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

**Physical Model:**
Similitude Requirements

**Numerical Model:** Solving Governing Equations

Flow In Forbay with ASW3
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.
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

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

Forces: Separation and Low Pressure on Downstream Side
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 $k-\varepsilon$, $k-\omega$, RNG $k-\varepsilon$, 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.
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
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

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
<table>
<thead>
<tr>
<th>Hydraulic Evaluation of</th>
<th>Current Choice of Model</th>
<th>Physical Model</th>
<th>Numerical Model</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Typical Scale</td>
<td>Typical Eqns</td>
</tr>
<tr>
<td>Lock filling and emptying systems</td>
<td>Physical model with 1D model for feasibility</td>
<td>1:25</td>
<td>1D energy</td>
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<td></td>
<td></td>
<td>Hawser forces, culvert pressures</td>
<td>1D provides systems information but no details</td>
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<td></td>
<td></td>
<td>Scale effects on filling times and intake vortices, air requirement D/S of culvert valves</td>
<td>Moving components (valves, gates), certain turbulence effects, vortex tendencies, air requirements</td>
</tr>
<tr>
<td>Navigation conditions at lock approaches</td>
<td>Physical model</td>
<td>1:100</td>
<td>Not modeled, but would require 2D SW</td>
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<td>Flow, vessel influence, human response</td>
<td>Flow and vessel interaction</td>
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<tr>
<td></td>
<td></td>
<td>There are scale effects that affect flow distributions, human response is from “bird’s-eye view, wind effects</td>
<td>There are limitations using 2D SW, human response, vessel operation</td>
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<td>Typical Scale</td>
<td>Well-Captured Physics</td>
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<tr>
<td>Spillways (section model)</td>
<td>Physical model</td>
<td>1:25</td>
<td>Discharge capacity, cavitation potential; stilling basin performance; bed protection D/S; loadings on the basin floor, end sill and baffles; deflector performance for fish</td>
</tr>
<tr>
<td>Pump intakes</td>
<td>Physical model</td>
<td>1:10 to 1:15</td>
<td>Vortex formation in vicinity, swirl in the pump column, velocity dist. in intake</td>
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<td>Required by ANSI/ Hydraulic Institute Standards</td>
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<tr>
<td></td>
<td>Typical Scale</td>
<td>Well-Captured Physics</td>
<td>Not Well-Captured Physics</td>
</tr>
<tr>
<td>Closed conduit such as outlet works</td>
<td>Physical model</td>
<td>1:25</td>
<td>Complex flow and geometry at intake, pressure fluctuations due to turb., potential for slug flow</td>
</tr>
<tr>
<td>Vessel effects: mooring forces, env. impact</td>
<td>Physical and/or 2D SW numerical model</td>
<td>1:25</td>
<td></td>
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<tr>
<td>Hydraulic component</td>
<td>Physical and/or 3D NS numerical model</td>
<td>1:10 to 1:20</td>
<td>Loss coefficients, flow patterns, pressures</td>
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</tbody>
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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  
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Questions?