Presentation 6:
Spillway Foundation Erosion

Dam Safety Workshop
Spillway Foundation Erosion

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Spillway Components

- Entrance channel
- Crest/control structure -- ungated, gated
- Conveyance -- chute, conduit, tunnel, or combination
- Terminal structure -- stilling basin, flip bucket, plunge pool

- Incidence of spillway foundation scour is relatively low
  - Cause generally result of discharge greater than design.
- Foundation undermined by scour from downstream
  - Major damage
  - Time constraints
  - High repair costs
  - Reservoir operations affected by foundation scour

Gibson Dam

June 8, 1964
20 hour duration
1 m overtopping

1979 Modification
$1,240,000

Colorado State University Experimental overtopping and foundation erosion facility

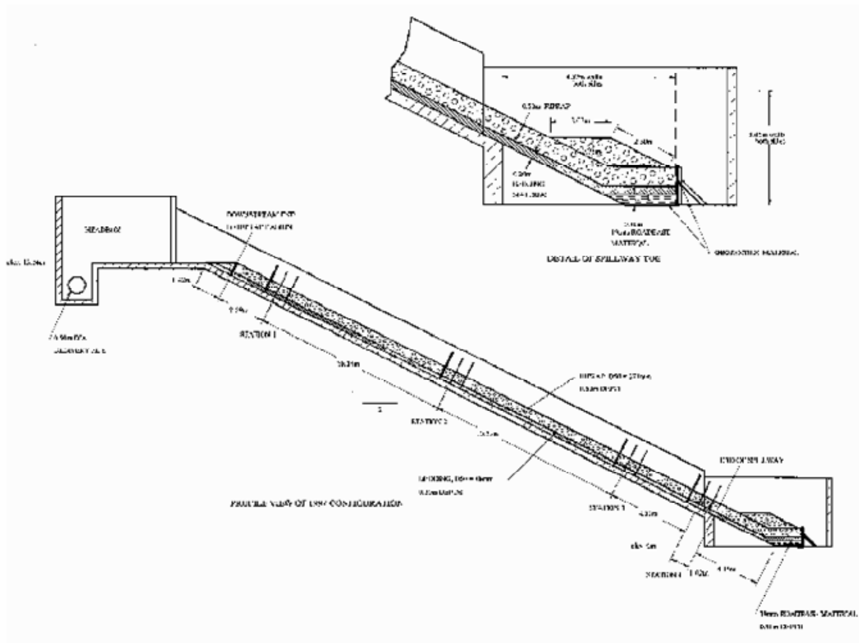


Figure 3.9: 1997 layout of the riprap slope with the piezometer towers before testing

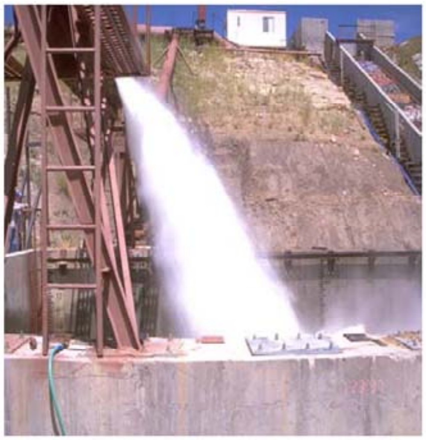
Scour Prevention & Research
Focus on Depth, Rate

Spillway models - component testing
- Small scale
  - estimate scour depth and location
  - pressures on chute and in stilling basin

Foundation erosion by plunging jets
- Near-prototype scale
  - gravel bed
  - simulated rock

Foundation protection
- concrete blocks
- riprap chute and toe

Scour of simulated fractured rock

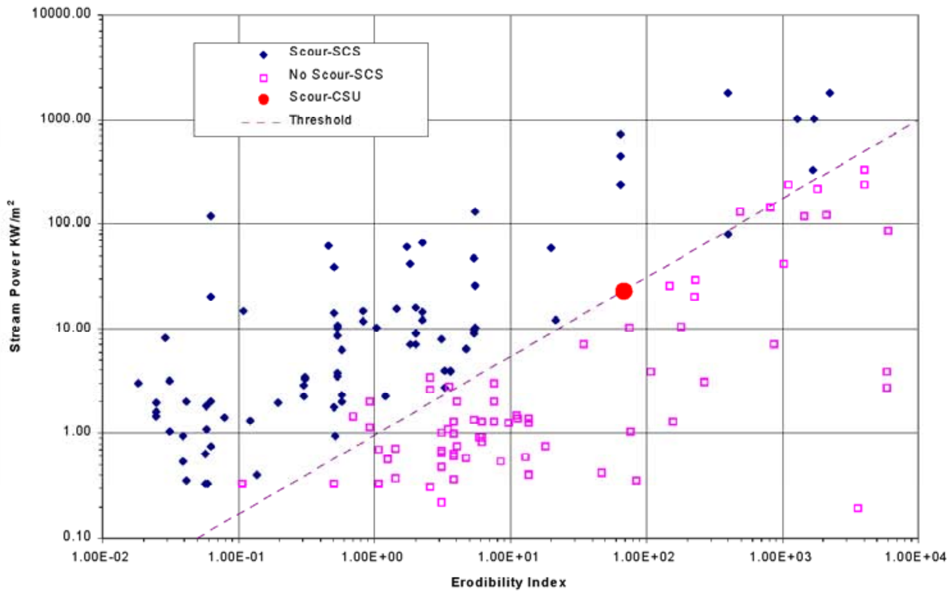


Spillway riprap protection

Figure 3.10: Numbering of rocks in 1995

Figure 4.9: Large plumes of water (1995) (Q=2.12 m^3/s)

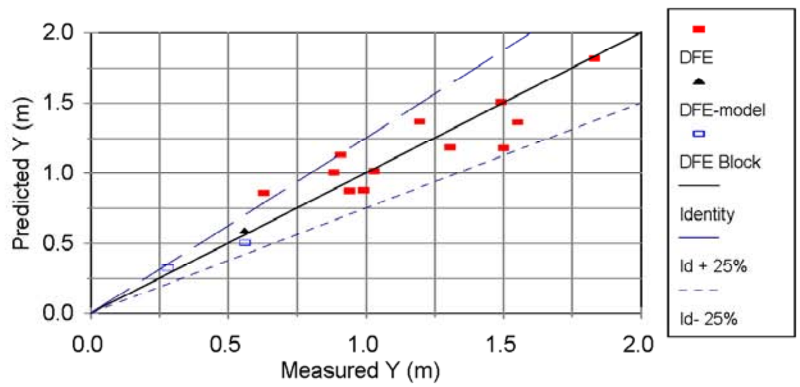
Prototype foundation scour data



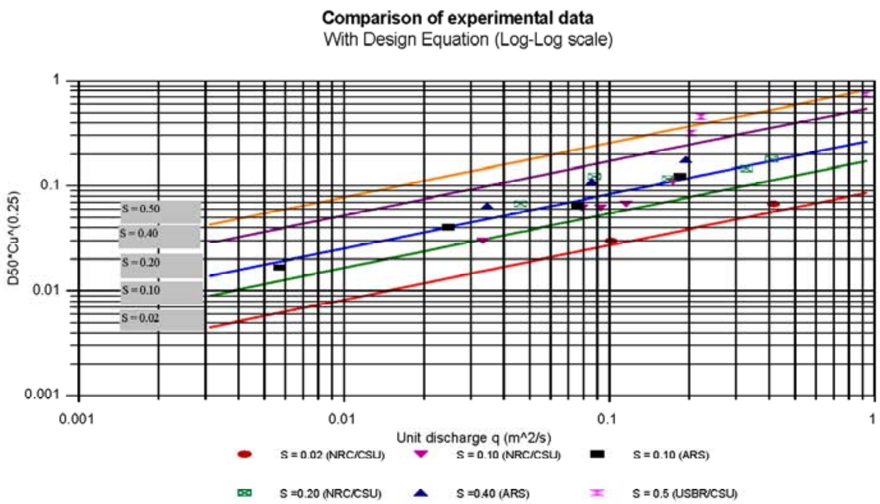
CSU Foundation scour depth equation for non-cohesive material and simulated fractured rock

$$\frac{Y}{y_c} \cong 3.111 \frac{\left(\frac{V_i}{\sqrt{g b_i}}\right)^{0.07}}{\left[\frac{(TW/\cos\delta)}{b_i}\right]^{0.39}\left(\frac{w}{\sqrt{g\ b_i}}\right)^{1.13}} \qquad (6.5)$$

CSU Foundation scour depth equation for non-cohesive material and simulated fractured rock

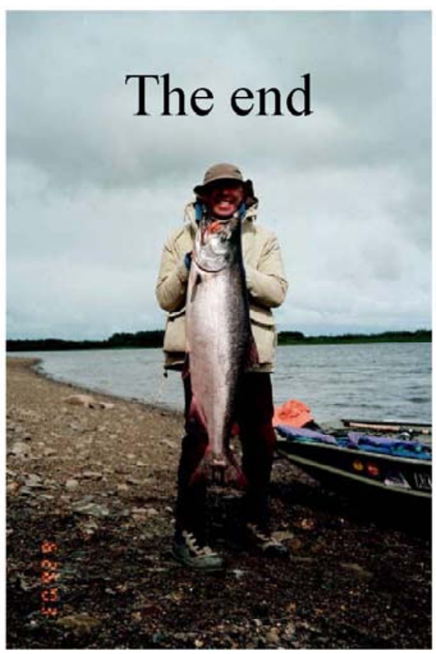


Universal design equation for overtopped riprap



Research needs on dam spillway foundation erosion

- Evolution of velocity and air concentration profiles along the jet, namely at the impact with plunge pool free surface.
- Lined plunge pools – slabs and foundation drainage design criteria.
- Mechanism of rock erosion due to the spillway operation and development/improvement of physically based analysis models.
- Prototype data collection for the improvement of scour prediction formula.
- Scour depth and shape evolution versus time of operation and hydraulic / geologic parameters.
- Evaluate effects of jet entry angle on plunge pool performance and scour.
- Investigate near-prototyope riprap protection at additional slopes.



Presentation 7:
Dam Overtopping Protection Technologies
State of Practice and Research Needs

DAM OVERTOPPING PROTECTION TECHNOLOGIES

STATE OF PRACTICE AND RESEARCH NEEDS

Kathy Frizell
US Bureau of Reclamation
Water Resources Research Laboratory
Denver, CO

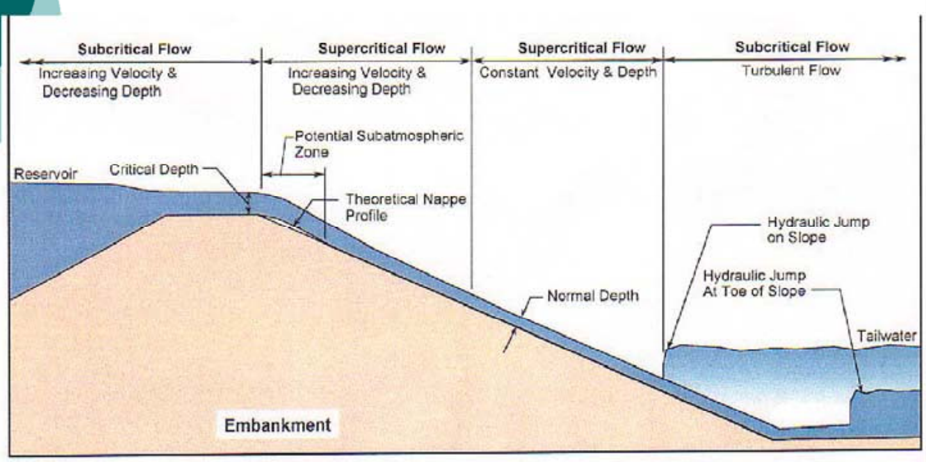
Overtopping Technologies

- Earthen embankments
- Grass covered earthen embankments
- Geotextiles & Membranes
- Gabion/Reno mattresses
- Riprap
- Concrete blocks
  - Cable-tied, interlocking, overlapping
- Soil cement
- Reinforced concrete slab
- RCC
  - Smooth
  - Rough lifts
  - Formed steps
- Stepped spillways over embankment or concrete dams
  - Formed RCC or reinforced concrete

Introduction

- Many options
- Overtopping protection methods all have hydraulic criteria that must be met
- VERY brief discussion of each method
- Design guidance or limitations
  - Based upon testing or field performance
- Maintenance requirements
- Research needs

Hydraulics of Overtopping



Earthen or grass lined embankments

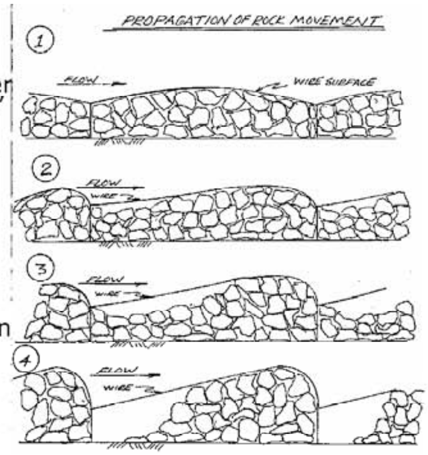
- Cannot add anything to Darrel's discussion!
- Grass covered limitations:
  - Overtopping up to 1.5' of head, short duration, velocities less than 12 ft/s.

Geotextiles & Membranes

- Protective fabric is placed over compacted earth w or w/o a filter
- FHWA tests: Enkamat w/asphalt, 2:1 slope, 6' high dam, V=13 ft/s; Geoweb, V=9.5 ft/s
- USBR field test: 36 mil Hypalon geomembrane, 6:1 slope, 19' high dam, V=10-25 ft/s
- Design & Construction
  - Must be placed over smooth surface
  - Must be anchored at crest, toe, sides
  - Must be covered for durability
  - Seams must overlap

Rock or Reno Mattresses

- Performance – FHWA & CSU testing
- Mattresses placed flat over slopes up to 2:1 with 3-6" size rock
- Design based upon shear stress of flow and critical shear stress of mattress
- Thickness 1.5*max rock size
- Max Velocity 24 ft/s
- Filter required
- Case 3 is max deformation allowed
- Grouting helps stability
- Anchoring essential!



Gabions

- Gabion baskets are filled with 4-8" rock and stacked leaving a stepped surface on slopes of 2:1 or greater
- Used where mattress criteria is exceeded; steeper slopes & higher velocities
- Performance – Peyras model testing
  - Dam ht. up to 3.3', slopes of 1:1, 2:1 & 3:1, gabions stacked from 2 to 7 steps high, q=30 cfs/ft, V= 20 ft/s
  - Design equation based upon slope, ht., q, allow determination of depth at the gabion slope toe for stilling basin design
- Manufacturer's: Maccaferri (w/design software) & Terra Aqua

Riprap

- Protection is achieved by placement of a designed rock size over an embankment slope or designed spillway channel
  - Application to fuse plug erosion rates and unintentionally overtopped riprap embankment slopes
- Design criteria for riprap size & layer thickness for steep slopes using existing experimental data (including ARS) and data from CSU test program

Test Facility

- 10′ wide, facility q=16 cfs/ft
- Dumped over angle iron & 8″ bedding
- Open frame or down full slope with toe berm
- Rock sizes tested: D_{50}=15.1″, D_{50}=25.8″ over previous, D_{50}=10.7″ full slope & toe (photo)

Flow Conditions, Measurements, Failure

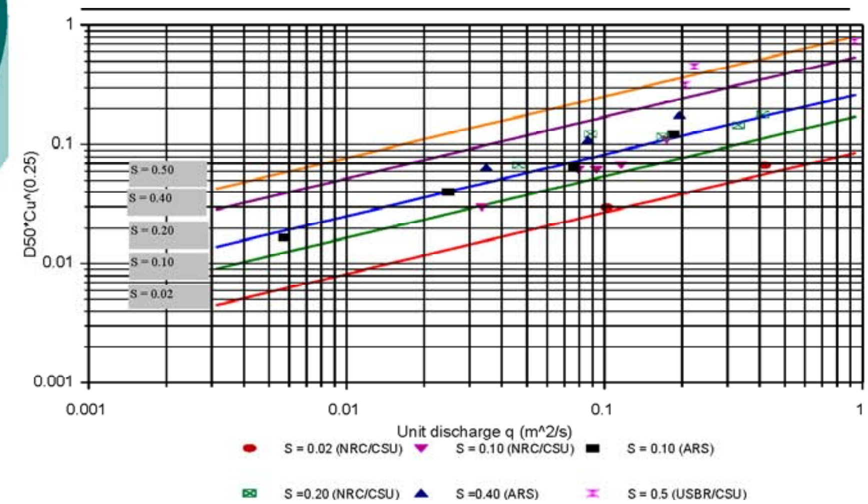
- Measured Q, V_i, d
- Velocities in each layer constant
  - Flow beneath the rock surface for 2:1 slope
- Failures (bedding exposed):
  - D_{50}=10.7″,q=2.2 cfs/ft
  - D_{50}=15.1″, q=2.4 cfs/ft
  - D_{50}=25.8″, q=10 cfs/ft

15″ rock

10.7″ rock
1.5 cfs/ft

Total failure
10.7″ rock

Riprap sizing chart based upon q, slope and rock properties – no SF



Riprap Performance

- Design chart and equation provides stable stone size as a function of discharge, stone gradation, and slope.

$$D_{50}C_u^{0.25} = 0.55(q_f)^{0.52}S^{-0.75}\left(\frac{\sin\alpha}{(2.65\cos\alpha - 1)(\cos\alpha\tan\phi - \sin\alpha)}\right)^{1.11}$$

- Layer thickness is a function of discharge, interstitial velocity, stone size and slope.

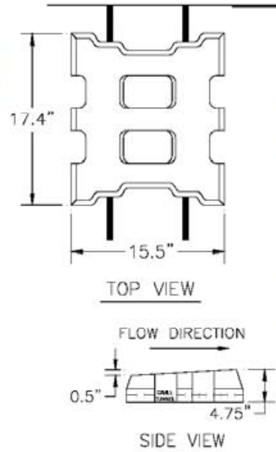
$$\frac{V_i}{\sqrt{(gD_{50})}} = 2.48C_u^{-2.22}S^{0.58}$$

- Interstitial flow for 2:1 slope, flow depth may exceed riprap layer thickness for slopes < 4:1
- Historically, min of $2D_{50}$ or D_{100}.
- Toe more stable than slope.

ACB's

- Concrete block systems widely varied geometries, test programs, applications
- Cable-tied
  - Weight, shape, filter, cabling for stability
- Interlocking
  - Weight, shape, interlocking, filter, careful placement for stability
- Overlapping
  - Shape, filter, maintaining overlap for stability

Cable-tied Concrete Block
Tested ArmorFlex Tapered Unit



Wt. = 66 lbs

Thickness = 4.75″

Forces on block evaluated under high velocity installation over compacted earth in CSU flume facility

ArmorFlex Mat Delivery

Strahl Lake Dam, Indiana, DNR

- Cable-tied mat sections
- Close up of cable tie section

Strahl Lake Dam

- Crest construction
- Completed system
- Grass covered system

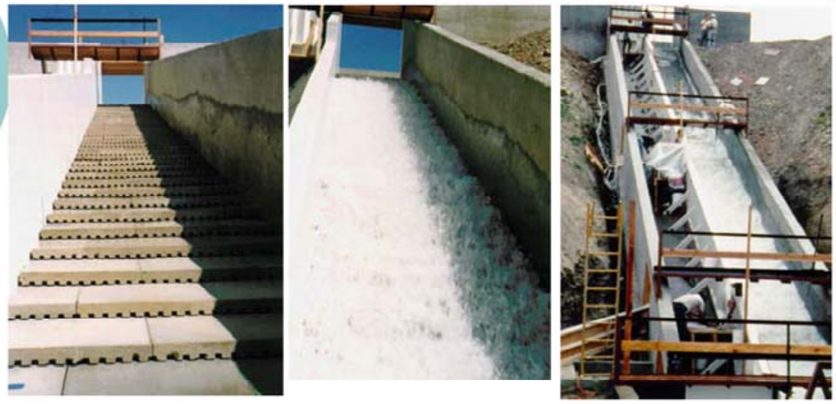
Armortec Tapered Cable-tied Block Design Factors & Performance Data

- Must anchor the crest and provide flow barrier.
- Drainage system enhances performance and is recommended.
- Successfully withstood test with 16- ft-high, 2:1 sloping embankment
  - q=20 cfs/ft, 4' of head, V=26 ft/s, shear stress= 25 lbs/ft^2
- Use maximum velocity and flow depth to determine product needed.
- The hydraulic jump should occur on an armored or non-erodible surface to prevent headcutting and undermining of the ACB layer.
- Needs uni-directional flow over the embankment surface.
- Make sure the specified product has been evaluated under high-velocity testing conditions with steep slopes.
- Maintenance:
  - Keep the protected slope and toe clear of woody vegetation.
  - Prevent vandalism or removal of block units.

Interlocking Concrete Blocks

- Conlok, Tri-lock, Armortec, others
- Testing
  - FHWA/Armortec/SAF
- Design guidance – Generally not as good a product for overtopping protection as other block systems.
- Construction – Critical feature of interlocking block systems exposed to high velocity flows. ANY portion of the block edge exposed to flow impact can fail the system. Install where base surface has NO discontinuities.
- Maintenance
  - Keep the protected slope and toe clear of woody vegetation.
  - Prevent vandalism or removal of block units.

Overlapping Tapered Concrete Wedge Blocks Performance Testing (Armorwedge)

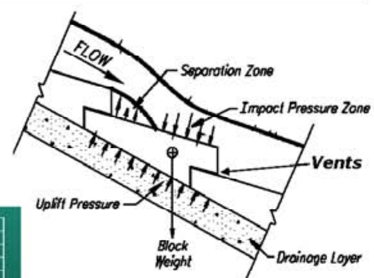


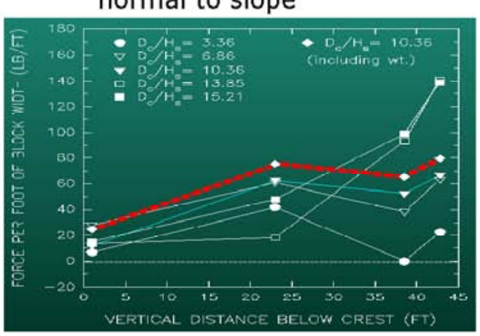
50-ft-high, 5-ft-wide, q=32.2 cfs/ft, blocks placed over angle with gravel filter, anchored at 3rd points on slope, held at toe.

Top slope, 4<hs/l<6, 2.8% vent area on face, min thickness 2″

Forces Acting on the Overlapping Tapered Wedge Block

- Inherently stable
  - Impact on tread & relief of uplift at low pressure zone by aspiration through vents
- Analyzed forces as sum normal to slope





Overlapping Tapered Concrete Block Performance Data

- Successfully withstood maximum flow from test facility:
  - q = 32 cfs/ft, overtopping depth ≈6.5 ft, velocities > 40 ft/s
  - Friction factor, f=0.08
  - Mean air concentration, C=0.39
  - Failed only after block was pried out of the matrix using 600 lb_f

Soil Cement

- Many designs protecting embankments with soil cement either rolled flat over the slope or in stepped lifts. (Freese & Nichols experienced designers)
- Similar to RCC except not the same mix strength
- Hydraulic characteristics the same as RCC and defer the discussion to then.

Reinforced Concrete Slab

- Concrete slab designed over an embankment or rock-fill dam
  - A.R. Bowman Dam (U.S.) feasibility design (full coverage)
  - Crotty Dam – Australia- spillway section
- Critical design features:
  - Drainage system
  - Preventing slab cracking and offsets
  - Designing for influence of tailwater and jump over slab

RCC

- Revolutionized dam rehabilitation & new dam construction
  - Rejuvenated the issue of stepped spillway design
- Ken Hansen will discuss

Stepped Spillways – Formed RCC or Reinforced Concrete

- Located over entire or a portion of the dam or on a separate abutment
  - Discuss embankment dam slopes as that is typically what is thought of when referring to "overtopping".
- Step ht typically driven by construction techniques
- Useful for energy dissipation
- Test programs – incredible number
- Design guidance – controversial
- Maintenance:
  - Ensure concrete is in good shape and cracking minimized

Large-scale Flume Facility – 2-ft-high Steps

Nappe flow – q=5 cfs/ft

Large-scale Flume Facility – 1-ft-high Steps

Skimming flow – q=15 cfs/ft

Embankment Slope Step Designs

- Optimum step ht. $h/d_c \approx 0.3$
- Use air concentration & velocity data to determine energy remaining in the flow.

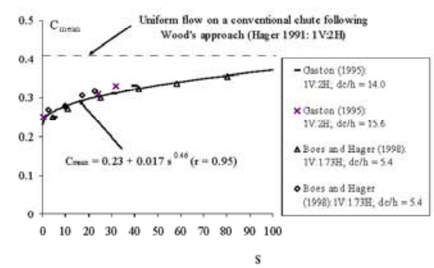
$$d = (1 - C_{mean})\,Y_{90}$$

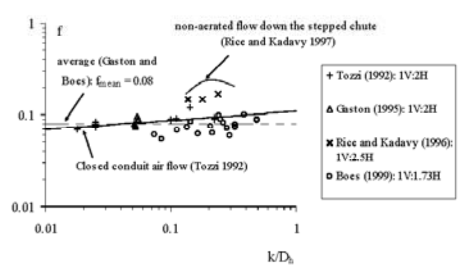
- Assumes uniform flow is attained.

$$U_w = \frac{q_w}{d}$$

- Shows that friction factor is nearly constant over a range of step ht. to hydraulic diameter.

$$f = \frac{2\,g\,\sin\alpha\,D_h}{U_w^2}$$





Hydraulic Design Considerations

- Calculate distance down the slope and depth at the aeration inception point. C_{mean}=0.23
- Determine mean air concentration down the slope
- Training wall height equal to the $Y_{90} = f(C_{mean},$ depth, friction factor)
- Energy at toe= *f(*dam ht, slope, head, friction)
- Design stilling basin using water depth and velocity.
- Cavitation damage has not occurred with designs to date, but might need to be considered for large q.

Design Criteria

- Debate: test facilities and data acquisition methods have dramatically varied. Which is correct?
  - Jorge Matos, IST, Portugal
  - Robert Boes, VAW, Zurich, Switzerland
  - Stephanie Andre, EPFL, Lausanne, Switzerland
  - USBR/CSU
  - Hubert Chanson, University of Queensland, Australia
  - Many other site specific studies added to the mix
- Debate: What presentation method of design criteria is the best? Those based upon:
  - Friction factor
  - Manning's equation
  - Residual energy computations based upon;
    - Continuity
    - Uniform flow equations
    - Both from various measurements of aerated & non-aerated flow from model and prototype tests

Stepped Spillway Research Needs

Development of peer reviewed manual for stepped spillway design that considers all techniques and meets requirements of practicing engineers

- Needed for low and high dams with high q, uniform & non-uniform flow regions, flatter and steeper slopes.
  - Possibly develop a chart of a ratio V_a/V_t versus total head for various sloping stepped spillways.