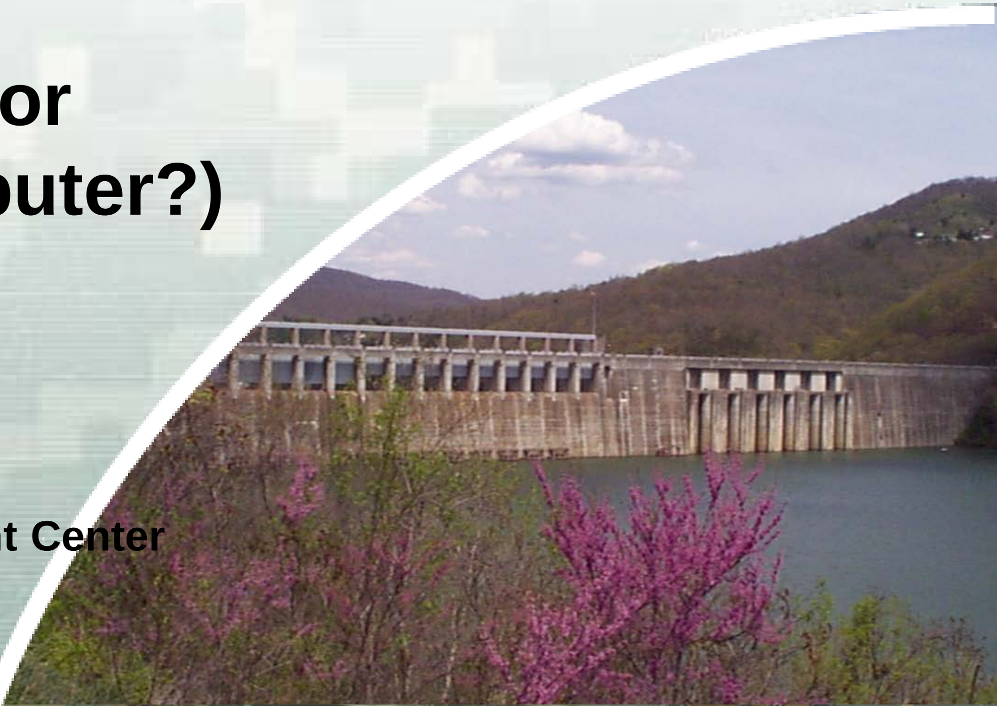
Hydraulic Modeling in 2015: Decisions on Design of Physical and Numerical Models

(are we using the hangar or a high-performance computer?)



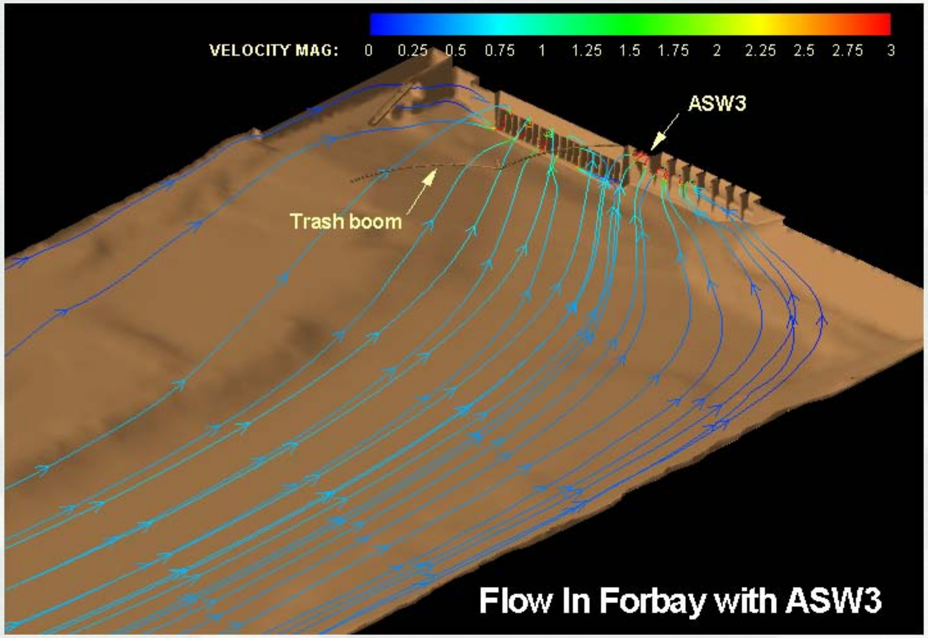
U.S. Army Corps of Engineers

U.S. Army Engineer Research & Development Center
Coastal and Hydraulics Laboratory

Model Details Required to Capture the Physics

<u>Physical Model:</u> Similitude Requirements

<u>Numerical Model:</u> Solving Governing Equations



General Information on Model Methods

Physical Model – hydraulic model at scales where $Re > 10^5$

Advantages

- Turbulence and turbulence fluctuations are reasonable
- Controlled environment: accurate discharge and pressures
- Flow visualization (although interior features are sometimes difficult to see)
- Direct measurement of forces
- Visual aid to demonstrate project conditions to others

Disadvantages

- Time & cost of construction, instrumentation, and operation
- Space requirement
- Scale effects are sometimes not known (e.g. air entrainment)
- Velocity and pressures are point values rather than continuum distribution of information

General Information on Model Methods

Numerical Model – 3D Reynolds-Averaged Navier-Stokes Equations with number of elements on the order of 10^6.

Advantages

- Reasonable price
- Reasonable time to completion
- Controlled input and output
- Detailed visualization of interior flows and pressures
- Effectively continuous velocity and pressure information

Disadvantages

- Computer requirement
- No turbulence information (results are Reynolds averaged)
- Methods of solving complex flows are not easily understood
- Forces must be computed from flow solution

Modeling Method Must Consider the Question(s) to be Answered

- Capacity (flood avoidance)?
- Low Pressure; Cavitation Potential?
- Forces on Hydraulic Components?
- Pressure Fluctuations?
- Stability of Bed Material (adjacent to structures)?

Features that are Difficult to Simulate

- Rough Free Surface

  Free surface location is an unknown
- Non-Hydrostatic Flow

  Pressure distribution is an unknown
- Proper Diffusion of Jets (free shear)

  Appropriate turbulence model
- Turbulent Fluctuations

  Requires Large Eddy Sim. or Detached Eddy Sim.
- Fluid/Structure Interaction with Human Response
- Air Entrainment

  Tricky in physical & numerical modeling

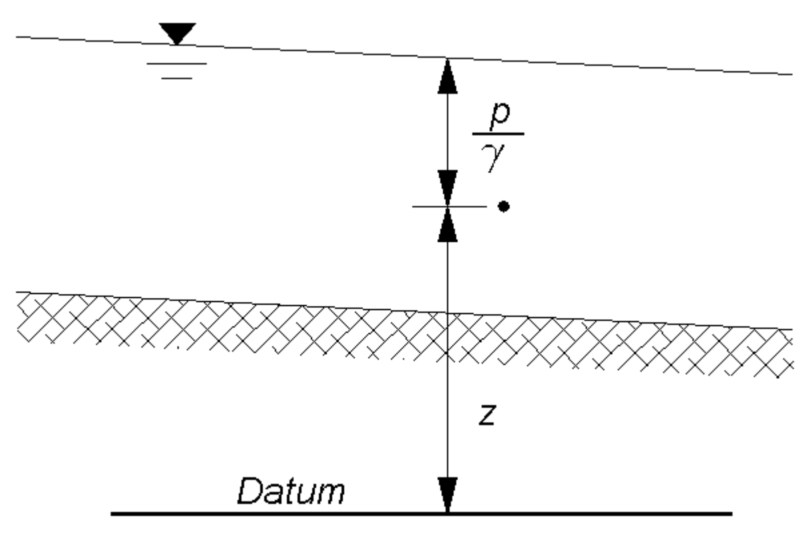
Describing Open Channel Flow using the Energy Equation

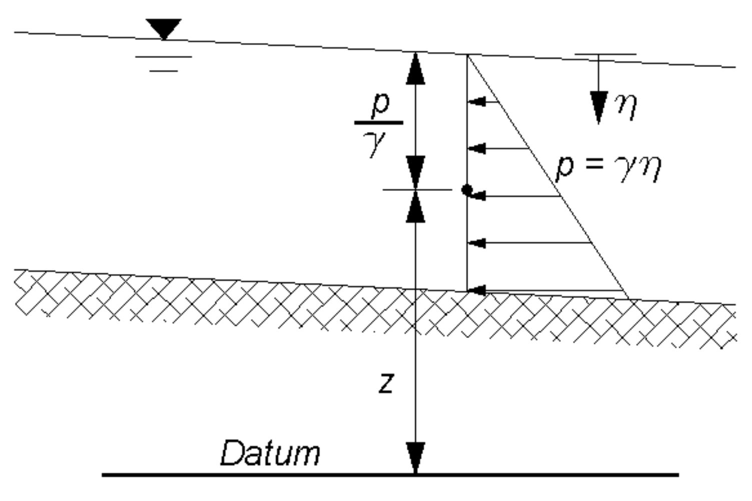
$$E = \frac{v^2}{2g} + \frac{p}{\gamma} + z$$

If the water-surface elevation is equal to

$$\left(\frac{p}{\gamma} + z \right)$$

then the pressure distribution must be hydrostatic.



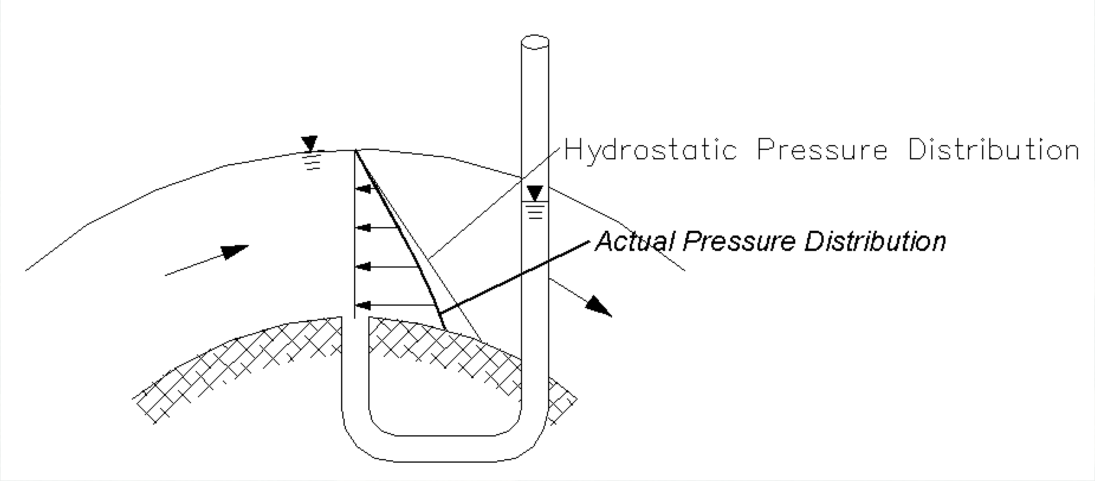


Hydrostatic Pressure Distribution

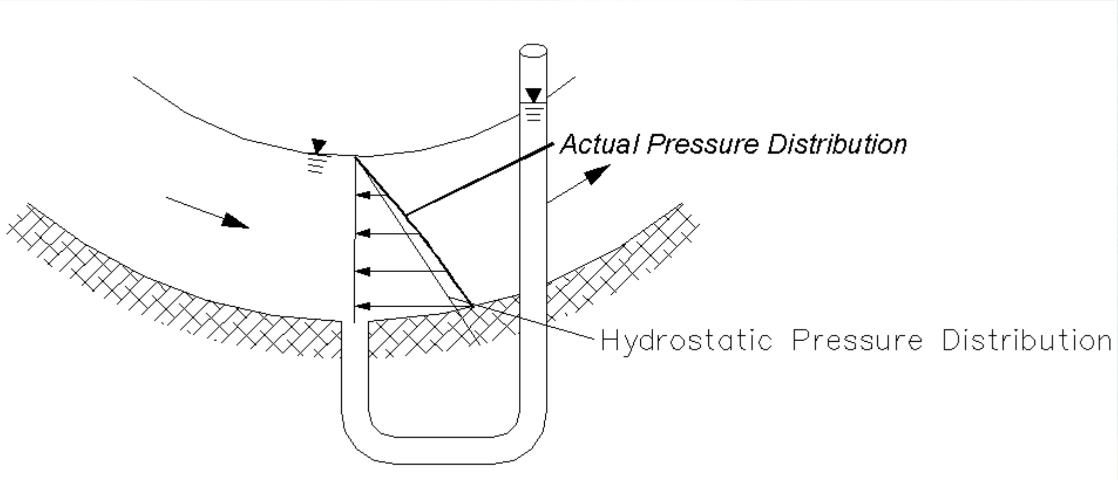
Non-hydrostatic Pressure Distribution Conditions

The pressure distribution deviates from hydrostatic if the vertical curvature of streamlines are significant. Cases in which the vertical curvature and accelerations are not negligible and the pressure distribution is non-hydrostatic.

Convex Flow



Concave Flow



Non-hydrostatic Pressure Distribution Conditions - Continued

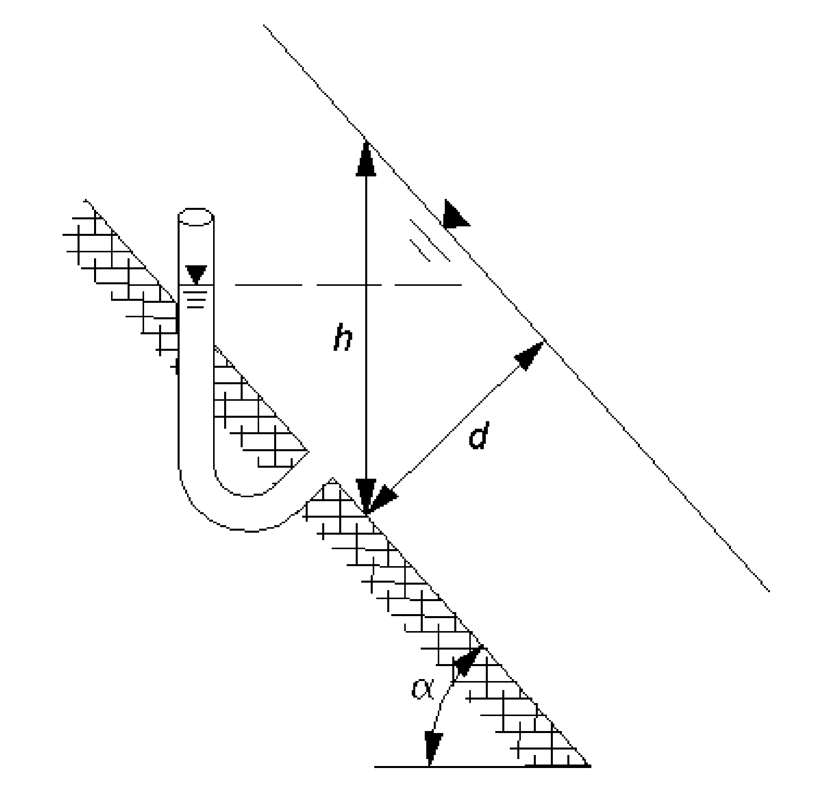
Very Steep Slopes

How is Depth Measured?

- Bed-Normal, *d*

  or

- Vertical, *h*



$$d = h\cos\alpha$$

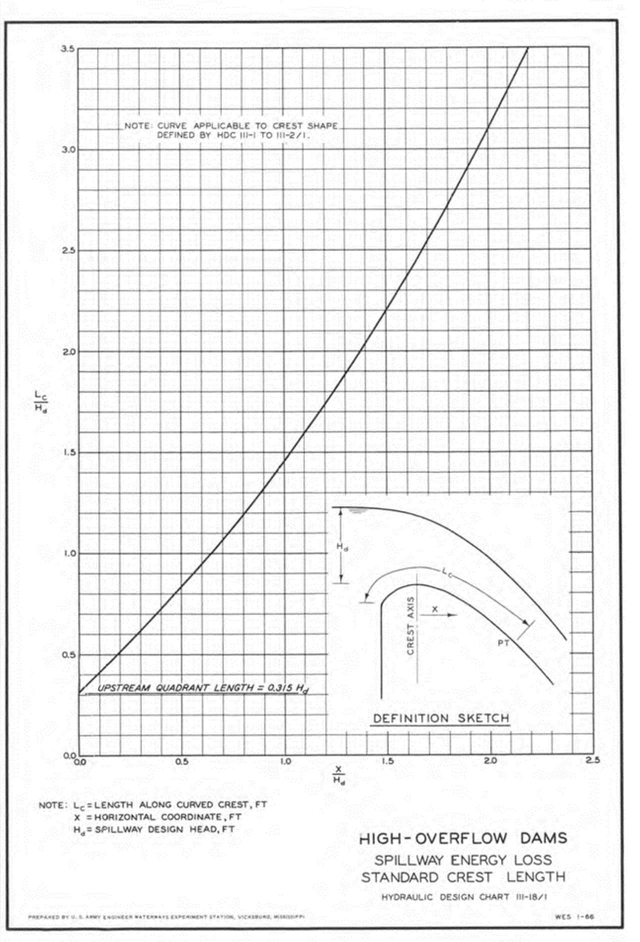
Hydraulic Projects that are Difficult to Evaluate with Computational Methods

- Spillways
- Navigation Conditions at Lock Approaches
- Stilling Basin Performance
- Scour Downstream of Stilling Basin & Piers
- Lock Filling & Emptying Systems
- Pump Intakes

Last 2 are special because criteria requires physical model

Spillway Model
Objective: Head-Discharge Relation & Dam Safety

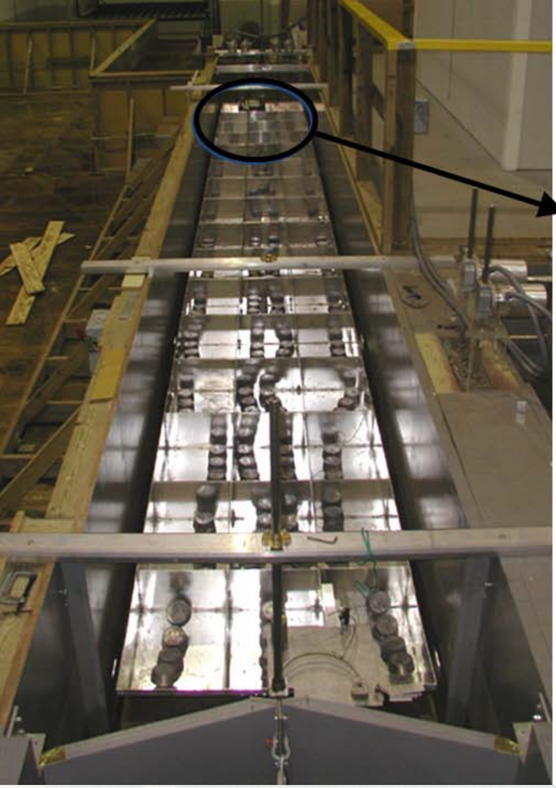
- Spillway flow has large vertical accelerations
- Free surface
- Cavitation potential (low pressure) is directly linked with the above 2

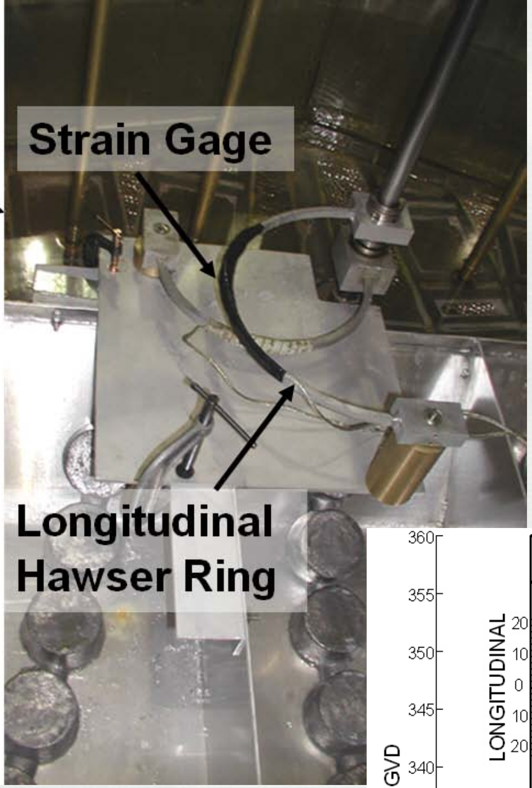


Lock Filling and Emptying System

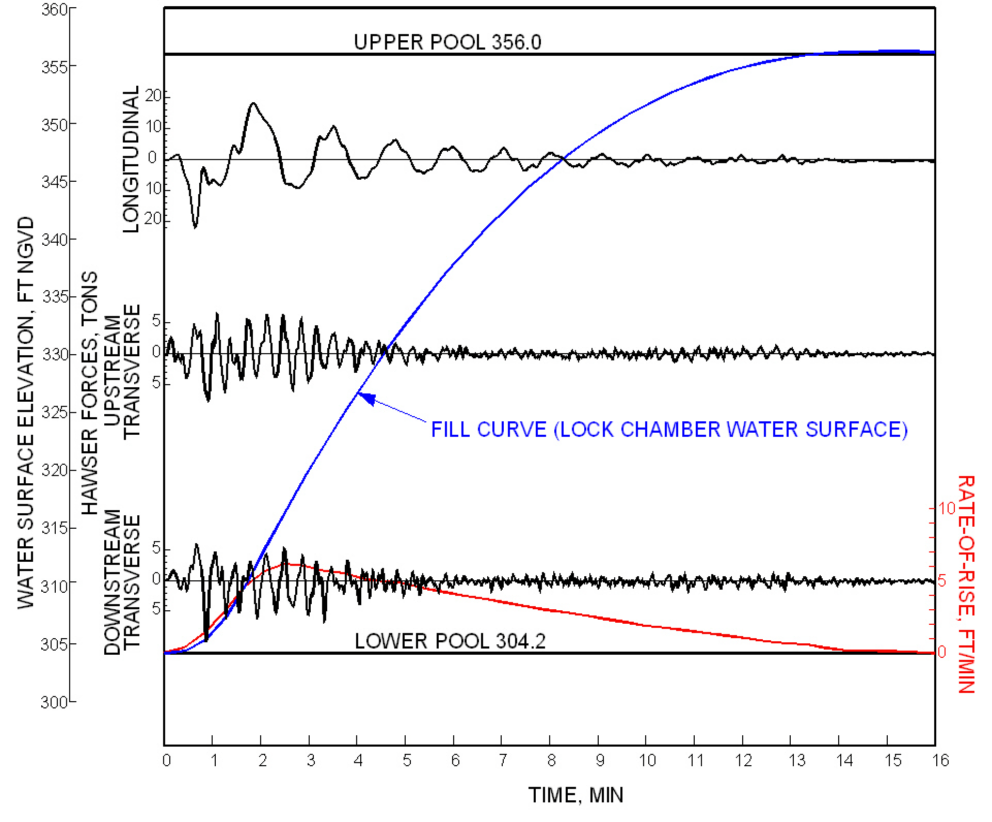
- Flow is controlled with moving valves
- Has moving free surface
- Fluid/Vessel interaction (free tow and hawser forces)
- Chamber Performance is defined in

EM 1110-2-1604 *Hydraulic Design of Locks* in terms of physical model results





Hawser Force Measuring Instruments



Hawser Force Data And Fill Curve

Navigation Conditions at Lock Approaches

- Flow affects vessel
- Vessel affects flow
- Human response to flow environment must be incorporated

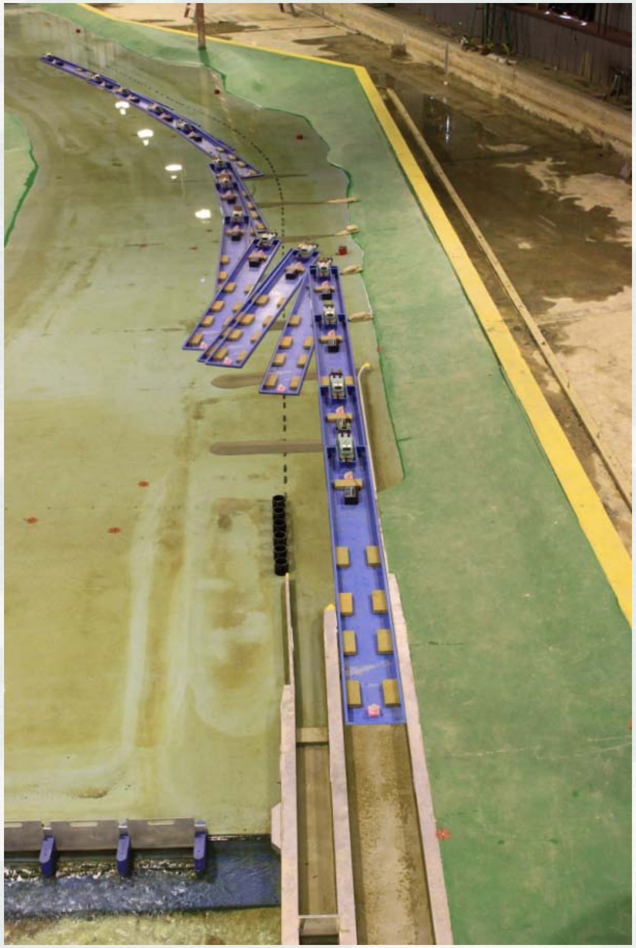
Navigation Model
Human Response to Flow Conditions

Navigation at Lock Approaches

Tow Boat with Helper

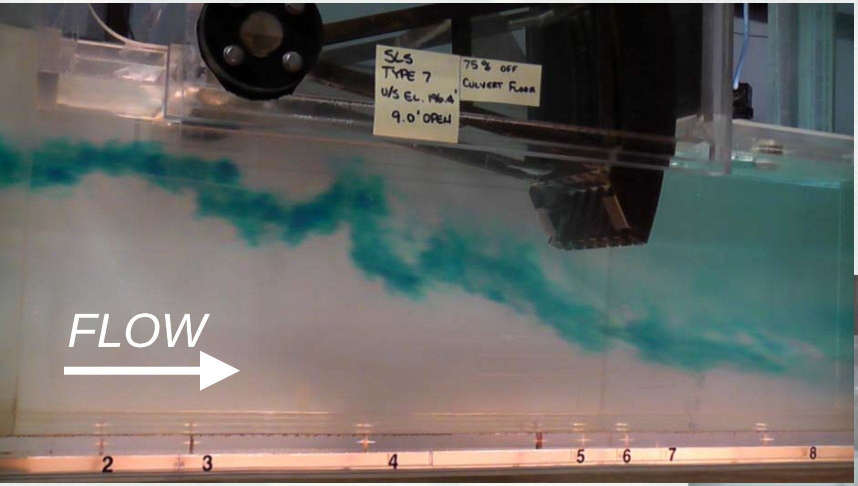
Remote Controlled Tow Boats

Maneuver of Downbound Tow

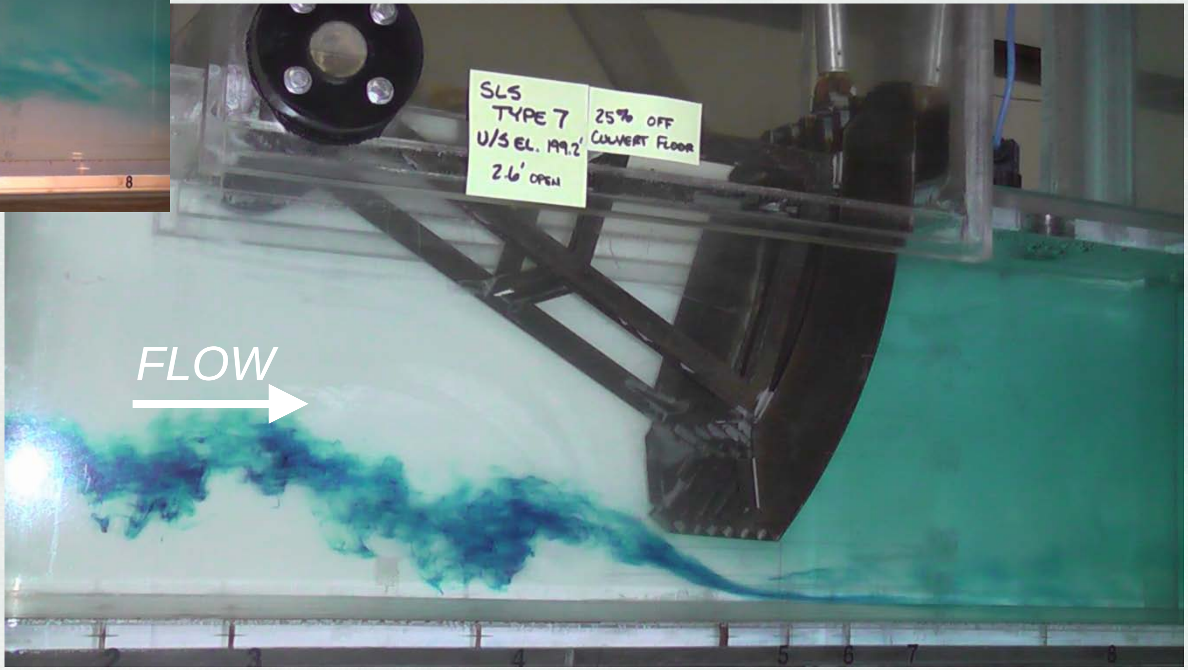


Forces on Components of Hydraulic Structures

Reverse Tainter Lock Culvert Valves



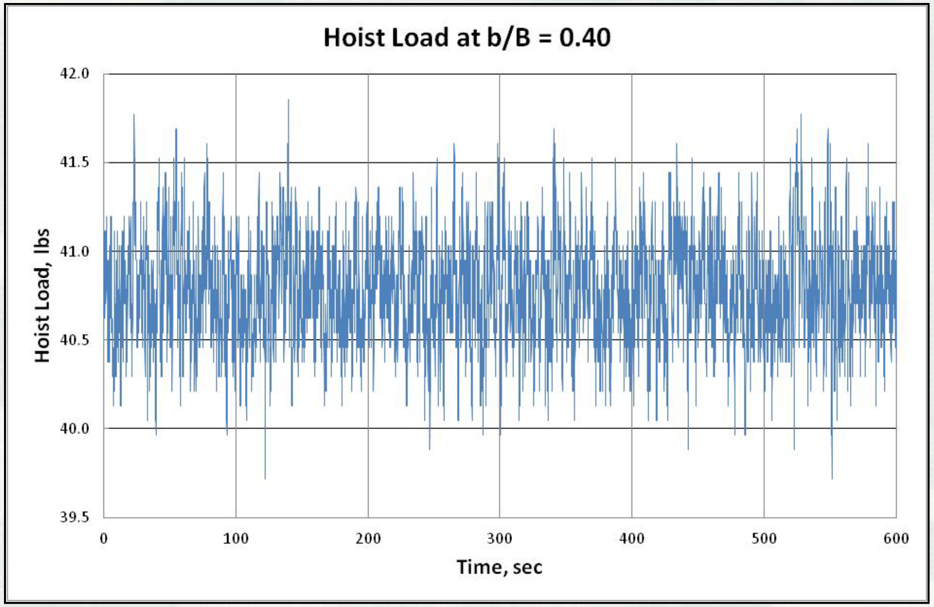
Forces: Separation and Low Pressure on Downstream Side



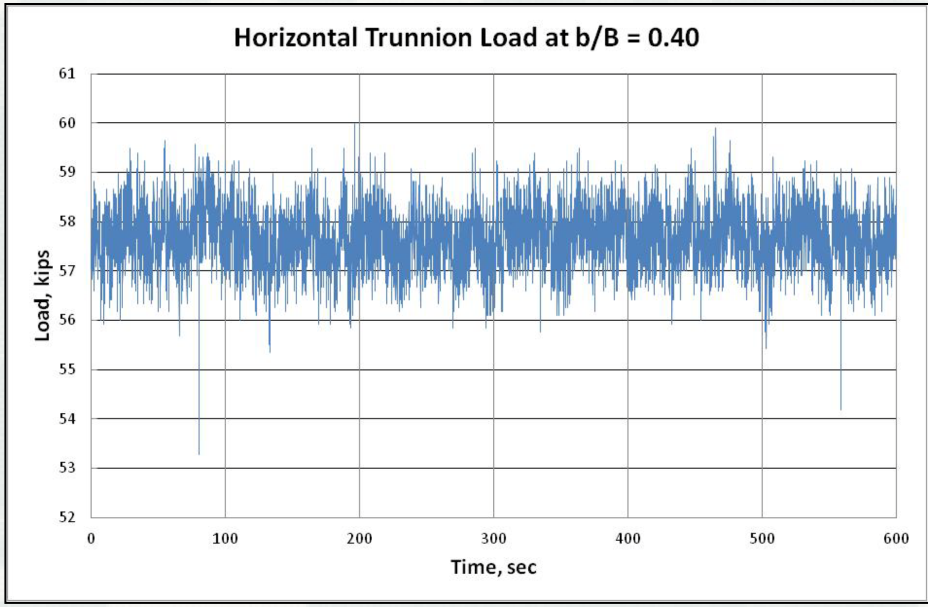
Large Range of Turbulent Velocity & Pressure Fluctuations over a Small Space

Forces on Components of Hydraulic Structures

Lock Culvert Valves
Physical Model Data



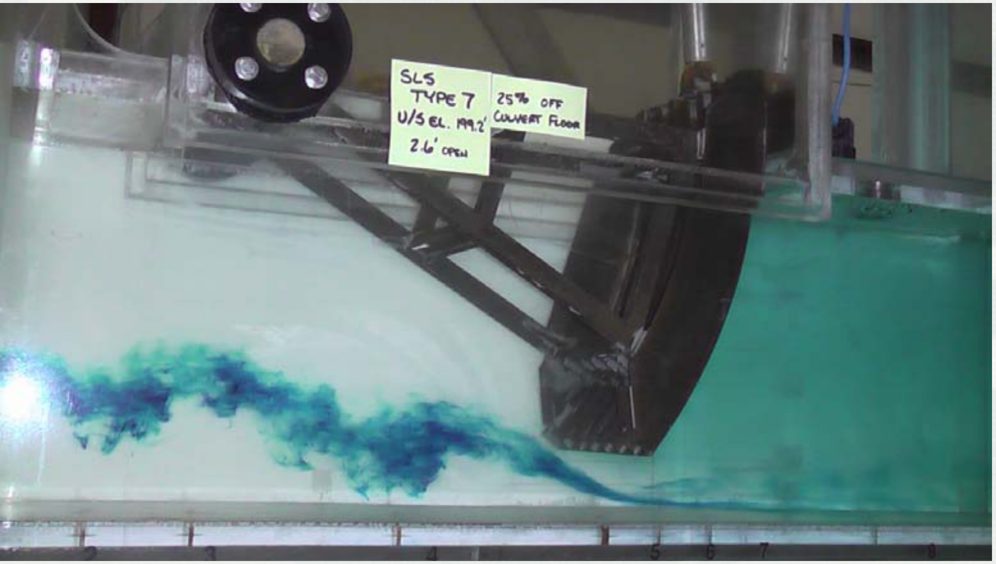
Valve Stem Hoist Load Variation in Time



Horizontal Trunnion Load Variation in Time

Free Shear such as Jets Requires Coordinated Validation of:

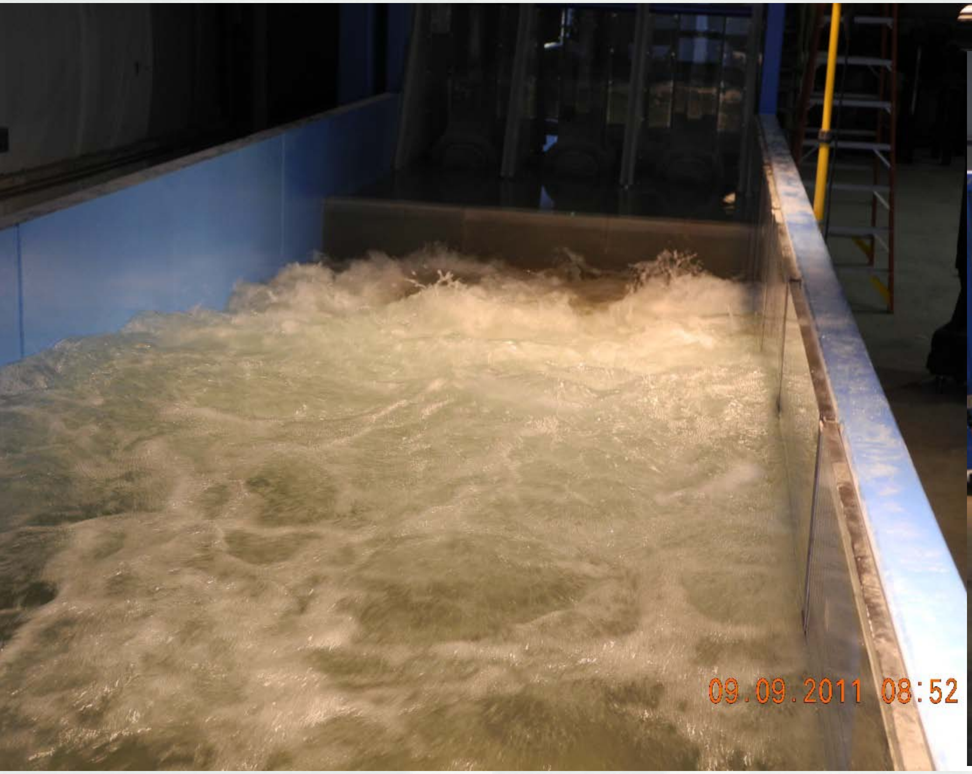
- Turbulence Model (e.g. 2 equation model such as k-ε, k-ω, RNG k-ε, etc.)
- Mesh Resolution
- Numerical Method used to Solve PDE's

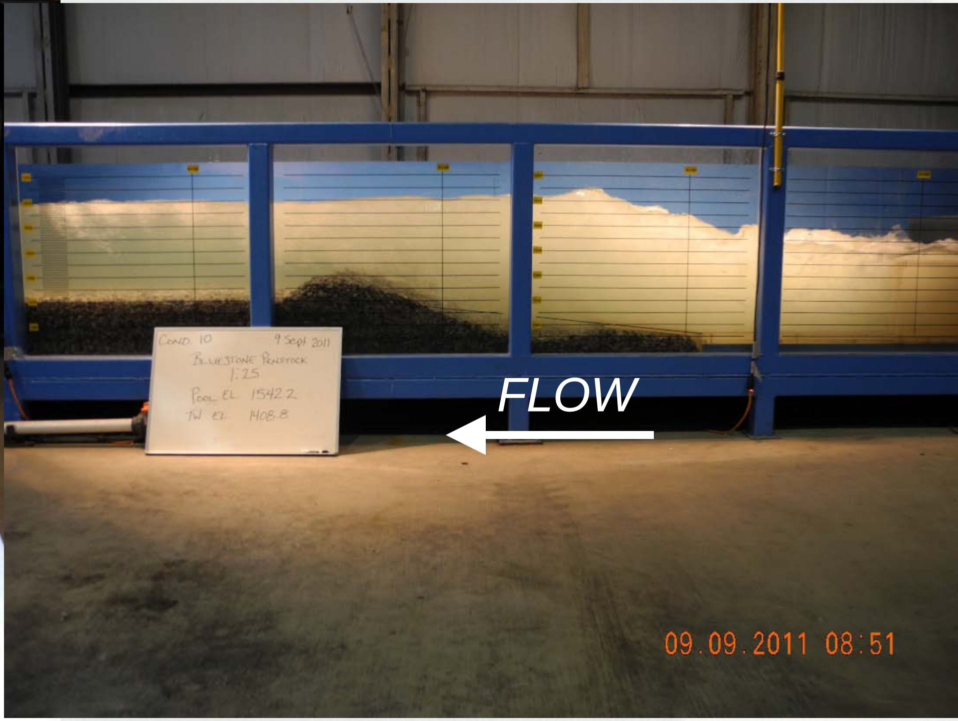


Computational models are too diffusive without sufficient mesh resolution. Sufficiency depends on method used to solve PDE's (Numerical Diffusion).

Modeling Stilling Basin

- Formation of hydraulic jump is primary design objective.
- Other interests concern forces on baffle blocks, pressure fluctuations on the basin floor, walls, and end sill.
- Scour downstream of basin (rip rap stability).





High-Speed Flow, Rough Water Surface, High *Re*, Large *V* and *P* Fluctuations

Stilling basin performance: Photos of a 1:65-scale model illustrate the variation of the air entrainment and roughness of the air/water interface.

Condition 4, 190,000 cfs

Condition 5, 360,000 cfs

Condition 6, 460,000 cfs

Condition 7, 570,000 cfs

Condition 8, 730,000 cfs

Condition 9, 860,000 cfs

Condition 10, 900,000 cfs

Scour Downstream of Stilling Basins

Consequence of Poor
Modeling can be Costly
Scour Repair

Placing Rip Rap
in the Wet

Dewatered Stilling Basin
for Scour Repair

Decisions Common to Either Model Method

- Section Model or General Model?
- Model Limits – you never have too much approach reproduced
- Boundary Conditions – inflow, tailwater, geometry

NOTE: Poor Geometry Information is the most common source of errors (numerical and physical models)

Section Model Decisions

Hydraulic: Larger Scale
Computational: Finer Mesh

Balance scale with flume width and the number of features reproduced

Symmetry is important

How many gate bays?

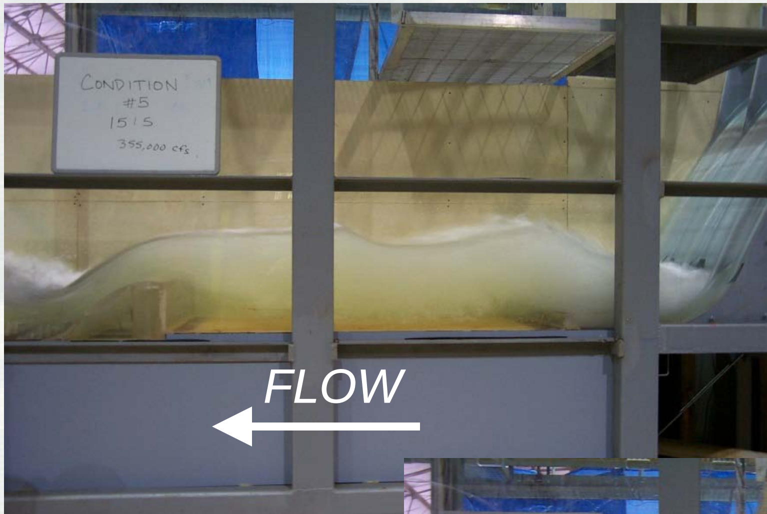
How many sluices?

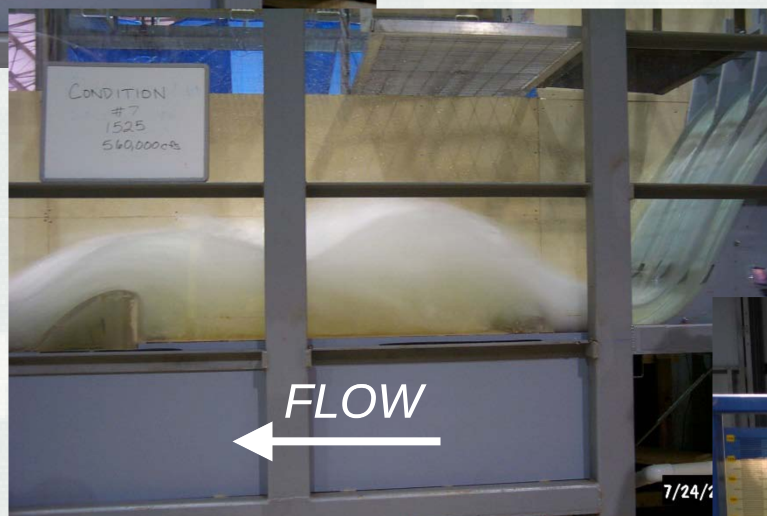
Section Models

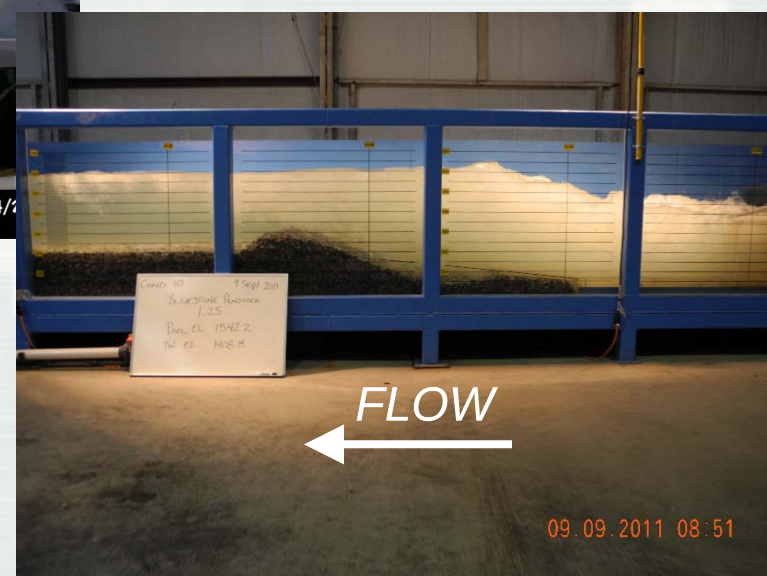
1:36-Scale Spillway Section Model

1:25-Scale Penstock Section Model

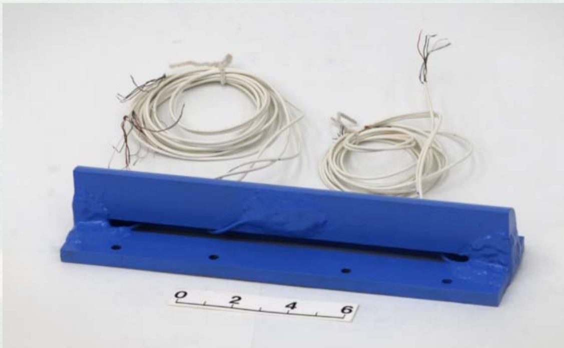
Bluestone Dam
1:25-Scale Penstock Section Model

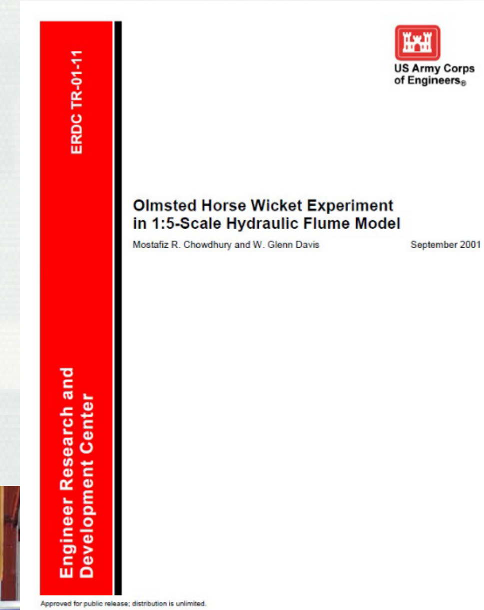






Olmsted Wicket Gate
1:5-Scale Section Model




ERDC TR-01-11

US Army Corps of Engineers®

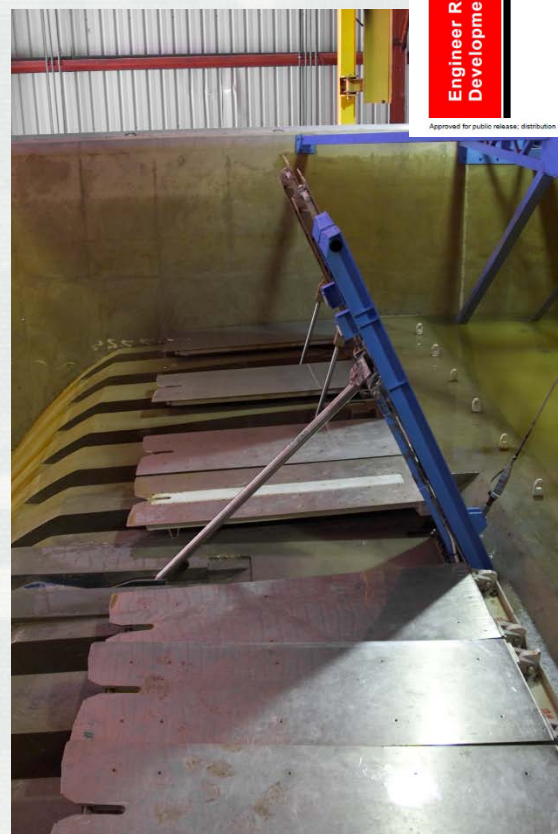
Olmsted Horse Wicket Experiment in 1:5-Scale Hydraulic Flume Model

Mostafiz R. Chowdhury and W. Glenn Davis

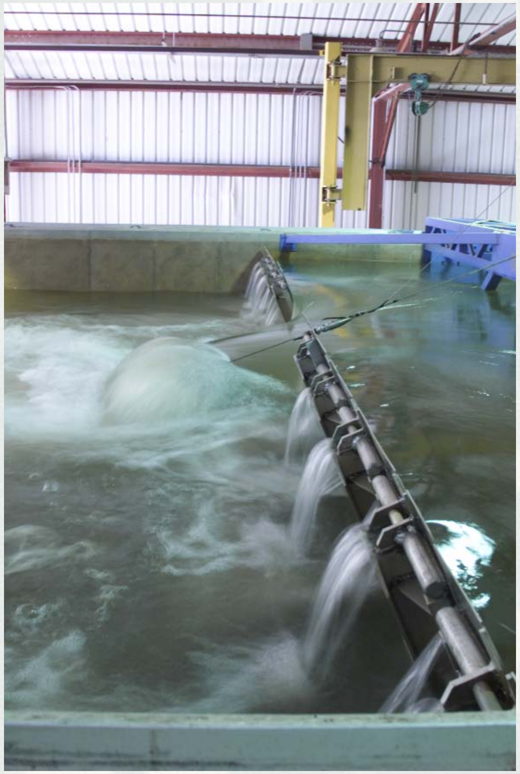
September 2001

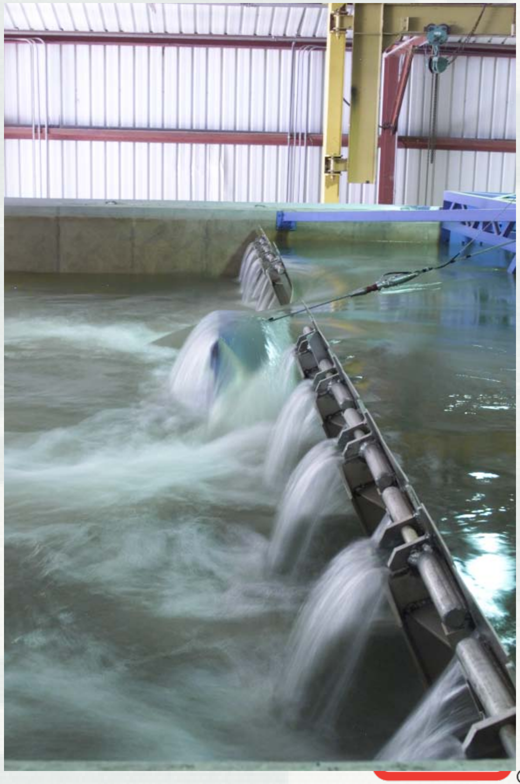
Engineer Research and Development Center

Approved for public release; distribution is unlimited.

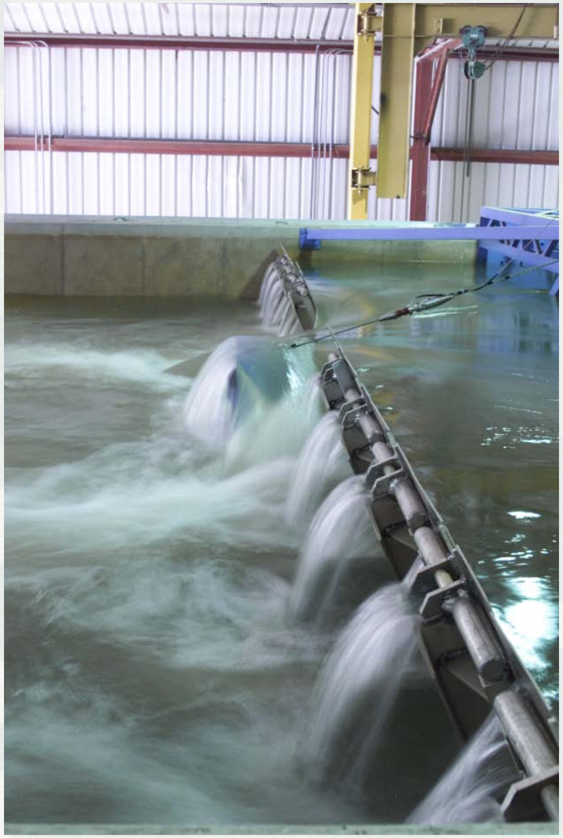


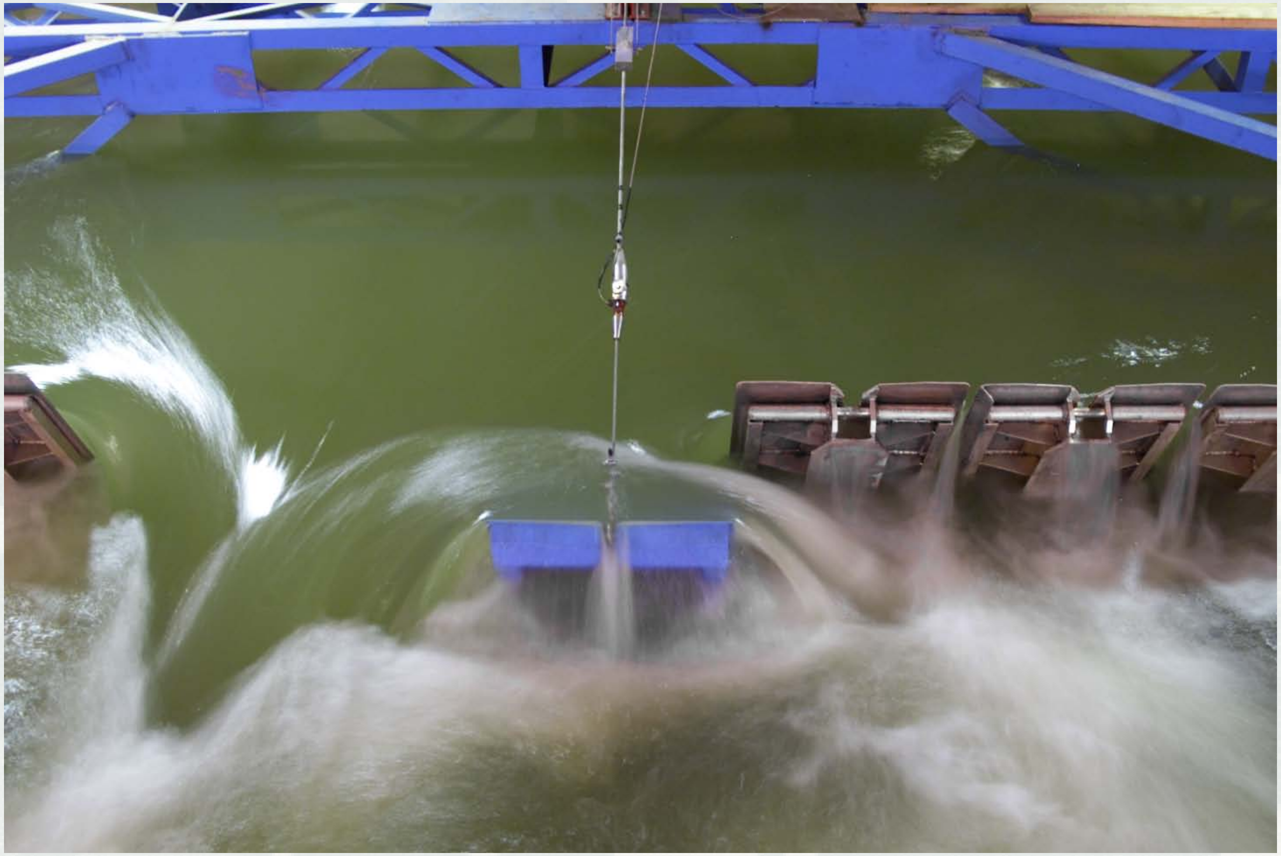
1:5 Model – Wicket Gate Raising Forces





1:5 Model – Wicket Gate Raising Forces





Credentials: Demonstrated Capability

- USACE must deliver defendable solutions
- Publish validation study – the accuracy of a particular modeling method must be demonstrated, e.g.
  - Observations vs. Calculations (same scale)
  - Same scale avoids differences in viscous forces (same *Re* in computation and observation system)
  - Peer review publication (available to public)

References: Model Verification and Validation

- Roache, P. J., 1998a. *Verification and Validation in Computational Science and Engineering*, Hermosa Publishers, Albuquerque, August 1998.
- Roache, P. J., 2009. "Perspective: Validation-what does it mean?", *Journal of Fluids Engineering, vol. 131, pp. 034503-1-4.*
- Department of Defense, 1996. "DoD Modeling and Simulation M&S Verification, Validation, and Accreditation VV&A," DoD Instruction No. 5000.61.
- Department of Defense, 1994, "DoD Modeling and Simulation M&S Management," DoD Directive No. 5000.59.
- AIAA, 1998, *Guide for the Verification and Validation of Computational Fluid Dynamics Simulations*, American Institute of Aeronautics and Astronautics, Reston, VA.
- ASME Committee PTC-60, 2006, ANSI Standard V&V 10. ASME Guide on Verification and Validation in Computational Solid Mechanics.
- ASME Committee PTC-61, 2008, ANSI Standard V&V 20. ASME Guide on Verification and Validation in Computational Fluid Dynamics and Heat Transfer.
- ASCE/EWRI Task Committee, 2009, *3D Free Surface Flow Model Verification/Validation*.

Effective Communication Requires Correct use of Terms

- Definitions and descriptions for terms related to Verification and Validation of computational hydraulic models
- Distinction made between Verification vs. Validation
- Verification is completed by the Code Developer
- Validation is completed by the Model User
- Distinctions made between:
  - Numerical Errors vs. Conceptual Modeling Errors
  - Confirmation, Calibration, Tuning, and Certification
  - Verification of Numerical Accuracy of Codes
  - Physical Process Validation vs. Site Validation.

Distinction between Code Verification and Model Validation

- Meanings
  - “Verification” ~ “solving the equations right”
  - “Validation” ~ “solving the right equations”
- Validations, unlike Verifications, are based on comparisons with experiments (must be at same Reynolds Number).
- Validation requires error tolerances. There are three distinct sets of uncertainty estimates in a Validation:
  - one associated with the experiments,
  - one with the calculations, and
  - one that defines agreement between the two
- What levels are acceptable depends on the use intended.
- Another difference is that Verification is *completed* whereas Validation is *ongoing*.

Say What You Mean and Mean What You Say

- Validation Considerations:
  - Captures flow features
  - Run computational model at same size as observations (model the model)
    - *Re* is important and so must be the same in the computational model and observed data
    - We know Darcy's *f*, so once validated at model scale, we're comfortable with prototype scale solutions
- Consider not using the term "Calibrate" since it has connotations of changing coefficient values to match observed data without concern for reasonableness of value
- Must answer the question "How good is good enough?"

Model Methods
Notes on Abbreviations

- 1D = One-Dimensional
- 2D = Two-Dimensional
- 3D = Three-Dimensional
- NS = Navier-Stokes
- SW = Shallow-Water Equations

  (may be 2D or 3D, but uses hydrostatic assumption)
- D/S = Downstream

Hydraulic Evaluation of	Current Choice of Model	Physical Model			Numerical Model		
		Typical Scale	Well-Captured Physics	Not Well-Captured Physics	Typical Eqns	Well-Captured Physics	Not Well-Captured Physics
Lock filling and emptying systems	Physical model with 1D model for feasibility	1:25	Hawser forces, culvert pressures	Scale effects on filling times and intake vortices, air requirement D/S of culvert valves	1D energy	1D provides systems information but no details	Moving components (valves, gates), certain turbulence effects, vortex tendencies, air requirements
Navigation conditions at lock approaches	Physical model	1:100	Flow, vessel influence, human response	There are scale effects that affect flow distributions, human response is from “bird’s-eye view, wind effects	Not modeled, but would require 2D SW	Flow and vessel interaction	There are limitations using 2D SW, human response, vessel operation

Hydraulic Evaluation of	Current Choice of Model	Physical Model			Numerical Model		
		Typical Scale	Well-Captured Physics	Not Well-Captured Physics	Typical Eqns	Well-Captured Physics	Not Well-Captured Physics
Spillways (section model)	Physical model	1:25	Discharge capacity, cavitation potential; stilling basin performance; bed protection D/S; loadings on the basin floor, endsill and baffles; deflector performance for fish	3D effects = lateral variations at the dam, air entrainment at water surface and in slot aerators	Not modeled but would require mature 3D NS with turb model and free surface capturing		Boundary layer, small scale turb. and cavitation potential, air entrainment
Pump intakes	Physical model Required by ANSI/ Hydraulic Institute Standards	1:10 to 1:15	Vortex formation in vicinity, swirl in the pump column, velocity dist. in intake				

Hydraulic Evaluation of	Current Choice of Model	Physical Model			Numerical Model		
		Typical Scale	Well-Captured Physics	Not Well-Captured Physics	Typical Eqns	Well-Captured Physics	Not Well-Captured Physics
Closed conduit such as outlet works	Physical model	1:25	Complex flow and geometry at intake, pressure fluctuations due to turb., potential for slug flow	Conduit energy losses due to friction (the conduit is too rough)	1D energy provides system information, 3D NS provides details	Friction losses	3D model requires free-surface capabilities to capture slug flow
Vessel effects: mooring forces, env. impact	Physical and/or 2D SW numerical model	1:25			2D SW	Long period wave effects	Short period waves
Hydraulic component	Physical and/or 3D NS numerical model	1:10 to 1:20	Loss coefficients, flow patterns, pressures		Not modeled, but requires mature 3D NS with turb.		

Summary

- Examples of features that are difficult to compute
  - Rough free surface
  - Non-hydrostatic flow
  - Free shear (jet expansion)
  - Turbulent fluctuations (pressure fluctuations needed for structural design)
  - Fluid/structure interaction with human response
- Use appropriate terms
- Modeler and model system must have demonstrated capability

Additional Information Regarding Near-Field Flow Modeling Can Be Obtained from the Following USACE Engineers

Allen Hammack

Research Mechanic Engineer

Coastal & Hydraulics Laboratory

US Army Engineer R&D Center

CEERD-HN-NL

Dr. Laurie Ebner

Regional Technical Expert, Computational Fluid Dynamics

Portland District

CENWP-EC-HD

Questions?