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14. ABSTRACT
This report is the result of a request made at the NRCS workshop on RCC stepped spillways in Austin, TX in December 2002. The report summarizes research already accomplished on stepped spillways and recommends additional research needed to determine parameters that can be used by practicing engineers to design stepped spillways. The report discusses the hydraulics of nappe flow and the regions of rapidly varying, gradually varying, and uniform flow over stepped spillways of various slopes. The skimming flow regime is primarily discussed with regard to research that has been performed regarding air entrainment and flow resistance under uniform fully aerated flow conditions. The outcome of various studies have been included. Continued research efforts to determine final design parameters are recommended.

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Peer review was performed by Clifford A. Pugh, Manager, US Bureau of Reclamation, Water Resources Research Laboratory, Technical Services Center, Denver, CO, Fares Abdo, Program Manager, Portland Cement Association, Birmingham, AL, and Tom Brown, Civil Engineer, USDA, Natural Resources Conservation Service, Fort Worth, TX.

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GLOSSARY OF SYMBOLS

α = kinetic energy correction factor

C = Local air concentration defined as the volume of air per unit volume of air and water

C_b = Local air concentration near the pseudo-bottom of a stepped spillway

C_{mean} = Mean depth-averaged air concentration

C_{meani} = Mean depth-averaged air concentration at the point of inception

D' = Dimensionless turbulent diffusivity

D_h = Hydraulic diameter based upon clear water depth (ft)

D_o = Dimensionless diffusivity term

d_c = Critical depth (ft)

d_i = Depth at inception point (ft)

d_w = Depth of clear water normal to the slope (ft)

E = Energy head (ft)

ΔE = Change in energy head

ε = Diffusivity of the average density

F_r = Roughness Froude number, $F_r = q_w \big/ \sqrt{g(\sin\theta)k^3}$

f = Darcy-Weisbach friction factor for non-aerated flow

f_b = Darcy-Weisbach friction factor at the pseudo-bottom

f_e = Darcy-Weisbach friction factor for air-water flow

g = Gravity (ft/s^2)

H_{dam} = Height of dam (ft)

H_{max} = Maximum energy head (ft) = H_{dam}+1.5d_c

H_o = Total head over the crest (ft)

H_{res} = Residual energy head (ft)

k = Step roughness height = s cosθ (ft)

l = Step tread or horizontal run (ft)

L = Slope length in streamwise direction from crest (ft)

L_i = Length along slope to inception point (ft)

$L_{i,crit}$ = Non-dimensional distance from the crest to the point where C_b=0.05

L_r = Scale factor

Glossary of Symbols (continued)

L_u = Length along the slope parallel to the pseudo-bottom from the spillway crest (ft)

n = Manning's roughness

N = Number of steps

θ = Dam or spillway slope (degrees)

ρ = Density (slugs/ft^3)

ρ_w = Density of water

Q = Total discharge (ft^3/s)

q = Design unit discharge (ft^3/s/ft)

q_w = Unit discharge of clear water (ft^3/s/ft)

R = Reynolds number

s' = Non-dimensional length to inception point $s' = (L-L_i)/d_i$

s = Step height (ft)

S_f = Friction slope on the spillway (ft)

SE = Specific Energy (ft)

u_f = fall velocity of water droplets (ft/s)

U_w = Clear water velocity (ft/s)

w = Spillway width (ft)

y = Depth normal to the slope (ft)

Y_{90} = Depth where the mean air concentration is 90 percent (ft)

ζ = Bulking factor

Executive Summary

A summary of previous studies on stepped spillways has been included in this report. The field of stepped spillways has drawn an incredible amount of interest and the publications are prolific. Stepped spillways have been studied for site specific applications and in general research facilities. The following points summarize the conclusions of the literature review.

- The important hydraulic features of stepped spillways are air inception location and flow depth, and initial air concentration, average air concentration, aerated and clear water flow depth, step height and spillway slope, flow resistance, and residual energy at the toe of the slope after the flow passing over the steps.
- Stepped spillway nappe and skimming flow conditions are discussed with the onset of skimming flow defined. Skimming flow is of particular interest for stepped spillways. The importance of this flow regime is driven by the cost effectiveness of narrow spillways, which produces greater unit flows.
- Definitions have been provided for the flow over the spillway crests, the inception of aeration in the rapidly varied flow region, the gradually varied flow region, and the uniform flow region.
- Crest dimensions and profiles are shown for embankment and steep concrete dams. Step height is driven, in reality, by cost and ease of construction. Hydraulically, step height is optimized at about one-third of the critical flow depth.
- Discussions about the location and depth of flow at the point of air inception are included. Free surface aeration begins sooner on a stepped spillway than on a smooth spillway due to the greater flow turbulence. The average air concentration at the point of inception is given. Discussions on aeration characteristics result in important conclusions. The equilibrium mean air concentration in skimming flow over stepped spillways is a unique function of the spillway slope (Ruff and Frizell, 1994; Gaston, 1995; Matos and Quintela, 1995c; Boes and Hager, 2003b).
- The air concentration profiles over stepped chutes show the same characteristic shape as for smooth chutes and may be estimated by a theoretical model described in this report (Chanson, 1994b; Matos and Quintela, 1995a; Matos and Frizell, 1997; Renna, et al., 2005).
- The characteristic flow depth where the air concentration is equal to 90 percent may be used with a safety factor to determine spillway wall heights (Ward, 2002). Methodology to determine the flow depth at 90 percent air concentration is described (Boes and Minor, 2000).

- Results from studies may be used to determine whether a spillway will operate under uniform or quasi-uniform flow conditions. This is a critically important aspect influencing computation of the friction loss and energy remaining in the flow at the toe of the spillway.
- Important findings regarding the definition and values of friction factors over stepped spillways are provided. Friction factors may be developed for uniform flow conditions on stepped spillways. The friction factor is a function of the uniform clear water depth – not the aerated or mixture flow depth.
- The friction factor in air-water flow decreases with increasing mean air concentration for constant relative step height.
- The residual energy at the toe of a stepped spillway chute may be computed with confidence for spillways where uniform flow has been attained. Where rapidly or gradually varied flow regions still exist on the spillway slope only estimates may be provided for the energy remaining in the flow (Chanson, 2001a; Ward, 2002; Matos, 2005).
- Manipulation of turbulence on stepped spillway slopes has been investigated by Gonzales & Chanson (2005) and Andre' (2004) with success. The benefit to cost of installing end sills or other blocks on the steps of a real structure is yet to be evaluated.
- Studies performed on converging walls on stepped spillways are discussed. Initial results indicate that the additional turbulence created by the steps produces less significant cross waves, but run up on the walls still occurs. Energy dissipation seems to be similar to a straight chute for the studies performed to date.
- Studies are presented that show how stepped spillways might be beneficial for promoting gas transfer in river environments that are environmentally sensitive. Stepped spillways may help in stripping excess gas or adding dissolved oxygen where needed.

Suggestions for further research regarding the hydraulics of stepped spillways for embankment and steep gravity dam slopes are proposed as follows:

- Perform comparison of the proposed formulas to determine if there is adequate information for design of stepped spillways in the uniform skimming flow region.
- Investigate residual energy in non-uniform or not fully developed flow regimes
    - Gather data from existing models of adequate size and determine if it is possible to determine residual energy at various locations downs the slope in the non-uniform flow region*.
        - If not, then use an adequately scaled flume facility to gather data on a flatter slope to determine

residual energy at various locations downs the slope in the non-uniform flow region..

- Determine the unit discharge for a given dam height where the stepped spillway energy remaining equals that of a smooth spillway.
- Chute wall convergence affects on flow depths and residual energy at the toe of the spillway
    - Use a scale model of an embankment slope of adequate size to modify the wall convergence angles and measure flow depths, velocities and air concentrations to determine residual energy.
        - Initial research shows that the step roughness attenuates formation of cross waves, and reduces run up on the converging walls compared to smooth spillways. In addition, it seems that the energy dissipation is similar to that of a non converging stepped chute, but the effects of increasing unit discharge with convergence at the toe still needs to be investigated.

*Information provided by Boes, Chanson, and Matos goes a long way towards achieving this goal. The residual energy is explained by André as a function of a dissipation coefficient. This approach includes both form drag and friction loss and may be the logical way to proceed in further research. This is because the designer is not really interested in what causes the energy loss, but what the actual loss is.

In addition, for hydraulics of steep stepped spillways the following research is suggested:

- Cavitation potential upstream from the point of aeration inception
    - This is an issue for high dams more than for embankment dams.
- Determine the crest to slope transitions necessary with a gated stepped spillway crest
    - This is not a high priority and could potentially be accomplished analytically or by adding gates to an existing flume study.

Other structural and environmental aspects of RCC steps are discussed in the body of the report.

Introduction

Roller compacted concrete (RCC) is a widely used process for providing overtopping protection and additional spillway capacity on dams. The popularity of roller compacted concrete placement on new and rehabilitated dams has prompted intense interest in researching the flow characteristics and design considerations associated with flow over the steps typically resulting from RCC use.

Stepped spillways have been used for over a century without much knowledge of the hydraulics (Chanson, 1995a). The key feature associated with stepped spillways is the amount of energy dissipated by flow over the steps producing cost savings in the size of the energy dissipater. This simple fact has led to research to determine the hydraulics of the flow conditions over stepped spillways and to provide standardized hydraulic design criteria.

Reclamation's interest in stepped spillways began with the investigation, design, and construction of Upper Stillwater Dam for the Strawberry Irrigation District in NE Utah (Houston, 1987). Upper Stillwater Dam was constructed of RCC with conventional concrete upstream facings and downstream steps that were slip-formed. The dam is 202-ft-high with a 0.32H: 1V upper downstream slope meeting a 0.6:1 lower portion leading into a stilling basin with a horizontal apron and an end sill. The spillway portion of the dam is 600-ft-long therefore benefiting greatly from the reduced energy in the flow after passing over the stepped face before entering the basin.

Reclamation also began investigation into a stepped block protection to be used as an overlay for embankment dams. This interest was prompted by the discovery of hundreds of embankment dams with inadequate spillway capacity. This led to formation of cooperative arrangements with Colorado State University (CSU) and Electric Power Research Institute (EPRI) to perform extensive laboratory and prototype size studies of a hydraulically stable overlapping concrete block to protect embankments during passage of flood flows over the dam (Frizell et al., 1994).

The Natural Resource Conservation Service (NRCS) and Portland Cement Association (PCA) have a mutual interest in developing a general design tool for stepped spillways. The NRCS has particular interest in determining design criteria for the flatter slopes more typical of the embankment dams at most of their sites. This document is intended to provide a summary of current world-wide research efforts and identify additional research needs for development of a generalized design tool for stepped spillways with emphasis on embankment dam slopes.

Applications

Stepped spillways have application for new RCC gravity dams with very steep downstream slopes and as overlays on embankment dams (Hanson and Bass, 1991).

Steep RCC gravity dams have been tested and constructed with slopes up to 0.32:1 changing to 0.6:1 (Houston, 1987). Most steep RCC gravity dams; however, have a downstream slope in the range of 0.5:1 to 0.8:1 (Dunstan, 1999). Steep RCC dams are also most likely to be higher dams with the opportunity for the flow to become fully developed and uniform in nature, although this is not always the case.

Stepped spillway applications for embankment dams generally have downstream slopes on the order of 4:1 to 2:1 (Matos el at., 2001a). Embankment dam applications tend to be of less height than steep gravity dam applications and issues of non-uniform flow conditions arise when designing the energy dissipation device. Rehabilitation of embankment dams of relatively low height seems to have come to the forefront in concern, certainly in some parts of the country and with some agencies.

Objective

The purpose of this document is to provide a comprehensive review of citations in the literature regarding stepped spillway research. This would include hydraulic model studies and prototype studies regarding all aspects of stepped spillway design. Design information or model studies particularly relating to embankment dam slopes of interest to Natural Resources Conservation Service (NRCS) will be highlighted in each section. In addition, ideas for future research are also discussed.

Evaluation of Current Research Efforts

The purpose of this section is to provide a comprehensive review of citations in the literature regarding the various elements associated with defining the hydraulics of stepped spillways. The aspects evaluated are:

- Stepped spillway flow conditions
- Scale effects and hydraulic model studies
- Crest shape and step height
- Aeration characteristics

- Uniform flow determination
- Flow resistance and residual energy
- Manipulation of turbulence
- Wall convergence
- Gas transfer on stepped spillways
- Summary of important hydraulic model studies

Stepped Spillway Flow Conditions

Flow conditions over stepped spillways are characterized by highly-aerated nappe or skimming flow regimes and the transition between the two flow regimes. Nappe and skimming flow occur on spillways of any slope. Nappe flow occurs up to a certain flow rate at which point the flow transitions to skimming flow. Both flow conditions are characterized by highly-aerated flows after the turbulent boundary layer reaches the flow surface. This section will provide definitions of aerated flow and discuss the characteristics of nappe and skimming flow.

Definitions

The local air concentration C is defined as the time averaged value of the volume of air per unit volume.

$$d_w = \int_0^{Y_{90}} (1 - C)\, dy \qquad (1)$$

The equivalent clear water, non-aerated, depth, d_w, is defined where the depth, y, is measured perpendicular to the spillway surface and Y_{90} is the depth where the local air concentration is 90 percent. A depth averaged mean air concentration for the flowing fluid can then be defined from

$$d_w = (1 - C_{mean})\, Y_{90} \qquad (2)$$

The average water velocity U_w is defined as

$$U_w = \frac{q_w}{d_w} \qquad (3)$$

Characteristics of Nappe Flow

In nappe or jet flow, the steps act as a series of overfalls with the water plunging from one step to another as shown on figures 1 and 2. Generally, nappe flow is found for low discharges and relatively large step heights.

Many early studies focused on nappe or jet flow conditions (Essery and Horner, 1978; Peyras, et al., 1992; Chanson, 1994a). Nappe flow regions have also been described as isolated nappe flow with or without formation of a hydraulic jump on the step and partial supercritical nappe flow where the jet does not fully impinge on the steps.

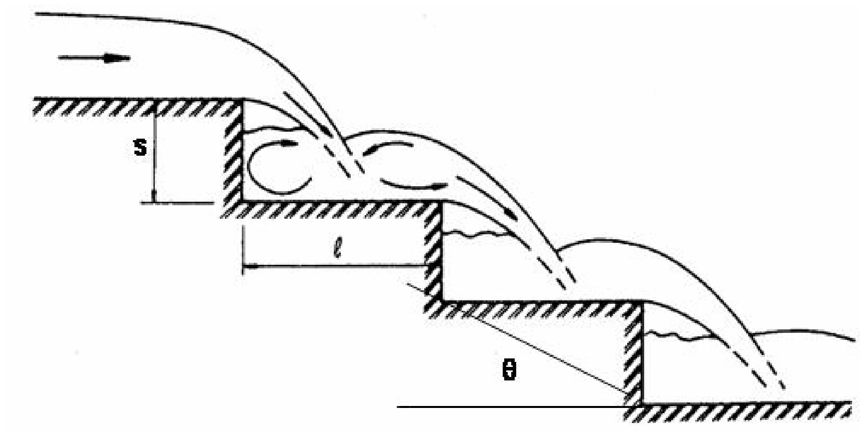

Figure 1. - Schematic of nappe flow over steps showing the flow impingement on the step tread and air pocket in the step offset.

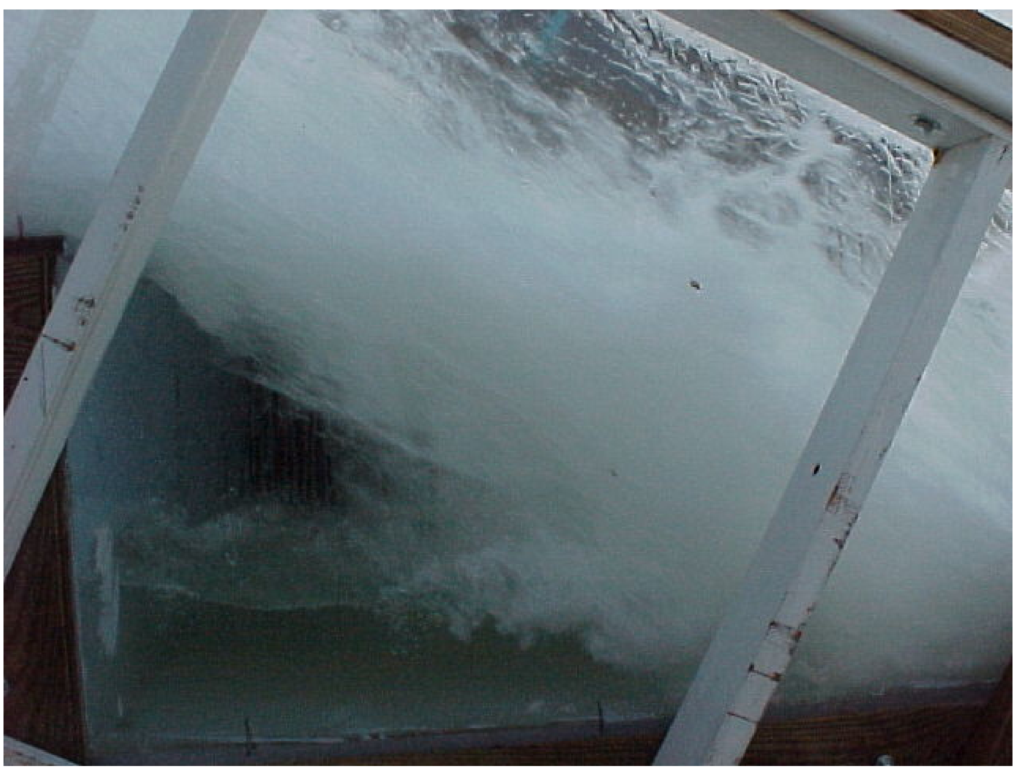

Figure 2. - Flow over a prototype 2-ft-high step showing nappe flow for q= 15 $ft^3/s/ft$.

Several recent studies on nappe flow have been performed on flatter embankment-type slopes, namely Pinheiro & Fael (2000); Fratino, et al (2000); Peruginelli & Pagliara (2000); Andre (2004). Pinhiero and Fael (2000) recommend the equation from Chanson (1994a) for slopes from 11.3°<θ<30° which corresponds to isolated nappe flow with a fully developed hydraulic jump in the steps:

$$\frac{d_c}{s} \leq 0.0916\left(\frac{s}{l}\right)^{-1.276} \tag{4}$$

Pinhiero and Fael (2000) also summarized and compared the energy dissipation characteristics of nappe flow and concluded that the equation presented by Chamani and Rajaratnam (1994) provided the best agreement among the equations presented.

$$\frac{\Delta E}{E} = \frac{\left\{(1-A)^N\left[1+1.5\left(\frac{d_c}{s}\right)\right]+\sum_{i=1}^{N-1}(1-A)^i\right\}}{N+1.5\left(\frac{d_c}{s}\right)} \tag{5}$$

where

$$A = \left[0.30-0.35\left(\frac{s}{l}\right)\right]-\left[0.54-0.27\left(\frac{s}{l}\right)\right]\log\left(\frac{d_c}{s}\right)$$

In the nappe flow regime, the total energy loss is greater for fewer steps for the same spillway height and discharge. The total energy loss in nappe flow decreases as the number of steps increases for the same slope, dam height and discharge (Chanson, 1994a; Matos and Quintela, 1995b; Peruginelli and Pagliara, 2000). Therefore, for low dams with large steps in the non-uniform flow region, nappe flow produces more energy loss than skimming flow (André, 2004). As the dam height increases and the number of steps increases, the flow approaches uniform flow and skimming flow is usually attained and dissipates more energy than nappe flow for the same dam height and discharge.

Generally, designing a spillway specifically for nappe flow would require larger steps and flatter slopes. The construction cost would most likely be too high and the spillway would be designed for the skimming flow regime. Designers are also specifying larger unit discharges to make narrower, more cost effective spillways. Nappe flow characteristics are then only significant because nappe flow will occur under low flow rates that would occur frequently at a project, and could lead to excessive splashing. Some investigators have studied various mechanisms attached to the steps or adverse slopes on the steps to force a hydraulic jump on the steps and increase energy dissipation (Essery and Horner, 1978; Peruginelli and Pagliara, 2000; André, 2004). These efforts have yet to be determined to be practical from a construction standpoint.

Onset of Skimming Flow

Flow will transition from nappe or jet flow to skimming flow as the discharge increases. The ability to predict the unit flow rate where nappe flow will transition to skimming flow is necessary if the designer is concerned with low flow operation and then skimming flow operation of the structure. A good summary of the proposed equations relating the onset of skimming flow, in terms of a ratio of critical depth to step height as a function of spillway slope, is presented by Pinhiero and Fael (2000) where equations are presented by several authors and compared to their work on flatter slopes.

Rajaratnam & Chamani (1994) stated that nappe or jet flow would occur up to $d_c/s = 0.8$ with work performed on steep sloped spillways. This relationship is obviously not dependant upon anything but the step height and the discharge. Rajaratnam & Chamani (1995) later defined a transition zone from nappe to skimming flow as occurring at:

$$\frac{s}{l} = 0.405\left(\frac{s}{l}\right)^{-0.62} \tag{6}$$

Chanson (1994a) proposed the following equation for the onset of skimming flow for dam slopes from 11.3°<θ<38.7°:

$$\frac{d_c}{s} > 1.057 - 0.465\frac{s}{l} \tag{7}$$

Boes and Hager (2003b) proposed a similar equation for a range of slopes from 25°<θ<55° or embankment and steep slopes:

$$\frac{d_c}{s} = 0.91 - 0.14(s/l) \tag{8}$$

The proposal by Rajaratnam and Chamani (1995) and Boes and Hager (2003b) produce very similar results with no change in the onset of skimming flow with spillway slope. The equation by Chanson (1994), is over a greater range of slopes, and shows that the onset of skimming flow occurs for higher values of d_c/s when the spillway slope decreases, as would be expected.

Characteristics of Skimming Flow

Most recently, research has concentrated on the skimming flow region where the water flows down the stepped face as a coherent stream skimming over the steps and cushioned by the recirculating fluid trapped between them. Extensive studies on the skimming flow regime have been carried out on stepped spillways of both embankment and gravity dam slopes. Primarily, the emphasis has been on determining the effects of the highly-aerated flow over the steps on the flow resistance, and determining the energy remaining at the toe of a long run of steps in quasi-uniform flow.

With this in mind, figure 3 shows the distinct regions of skimming flow over stepped spillways, are the same as flow regions over smooth invert spillways (Wood, 1983, 1991; Chanson and Toombes, 2001b). The regions of skimming flow down stepped spillways are; (1) the non-aerated flow region close to the crest, (2) the rapidly varying flow region with partially aerated flow, (3) the gradually varied fully-aerated flow region, and lastly, (4) the region of uniform flow where the flow depth, velocity, and air concentration are in a state of equilibrium. A schematic showing the parameters defining the step geometry and a photograph from a prototype test facility are shown on figures 4 and 5. All investigators refer to the pseudo-bottom, which is defined in figure 4, as a hypothetical line drawn parallel to the slope between the tips of the steps. A roughness Froude number is also defined as:

$$F_r = q_w / \sqrt{g \sin\theta k^3} \tag{9}$$

and is a function of the unit discharge, step roughness height normal to the slope, $k = s\cos\theta$, and slope. A roughness Froude number, F_*, has been described by Boes and Hager (2003a) using the vertical step height, s, instead of k, the roughness height normal to the slope. In this document, all equations have been converted to a common roughness Froude number, F_r, with $F_*=F_r(\cos\theta)^{3/2}$.

The importance of aeration cannot be overlooked when investigating skimming flow over steps. Aeration has an affect on all important parameters required for design of skimming flow over stepped spillways including flow depth, velocity, pressures, cavitation potential, flow resistance, and residual energy.

Matos (2000a) clearly describes the flow conditions down a stepped chute as the boundary layer grows until free surface aeration begins and how the flow depths vary as the flow becomes fully aerated. Matos (1999) describes the flow regions with comparisons of visual observations to depths, velocities, and air concentrations measured in an experimental facility. There is a short section of rapidly varying flow where the curvature of the water surface aids in air entrainment, leading to gradually varied flow characterized by air water mixture with increasing air concentration, and, finally, uniformly aerated flow conditions where the velocity and air concentration are stable and no longer increasing.

The boundary layer grows from the spillway floor in the non-aerated flow region close to the spillway crest. The water surface becomes contorted upstream from the inception of air entrainment transporting air between the irregular waves in the contorted surface. At the inception point, where the boundary layer reaches the free-surface, entrainment of air by the multitude of vortices in the turbulent flow commences.

As with air entrainment on smooth-invert spillways downstream of the inception point, the layer containing the mixture of both air and water extends very rapidly through the flowing fluid, and the mean air concentration, C_{mean}, increases significantly, attaining a local maximum quickly. Immediately downstream from the inception point, the mean air concentration attains a local minimum corresponding to the region where the flow curvature promotes the release of entrained air bubbles. In this region of the chute, the flow is defined as rapidly varied and should occur within the streamwise non-dimensionalized distance, s' <30 from the crest, independent from the relative critical depth, d_c/s.

The downstream gradually varied flow region is then defined as the region where the mean air concentration follows a wavy pattern, the amplitude of which decreases significantly down the chute. Undulating profiles of the median position of the surface were obtained by Pegram et al. (1999), by using a contact probe to map the time distribution of the connected surface of the flow. A trend of increasing C_{mean} down the chute is noticeable in the gradually varied flow region.

In the fully aerated uniform flow region, the important feature is the evaluation of the clear water depth. Both the aerated depth measured through the flume sidewalls and the characteristic depth Y_{90} show a wavy pattern of decreasing amplitude along the chute; however, this is not observed in the equivalent clear water depth. The equivalent clear water depth is much less than Y_{90} due to both the entrained and entrapped air in the depth where the air concentration is equal to $Y_{90.}$ This confirms that the friction factor and energy dissipation will be significantly overestimated if the aerated flow depth is used in the computation (Matos and Quintela (1995a,b). In the uniform flow region, near the downstream end of the chute, both Y_{90} and the observed aerated depth become practically constant. Experimental evidence has shown that the equilibrium mean air concentration in skimming flows is similar to the mean air concentration in uniform aerated flow on smooth-invert chutes of identical slope (e.g., Ruff and Frizell, 1994, Gaston 1995, Matos, 2000a, Boes and Hager, 2003a).

Energy dissipation on stepped spillways with skimming flow will be discussed in much more detail in a following section.

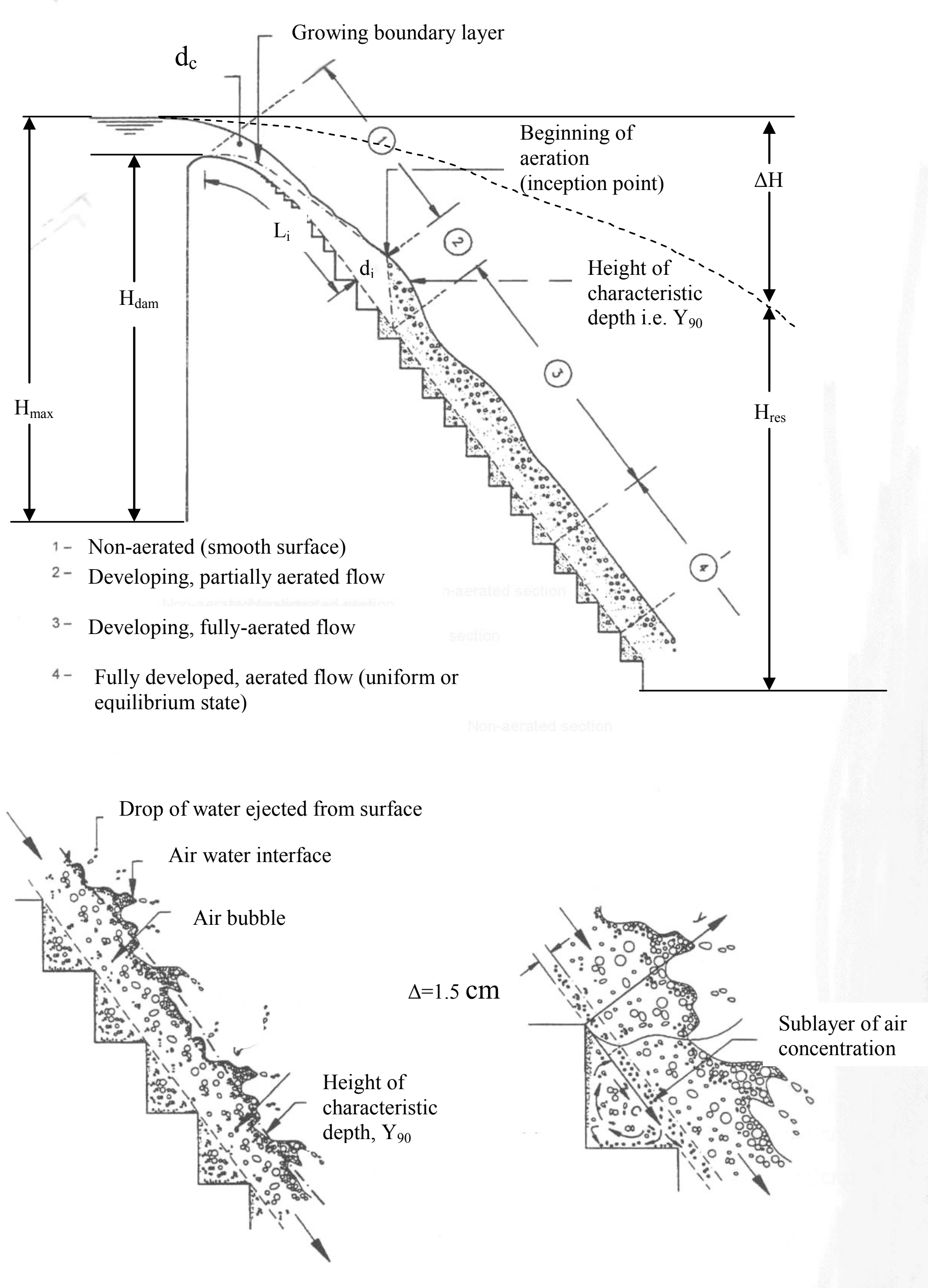

Figure 3. - Definition of flow regimes for stepped spillways per Matos, 1999.

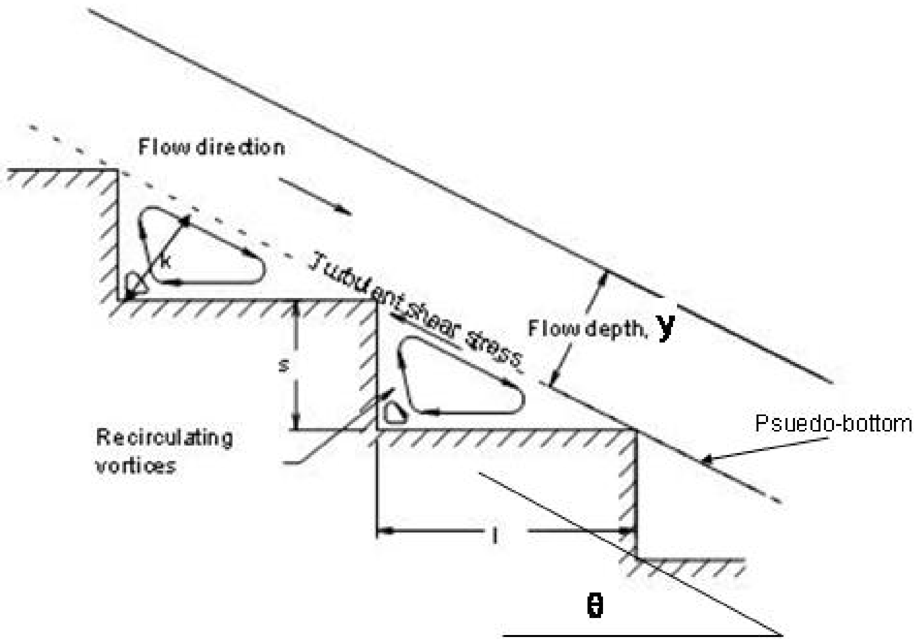

Figure 4. - Schematic of the skimming flow regime over steps.

Figure 5. - Skimming flow over 1-ft-high steps at the CSU flume for a 15 $ft^3/s/ft$ unit discharge at step 40 down from the crest near the bottom of the flume.

Scale Effects and Hydraulic Model Studies

At what scale will a model replicate geometric, viscous, gravitational, and two-phase flow concerns without significant scale effects?

Most physical hydraulic models are based upon Froude similitude which provides for replication of gravitational forces. Where gravitational forces predominate Froude similitude is used to equate the inertial and gravity forces. Unfortunately, viscous forces cannot be ignored when modeling highly turbulent air-water flow and must be considered when determining the scale of a Froude model for stepped spillways. To investigate scale effects on stepped spillways, several investigators have constructed flumes of various slopes with varied step heights, and compared results. A summary of these studies was presented by Boes (2000a), Boes and Hager (2003a), Gonzales and Chanson (2004, 2005a), and Takahashi et al., (2005).

Scale Effects

The key feature when scaling and modeling stepped spillways is the relationship between the step heights and flow rates in the model and the prototype. These physical parameters usually drive the model scale chosen by the experimenter when considering Froude scaling. The prototype step size is usually driven by the construction technique used in roller-compacted concrete placement and is typically 1 or 2 ft vertically. Most experiments have been conducted assuming a step height, s, of 2 ft prototype and scaled the models based upon that height. Therefore, the Froude scale must be chosen to geometrically scale a 2-ft-high prototype step with consideration of the Weber and Reynolds numbers. Chanson et al. (2002a), Gonzales and Chanson (2004a), and Chanson and Gonzales (2005) state that Froude similitude may be used if flow conditions satisfy $s > 0.0656$ ft and $R > 10^5$. For stepped spillways Boes and Hager (2003a) and Gonzales and Chanson (2004) found that the Weber number should be at least 100.

Mateos (2001) found that model scales of 1/6- 1/25 provided similar results when investigating the point of aeration inception. Bindo, et al, (1993) conducted Froude scale modeling of stepped spillways with scales of 10, 21.3, 25 and 4.7:1 for M'Bali Dam spillway. Gonazales and Chanson (2004) determined that flow resistance was improperly reproduced for the 25 and 42.7 scale models.

Gonzales and Chanson (2004), Boes (2003) and Matos (2001) found that velocity, depth, mean air concentration, and flow resistance were properly scaled with Froude scaling when scales were large enough. Boes concluded that Froude models of stepped spillways should have a length scale less than 10:1 to 15:1. (Boes, 2000a; Boes and Hager, 2003). Gonzales and Chanson (2004) and Chanson and Gonzales (2005) conclude that adequate scaling of air entrainment does not occur unless the Froude scale is less than 10.

Investigation of Reynolds number effects on stepped spillway models has also been conducted. An investigation of the effect of Reynolds number on skimming flows in stepped channels by Takahashi, et al. (2005) found that scale effects were negligible if R > 4 x 10^4; however, most other investigators conclude that the Reynolds number should be at least 10^5 to satisfy viscous effects (Wood, 1991).

Gonzales and Chanson (2004) found significant scale effects when investigating turbulence intensity, bubble size and distributions – even with a Froude scaling of 2. This is also discussed by Wood (1991) with regard to bubble size and scaling, but does not mean that prototype investigations must be used for determining mass quantities of air in the flow.

For purposes of defining the quantity of air in the flow and energy dissipation, Froude scaling that meets Reynolds and Weber number criteria is adequate.

Hydraulic Model Studies

Table 1 is a compilation of many studies that have been performed in laboratory, near-prototype, and prototype installations of stepped spillways. These studies have covered the full range of steep to flat slopes and from high to low structures with non uniform non aerated flow conditions and uniform fully aerated flow conditions. Model scales were determined, when the author did not indicate scale, based upon the given step height as a ratio to 2 ft prototype step size.

Many studies, particularly the earliest ones used technologies available at the time, i.e. high-speed video or back calculating the flow depth entering the hydraulic jump, to determine critical components of flow velocity and depth, with no measurement of aeration characteristics. This means that in many of the studies, data must be reanalyzed and reworked, which may lead to inappropriate results. Even the newer studies use a variety of instruments to record the effects of aeration on the flow velocity and depth. These instruments include single and double-tip conductivity probes, double-tip optical probes, and back-flushing pitot tubes for velocity; and flow observations, probability probes, and point gages for depth (Chanson, 2002b).

The variability of the large number of studies results in questions about applicability. Therefore, confirmation of results was sought in drawing conclusions.

Table 1. - Summary of hydraulic modeling efforts related to stepped spillways.

Reference	Slope θ (degrees) H:V	Geometric Scale	Dam Height (ft)	Number of steps	Step Height (ft)	Facility Width (ft)	Discharge Q, (ft^3/s)	Unit Discharge q, (ft^2/s)	Type of flow	Observations
Essery and Horner (1978)	11.3 & 45.0 5.7:1 & 1:1	-	1.97 to 11.78	8 to 30	0.095 to 1.47	-	-	0.0215 to 1.31	Nappe & Skimming	
Stephenson (1979)	18.4 & 45.0 3:1 & 1:1	-	-	1 to 4	.49	-	-	-	Nappe & Skimming	Gabion steps
Frizell (1990a)	53.13 0.75:1	1/12	15	90	0.167	1.5	0.9 to 5.56	0.6 to 3.71	Skimming	Milltown Hill Dam
Peyras, Royet and Degoutte (1991, 1992)	18.4 & 45 3:1 & 1:1	1/5	1.97 to 3.28	3;4;5	0.656	2.62	1.7 to 7	0.65 to1	Nappe & Skimming	Gabion steps
Kells (1995)	26.6 & 45.0 2:1 & 1:1	1/8	-	3	-	-	-	-	Nappe & skimming	
Ohtsu & Yasuda (1995 a, b)	30.0 & 55.0 1.73:1 & 0.7:1	-	-	8 to 64 30°; 13 to 20 (55°)	-	-	-	-	Nappe & Skimming	Laboratory flume studies
Ohtsu & Yasuda (1997a, b)	19 & 55 2.9:1 & 0.7:1	-	-	11 to 64	-	-	-	-	Nappe & Skimming	Laboratory flume studies
Chanson & Toombes (1997)	4.0 14.3:1	-	5.70	12	0.55	1.64	0.67 to 2.88	0.41 to 1.76	Nappe	
Sorensen (1985)	52.0 0.78:1	1/10; 1/25	2.26(1/10); 4.79 (1/25)	15 (1/10); 59 (1/25)	0.200	.98	0.052 to 2.49 (1/10); 0.063 to 1.16 (1/25)	0.05 to 2.54 (1/10); 0.06 to 1.18 (1/25)	Nappe & Skimming	Monksville Dam
Hollingworth & Druuts (1986)	59.0 0.6:1	1/20, 1/75	.78 (1/75)	-	0.16 (1/20); 0.042 (1/75)	-	-	0.45 to 1.17 (1/20); 0.06 to 0.16 (1/25)	Nappe & Skimming	De Mist Kraal Dam

Reference	Slope θ (degrees) H:V	Geometric Scale	Dam Height (ft)	Number of steps	Step Height (ft)	Facility Width (ft)	Discharge Q, (ft^3/s)	Unit Discharge q, (ft^2/s)	Type of flow	Observations
Stephenson (1991)	54.5 0.7:1	-	-	-	-	-	-	-	?	Vale Kennedy Dam
Diez-Cascon et al. (1991)	51.3 0.8:1	1/10	3.80	-	0.099; 0.197	2.62	0.64;7.91	0.24;3.02	Skimming	
Bayat (1991)	51.3 0.8:1	1/25	-	-	0.079; .57;0.098	0.98	-	0.06 to 0.75	Skimming	
Beitz & Lawless (1992)	48.0 & 51.3 0.8:1	1/60	-	10	.0.07	-	-	0.007 to 1.0	Nappe & Skimming	
Pegram (1999)	59 0.6:1	1/10 & 1/20	9.84	120;240	4 hts 0.082 to 0.66 (1/10)	2	2.6 (1/10); 5.2 (1/20)	1.3 (1/10); 2.6 (1/20)	All	Laboratory flume studies
Christodoulou (1993)	55 0.7:1	24.39	1.18	15	0.082	1.64	0.35 to 1.59	0.215 to 0.97		Laboratory flume studies
Chamani (1994, 1999)	59 & 51.3 0.6:1 & 0.8:1	1/4.87, 1/10, 1/20	8.2		0.41, 0.2, 0.1	1	0.74 to 2..2	0.74 to 2..2		Laboratory flume studies
Mateos & Elviro (1997a)	Adjustable	-	22.9	-	0.19; 0.26; 0.49	-	≥ 14.13	?	Skimming	Laboratory flume studies
Mateos & Elviro (1997b)	51.3 to 71.6 0.8:1 & 0.33:1	1/6 to 1/25	-	-	2.95 to 3.94	-	-	?	Skimming	
Matos & Frizell (1997)	53.1 0.75:1	1/7.5 to 1/11	9.5	44	0.26	3.28	1.77 to 7.06	.54 to 2.15	Skimming	Laboratory flume studies
Tozzi *et al.* (1998)	52.2 0.77:1 8.5 6.7:1	- -	- -	>50 ≥20	2.62 -	- -	- -	- -	 Skimming	Laboratory flume studies

Reference	Slope θ (degrees) H:V	Geometric Scale	Dam Height (ft)	Number of steps	Step Height (ft)	Facility Width (ft)	Discharge Q, (ft^3/s)	Unit Discharge q, (ft^2/s)	Type of flow	Observations
Yildiz & Kas (1998)	30;51.3;60 1.73:1;0.8:1;0.58:1	- - -	- - -	- - -	0.08; 0.25	1.64	0.71 to 4.24	0.43 to 2.58	Skimming	
Boes & Hager (1998)	30 1.73:1	-	9.35	-	0.07 to 0.30	1.64	≥ 6.36	3.88	Skimming	
Boes (1998)	30;40;50 1.73:1;1.19:1,0.84:1	-	-	-	0.07 to 0.30	-	-	-	Skimming	
Noori (1984)	5.7 10:1 11.3 5:1	- -	- -	100 70	0.013 0.042	1.64 1.64	0.12 to 1.59 0.44 to 3.53	0.073 to 0.97 0.27 to 2.15	Skimming	
Bramley, May & Baker (1998) & Baker (1992)	33.7 1.5:1	-	13.12	22 under study	0.82	1.97	≥10.59	5.38	Skimming	
Baker (1990 [3] 1991, 1992)	21.8 2.5:1	-	13.12	>50	0.03 to 0.19	1.97	0.53 to 10.59	0.27 to 5.38	Skimming	
Frizell & Mefford (1991)	26.6 2:1	-	-	-	-	1.51	-	?	Skimming	
Frizell (1992)	26.6 2:1	-	-	-	0.16	15	6 to 17.6	0.4 to 1.17	Skimming	
Frizell, Smith & Ruff (1994)	26.6 2:1	-	15.24	-	0.21	4.99	3.23 to 159.84	0.65 to 32.03	Skimming	
Young (1982) Houston (1987)	72.3 initially & 59.0 at bottom 0.32:1 initially & 0.6:1 at bottom	1/5, 1/10, 1/15	2.99 (1/5); 3.61 (1/10); .45 (1/15)	6 (1/15); 20 (1/10); 104 (1/15)	0.19 (1/10); 0.13 (1/15)	2.49 (1/10, 1/15); 4.00 (1/15)	≥0.09 (1/5); ≥1.88 (1/10); ≥1.73 (1/15)	?	Nappe & Skimming	Upper Stillwater Dam

Reference	Slope θ (degrees) H:V	Geometric Scale	Dam Height (ft)	Number of steps	Step Height (ft)	Facility Width (ft)	Discharge Q, (ft^3/s)	Unit Discharge q, (ft^2/s)	Type of flow	Observations
Rice & Kadavy (1994, 1997)	21.8 2.5:1	1/20	2.76	27	0.10	2.49	1.74 to 4.34	0.70 to 1.74	Skimming	
Frizell & Hanna (1997)	48 0.9:1	1/10	4.4	22	0.2	2	.11 to 5.2	.22 to 10.4		Buckhorn Dam
Hanna & Pugh (1997)	51.3 0.8:1	1/40	5.33	107	0.05	18.6	0.1 to 0.47	1.75 to 8.72		Pilar Dam
Ahmann & Zapel (2000)	45; 26.6; 18.4 1:1; 2:1; 3:1	1/8	10	40	0.25	1.5	2.7-5.7	1.3-3.8	All	Fillets in steps
Matos,Sanchez & Dolz (2000)	51.34 0.8:1		14.1	43	0.328, 0.23, 0.164	2	<7.06	3.53		
Fratino, Piccinni & de Marinis (2000)	Varying 25.6; 13.5; 6.8 2.08:1; 4.16:1; 8.38:1		1.12	14	0.08	2.46	1.32	0.54	All	
Peruginelli & Pagliara (2000)	26.6 2:1		5.164, 3.62, 2.32	20, 14, 9	0.259	1.31	0.124-2.72	0.095-2.07	All	Steps, rocks, drop
Andre, Boillat, & Schleiss (2003)	30; 18.5 1.73:1; 3:1	1/5 to 1/10	13.12	67	0.197	1.64	4.92	<3	All	Jet box entrance
Pinheiro & Fael (2000)	26.6; 11.3 2:1; 5”1		1.64	10	0.164	2.3	1.41	0.614	Nappe	
André (2004)	18.5; 30 3:1; 1.73:1	1/5 to 1/10	13.12	67	0.197	1.64	4.92	<3	All	Jet box entrance
Chanson (2002)	21.8 2.5:1		2.95	9	0.328	3.28	1.41-6.36	0.43-1.94	Transition & skimming	

Reference	Slope θ (degrees) H:V	Geometric Scale	Dam Height (ft)	Number of steps	Step Height (ft)	Facility Width (ft)	Discharge Q, (ft^3/s)	Unit Discharge q, (ft^2/s)	Type of flow	Observations
Bindo (1993)	51.34 0.8:1	1/20	4	25 + varying ht. at crest	0.13	9.84	18.95	1.92		M'Bali Dam
Prototype or Near Prototype Studies										
Frizell & Ruff (1994)	26.6 2:1	-	50	-	0.21	4.99	14.0 to 158.2	2.80 to 31.70	Skimming	Prototype flume
Gaston (1995)	26.6 2:1	-	50	-	0.21	4.99	16.60 to 160.9	3.33 to 0.03	Nappe & Skimming	Prototype flume
Grinchuk, Pravdivest & Shekhtan (1977)	8.7 6.5:1	-	-	12	1.35	46.59	90.26 to 30.08 x 10^3	1.94 to 0.65	Skimming	Prototype tests
Baker (1995)	18.4 3:1	-	-	-	0.41	?	24.72 to 71.33	?	Skimming	Prototype tests
Gonzales & Chanson (2004)	15.9 3.5:1	1/2	2.95	9	0.328 & 0.164	3.28	5.28 & 2.12-2.82	1.61 & 0.646-0.86	Transition & skimming	
Gonzales & Chanson (2004)	3.4 16.83:1	1/2	2.95	18	0.469 & 0.2346	1.64	1.31-3.89 & 0.35-1.41	0.8-2.37 & 0.215-0.86	Transition flow	

Author's that performed some or all of there studies with typical embankment dam slopes are highlighted in gray.

Crest Shape and Step Height

Crest Shape

The crest shape requirements vary depending upon whether the downstream slope of the spillway is steep for a gravity-type dam or flatter as is usual for an embankment dam.

Either the US Bureau of Reclamation (1987) or the US Army Corps of Engineers (1977) equations may be used to predict the underside of a nappe profile to design the step profile for a steeply sloping dam crest. The profile equations are the same for a vertical upstream face with low approach velocity:

$$y = \frac{x^{1.85}}{2H_o^{0.85}} \tag{10}$$

where x and y are the horizontal and downward vertical coordinates from the apex of the crest. Figure 6 shows a typical ogee crest profile for a steep stepped spillway. A profile consists of a smooth portion for a short distance until the flow is turned, then a series of smaller steps with varying step height to match the tips of the steps to the underside of the nappe profile (Houston, 1987; Sorenson, 1985; Frizell, 1990a; Bindo, 1993; Mateos, 2000). The steps down the remainder of the spillway from the point of tangency with the profile are designed as a constant height (i.e. 2 ft).

Smaller steps are used in the upper portion of the crest shape to prevent splashing at flows that are significantly less than the design flow and would potentially occur more frequently. Splashing under low flow conditions may be critical when the spillway structure is located within the confines of an embankment dam (Chanson and Gonzales, 2004), but obviously not as critical when centered within a concrete structure. In addition, small steps prevent the flow jet from impacting a large step, leaving the face of the spillway, and skipping over a number of steps on the slope.

A unique design was required for the stepped spillway crest profile for Upper Stillwater Dam (Houston, 1987) because of the extremely steep 0.32:1 slope on the upper portion of the dam. The profile was designed for less than the design head and the step tips gradually protruded into the profile to prevent the flow from leaving the stepped surface. Hanna and Frizell (1997) determined during testing of Buckhorn Dam that it could be important to design the profile shape for less than the design head to prevent the flow from springing free near the top of a very steep stepped slope spillway.

For an embankment dam, the step height does not usually vary and the steps begin immediately downstream from the flat broad crest on the top of the dam. Two issues arise with flow over a broad crest type spillway including a road across the top of the embankment dam; (1) flow acceleration, and (2) lower pressures at the brink.

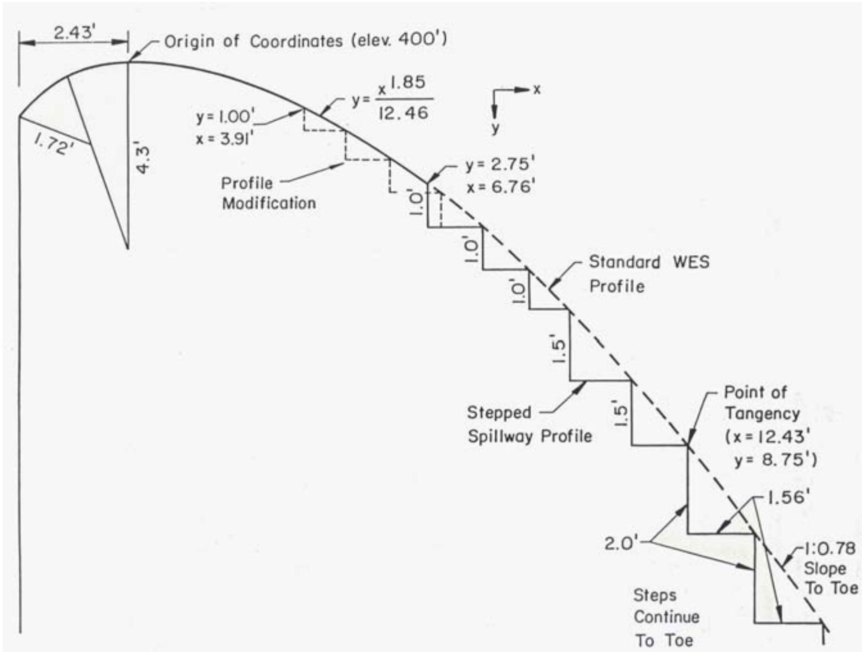

Figure 6. - Schematic of a typical crest profile for a steep stepped spillway with the step heights varying in the upper portion and becoming constant after the point of tangency with the dam slope.

For an embankment dam, the reports by Frizell et al., (1991a) provides guidance to design for the upstream head above the crest between limits of about 1/20 and 1/2 of the crest length in the flow direction which encourages critical depth to occur in the downstream 1/3 to 1/4 of the crest length for any shape channel.

Investigations have shown that erosion often begins just downstream from the brink of the dam (Dodge, 1988). In addition, Frizell et al., (1991a) also investigated pressures at the brink of various fixed embankment slopes and determined that from the location of critical depth over the crest, the flow depth and pressure profiles decrease from hydrostatic pressure, and the flow begins curving toward the direction of the slope as it approaches the brink. Curvilinear flow and the resulting forces were documented with the largest minimum pressure occurring within the first ½ foot of the embankment slope. Pressure measurements indicated that the head decreases gradually from hydrostatic pressure, matching the water surface, at about 1 ½ ft upstream from the brink, drops rapidly, then returns quickly to the water surface downstream of the brink.

Step Height

Step height is always a point of discussion in design of stepped spillways with regard to flow resistance, energy dissipation, and attainment of uniform flow. In reality, step height is usually a function of the construction technique and cost effectiveness. This usually means that stepped spillways are constructed of 1, 2 or 3 ft high steps without regard to energy dissipation. Step height generally remains the same with varying tread length depending upon the slope, whether the slope is steep for a concrete dam or flatter for an embankment dam.

Initial recommendations for optimum step heights were made by Stephenson (1991). He determined that for the steep slope of 0.7:1 the optimum step height in skimming uniform flow above which energy dissipation was negligible was $s \approx \frac{1}{3}d_c$.

Others have confirmed that for uniform skimming flow the step height is not a factor (Boes and Hager, 2003b; Matos, 2001). In addition, for skimming uniform flow, Boes and Minor (2002) and Boes and Hager (2003b) describe the clear water depth in terms of slope only, with no reference to step height.

For embankment dams, Ward (2002), and Matos (2000a) who referenced Tozzi (1992) in describing the optimum step heights above which there is no appreciable difference in energy dissipation for given unit discharges as shown in Table 2.

Table 2. - Table showing step heights versus unit discharge above which the increase in energy dissipation is negligible (Tozzi, 1992).

Unit Discharge, q (ft^3/s/ft)	Critical Depth d_c, (ft)	Step Height s, (ft)
53.8	4.5	1.31
107.6	7.12	2.13
161.5	9.32	2.79
215.3	11.3	3.38

Frizell et al., (2000) discuss the roughness height or step height relating to the friction factor and show that, for embankment dam slopes, there appears to be a constant friction factor versus the non-dimensional parameter of relative roughness, s/D_h. Ward (2002) found the same result on a 2:1 slope with 1 and 2 ft high steps in a prototype study. Rau (1994) observed no appreciable difference in friction factor, thus energy dissipation, with step height after performing flume studies of scaled 1 and 2 ft prototype step heights.

If the design unit discharge is large or the height of the dam is low, then uniform flow will most likely not be attained. This is common for many small dam applications and it is difficult to estimate the effect of step height versus energy dissipation under those conditions (Chanson, 2001a).

Aeration Characteristics

Void fraction of bubbles in flowing water is commonly referred to as air concentration and the latter terminology is used in this document.

Many investigations have been performed in regard to self-aeration of free surface flows on smooth spillways (Cain, 1978; Wood, 1983, 1991; Wilhelms and Gulliver, 1994).

Air concentration plays a vital role in determining the flow depth, velocity, and energy dissipation characteristics of stepped spillways. Aerated flow will impact the energy dissipation characteristic depending upon which depth is used to compute the depth at the toe of the dam, the equivalent clear water depth, d_w, or the aerated mixture depth.

The following sections will describe the location and depth of the aeration inception point and the mean amount of air expected at the point of free-surface aeration. The distribution of the air concentration or the air concentration profiles will be shown and methods suggested to predict the amount of air in the flow below the inception point through the non-uniform flow region. The distribution of air, particularly near the pseudo-bottom, affects the potential for cavitation damage on the step surfaces. Findings regarding the mean air concentration under uniform or quasi-uniform skimming flow will be shown. Selection of the flow depth where the air concentration is 90 percent for training wall height design will be discussed.

Aeration Inception Location and Depth

There have been numerous studies regarding the location of and the depth at the inception point for self-aeration of stepped spillways. Several formulae have been proposed for predicting the location and flow properties at the inception point based upon experimental data, such as those by Chanson (1994b, 2001b) and Boes and Hager (2003a), valid for a wide range of chute slopes, as well as those by Matos at al. (2000b) and Chamani (2000) for chute slopes typical of RCC dam spillways.

Matos (2000b) averaged the experimental values from others and determined the following equations for the location and depth at the inception point on a 53 degree slope as:

$$\frac{L_i}{k} = 6.289 F_r^{0.734} \tag{11}$$

$$\frac{d_i}{k} = 0.361 F_r^{0.606} \tag{12}$$

Chamani (2000) used high speed video footage to determine the length to the inception point for slopes from $51.3^{\circ} \leq \theta \leq 59°$ was

$$\frac{L_i}{k} = 8.29 F_r^{0.85} \tag{13}$$

He concluded that this developed equation agreed well with that of other investigators.

According to Matos et al. (2001), Chanson (1994, 2002c), and Renna et al. (2005), the following equations are valid for the location and flow depth at the inception point for slopes from $6.8° \leq \theta \leq 59°$:

$$\frac{L_i}{k} = 9.719 (\sin\theta)^{0.0796} F_r^{0.713} \tag{14}$$

$$\frac{d_i}{k} = \frac{0.4034 F_r^{\ 0.592}}{(\sin\theta)^{0.04}} \tag{15}$$

Additionally, Boes and Hager (2003a) have developed the following equations for the location along the slope at the inception point for slopes from 26° < θ < 75°:

$$L_i = \frac{5.9 d_c^{1.2}}{(\sin\theta)^{1.4} s^{0.2}} \tag{16}$$

or in terms of the roughness Froude number

$$\frac{L_i}{k} = 5.90(\cos\theta)^{0.2}(\sin\theta)^{-1} F_r^{0.80} \tag{17}$$

And rewriting the equation for the flow depth at the point of inception with $s = k/\cos\theta$ for slopes from 26° < θ < 55°:

$$\frac{d_i}{k} = 0.40(\cos\theta)^{-0.1} F_r^{0.6} \tag{18}$$

It can be seen that the distance along the chute to the point of air inception is primarily dependent upon the discharge and less dependent upon channel slope and step height. Observations indicate that a steeper slope will aerate sooner than a flatter slope and that, obviously, the step roughness causes initiation of aeration sooner than a smooth spillway.

The differences in the inception point equations may be partially explained by the different definitions of the inception point. Boes and Hager (2003a) described it as where the local air concentration near the bottom is equal to 1 percent. Matos (2000a) describes the location of the inception point by visual examination and measurements of air concentration, velocities, and depths. Measurements show that the inception point occurs upstream of the location indicated by visual observation.

Renna et al. (2005) discuss the difference between the expressions and determined that the differences are minor, specifically for $F_r \cong 30 - 100$, given the varying definitions for the inception point. Measurements made by Matos (1999, 2000a) show that the equations will slightly overestimate the distance to the inception point, particularly for $F_r < 10$. However, the author feels there is quite a difference in the computation of the distance down the slope to the inception point based upon the definition of the inception point and needs further investigation.

Mean Air Concentration at Inception Point

The mean air concentration at the point of inception has been investigated for both embankment dam and steeper gravity dam slopes.

Matos (2000a) developed the following equation

$$C_{meani} = 0.163 F_r^{\ 0.154} \tag{19}$$

and stated that the average value of $C_{meani} \cong 0.2$ for steep slopes. Matos' criteria for determining the point of inception was where the boundary layer reached the free surface.

Matos et al. (2001) described the mean air concentration for embankment slopes of $26^\circ < \theta < 30^\circ$ as:

$$C_{mean} = 0.262 + \frac{0.158}{\left[1 + (0.031\, s')^{-2.389}\right]} \quad , s' > 0 \tag{20}$$

The average air concentration for embankment slopes in this range at the point of inception where $s' = 0$ is about 0.26.

Boes and Hager (2003a) found that the mean air concentration at the point of inception, with the definition of 0.01 percent air at inception, for slopes of $26° \leq \theta \leq 55°$ was:

$$C_{meani} = 1.2 \times 10^{-3} (240° - \theta) \tag{21}$$

Both equations show that the mean air concentration at inception is not dependent on step height, but only on the stepped spillway slope. For a slope of 53°, equal to the slope of Matos' experiments, equation 21 returns a mean air concentration at inception of 0.22 which agrees well with 0.20 found by Matos et al. (2000b).

The mean air concentration at the point of inception is useful information in determining the risk of cavitation on a stepped spillway of significant height and design unit discharge.

Air Concentration Distribution

The distribution of air over a smooth spillway surface has been well documented by Straub and Anderson (1958), Wood (1983, 1991), and Cain (1978). Wood (1991) developed an equation for determining the mixture density or air concentration as a function of the slope, air concentration, turbulent diffusivity, and fall velocity of water droplets.

The distribution of air over the pseudo-bottom of stepped spillways has been measured by many investigators (Ruff and Frizell 1994, Matos and Frizell 1997, Ohtsu and Yasuda 1997, Chamani and Rajaratnam 1999, and Chanson et al. 2000). The distribution in terms of air concentration profiles have been compared to air concentration profiles over smooth spillways by Matos and Chanson. Chanson (1995b, 2001b) has proposed an advective diffusion model for stepped spillways that is very similar to that of Wood (1983).

Wood (1983, 1991)

$$\varepsilon \frac{d}{dy}\left[\rho_w (1 - C)\right] = \rho_w (1 - C) u_f \cos\theta \tag{22}$$

Integrating with ε constant and u_f proportional to C*y gives:

$$C = \frac{\beta'}{\beta' + e^{-\gamma' \cos\theta (y/Y_{90})}} \tag{23}$$

When $C = 0.9$ at $y/Y_{90} = 1$ then

$$\beta' = 9 * e^{-\gamma' \cos\theta} \tag{24}$$

and with numerical integration of equation 22 with depth Matos (1999) obtained:

$$\gamma' \cos\theta = 1.437 - 2.635 C_{mean}^{5/2} + \frac{1.114}{C_{mean}} \tag{25}$$

Chanson (1995b) proposed based upon the continuity equation for air in air-water flow and the air bubble rise velocity:

$$C = 1 - \tanh^2\left(K' - \frac{y}{2D' Y_{90}}\right) \tag{26}$$

where K' and D' are given by:

$$K' = \tanh^{-1}\sqrt{0.1} + \frac{1}{2D'}$$

$$D' = \frac{(0.848 C_{mean} - 0.00302)}{(1 + 1.1375 C_{mean} - 2.2925 C_{mean}^2)} \quad C_{mean} < 0.7$$

Chanson and Toombes (2001b) proposed:

$$C = 1 - \tanh^2\left(K' - \frac{y'}{2D_o} + \frac{(y/Y_{90} - 1/3)^3}{3D_o}\right) \tag{27}$$

where D_o is a dimensionless diffusivity term depending upon the mean air concentration:

$$C_{mean} = 0.7622(1.04034 - \exp(-3.614 D_o)) \tag{28}$$

Figure 7 (Renna et al., 2005) shows that in the rapidly (RVR) and gradually (GVR) varying flow regions above the dimensionless depth $y/Y_{90} > 0.4$ there is very good agreement with all proposed equations. The profiles also show the presence of an air concentration boundary layer of about 0.05 ft near the step tips (Matos, 1999; Chanson, 1997). In the region nearer the step tips the model of Wood and Chanson (1995) provide an adequate fit to the data. The equation of Chanson & Toombes (2001b) was developed for skimming flows and has been reported (Gonzales & Chanson, 2004) to adequately describe the air distribution of steeply sloping stepped spillways.

In addition, Boes and Hager (2003a) showed good agreement with the proposed equations by Chanson (1995b) for spillway slopes from 30 to 50 degrees except very near the pseudo-bottom where $y/Y_{90} < 0.3$.

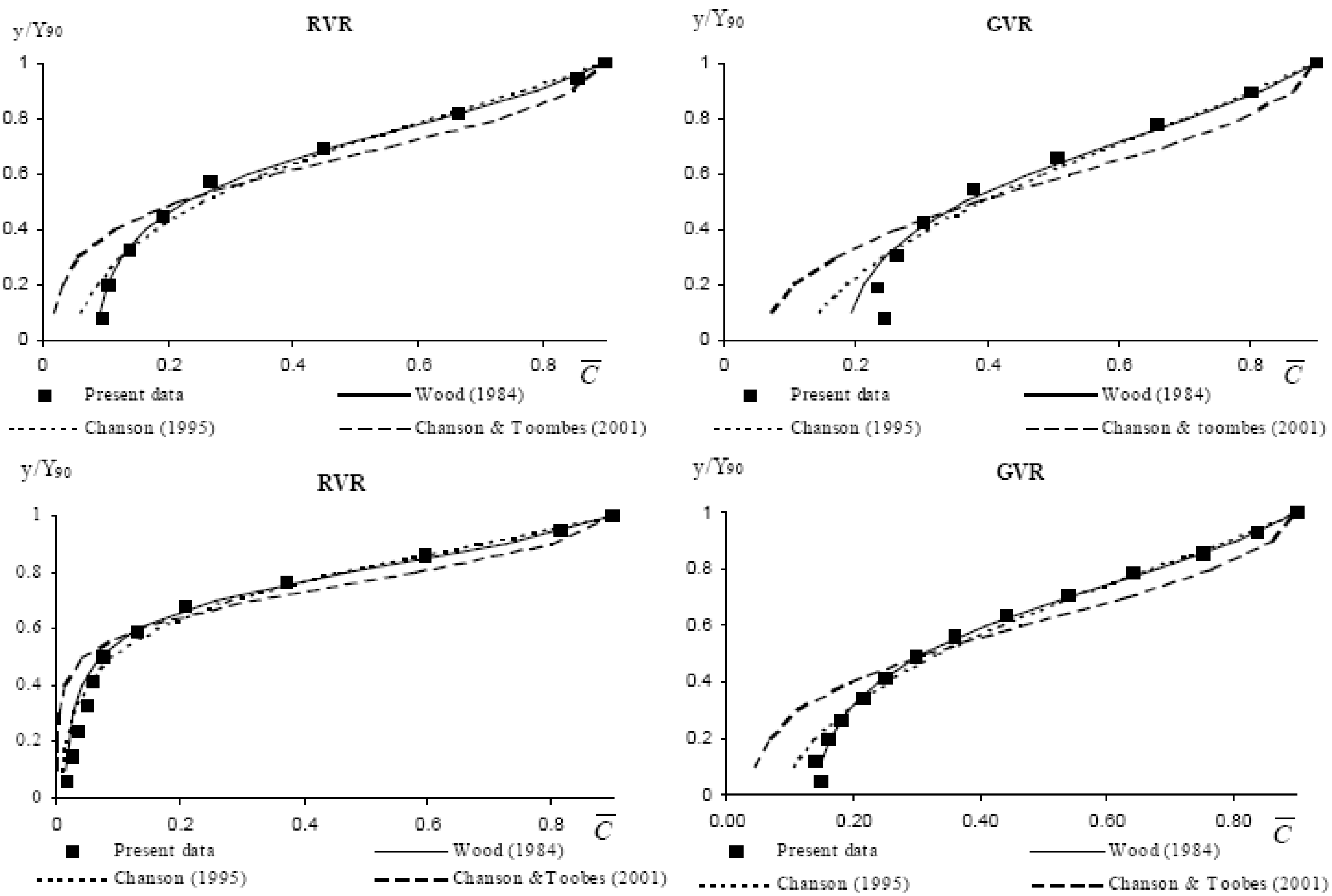

Figure 7. - Air concentration distributions with experimental data and proposed air concentration distribution equations by Wood (1983), Chanson (1995b) and Chanson & Toombes (2001b). (Figure from Renna et al, 2005)

Cavitation Risk

Cavitation is always a concern when discussing high velocity flow over a concrete surface. Providing aeration to the surface of the spillway has been a successful means of preventing cavitation. The classical work of Peterka (1953) states that an air concentration near the bottom surface of 5 to 8 percent is enough to avoid cavitation damage.

A stepped spillway is unique in that most spillway surfaces subjected to high velocity flow are specified to be finished to a smooth trowel finish. A stepped spillway has many offsets away from the flow and; therefore, could potentially be a candidate for cavitation. However, the turbulence associated with the steps leads to faster free surface aeration; therefore, lower velocities in the non-aerated zone.

The length to the aeration inception point is a valuable parameter as cavitation should not occur once air is near the stepped surface and the flow is self-aerating. The location of the inception point on stepped spillway is significantly closer to the spillway crest than on smooth chutes due to the larger growth of the boundary layer (Chanson, 1994b). The equations presented in the previous section outline when free-surface aeration would be expected.

In addition, the mean air concentration at the point of inception has been shown (Matos, 2000a; Boes and Hager, 2003a) to be from 20 to 26 percent. Therefore, by the time air is visually observed and even the measured length to air inception, the mean air concentration exceeds requirements.

However, these are the mean values of air concentration and the air concentration near the pseudo-bottom is of interest. From figure 7 it may be seen that the air concentration near the pseudo-bottom is quite low. There is the also presence of a steeper profile near the bottom compared to smooth chutes that indicates the step roughness does cause initiation of aeration sooner on the stepped surface than the smooth surface.

Falvey (1990) defines cavitation inception as a function of the velocity, pressure, and water density and is expressed by the cavitation index, σ:

$$\sigma = \frac{P_o - P_v}{\rho V_o^2 / 2} \tag{29}$$

Therefore, a certain velocity must generally be attained before cavitation becomes a problem. Most research has been conducted on steeper slopes because they are generally associated with higher dams that would have the energy available to produce velocities capable of causing cavitation. The research dealing with cavitation risk is based upon measurement of velocities, air concentrations near the bottom, and pressures on the faces of the steps.

Air Concentration Near the Pseudo-bottom

Matos et al., 2000b presents a plot of C_b versus non-dimensional distance down the 0.75:1 slope for various distances away from the pseudo-bottom.

The following equation provides the fit to the experimental data at 0.0105, 0.0269 and 0.0433 ft away from the step tips on a 53 degree slope:

$$C_b = \frac{a}{1 + \left(\frac{s'}{b}\right)^c} \tag{30}$$

The equation coefficients are defined by table 3.

Table 3. - Coefficients for regression equation 28 defining the air concentration near the pseudo-bottom (Matos et al., 2000b).

y (ft)	a	b	c	r (correlation coefficient)
0.0105	0.324	10.195	-1.790	0.977
0.0269	.417	11.028	-1.644	0.961
0.0433	.424	9.514	-1.798	0.943

A plot of the equation for the air concentration near the pseudo-bottom versus the non-dimensional distance, s', below the crest showed that near the boundary at a distance of 0.01 ft, the bottom air concentration of 8 percent will occur at a distance of $s' > 6$. Matos states that to prevent cavitation damage a distance from the point of inception of air entrainment six times larger than the equivalent clear water depth at that location is needed. This implies that not only the black water region near the crest, but some distance into the developing region the air near the pseudo-bottom may not be adequate to prevent cavitation damage. Prototype velocities were not given relating this clear water depth and discharge. Matos et al. (2001a) states that cavitation should not occur for unit discharges up to 215-320 $ft^3/s/ft$ corresponding to mean velocities of 55-75 ft/s. In addition, the Dneiper test chute, with a height of 121 ft, passed 645 $ft^3/s/ft$ with mean velocities up to 75 ft/s without reports of cavitation damage on an 8.8 degree chute (Pravdivets and Bramley, 1989).

Boes and Hager (2003a) also measured air concentrations near the step tips at two locations 0.005 ft and somewhat higher. They developed the following relationship for C_b versus non-dimensional distance down the slope for 30, 40, and 50° slopes:

$$C_b(L_i) = 0.015 L_i^{\sqrt{\tan\theta/2}} \tag{31}$$

Boes and Hager simplify this equation further and select the bottom air concentration of 0.05 for an acceptable value producing the critical non-dimensional distance until the bottom air concentration equals 0.05 as:

$$L_{i,crit} = L_i\left(C_{b,crit} = 0.05\right) = 5.0(\sin\theta)^{-2.3} \tag{32}$$

They conclude that for slopes typical of gravity RCC dams, the critical distance from the inception point is about $9d_i$. Boes and Hager (2003a) claim that this region where the flow is developing might be prone to cavitation damage for velocities greater than about 66 ft/s for a unit discharge of 270 $ft^3/s/ft$.

Step Pressures

There are two issues relating to the pressures on the faces of the steps:

- low pressures or cavitation zones
- high pressures or durability of the step tread

This section will discuss pressure measurements gathered on the vertical face of the steps to determine if they are low enough to produce cavitation (Falvey, 1990). Pressures have been measured on step faces by many investigators (Houston (1987), Gaston (1995), Matos et al. (2000b), Mateos and Elviro (2000), Ward (2002), Amador et al. (2005)). Most of these emphasized investigating the average pressures on the step faces and defined the location of impact and low pressure on the horizontal face near the edge and the top of the vertical face where flow separation occurs, respectively.

Diez-Cascon (1991) determined that the critical velocity above which cavitation could occur was about 43 ft/s by making pressure measurements on the step faces. However, Mateos and Elviro (2001) discuss that the speed of sound in low pressure zones ranges from 49-66 ft/s so it might be reasonable to assume that with air, there will be no cavitation for discharges up to 39 $ft^3/s/ft$.

The latest work by Amador et al (2005) discusses the probability of attaining low pressures that could cause cavitation damage on a stepped spillway. Tests were performed on three step heights and various discharges at three locations down the slope near the inception point.

On the horizontal step face the main stream hits the downstream half of the step with the maximum pressures located on the outer edges. In the inner region of the step, the pressure is governed by the recirculation in the cavity and even negative pressures can be measured. On the vertical step face, the area near the outer edge of the step experiences a separation of the flow. The mean pressures are close to zero and often sub-atmospheric. Pressure fluctuations occur and the amplitude of the fluctuations is greater as the flow increases.

Pressure fluctuations occurring with the probability of 0.1 percent were used to determine if cavitation could occur. Results showed that pressures below a non-dimensional presentation of vapor pressure including the step height would occur with a probability of 0.1 percent. The flow rates under which these pressures occurred were scaled up to about 49 ft/s. Therefore, Amador et al (2005) concluded that cavitation inception could occur on a stepped spillway at a velocity about half as large as that on a smooth spillway (Falvey, 1990), due to the low pressure zone occurring in the step offset.

Ohtsu and Yasuda (1997), and Matos et al. (2001b) have studied the amount of air bubbles in the step recirculation zone. Enough air in the recirculation zone near the step faces may prevent cavitation inception. A stepped spillway may also perform like a surface of uniform roughness and an aeration boundary has already been defined (Matos, 1999). This region of shear above the pseudo-bottom of the step surface may or may not influence the occurrence of cavitation on the step surfaces (Falvey and Mefford, 1986). Or offsets away from the flow as steps, might prevent cavitation from occurring on the stepped surfaces (Frizell and Mefford, 1991).

There is some disagreement about the distance below the crest and; therefore, the velocities above which cavitation will occur on stepped spillways. Velocities tend to vary depending upon the methodology used to formulate the opinion.

Mean Air Concentration

A major concern is whether or not uniform or equilibrium flow has been reached on the spillway chute for skimming flow conditions. Uniform flow conditions are defined as the location on the spillway chute where the incremental flow depth, velocity, and air concentration are essentially constant.

Only Matos (2000a) has presented data and equations to predict the mean air concentration in the rapidly and gradually varying flow regions. Equations 31 and 32 were developed for steep slopes:

$$C_{mean} = 0.21 + 0297e\left[-0.497(\ln s' - 2.972)^2\right] \text{ for } 0 < s' < 30 \qquad (33)$$

$$C_{mean} = \left[0.888 - \frac{1.065}{\sqrt{s'}}\right]^2 \text{ for } 30 \le s' \le 100 \qquad (34)$$

For s' greater than 100 the uniform mean air concentration of a conventional smooth chute should be used. Matos presented plots of the developing flow regions where the mean air concentration did not vary significantly with unit discharge.

Assuming that uniform flow has been attained down the slope, early laboratory studies of Straub & Anderson (1958) show that the air concentration is dependant only upon the spillway slope. Prototype flume studies by Ruff and Frizell (1994) on a 26.6 degree slope and later laboratory studies by Matos and Frizell (1997), Boes and Hager (2003b), Tozzi (1992), show that the mean air concentration of a stepped spillway – once uniform flow has been attained – is very similar to that of a smooth spillway. Therefore, the mean air concentration on a stepped spillway of slopes between 7.5 to 75 degrees can be determined from figure 8.

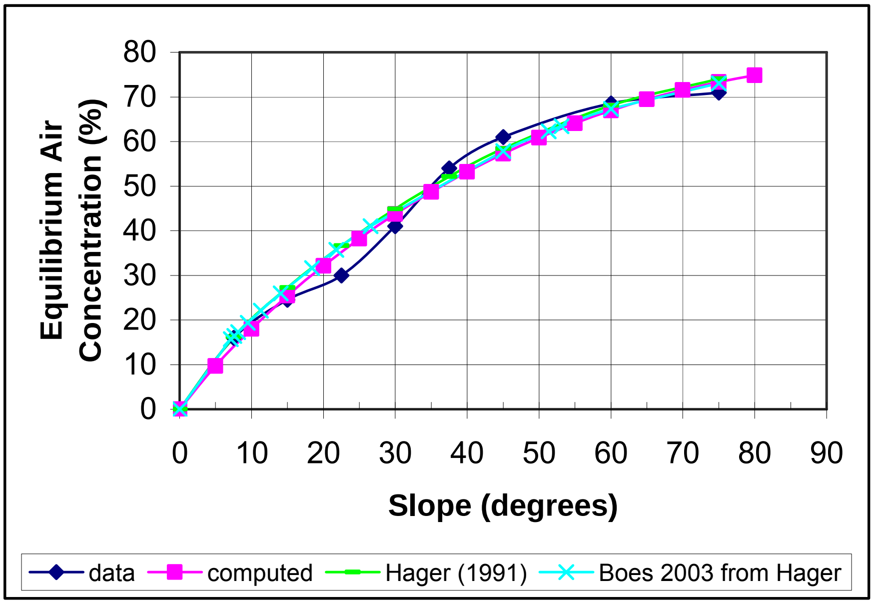

Figure 8. - Plot of air concentration for the uniform flow region on a smooth surface spillway comparing the experimental data of Wood and the proposed equation by Hager (1991).

The following equation may be used to determine with reasonable accuracy the air concentration for uniform flow down a stepped spillway instead of using graphical interpolation. The simplified equation of Hager (1991) was developed for prediction of mean air concentration in uniform flow:

$$C_{mean} = 0.75(\sin\theta)^{0.75} \qquad (35)$$

The mean air concentration may then be used to determine the clear water depth and the bulked depth, for energy dissipation characteristics and training wall heights, respectively.

Bulked Depth for Training Wall Heights

Many investigators have proposed the appropriate bulked depth or mixture depth to use for determining wall heights along a smooth or stepped spillway chute (Straub & Anderson, 1958; Wilhelms, 1994; Falvey, 1990; Boes and Hager, 2003a).

For stepped spillways, the first consideration is the flow regime under which the spillway is expected to operate, nappe or skimming flow. Nappe flow has been proven to cause quite a bit of splash that would require high training walls due to excessive splashing (Houston, 1987). If nappe flow is expected on a concrete dam then splash is not considered to be a major concern; however, if the spillway is over on embankment, then the wall heights might need to be increased or the embankment might need to have additional protection provided near the walls to transport the estimated amount of flow produced by the splash safely to the toe without eroding the contact with the wall. There has not been much research performed to address the wall heights necessary to contain splash from nappe flows on stepped spillways. Wall heights have been investigated extensively for the uniform, self-aerated skimming flow regime.

All investigators agree that the training wall height should be designed based upon the bulked flow depth, Y_{90}, according to equation 2, where the air concentration is equal to 90 percent. Boes and Hager (2002, 2003b) proposed an equation for the bulked or mixture depth.

$$\frac{Y_{90}}{k} = 0.50 \cos\theta^{1.5(0.1\tan\theta+0.5)} F_r^{(0.1\tan\theta+0.5)} / \cos\theta \qquad (36)$$

Ward (2002) performed prototype testing with 1 and 2 ft high steps on a 2:1 slope. They recorded air concentration profiles and computed clear water depths using the formula using equation 2 and defined a bulking factor, $\zeta = Y_{90}/d_w$, with a recommended value of 1.75 as the bulking factor for skimming flow. This method precludes knowledge of the air concentration for simplified design.

Safety Factor

Training walls designed for stepped spillways over embankment materials or emergency spillways over erodible materials should include a safety factor. From a practical standpoint each agency or design organization most likely has their own criteria for training wall safety factors.

Some investigations have been made of the depth needed to contain bulked depth up to 95 or 99 percent air concentration (Straub & Anderson, 1958; Wilhelms, 1994; Ward, 2002; Boes and Hager, 2003a). These could be used for specific guidance.

A suggested value of 1.2 times the Y_{90} depth is supported in the literature for smooth spillways (Wood, 1991) as the depth where the surface turbulence would be contained and the velocity would be the free stream velocity of the air.

Boes and Hager (2003a) suggest 1.2 times Y_{90} and 1.5 times Y_{90} for concrete dams and embankment dams, respectively. They caution that nappe flow will produce more splashing.

It is assumed that a very small portion of the total discharge is carried above this depth. However, a considerable amount of splash may be projected above Y_{90} with water particles ejected from the main spillway channel necessitating additional freeboard (Ward, 2002). At maximum flow rates tested, sidewall heights of approximately 5-ft above the tips of the steps, measured perpendicular to the spillway, provided freeboard of approximately $2.5Y_{90}$, which essentially contained the entire splash within the test channel. Based on observations from the study, it appears that a minimum of $2.0Y_{90}$ is required to minimize splash over the wall.

Ward (2002) discussed observations from the testing that for the same flow rates, the relative bulking appeared less for the 1 ft than the 2 ft high steps. Projections of water droplets above the main stream of flow were much lower for 1-ft-high steps than for the 2 ft steps (figure 9). These were only visual observations, not measured with instrumentation.

Figure 9. - Step ht of 1 ft on the left and 2 ft on the right showing the difference in turbulence and splashing at a similar length down a 26 degree slope for a unit discharge of 20 $ft^3/s/ft$. Photos from Ward (2002) in the prototype size flume facility.

Gonzales and Chanson (2004a), and Chanson and Gonzales (2005) studied scale effects and turbulence associated with relatively flat slopes 3.4 and 16 degrees with 2 step sizes on each slope. The results for a scale factor, $L_r = 2$ for scaling the steps, were that scale effects were seen for smaller size steps. Flow over smaller steps produced less turbulence and lesser number of entrained air bubbles with larger bubble sizes. These conclusions were drawn after extensive study of the air-water flow at the microscopic level only and a Froude scale model that meets Reynolds and Weber number criteria is adequate for quantifying aeration.

Uniform Flow Determination

The first important decision regarding design of stepped spillway parameters is determination of whether the flow will reach uniform flow conditions or not. Whether uniform flow will exist or not is normally thought to be a function of the discharge, dam height, step roughness, and slope. The attainment of uniform flow is the ideal situation because then uniform flow equations may be applied to the analysis of energy dissipation. Many researchers have proposed equations to predict whether or not flow has reached the uniform state in stepped spillways.

Kells (1995) states that once terminal velocity is reached, i.e. uniform flow is attained, the energy dissipation ratio $\Delta H/H_{max}$ will very quickly asymptotically approach 1 as the height of the dam is increased regardless of the flow regime. In essence, every increment of additional dam height results in an equal increment of energy dissipation.

Yildiz and Kaz (1998) and Matos and Quintela (1995a) show that uniform flow will occur for approximate relative dam heights of $H_{dam}/d_c \geq 20$ and ≥ 25 to 30, respectively.

Christodoulou (1993) provides equation 37 to estimate the length parallel to the pseudo-bottom from the crest to uniform flow as

$$L_u = \frac{8.6q^{0.71}}{s^{0.07}(\cos\theta)^{0.07}(\sin\theta)^{0.28}} \tag{37}$$

Boes and Minor (2000b) computed residual energy based upon uniform flow equation and determined where the data departed from the equation as the location where uniform flow would occur. He determined that the attainment of uniform flow was a function of critical depth and spillway slope and roughly followed the following equations:

$$L_u \approx 15d_c / \sin\theta \text{ for } \theta = 30° \tag{38}$$

$$L_u \approx 35d_c / \sin\theta \text{ for } \theta = 50° \tag{39}$$

The simple result of these equations is that the distance from the crest to uniform flow development was greater for steeper slopes than flat slopes.

Boes and Hager (2003b) later combined the previous two equations into a proposed equation that changes with the flow rate, dam height, and chute slope:

$$\frac{H_{dam}}{d_c} \approx 24(\sin\theta)^{2/3} \tag{40}$$

In addition, Boes and Hager (2003b) further simplified this equation to refer only to the dam height and critical flow depth:

$$\frac{H_{dam}}{d_c} \geq 15 to 20 \qquad (41$$

Matos et al (2001a) and Matos (2000) also stated that if the non-dimensional distance down the slope $s' > 100$ then a uniform self-aerated flow regime has been attained for both embankment and steep dam slopes.

Once it has been determined that uniform flow will occur, then the mean air concentration for a stepped spillway of a given slope, equal to that of a smooth spillway, may be used from equation 35. Notice that the step height is not included in the determination of uniform flow.

Uniform Flow Depth

Boes & Hager (2003b) present a method for estimating the equivalent or uniform clear water depth as a function of only the chute slope:

$$\frac{d_w}{d_c} = 0.215(\sin\theta)^{-1/3} \tag{42}$$

Flow Resistance and Residual Energy

The main reason for designing a stepped spillway is to take advantage of the energy dissipation expected with flow over the steps. The initial investigations of stepped spillways showed so much promise for dissipating energy that designers wanted to pass larger unit discharges driving the research into the skimming flow regime over high dams.

Energy dissipation was reported in initial studies of stepped spillways as a function of the relative energy loss compared to smooth spillways or the theoretical available head such as Houston (1988), Stephenson (1991), (Frizell (1992), and Chamani and Rajaratnam (1999) to list a few. This trend continued for many years including discussions by Chanson (1994a,b), and Matos and Quintela (1995a). The preferred method of presentation for energy dissipation, which has evolved from these early comparisons to theoretical available energy head, is to discuss energy dissipation in terms of residual energy head at the toe of the chute.

Residual energy is a function of the unit discharge or velocity and depth at the chute toe, and the chute slope. The velocity is a function of the chute roughness and dam height as well as the flow depth. Stepped spillway model studies have all been conducted with energy dissipation or the amount of energy remaining in the flow the final desired outcome. Herein lays the problem – determining which studies have produced valid information. The friction factor is greatly influenced, and reduced, by the aeration in the flow depth. The friction factor must be calculated with a non-aerated flow depth or clear water flow depth. MANY studies have been conducted without aeration in the flow, thus over predicting the energy dissipation. MANY studies have been conducted with aeration but not making proper measurements in the aerated flow, thus reporting aerated or mixture depth and generally over predicting the energy dissipation. MANY studies have been conducted where uniform flow or quasi-uniform flow was not attained, but uniform flow equations were used to determine important parameters.

Experimental Techniques

Methods used to investigate residual energy in the flow include:

- Computing residual energy after measuring air concentration, velocity, and depth at the toe of the slope by using:
    - Back-flushing pitot tubes
    - single- or double-tipped resistivity probes
    - single-or double-tipped optical probes
    - single-or double-tipped conductivity probes
    - Laser doppler systems
- Forcing a hydraulic jump and back calculating the initial clear water depth entering the jump.
- Using high-speed cameras and video techniques and targets.

Various methods have produced various results as would be expected. Chanson (2002b) and Matos (2005) have discussed the appropriateness of the various techniques and how the results have affected the conclusions drawn by various investigators.

Friction Factor

Critical to determining the residual energy below a stepped spillway is to understand the variables involved, namely the friction, drag, and aeration effects.

Chanson et al. (2000) state that the difference between smooth spillways and stepped spillways is that, on smooth spillways skin friction predominates and on stepped spillways form drag predominates. In skimming flow, the step tips form a pseudo-bottom parallel to the chute bottom over which the flow passes. Water skims over the step edges with formation of recirculating vortices between the main stream and the step corners. Momentum transfer occurs between the recirculating eddies in the step offsets and the main skimming flow increasing energy dissipation. On steep slopes, the recirculating eddies are the primary mechanism for form drag and energy dissipation, whereas on flatter slopes, the recirculating eddies produce form drag in addition to skin friction on the step surface and free-surface wakes.

Even though form drag predominates, the Darcy-Weisbach friction factor is the accepted parameter used to determine energy dissipation. The Darcy-Weisbach friction factor for air-water flow is given by:

$$f_e = \frac{8gS_f d_w^2}{q_w^2}\left(\frac{D_h}{4}\right) \qquad (43)$$

where for a hydraulically wide chute $D_h/4 \cong d_w$, the clear water depth giving

$$f_e = \frac{8gS_f d_w^3}{q_w^2} \quad \text{non-uniform gradually-varied flow} \quad (44)$$

For uniform flow conditions, the friction slope, S_f, is equal to the bottom slope, $\sin\theta$, and the following equation applies for skimming flow over hydraulic wide stepped spillway channels:

$$f_e = \frac{8gd_w^3 \sin\theta}{q_w^2} \quad \text{uniform flow} \quad (45)$$

Most work has been conducted in the uniform or nearly (quasi) uniform skimming flow region of stepped spillways.

The aeration effects have already been discussed, but are reiterated here. The friction factor and residual energy in the flow must be determined using the clear water values for the depth and velocity even though the flow is highly turbulent and aerated.

The mean flow depth as measured by visual observation is of the same order of magnitude as the characteristic depth Y_{90}. The equivalent clear water depth d_w is much lower than Y_{90}, confirming the significant overestimation of the friction factor and the energy dissipation based on the aerated flow depth measurement or visual observation, as suggested by Matos and Quintela (1995a,b). Near the downstream end of a long spillway chute, where uniform flow is attained, both Y_{90} and d_w become practically constant.

However, making measurements in highly aerated flow is difficult and results can vary depending upon the methods used to perform the depth, air concentration, and velocities. Many early investigations did not measure the air concentration, and determined depths that were most likely mixture depths or aerated flow depths. Using aerated flow depths to determine a friction factor produced greatly overestimated friction factor results in Christodoulou (1993), Rice and Kadavy (1996, 1997), and Stephenson (1991), etc. Other times scale factors were not adequate to produce aeration that would normally occur and friction factor results were overestimated (Yasuda and Othsu, 1999). In addition, the length or height of the facility was not adequate for uniform flow to be attained and friction factors were generally also overestimated.

Several authors have computed the friction factor for stepped spillways of various slopes using equation 45, assuming uniform, skimming flow conditions were attained. The following is a synopsis of various study results.

Air flow over steps in a closed conduit of a 53 degree slope was investigated by Tozzi (1994) to avoid the issue of measuring flow depths in an air-water flow mixture. Although there would not be drag reduction due to the air/water interface, this might be used for determining a single phase flow over stepped spillways. Tozzi's equation for the friction factor on a steep 53 degree slope which can be used with a clear water depth is:

$$\frac{1}{\sqrt{f}} = 2.16 + 1.24\log\left(\frac{y}{k}\right) \qquad \text{53 degree slope and y/k>1.8} \quad (46)$$

Tozzi's data shows that this equation produced an almost constant friction factor of 0.163 for low values of y/k.

In addition, Tozzi developed friction factor equations for flatter slopes given as:

$$\frac{1}{\sqrt{f}} = 3.25 + 0.39\log\left(\frac{y}{k}\right) \qquad \text{26 degree slope and y/k>1.8} \quad (47)$$

where the friction factor varied throughout the values of y/k tested but only between the values of 0.07 to 0.1; and

$$\frac{1}{\sqrt{f}} = 3.68 + 0.28\log\left(\frac{y}{k}\right) \qquad \text{8.5 degree slope and y/k>1.8} \quad (48)$$

where the friction factor could be considered constant at 0.07.

Gaston (1995) determined from prototype flume tests on a 26.6 degree slope that the friction factor in the quasi-uniform flow region was 0.11 for unit discharges up to 34 ft^3/s/ft.

The friction factor for steep gravity dam slopes has been estimated by Matos (2000) and Boes and Minor (2000b) to be 0.1 and 0.07, respectively.

For slopes associated with embankment slopes Frizell et al. (2000) and Boes and Minor (2000b) suggest friction factors of 0.08 and 0.09, respectively.

Ward (2002) on a 26.6 degree slope determined a friction factor of 0.25 for 1 and 2-ft-high prototype steps under unit discharges up to 34 ft^3/s/ft.

Reanalysis of Yasuda and Ohtsu (1999, 2000) data by Boes (2000a) and Boes and Hager (2003b) and Matos et al. (2001) showed that scale effects had probably not been entirely mitigated in their study where the friction factor was reported as a range equal to 0.11 to 0.16 for a range of $5.7° < \theta < 55°$.

Friction factors reported by Chamani and Rajaratnam (1997, 1999) are larger than others in the range of 0.13 to 0.33 for a 59 degree slope and 0.12 to 0.31 for a 51 degree slope. Analysis by Matos (2000b) suggests that uniform flow was not attained and the use of the friction slope, $S_f = \sin\theta$, in the gradually varied flow region may also overestimate the friction factor.

Chanson (2000) evaluated data by many experimenters and found a friction factor for flat slopes varying depending on whether they were comparing model or prototype data and proposed two equations. For steep chutes the data were very scattered – because of incorrect scale factors in the models – but grouped around two dominant values of 0.17 and 0.3.

Chanson et al. (2000) and Chanson and Toombes (2002b) proposed an average non-aerated friction factor of 0.2 using recent large scale data. Chanson proposed that an equation of the form

$$f_e = \frac{2}{\sqrt{\pi}}\left(\frac{1}{K}\right) \tag{49}$$

with $1/K$ equal to the dimensionless expansion rate of the shear layer (Chanson, et all 2000) fits the reported data well. Gonzales & Chanson (2005) provide a proposal for $K = 6$ for stepped spillways which results in a reasonable estimate of $f_e \cong 0.2$.

Gonzales and Chanson (2004b) determined a friction factor of 0.15 from recent experiments on a 15.9 degree slope using comparisons between cavity shear stress and the friction slope.

Chanson (2005) for a 21.8 degree slope indicated a friction factor of 0.25 on average with 0.328-ft-high steps.

Boes and Hager (2002, 2003b) developed a bottom friction factor, f_b, computed from the non-aerated flow depth. The bottom friction factor was computed by accounting for sidewall effects and a shape correction factor from round to rectangular in the flume studies. The friction factor at the pseudo-bottom in uniform skimming flow, f_b, is defined by Boes and Hager (2003b) for $19° < \theta < 50°$ slopes as:

$$\frac{1}{\sqrt{f_b}} = \frac{1}{\sqrt{0.5 - 0.42\sin(2\theta)}}\left[1.0 - 0.25\log\left(\frac{k}{D_h}\right)\right] \tag{50}$$

This equation demonstrates that the effect of the chute angle is larger than the effect of the relative roughness on the friction factor for skimming flow. In addition, Boes and Minor (2002) and Boes and Hager (2003a, 2003b) do not approximate the hydraulic diameter equal to four times the clear water depth, but use the hydraulic radius equal to the area over the wetted perimeter of the chute.

Matos (2005) compared the data from Matos and Boes and Hager (2003b), where Boes uses the bottom friction and showed good agreement between the friction factors regardless of definition as long the clear water depth is used in the computation and quasi-uniform flow is attained.

The friction factor for air-water flow is found to decrease with increasing mean air concentration for constant relative step roughness height (Matos, 2005) and the drag reduction over stepped spillways may be greater than that over smooth spillways. Matos (2005) presents the following equation to predict the drag reduction in aerated flow versus non-aerated flow for typical steep, not embankment dam slopes, i.e. 0.75:1, as:

$$\frac{f_e}{f} = (1 - C_{mean})^{\omega} \tag{51}$$

with ω=1.43 regardless of relative step roughness and

$$\omega = \frac{1}{0.489 + 0.055\left(\frac{d_c}{s}\right)^3} \tag{52}$$

with the effect of the relative step roughness.

André proposes a global dissipation coefficient that encompasses both friction and drag into one expression. The mixture friction coefficient for a 30 degree stepped slope is equal to a constant value of 0.126. André states that this will produce an 8 to 15 percent underestimation of the residual energy when input into equation 54.

Assuming uniform skimming flow, the friction slope should equal the spillway slope. This is a good check on whether data presented on the friction factor is logical.

Residual Energy Head

Chow (1959) provides the following equation for residual energy for uniform and non-uniform flow over smooth chutes:

$$H_{res} = SE = d_w \cos\theta + \alpha \frac{q_w^2}{2gd_w^2} \tag{53}$$

with Chanson (1994b), Boes and Hager (2003a,b), Matos (2000), and Matos et al. (2001a) developing the kinetic energy coefficient for skimming flow over stepped chutes α = 1.1 to 1.16.

Equation 51 is for uniform or non-uniform flow; however, determining the values of d_w or the clear water depth require a significantly different effort depending upon whether the flow is in the uniform or non-uniform region.

In the uniform flow region, a direct computation of the residual energy head remaining under uniform flow conditions may be based upon the simpler computation of the uniform clear water depth provided by equation 40 that requires no direct knowledge of the friction factor.

In addition, Chanson (1994b), Matos and Quintela (1995a,c), and Boes (2000) plotted experimental data based upon the relative residual energy as a function of the relative dam height using the analytical equation for uniform flow presented by:

$$\frac{H_{res}}{H_{\max}} = \frac{\left(\frac{f}{8\sin\theta}\right)^{1/3}\cos\theta + \frac{\alpha}{2}\left(\frac{f}{8\sin\theta}\right)^{-2/3}}{\frac{H_{dam}}{d_c} + \frac{3}{2}} \tag{54}$$

where $\alpha \cong$ 1.1-1.16.

Figure 10 shows the relationship developed by Boes and Minor (2002) and Boes and Hager (2003b) in both the uniform $H_{dam}/d_c \geq$ 15 to 20 and non-uniform or gradually-varied flow region in the area of lower relative dam heights. Equations 53 and 55 for uniform and non-uniform gradually-varied flow, respectively, were developed by fitting to the data in this graph.

Boes and Minor (2002) and Boes and Hager (2003b) propose modifying equation 54 to include the condition where the relative energy is equal to unity when the relative depth is equal to zero and provide the following equation to determine the residual energy for uniform flow conditions over stepped spillways:

$$\frac{H_{res}}{H_{\max}} = \frac{\left(\dfrac{f_b}{8\sin\theta}\right)^{1/3}\cos\theta + \dfrac{\alpha}{2}\left(\dfrac{f_b}{8\sin\theta}\right)^{-2/3}}{\dfrac{H_{dam}}{d_c} + \left(\dfrac{f_b}{8\sin\theta}\right)^{1/3}\cos\theta + \dfrac{\alpha}{2}\left(\dfrac{f_b}{8\sin\theta}\right)^{-2/3}} \tag{55}$$

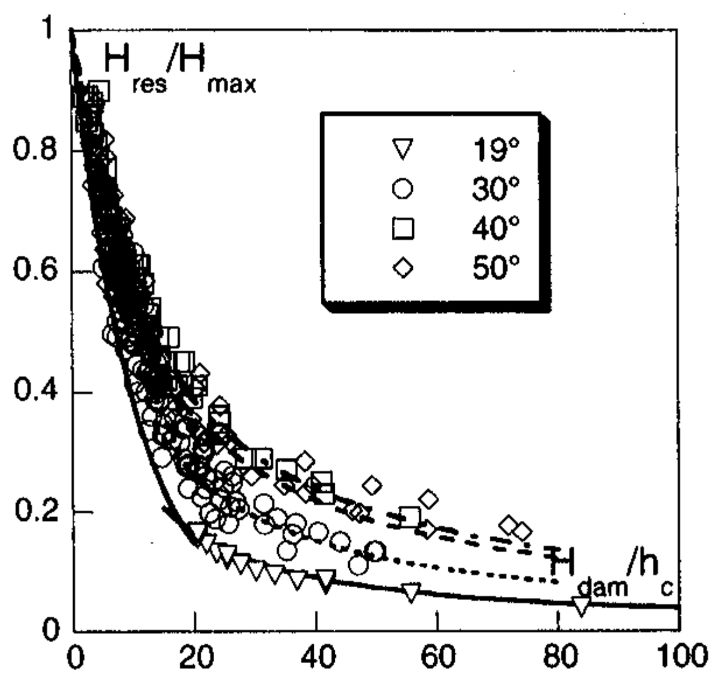

Figure 10. - Relative residual energy head ratio H_{res}/H_{max} as a function of relative spillway height, H_{dam}/d_c. (H_{dam}/h_c=H_{dam}/d_c) Data plotted is from θ= 19° (∇) Yasuda and Ohtsu (1999), and θ= 30° (○), θ= 40° (□) and θ= 50° (◊) Boes and Hager (2003b). (Courtesy of Boes and Hager (2003b))

Non-uniform flow conditions often exist when small dams are considered. Non-uniform flow will exist when terminal velocity and fully aerated flow conditions are not attained. These flow conditions often exist when a large unit discharge is passed by a low dam or even a relatively high dam if the unit discharge is very large. Most general lab and near-prototype studies have determined flow velocities, depths, and air concentration for uniform or quasi-uniform flow conditions. In addition, many site specific models have not had an adequate model scale to allow correct modeling of aeration characteristics (Yasuda and Ohtsu, 1997, 1999). There have been several site specific studies performed with no aeration under the design unit discharge, such as those by Rice and Kadavy (1996, 1997) for Salado Creek and Cedar Run 6 dams where uniform flow was also not attained as indicated by the velocity profiles. Also, studies by Christodoulou (1993), and Chamani (1997) and Chamani and Rajaratnam (1999) most likely did not reach uniform flow as indicted by large friction factors and low spillway heights.

In the non-uniform flow range, the energy equation is used to determine the friction factor based upon the friction slope not equal to the bed slope:

$$S_f = \sin\theta - \frac{d}{ds}SE \qquad (56)$$

where $S_f = -dH/ds$ with H equal to the total head, s is the streamwise coordinate. This leads to only estimates of the energy remaining in the flow (Chanson, 2001). Matos (2000) presented equations 33 and 34 for estimating the mean air concentration and clear water depth in the rapidly and gradually varying flow regions on a steeply sloping spillway chute. Matos (2005) computed the specific energy using air and velocity profiles down a steep stepped spillway in the rapidly and gradually varying flow regions. The specific energy increased significantly at the point of air inception and gradually increased in the gradually varied flow region. He presented an attempt to compute the friction slope over a steep stepped spillway. It was difficult to obtain accurate estimates of the friction slope, thus the friction factor, in these regions due to the waviness of the flow profiles. The conclusion was that the residual energy in the gradually varied flow region would be difficult to obtain with accuracy as air entrainment becomes a factor.

Boes and Hager (2003a,b) with estimations suggested by Chanson (1994b) provides the following equation to determine the residual energy head in the gradually-varied skimming flow region for slopes from $19° \leq \theta \leq 55°$:

$$\frac{H_{res}}{H_{\max}} = \exp\left[\left(-0.045\left(\frac{k}{D_h}\right)^{0.1}(\sin\theta)^{-0.8}\right)\frac{H_{dam}}{d_c}\right] \text{ for } H_{dam}/d_c < 15 \text{ to } 20 \qquad (57)$$

In addition, the hydraulic diameter is not approximated, but equal to the hydraulic radius or the area over the wetted perimeter of the chute.

Knowledge of the friction factor and an estimate of the air concentration profile allow the computation of the non-aerated flow depth along the chute for the gradually-varied flow profile through application of the standard step method; however, this is not considered very accurate.

Mateos and Elviro (2000) have performed extensive site specific studies and generalized flume studies of stepped spillway with various slopes. They propose that the energy dissipated by a stepped spillway is limited by the discharge to be equal to that of a smooth spillway of the same height when $H_{dam}/d_c < 10$. This is stating that if the flow depth is large or the dam is low then stepped spillways should provide no additional energy dissipation benefit over a smooth spillway of the same height. This does not seem to be supported by other studies; however, development of an upper limit for stepped spillway usefulness would be valuable.

Manipulation of Turbulence on Stepped Spillways

Recent literature includes several references by Gonzales & Chanson (2004, 2005) where vanes have been inserted parallel to the flow in the offsets of the steps. In addition, André (2004) investigated the use of end sills and spaced blocks to produce more turbulence, thus energy dissipation on stepped spillways. Both sets of experiments were performed on flatter embankment-type slopes. Both investigators assert that more energy is dissipated by the additional structures. It remains to be seen if contractors feel these approaches would be applicable for construction on an actual dam or is useful only in the understanding of the drag reduction over stepped spillways.

Wall Convergence

Several stepped spillways have been designed and constructed with converging chute walls. Some of these spillways were model tested; however, several were constructed without the benefit of model testing to ensure proper design of wall heights and energy dissipation.

Model Studies

The following two studies discuss the use of troughs to protect abutments and dissipate energy from flow over the top of a dam. The first is a rehabilitation project for an embankment dam; the second a newly constructed gravity dam.

The rehabilitation of Black Rock Dam was investigated to determine the hydraulic performance of a stepped overtopping protection on an existing 60-ft-high embankment dam with a 1.25:1 downstream slope and a damaged existing spillway on the left abutment. Two three dimensional 1:36 models were used to separately investigate the right abutment protection and the existing spillway modification with sections of the protected dam (Frizell, 1995). The unit discharge over the dam was large at 126.9 $ft^3/s/ft$. The right abutment design was a 20-ft-high 117 degree converging wall that formed a trough to collect and redirect the overtopping flow away from the outlet works and into a newly constructed RCC apron (figure 11). The existing spillway model was used to redesign the walls, redirect the flow and determine the length of the apron required at the toe. The spillway walls also converged producing a 246 to 439 $ft^3/s/ft$ increase in unit discharge at the toe. This model study is only discussed in regard to the highly converging wall on the right abutment. This wall is more of a trough than a typical wall convergence and is very site specific. The wall forced a hydraulic jump to form from the overtopping flows and didn't just convey the water downstream to a basin as would be a more typical application of wall convergence.

Figure 11. - Black Rock Dam with 117 degree converging side wall to protect the right abutment during PMF overtopping.

The stepped spillway for Nakasujigawa Dam in Japan was model tested in the hydraulic laboratory of the Public Works Research Institute of the Ministry of Construction (Hakoishi and Sumi, 2000). Several models of various scales 1:31.25, 1:20, and 1:10 were used to determine the final geometry of the main overflow section and the severely converging walls abutment training walls to the foot or toe of the dam. The final result was the selection of a stepped face with 2.5-ft-high steps and troughs with steps to transport the flow down to the narrow toe of the dam. The steps were chosen because the flow depths in the troughs were less with the stepped face and troughs than with smooth surfaces. This study was very similar to the Black Rock Dam study and is also very site specific.

These two studies; however, indicated that the turbulence and jet break up from the stepped surfaces can benefit projects by allowing more convergence and reducing wall heights compared to smooth spillway surfaces.

More traditional converging chute walls were studied for Pilar Dam in Brazil (Hanna and Pugh, 1997). This site specific model study was conducted with a 1:40 scale, which precluded modeling aeration aspects. The 213-ft-high dam had a steep 0.8:1 slope with a 590-ft-wide crest and a convergence angle of 16° with 2-ft-high steps (figures 12 and 13). Unit discharges up to 150 $ft^3/s/ft$ were investigated. Velocities were not measured but computed assuming n=0.013. A Manning's n value of this magnitude would produce conservative velocities. The water surface profiles along the converging walls consistently showed an increase at the location of the flow aeration. An additional 37 percent wall height was recommended based upon the lack of model aeration. The residual energy computed to remain in the flow was 30 percent or 70 percent of the energy was dissipated by the steps. The sweepout discharge in the stilling basin was used to compute the energy dissipated by the steps.

Figure 12. - Pilar Dam model of a steep stepped spillway with converging side walls, Q=35,300 ft^3/s. Note the flow concentrations along both ends of the stilling basin.

Figure 13. - Pilar Dam model of a steep stepped spillway with converging side walls, Q=70,600 ft^3/s. Note less flow concentration along the ends of the stilling basin.

McClure Dam modifications were modeled in a 3D model with a 1:30 Froude scale of the embankment dam and existing service spillway (Frizell, 1990). The RCC section over the 2.18:1embankment slope was 167-ft-wide and 108-ft-high with 0.8:1 sloping side walls containing the flow. One and 4-ft-high steps were modeled with a 0.8:1 chamfer on the 4-ft-high steps. Unit discharges up to 148.5 $ft^3/s/ft$ were tested, figure 14, and velocities were measured with no convergence and convergence angles of 5.6, and 12.68 degrees. Aeration occurred on the face of the stepped spillway for all flows including the design flow; however, the model scale did not allow full similitude of aeration effects. No measurable difference was obtained between the velocity results for 1 and 4 ft step heights; however, there appeared to be a slightly less turbulent hydraulic jump closer to the toe of the dam for the 4-ft-high steps. The model measurements indicated that 53 percent of the total energy available was dissipated by the steps. The 12.68° convergence was recommended. This modification was never constructed as the owner decided to go with a different alternative.

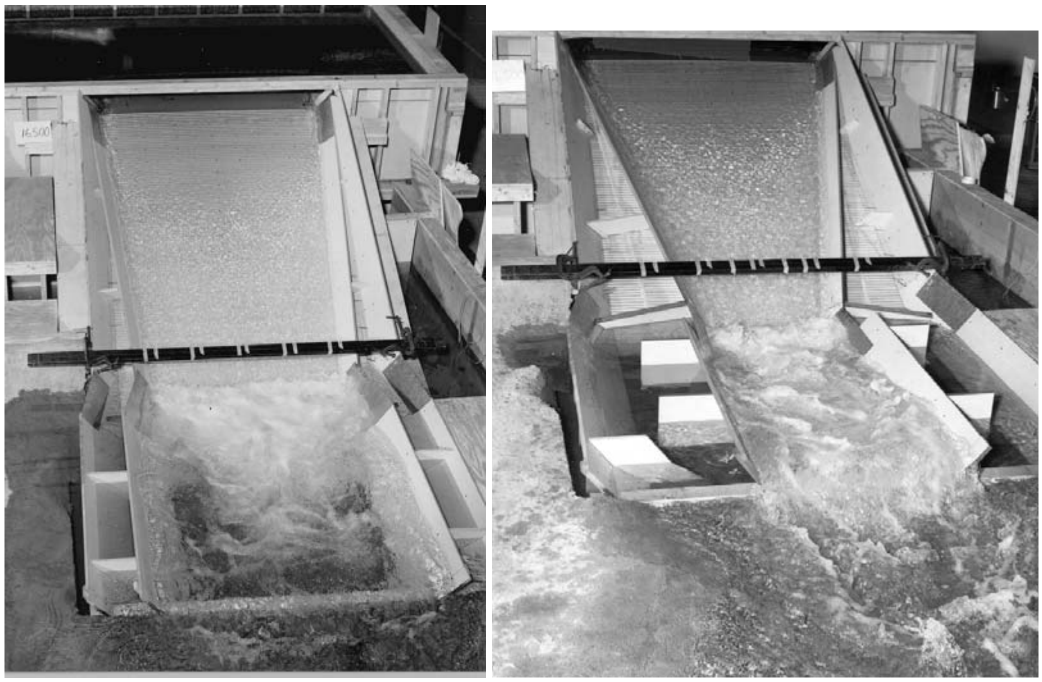

Figure 14. - McClure Dam model with 5.6° and 12.68° side wall convergence (left and right photos) with 1-ft-high steps on a stepped spillway over a 2.18:1 sloping embankment dam.

Randleman Lake Dam (Talbot et al., 1997; Robinson et al., 1998) was modeled with both 2 and 3 dimensional models of 1:40 Froude scales. The 2 dimensional tests were conducted in a 2.5-ft-wide flume to size steps and investigate energy dissipation on the 0.75:1 steeply sloping chute. Smooth, 3 ft and 6 ft-high steps were investigated for discharges up to 400 $ft^3/s/ft$. Little difference in velocity or performance was documented between the two step heights. The percentage decrease in total energy for either height step averaged 42, 37, and 34 for unit discharges of 200, 266, and 400 $ft^3/s/ft$, respectively. Three foot high steps were selected because there was little difference in energy dissipation, better performance at low flows, and easier construction. The 3 dimensional model investigated wall convergence aspects with the 3-ft-high steps. Results were that wave run up and wall overtopping occurred with the 32.5 degree converging wall and that the 20.9-degree wall convergence matched the flow contraction at the crest abutment, thus producing acceptable flow conditions. Acceptable energy dissipation occurred for both due to the high tailwater conditions. Non-aerated flow conditions were reported and the model scale was too small to model aeration characteristics.

Two publications (in Portuguese) were recently obtained (André et al., 2005; André and Matos, 2005) regarding small scale flume testing of a half chute with one converging side wall with a smooth chute, and two step heights. The study was quite thorough, although limited by the size of the facility in both height and width. The initial conclusions from this study were that the energy loss on stepped chutes with side wall convergence, determined by measuring the sequent depth of the hydraulic jump, was similar to that obtained on constant width chutes. The difference in energy loss was less than 11 percent and within 5 percent on average. The increase in flow depth along the converging wall was significant on the smooth chute, but mitigated to 1.3 to 2.8 times the flow depth of a constant width chute with steps. The increase in flow depth caused by cross waves from the converging wall, tended to decrease with increasing step roughness. Near the end of the chute, a reduction of 40-50 percent in the wave run up was attained with a stepped versus a smooth converging chute.

For an improperly designed converging section, shock waves form after impingement on the walls and transfer downstream (USBR, 1987). Separation of the flow from the wall may also occur. Flow run up also occurs. Stepped spillways with the roughened surface seem to be characterized by less shock wave formation, but still results in run up along the converging walls.

Results from a new study by the Agricultural Resource Service (Hunt, et al., 2005) show that flow run-up near the walls increases with an increase in wall convergence angle. No transverse waves were observed in the chute with any of the wall convergence angles tested. The influence of the wall convergence was noted across the width of the chute. Design values for increasing the wall heights in terms of critical depth for the various wall convergence angles are given. The model scale did not allow for accurate modeling of aeration, as pointed out by the authors.

Constructed Dams

There have been several dams constructed with converging side walls without the benefit of model studies. The list is probably not complete as often the projects are constructed by private consulting firms without consideration of energy remaining at the toe of the spillway, due to the ease of construction with RCC.

Spring Creek Dam, near Gunnison, Colorado, was constructed by Morrison and Knutson in 1986 and was the first embankment dam to be modified to increase spillway capacity using RCC (figure 15). The RCC overtopping section is designed to pass the PMF discharge of 20,000 ft^3/s. The dam is 50-ft-high with the overtopping section 250-ft-wide at the crest and converging side walls. The downstream slope was formed with 1-ft-high steps over a 2.3:1 slope near the crest that flattens to 3:1 further down the slope. The right wall was formed by the existing service spillway and the left wall of a massive sloped RCC section. This construction technique has since become popular.

Figure 15.- Finished RCC overtopping protection at Spring Creek Dam with 1-ft-high steps and converging side walls. (Courtesy of MK Engineers, Denver, CO)

Vesuvius Dam, a 35-ft-high, about 400-ft-long Forest Service dam has been rehabilitated using RCC (Bureau of Reclamation, 2000). The 2.5:1 downstream slope was covered with stepped RCC to form a 360-ft-wide spillway with a 50-ft-long stilling basin at the toe. A uniquely shaped spillway was rehabilitated on the left abutment with the right dam abutment protected by placing sloped RCC on a short, 44 degree converging side wall that directed flow away from the abutment and towards the river channel.

Gas Transfer on Stepped Spillways

Highly aerated stepped spillway flow could be used to improve water quality on projects where low dissolved oxygen or highly supersaturated flow conditions exist. These seem to be dissimilar goals, but the common goal would be to produce aerated flow near saturation levels at the toe of the stepped spillway and prevent plunging of the flow to depth in the channel below, thus causing potentially supersaturated dissolved gas levels.

McKenna (2001) performed prototype scale model studies to evaluate the transfer efficiencies of a smooth spillway surface and 1 and 2-ft-high steps on a 26 degree sloping flume about 50 ft high. Flow into the flume was supersaturated with nitrogen gas. Unit discharges tested ranged from 5 to 20 $ft^3/s/ft$. Total dissolved gas measurements were made at various locations down the flume slope.

The results from this study were:

- A stepped spillway was more efficient at transferring dissolved gasses than a smooth spillway
  - Transfer efficiencies were a minimum (0.444) near the top of the smooth chute for 15 $ft^3/s/ft$ and a maximum (0.991) at the bottom of the stepped slope for 5 $ft^3/s/ft$.

    - Larger steps produced slightly higher transfer efficiency
- Flow rate and vertical drop had a larger influence on transfer rate than step height.
    - At the toe of the spillway, transfer efficiency was the same for the smooth and stepped chute
    - Lower drops, in the developing flow region, showed much greater benefit to gas transfer efficiency
    - Decreasing the unit discharge by 5 ft^3/s/ft produced a larger gas transfer than increasing step size.

Low dams with large steps and small unit discharges could be valuable in transferring gas to improve water quality.

Northwest Hydraulic Consultants, Inc (1998), and Ahmann and Zapel (2000) performed a model study at a 1:8 scale of a stepped spillway with and without fillets in the notch of the steps. The study was performed as part of the US Army Corps of Engineers Gas Abatement Program for the Pacific Northwest Columbia and Snake Rivers. They investigated slopes of 45, 26, and 18 degrees with step heights representing 2 or 4 ft and unit discharges representing 29, 42, 60, and 85 ft^3/s/ft in the prototype. Their work was being performed to investigate the possibility of using stepped spillways to decrease total dissolved gas supersaturation and for downstream fish passage. Energy dissipation is considered key to preventing the flow from plunging to great depths, thus supersaturating the downstream river.

The investigators found that use of triangular fillets in the step offsets reduced turbulence thought hazardous to juvenile fish but maintained similar energy dissipation characteristics as the full steps. The parabolic fillets reduced the energy dissipation characteristics.

Toombes and Chanson (2000), and Chanson and Toombes (2002e) studied gas transfer in the nappe flow regime over stepped cascades proposed for use in improving water quality. They performed experiments on long relatively flat chutes and measured air concentration, velocity and bubble frequency. Their findings were that a long stepped cascade was at least 10 times more efficient for re-oxygenation purposes. These results were not compared to actual measurements of dissolved oxygen content.

Summary of Important Hydraulic Model Studies

The most important practical works for stepped spillways include those that represent correct scaling of aeration effects and use appropriate techniques for determining flow depth, air concentration, velocity and computation of residual energy.

The recent laboratory studies by Matos et al., Boes et al., Chanson et al., from 2000 to current, and Andre (2004) provide the most comprehensive studies. The work by Andre (2004) particularly addresses flatter embankment slopes of 1.73 and 3:1. The prototype studies of Gaston (1995) and Ward (2002) represent the most appropriate studies on embankment slopes.

Research Needs

This current state-of-the-art report goes a long way towards the preparation of a summarized design tool for stepped spillways with embankment dam or steeper gravity dam slopes. However, further research is still needed to confirm specific aspects of stepped spillway design.

The research needs for stepped spillways will be discussed in four separate categories:

- Hydraulics of embankment dam stepped spillways.
- Structural aspects of embankment dam stepped spillway overlays.
- Hydraulics of stepped spillways for steep gravity dams.
- Environmental aspects of stepped spillways.

In each category the proposed research will be listed in order of highest to lowest priority based upon the author's opinion.

As a starting point, the general opinion on research needs relating to dam service or emergency spillways was determined at the Federal Dam Safety Program sponsored a workshop entitled "Issues, Remedies, and Research Needs Relating to Dam Service and/or Emergency Spillways" in August 2003 (Bureau of Reclamation, 2004). The workshop was hosted by Reclamation in Denver, Colorado. Two of the categories identified by the attendees for needing future research were:

- RCC structural aspects when placed over an embankment dam and
- Hydraulic design aspects of stepped spillways.

These broad categories had several topics under them as shown in table 4.

Table 4. - Research topics relating to stepped spillways from the "Issues, Remedies, and Research Needs Relating to Dam Service and/or Emergency Spillways," workshop. Letters refer to the topics as listed in the final report.

Topic letter	***RCC and Other Dam Overlays***
H	Develop a guideline document to be used by designers and review agencies that includes: • Design criteria for groin flow, constriction areas and energy dissipation. • Design criteria regarding drainage blanket/filter criteria and foundation uplift

pressure.
• Long-term effects of differential settlements on RCC stability under flow conditions.

L Develop guidelines to address the following aspects of RCC overlays:
- Determine energy dissipation characteristics of weathered RCC steps.
- Conduct research on hydraulic issues associated with RCC overlay thickness based on upon unit discharge
- Define upper limit for unit discharge with stepped spillways.
- Dynamic effects of water pressure transmitted to the foundation through cracks in the RCC.
- Determine design criteria for stepped spillway energy dissipater.
- Determine flow characteristic and energy dissipater with stepped spillway
- Side wall convergence.
- Determine relationship of various height and shaped steps and energy dissipation.
- Determine flow conditions upstream of the point of inception for high discharges and for a wide range of dam heights.
- Effects of slope on air entrainment and energy dissipation.

N Compile historical information on performance of spillways on non-rock foundations or spillways on embankment dams (how have they failed, uplift/seepage/foundation-how have they operated)

Stepped Spillway Design

M Document and finish research where needed for hydraulic design criteria, including limitations on step effectiveness for typical formed RCC stepped embankment slopes.

O Determine crest profiles for gated stepped spillway.

P Determine cavitation potential and designs for artificial aeration.

Q Determine model/prototype scale effect.

Of interest to this report is that coincidentally, topics H and M were ranked as the highest priority out of the entire workshop, by the evaluation of the attendees. Topic L includes repetition of many of the items in topic H and more specific aspects of topic M. These ideas will be incorporated into the general prioritized research list developed under each heading.

Hydraulics of Embankment Dam Stepped Spillways

Suggestions for further research regarding the hydraulics of stepped spillways for embankment dam slopes are proposed in the following areas:

- Perform comparison of the proposed formulas to determine if there is adequate information for design of stepped spillways in the uniform skimming flow region.
- Investigate residual energy in non-uniform or not fully developed flow regimes

- Gather data from existing models of adequate size and determine if it is possible to determine residual energy at various locations downs the slope in the non-uniform flow region*.
  - If not, then use an adequately scaled flume facility to gather data on a flatter slope to determine residual energy at various locations downs the slope in the non-uniform flow region..

- Determine the unit discharge for a given dam height where the stepped spillway energy remaining equals that of a smooth spillway.
- Chute wall convergence affects on flow depths and residual energy at the toe of the spillway
  - Use a scale model of an embankment slope of adequate size to modify the wall convergence angles and measure flow depths, velocities and air concentrations to determine residual energy.
    - Initial research shows that the step roughness attenuates formation of cross waves, and reduces run up on the converging walls compared to smooth spillways. In addition, it seems that the energy dissipation is similar to that of a non converging stepped chute, but the effects of increasing unit discharge with convergence at the toe still needs to be investigated. (Recently, the USDA, Agricultural Resource Service Laboratory has begun studying the affects of wall convergence on stepped spillways with embankment dam slopes, (Hunt, et al, 2005. "Impact of Converging Chute Walls for RCC Stepped Spillways".)

*Information provided by Boes, Chanson, and Matos goes a long way towards achieving this goal. The residual energy is explained by André (2004) as a function of a dissipation coefficient. This approach includes both form drag and friction loss and may be the logical way to proceed in further research. This is because the designer is not really interested in what causes the energy loss, but what the actual loss is.

Structural Aspects of Embankment Dam Stepped Spillway Overlays

Structural aspects of RCC construction, operational features, and durability over an embankment need to be investigated:

- Design criteria for construction of groin areas including additional loading at walls, cutoff walls and energy dissipator foundation requirements.

- Design criteria regarding drainage blanket/filter criteria and foundation uplift pressures.
- Long-term effects of differential settlements on RCC stability under flow conditions and durability of the RCC after repeated operation
    - Includes potential erosion of the RCC and how the steps and stilling basin features have withstood pressure fluctuations.
- Compile historical information on performance of spillways on non-rock foundations or spillways on embankment dams (how have they failed, uplift/seepage/foundation-how have they operated)

It is suggested that the design and operational features be addressed at a full-scale test facility or prototype structure that could be easily monitored where RCC is placed over an actual embankment.

The historical performance of existing spillways, whether stepped or not, on embankment materials would be accomplished using existing databases, internet searches, ASDSO member surveys, etc.

Hydraulics of Stepped Spillways for Steep Gravity Dams

Suggestions for further research regarding the hydraulics for stepped spillways for steep gravity dam slopes match that of flatter embankment slopes with the addition of the following proposals:

- Cavitation potential upstream from the point of aeration inception
    - This is an issue for high dams more than for embankment dams.
- Determine the crest to slope transitions necessary with a gated stepped spillway crest
    - This is not a high priority and could potentially be accomplished analytically or by adding gates to an existing flume study.

Investigators disagree as to the definition of the inception point for aeration, thus at what location on the slope adequate air will be present along the pseudo-bottom to prevent cavitation. Investigation of the inception point and cavitation potential could be performed at the Reclamation's Water Resources Research Laboratory in the low-ambient pressure chamber test facility. The work would include determining the velocities near the pseudo-bottom, possibly using PIV instrumentation, air concentration measurements, and applying a pressure in the facility low enough for cavitation to occur if the geometry and flow velocities are appropriate. A just acquired paper by Amador, et al, "Characterization of the flow field in a stepped spillway by PIV", University of Catalunya, Barcelona, Spain discusses this very idea.

Environmental Aspects of Stepped Spillways

There are two areas where stepped spillways may be utilized to improve the environment:

- Improving water quality through degassing or oxygenating waters
- Investigating fish passage over small in-river stepped structures.

Studies are currently ongoing in Reclamation's Water Resources Research Laboratory regarding stepped spillways and fish passage under the nappe flow regime with 1-ft-high steps that shows promise. Additional work could be performed on other step sizes and larger flow ranges to determine the affect on fish injury or mortality..

Improvements in water quality could be further investigated in a large scale-facility as performed by M^{c}Kenna (2001) at Colorado State University. Additional research is needed to determine the transfer efficiency of different step heights at various locations along a slope with a facility that has a large range of flow capability.

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