially saturated with air bubbles on reaching the next slot (Additional costs will then result).

Model and Prototype Tests

Reduced Froude scale model may be used to aid the design of air slots. Models should not be smaller than 1:25. If this condition is met, they can be used to evaluate the following

- the best shape of air slots
- an approximate length of the jet, and
- variable supply systems.

According to Peterka (1953), VAW (1981), Pinto et al, (1982), and Vischer et al, (1982), air entrainment can be estimated from hydraulic models scaled larger than about 1:15 or 1:10 with Weber numbers exceeding 500 to 1000. To simulate sufficiently prototype behaviour, spray must appear beneath the nappe in these models. Vischer et al, 1982, demonstrate that a family of models at different scales will overcome the following effects:

- Influence of bubble rise velocity
- Influence of surface roughness
- Influence of channel width

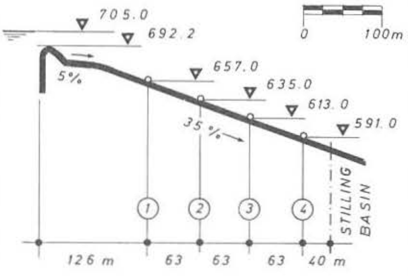
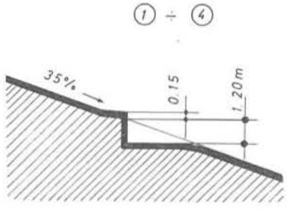
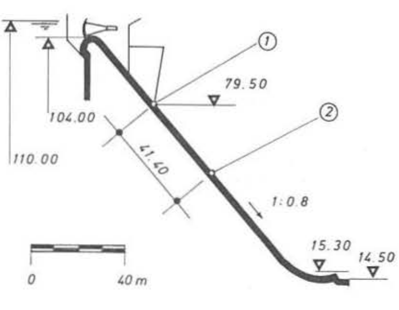
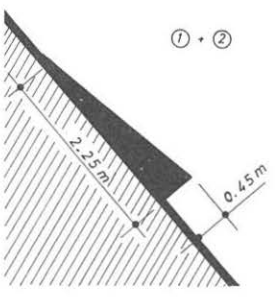
and - Influence of the air supply system.

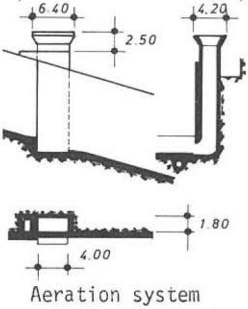
Air concentration data measured from prototype examples provides the best guide to design. Valuable information is given in references 34, 52, 18, 69, 42 and 24. Attention must be paid to the tremendous influence that the supply system exerts on the total quantity of air entrainment. Hence, for comparison the supply system and the specific discharge q_w should be more or less similar.

ANNEX 1

Tables

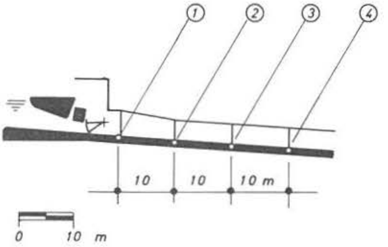
Object	Hydraulic Data	Interdistance between aerators	Remarks	Ref.
ALICURA 1984 Argentina	H = 126 m J_{max} = 35 % B = 39 m Q_{max} = 3000 m^3/s u_{max} = 45 m/s q_{max} = 77 m^2/s	1 ÷ 2 = 67 m 2 ÷ 3 = 67 m 3 ÷ 4 = 67 m	Air is supplied to the offsets by two lateral air ducts (3 x 1.30 m^2) integrated in the walls. Model tests limited to three-dimensional hydraulic modelling	[55]
BRATSK 1964 USSR	H = 106 m J = 125 % B = 60 m Q_{max} = 6050 m^3/s u = 24 m/s q_{max} = 101 m^3/s m	0 ÷ 1 ~ 35 m 1 ÷ 2 = 41 m	Aeration at (1) with direct aeration through the cavities created by pier-ends and deflector. Aeration at (2) with air duct of 0.25 m^2 cross sectional area. After prototype measurement, aerator No. (2) was considered unnecessary because the mean air concentration was only increased by 5 ÷ 10 %.	[37] [38] [31] [42] [34] [53] [33]

Longitudinal Section	Air Slot Design
ALICURA 	
BRATSK 	

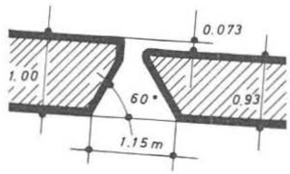
Object	Hydraulic Data	Interdistance between aerators	Remarks	Ref.
CALACUCCIA 1968 France Bottom Outlet	H = 61.4 m J = B = Q_{max}= 100 m^3/s u_{max}= 31 m/s q_w =	1 ÷ 2 = 10 m 2 ÷ 3 = 10 m	Aeration without special ducts through the grooves	[45] [42]
FOZ DO AREIA 1980 Brazil	H = 118.5 m J = 25.84% B = 70.6 m Q_{max}=11000 m^3/s u_{max}= ∿ 40 m/s q_{max}= 156 $m^3/s\ m$	0 ÷ 1 = 150 m 1 ÷ 2 = 74 m 2 ÷ 3 = 93 m	Aeration at (1), (2) and (3) with identical aeration system:  Aeration system was already provided in the design of the chute. The good experiences are underpinned with several prototype measurements.	[37] [38] [31] [39]

Longitudinal Section	Air Slot Design

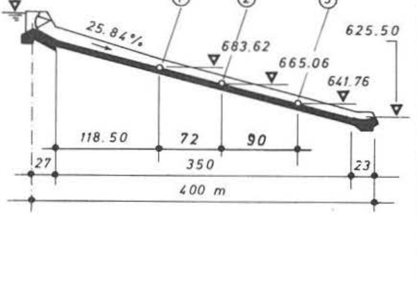
CALACUCCIA



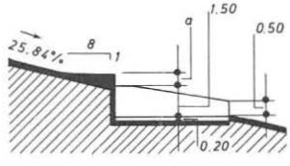
(1) et seq.



FOZ DO AREIA



(1) + (2) + (3)



(1) a = 0.20 m
(2) a = 0.15 m
(3) a = 0.10 m

Object	Hydraulic Data	Interdistance between aerators	Remarks	Ref.
GURI 1968 (1986) Venezuela	H = 115 ÷ 130 m J = ÷ 120 % B = 120 m Q_{max}=30000 m^3/s u_{max}> 50 m/s q_{max}= 250 m^3/s m	0 ÷ 1 = 60 m 0 ÷ 2 = 90 m 0 ÷ 3 ~ 25 m 3 ÷ 2 ~ 110 m	(1) + (3) without special aeration system. Aeration is accomplished through the flow opening due to separation behind the piers and at the deflector. (2) Supply gallery with 8 m^2 cross sectional aera and six square ducts with 1.25 m length. Different stages require several aeration designs. Extensive prototype measurements will be presented and could give useful additional information	[68] [38] [9]
ITAIPU 1982 Brazil / Paraguay	H = 80 m J ~ 16 % B = 280 m Q_{max}=62200 m^3/s u_{max}= q_{max}= 222 m^3/s m	0 ÷ 1 ~ 315 m 1 ÷ 2 ~ 78 m	Facilities for installation of an aeration system is provided but will only be built if satisfactory operation without these devices is not possible.	[57]

<table>
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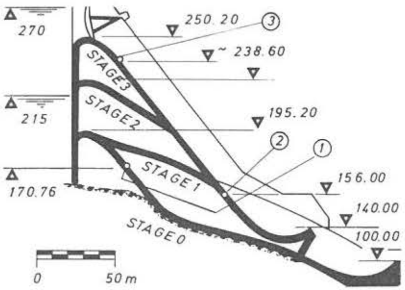
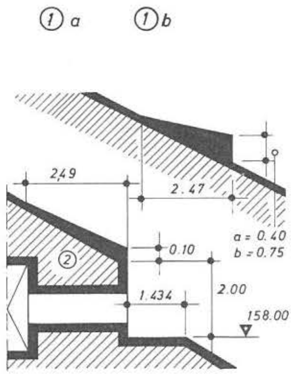
</td><td></td></tr>
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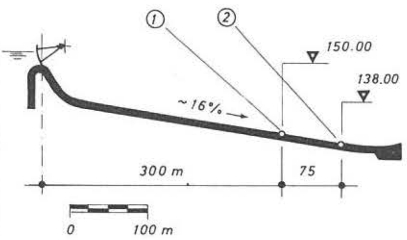</td><td></td></tr>
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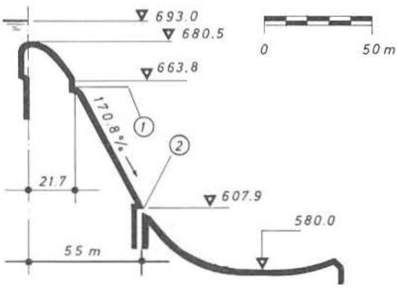
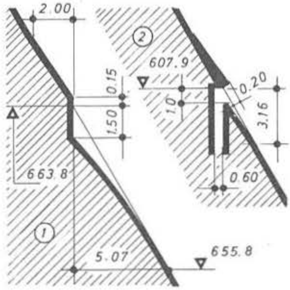
Object	Hydraulic Data	Interdistance between aerators	Remarks	Ref.
KARAKAYA 1987 Turkey	H = 113 m J_{max}= 170.8 % B = 10x(14)m Q_{max}=17000 m^3/s u_{max}= 47 m/s q_{max}= 121 m^3/s m	1 ÷ 2 = 65 m	At aerator (1) air is supplied by two lateral air ducts integrated in the piers of the crest; At aerator (2) from the joint Dam - power house. Extensive model tests including general hydraulic modelling and two dimensional air modelling	[45] [31] [55] [56]
MANILA WATER SUPPLY III uc Philippines	H = 90 m J_{max}= 37 % B = 25 m Q_{max}= 3000 m^3/s u_{max}= 37 m/s q_{max}= 120 m^3/s m	1 ÷ 2 = 43 m 2 ÷ 3 = 62 m 3 ÷ 4 = 60 m	Air is supplied to the offset groove by two lateral air ducts (2 x 1 m^2) integrated in the walls. Extensive model tests, including general three-dimensional hydraulic modelling and two-dimensional air modelling	[55]

Longitudinal Section	Air Slot Design

KARAKAYA





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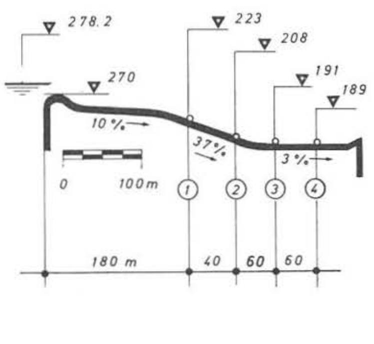

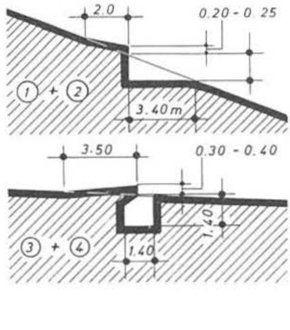

Object	Hydraulic Data	Interdistance between aerators	Remarks	Ref.
MICA 1972 (Bottom Outlet)	H = 186 m J_{max} = 120 % D = 9.00÷13.7m Q_{max} = 1000 m^3/s u_{max} = 16 m/s	0 - 1 = 0 m 1 - 2 ~270 m	Air supply is accomplished with an air shaft at (1) and a ventilation gallery at (2).	[11] [45]
NUREK 1972 USSR	H = D = 10 m * Q_{max} = 2400 m^3/s u_{max} = 42 m/s * Transition from circular to open rectangular section.	0 ÷ 1 = 1 ÷ 2 = 10 m 2 ÷ 3 = 12 m 3 ÷ 4 = 14 m 4 ÷ 5 = 15 m 5 ÷ 6 = 15 m 6 ÷ 7 = 15 m 7 ÷ 8 = 15 m	Air supply is guaranteed with air vents and by the help of the grooves. A lot of prototype measurements were undertaken. It is known that air entrainment was too high and that some grooves were eliminated.	[18] [19] [42] [31] [38] [37] [45]

<table>
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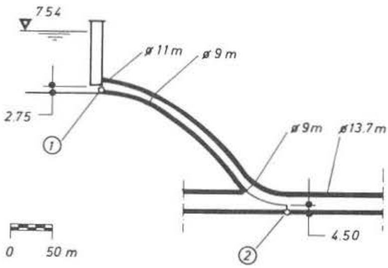
MICA



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①, ②

Offsets with aeration gallery being 2.75 m and 4.50 m high respectively.
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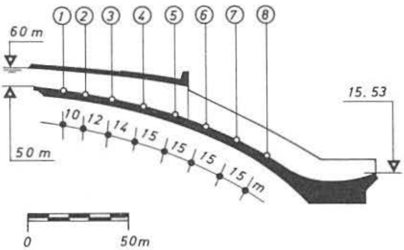
NUREK



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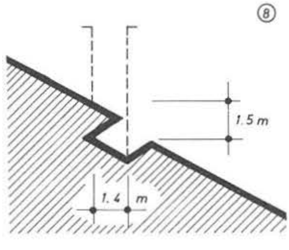

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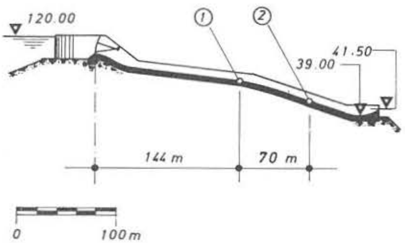
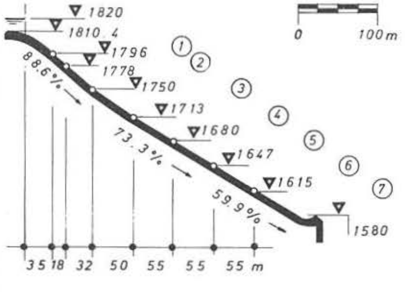
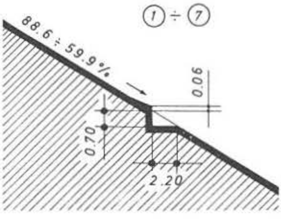
Object	Hydraulic Data	Interdistance between aerators	Remarks	Ref.
PEDRA DO CAVALO 1986 Brazil	H = J = B = 93 m Q_{max}=12000 m^3/s u_{max}= q_{max}= 130 m^3/s m	0 ÷ 1 ∿156 m 1 ÷ 2 ∿ 74 m	No special aeration system.	
RESTITUCION (MANTARO I.3) 1984 Peru	H_e = 240 m J_{max}= 88.6 % B = 4.0 m Q_{max}= 96 m^3/s u_{max}= 39 m/s q_{max}= 24 m^3/s m	1 ÷ 2 = 24 m 2 ÷ 3 = 43 m 3 ÷ 4 = 62 m 4 ÷ 5 = 64 m 5 ÷ 6 = 64 m 6 ÷ 7 = 64 m	Air is supplied to the offsets by two lateral air ducts (0.65 x 0.75 m^2) integrated in the walls. Model tests limited to three-dimensional hydraulic modelling.	[55]

Longitudinal Section	Air Slot Design
PEDRA DO CAVALO	
RESTITUCION (MANTARO I.3)	







Object	Hydraulic Data	Interdistance between aerators	Remarks	Ref.
SAN ROQUE uc Philippines	H = 128.4 m J = 25 % B = 105 m Q_{max}=12800 m^3/s u_{max}= 45 m/s q_{max}= 122 m^3/s m	0 ÷ 1 = 170 m 1 ÷ 2 = 52 m 2 ÷ 3 = 52 m 3 ÷ 4 = 52 m 4 ÷ 5 = 52 m 5 ÷ 6 = 52 m 6 ÷ 7 = 62 m	Special aeration system is provided. The design of aeration devices was obtained with the help of hydraulic model tests. Prototype data are not available at the moment.	[62] [12] [69]
SAYANO-SHUSHENSKOE USSR	H = 220 m J_{max}∿ 275 % B = 55 Q_{max}=13600 m^3/s u_{max}= 50 m/s q_{max}= 247 m^3/sm	1 ÷ 2 2 ÷ 3	Aeration is achieved through the cavities formed by the water jet. Extensive model tests were undertaken. As a result aerator No. (3) was not built in because of flow problems and sufficient aeration by the devices (1) and (2).	[39] [45] [24]

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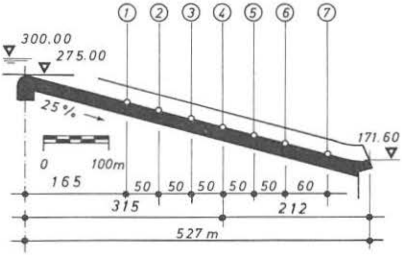
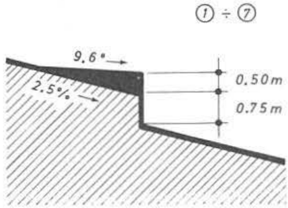

</td><td>
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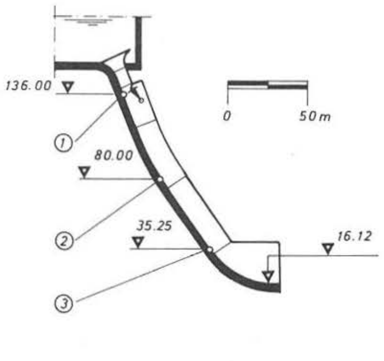
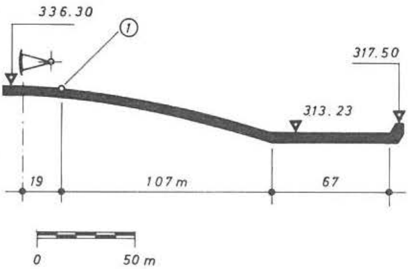
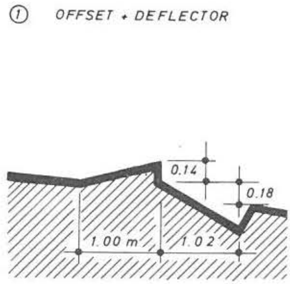

</td><td>① Offset
② ③ Grooves</td></tr>
</table>

Object	Hydraulic Data	Interdistance between aerators	Remarks	Ref.
TARBELA Pakistan (Bottom Outlet)	H = 140 m B = variable Q_{max} = 2690 m^3/s u_{max} = 49 m/s	0 ÷ 1 = 19 m	Aeration system is provided. Aeration was installed after serious cavitation damages. After installation of the described air slot no further damage was observed.	[58] [28] [6]
TOKTOGUL 1978 USSR	H = 116 m J = 150 % B = Q_{max} = 2340 m^3/s u_{max} = q_{max} =	0 - 1 ~ 60 m 1 - 2 ~ 105 m	(1) Aeration is achieved by the cavities formed by pier ends offset with deflector and chicanes at the chute sides. Aeration at (2) is accomplished with a special system figured in the aerator sketch. The second aerator serves as protection for the joint between chute and power-house which might develop to an offset as a consequence of settlement of the power-house.	[31] [34] [33] [45]

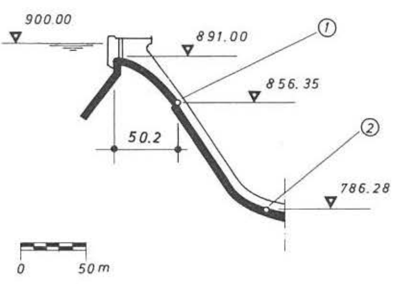
Longitudinal Section	Air Slot Design

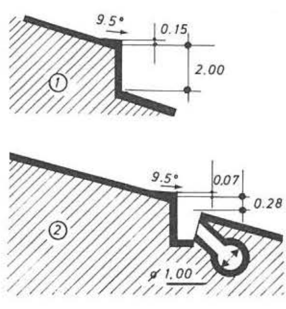
TARBELA



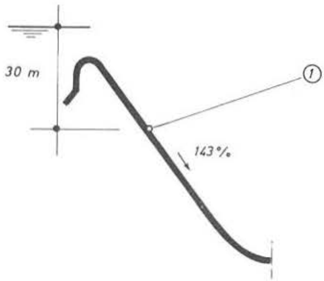
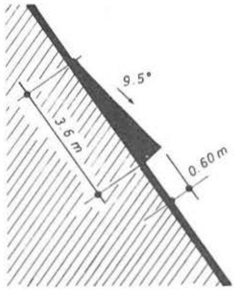


TOKTOGUL





Object	Hydraulic Data	Interdistance between aerators	Remarks	Ref.
UST-ILIM 1977 USSR	H = 88 m J = 143 % Q_{max}= 9700 m^3/s u_{max}= q_{max}=	0 ÷ 1 =	Aeration by a system of four air ducts, two at each side. Area of the inlet section is 20 m^2, of the outlet section 9 m^2. The system is integrated in side and splitterwall.	[17] [39] [34]
YELLOWTAIL 1966 USA	H = 152.80 m J_{max}= 143 % D = 9.75 m Q_{max}= 2600 m^3/s u_{max}= 49 m/s	0 ÷ 1	The groove of 0.9 x 0.9 m cross sectional area guarantees a satisfactory aeration of the flow. The aeration device was installed after cavitation damage had occurred. It works absolutely satisfactorily and no further cavitation has been observed.	[42] [16] [45]

Longitudinal Section	Air Slot Design
UST-ILIM 	
YELLOWTAIL	

Object	Hydraulic Data	Interdistance between aerators	Remarks	Ref.
EMBORCACAO 1982 Brazil	H = 79.85 m J_{max}= 29.8 % B = Q_{max}= 7800 m^3/s u_{max}= 35 m/s q_{max}=	0 ÷ 1 1 ÷ 2 = 103 m		[37]
GRAND COULEE 1942 USA (Bottom Outlet)	H = 61 ÷ 76 m D = 2.59 m Q_{max}= u_{max}∿ 30 m/s q_{max}=		Without special aeration system. The aeration was provided after cavitation damage hab been noticed. The structure now works satisfactorily.	[31] [42] [36] [65]
HEART BUTTE 1949 USA	H = D = 4.27 m Q_{max}= 160 m^3/s u_{max}= 35 m/s	0 ÷ 1 = 9.6 m	Special air supply system is provided. No cavitation damage was detected after several flood events.	[27]
LIBBY DAM uc USA (Bottom Outlet)	H = D = 6.70 m Q_{max}= u_{max}=		Aeration through groove at bottom and side wall. Prototype measurements were undertaken.	[4]
YACAMBU 1982 Venezuela	Q = 480 m^3/s			[39]

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