CIVE 717 HW #6

Physical River Modeling

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5/5/2016

Terminology

- Prototype – full-scale field conditions
- Model – scaled down laboratory version of prototype
- Similitude – physical similarity between the prototype and a model
- Distorted model – vertical and lateral scales differ
- Tilted model – vertical and downstream scales differ

Hydraulic Similitude

- **Geometric similitude (length):**
  - Length $L_r = L_{prototype}/L_{model}$
    - x_r , y_r , z_r
  - Area $A_r = (x_r)(y_r)$
  - Volume $Vol_r = (x_r)(y_r)(z_r)$
- **Kinematic similitude (length and time):**
  - Velocity v_r
  - Time t_r
  - Acceleration $a_r = g_r$
  - Kinematic viscosity υ_r

Hydraulic Similitude

- **Dynamic similitude (length, time, and mass):**
  - Density ρ_r
  - Mass M_r
  - Dynamic viscosity μ_r
  - Specific weight γ_r
- Typically, $g_r = \rho_r = \upsilon_r = \gamma_r = \mu_r = 1$

Hydraulic Similitude

- Cannot satisfy Froude number and Reynolds number similitude simultaneously
  - Gravitational or viscous effects dominant?
    - For rivers, gravitational effects (Froude number similitude)
    - With the typical assumptions:

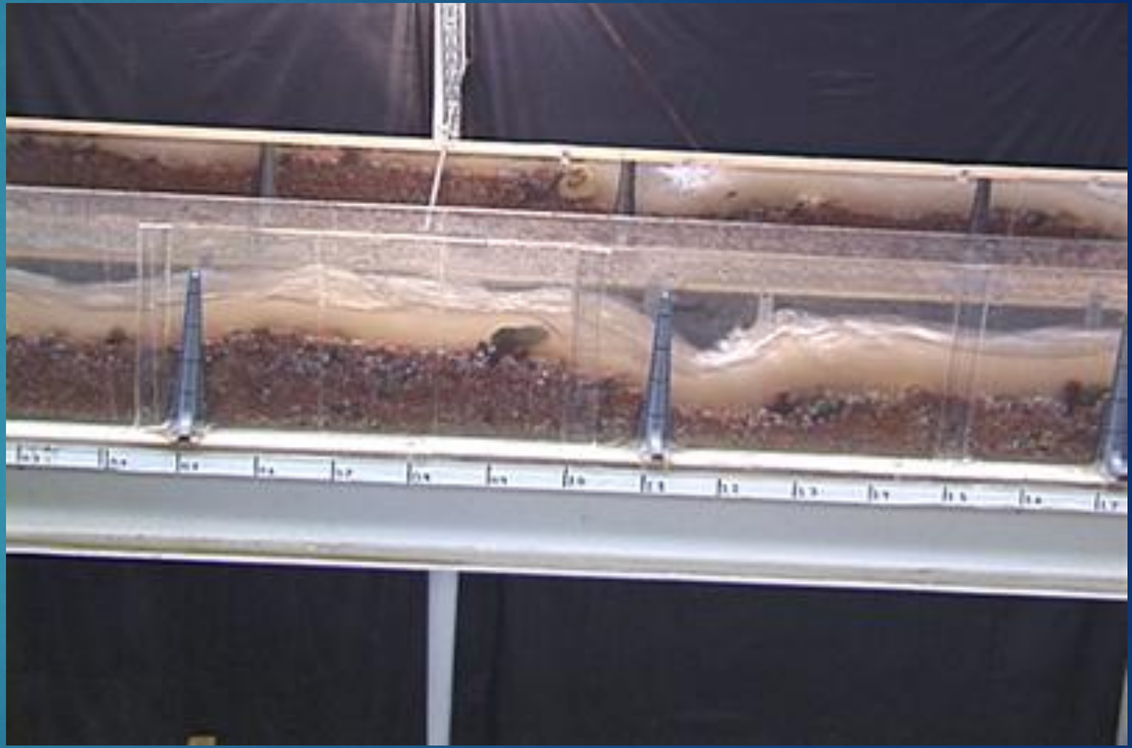
$$V_r/z_r^{0.5} = 1 = Fr_r$$

Rigid-bed Modelling

- No sediment transport
- Simulate flow around hydraulic structures and in-stream features
- **Exact geometric similitude** (neglect flow resistance)
  - 3D flow with vertical accelerations
  - Coupled with exact Froude similitude
- **Distorted/tilted models** (do not neglect flow resistance)
  - 1D flow with vertical and lateral accelerations neglected
  - Froude and Manning-Strickler (flow resistance) similitude

Mobile-bed Modelling

- Sediment transport is significant
- Drop structures, local scour, erosion below spillways, sills, locks and dams, reservoir sedimentation
- Four similitude criteria:
  - Froude
  - Resistance (Manning-Strickler)
  - Dimensionless grain diameter
  - Shields parameter (or bed-material entrainment)

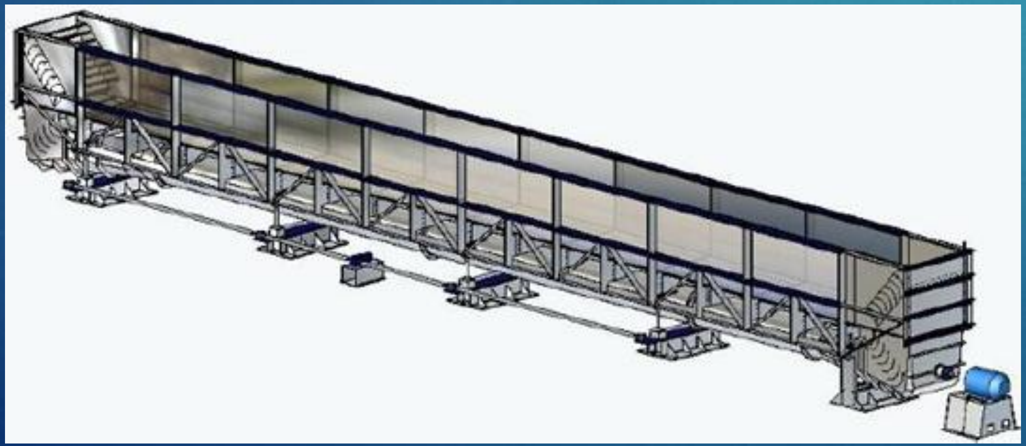


Mobile-bed Modelling

- **Complete similitude**
  - 1D flow with negligible vertical and lateral accelerations
  - Dimensionless particle diameter $d_{*_r} = 1$
    - Typically, lightweight artificial sediment required
  - Shields parameter $\tau_{*_r} = 1$

Mobile-bed Modelling

- **Incomplete similitude**
  - non-Froudian similitude $Fr_r \neq 1$
    - Appropriate when the prototype has a fairly constant Fr
  - Sediment transport quasi-similitude $d_{*r} \neq 1$
    - Appropriate when the prototype sediment must be used for the



Summary of Scale Ratios

Table 10.1. *Scale ratios for hydraulic models*

	Rigid-bed (Froude)			Mobile-bed			
	Scale	Exact	Tilted	Complete General	$(d_{*r} = \tau_{*r} = 1)$ $m = 1/6$	$d_{*r} \neq 1$	Incomplete $Fr_r \neq 1$
Geometric							
Depth	h_r	L_r	z_r	z_r	z_r	z_r	z_r
Width	W_r	L_r	y_r	y_r	y_r	y_r	y_r
Length	x_r	L_r	x_r	$z_r \left(\frac{1+4m}{1+m}\right)$	$z_r^{1.43}$	$z_r^{1+2m} d_{sr}^{-2m}$	$z_r^2 d_{sr}^2$
Particle diameter	d_{sr}	L_r	$z_r^4 x_r^{-3}$	$z_r \left(\frac{2m-1}{2+2m}\right)$	$z_r^{-0.286}$	d_{sr}	d_{sr}
X-section area	$W_r h_r$	L_r^2	$z_r y_r$	$y_r z_r$	$y_r z_r$	$y_r z_r$	$z_r y_r$
Volume	$X_r W_r h_r$	L_r^3	$x_r y_r z_r$	$y_r z_r \left(\frac{2+5m}{1+m}\right)$	$y_r z_r^{2.43}$	$y_r z_r^{2+2m} d_{sr}^{-2m}$	$y_r z_r^3 d_{sr}^2$
Kinematic							
Time (flow)	t_r	$L_r^{1/2}$	$x_r z_r^{-1/2}$	$z_r \left(\frac{1+7m}{2+2m}\right)$	$z_r^{0.928}$	$z_r^{0.5+2m} d_{sr}^{-2m}$	$z_r^{2-m} d_{sr}^{3+m}$
Time (bed)	t_{br}	—	—	$z_r \left(\frac{2+5m}{1+m}\right)$	$z_r^{2.428}$	$z_r^{1.5+3m} d_{sr}^{-1-3m}$	$z_r^3 d_{sr}^2$
Velocity	V_r	$L_r^{1/2}$	$z_r^{1/2}$	$z_r^{1/2}$	$z_r^{1/2}$	$z_r^{1/2}$	$z_r^m d_{sr}^{-1-m}$
Shear velocity	u_{*r}	$L_r^{1/2}$	$z_r x_r^{-1/2}$	$z_r \left(\frac{1-2m}{2+2m}\right)$	$z_r^{0.286}$	$z_r^{0.5-m} d_{sr}^m$	d_{sr}^{-1}
Settling velocity	ω_r	—	—	$z_r \left(\frac{1-2m}{2+2m}\right)$	$z_r^{0.286}$	—	d_{sr}^{-1}
Discharge	Q_r	$L_r^{5/2}$	$y_r z_r^{3/2}$	$y_r z_r^{3/2}$	$y_r z_r^{1.5}$	$y_r z_r^{1.5}$	$y_r z_r^{1+m} d_{sr}^{-1-m}$
Unit bedload discharge	q_{br}	—	—	1	1	$d_{sr}^{1+m} z_r^{0.5-m}$	1
Dynamic							
Mass	M_r	L_r^3	$x_r y_r z_r$	$y_r z_r \left(\frac{2+5m}{1+m}\right)$	$y_r z_r^{2.43}$	$y_r z_r^{2+2m} d_{sr}^{-2m}$	$y_r z_r^3 d_{sr}^2$
Pressure	p_r	L_r	z_r	z_r	z_r	z_r	z_r
Shear stress	τ_r	L_r	$z_r^2 x_r^{-1}$	$z_r \left(\frac{1-2m}{1+m}\right)$	$z_r^{0.57}$	$z_r^{1-2m} d_{sr}^{2m}$	d_{sr}^{-2}
Force	F_r	L_r^3	$x_r y_r z_r$	$y_r z_r \left(\frac{2+5m}{1+m}\right)$	$y_r z_r^{2.43}$	$y_r z_r^{2+2m} d_{sr}^{-2m}$	$y_r z_r^3 d_{sr}^2$
Dimensionless							
Slope	S_r	1	$z_r x_r^{-1}$	$z_r \left(\frac{-3m}{1+m}\right)$	$z_r^{-0.43}$	$d_{sr}^{2m} z_r^{-2m}$	$z_r^{-1} d_{sr}^{-2}$
Darcy–Weisbach	f_r	1	$z_r x_r^{-1}$	$z_r \left(\frac{-3m}{1+m}\right)$	$z_r^{-0.43}$	$d_{sr}^{2m} z_r^{-2m}$	$z_r^{-2m} d_{sr}^{2m}$
Froude	Fr_r	1	1	1	1	1	$z_r^{m-0.5} d_{sr}^{-1-m}$
Reynolds	Re_r	$L_r^{3/2}$	$z_r^{3/2}$	$z_r^{3/2}$	$z_r^{1.5}$	$z_r^{3/2}$	$z_r^{1+1m} d_{sr}^{-1-m}$
Shields	τ_{*r}	—	—	1	1	1	1
Grain Reynolds	Re_{*r}	$L_r^{3/2}$	$z_r^5 x_r^{-3.5}$	1	1	$d_{sr}^{1+m} z_r^{0.5-m}$	1
Dimensionless diameter	d_{*r}	—	—	1	1	$d_{sr}^{\frac{2+2m}{3}} z_r^{\frac{1-2m}{3}}$	1
Sediment density	$(G-1)_r$	—	—	$z_r \left(\frac{3-6m}{2+2m}\right)$	$z_r^{0.857}$	$z_r^{1-2m} d_{sr}^{2m-1}$	d_{sr}^{-3}

Alternative Sediment Material

- Often needed for complete similitude of mobile-bed models
- Can be expensive so sediment transport quasi-similitude with prototype sediment may be chosen instead

Table 10.2. *Lightweight sediment properties for mobile-bed models*

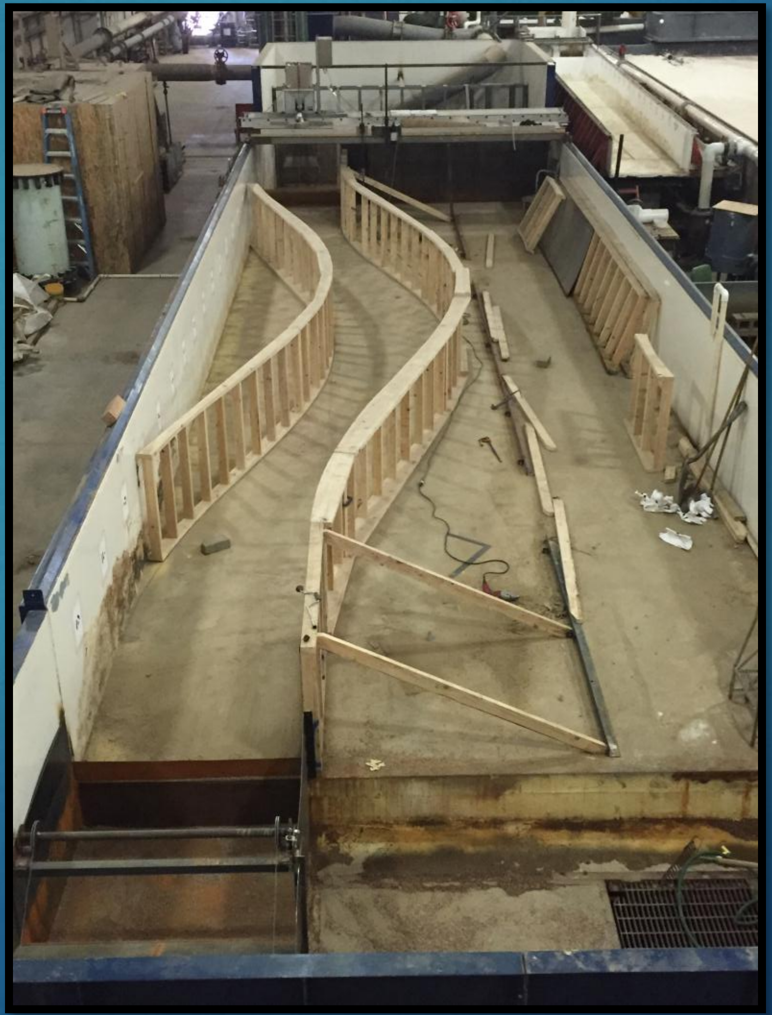
Material	Specific gravity G	Typical size d_s (mm)	Comment
Polystyrene	1.035–1.05	0.5–3	Durable but difficult to wet and tends to float
Gilsonite	1.04		
Nylon (polyamidic resins)	1.16	0.1–5	
Lucite	1.18		
PVC	1.14–1.25	1.5–4	Hydrophobic
Perspex	1.18–1.19	0.3–1	Dusty
Acrylonitrile butadiene styrene	1.22	2–3	Adds detergent against air-bubble adherence
Coal	1.2–1.43 (up to 1.6)	0.3–4	Possible inhomogenity in specific gravity and sorting
Ground walnut shells	1.33	0.15–0.41	Deteriorate in 2–3 months, color water (dark brown)
Bakelite	1.38–1.49	0.3–4.0	Porous, tends to rot, changes diameter, and floats
Pumice	1.4–1.7		
Loire sand	1.5	0.63–2.25	Dusty
Lytag (fly-ash)	1.7	1–3	Porous
Quartz sand	2.65	0.1–1	

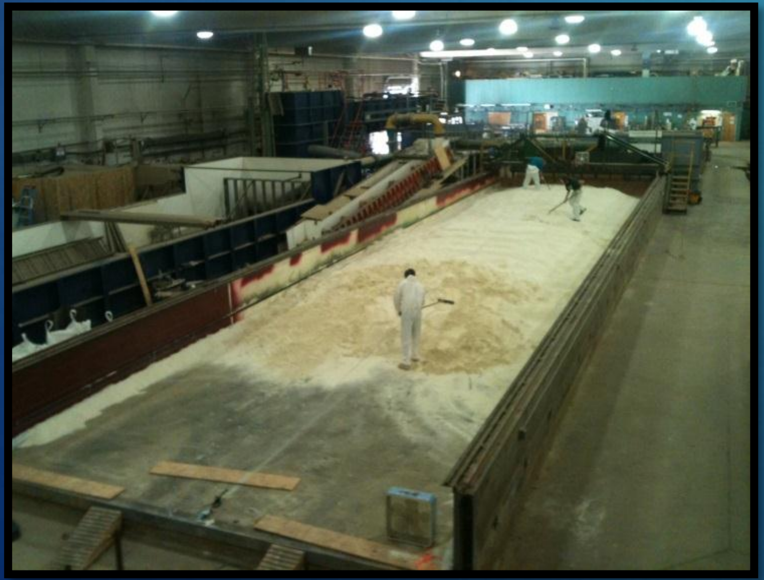
CSU Hydraulics Lab

- Colorado State University's Hydraulic lab is part of a unique research facility designed for hydraulic model studies such as:
  - Scour and sediment transport studies
  - Channel stability
  - Hydraulic structures
  - Sediment transport
  - Sediment sorting
- Over 20,000 square feet of covered laboratory space is available for model studies in recirculating flumes.

Building a Physical Model

- Building a river is not easy work!
  - Materials
  - Tools
  - Planning
  - People
  - Hard labor
  - Construction savvy
  - Heavy machinery





Physical Model Data Collection

- Extensive data collection is to be done during the testing of a model
  - Velocity
    - March McBirney (1D Flow)
    - ADV (1D-3D flow)
    - LPSIV use of video camera and to track and map surface flow.
  - Survey
    - Total station
    - Lidar
    - Structure for motion
  - Sediment Analysis
    - Sieve testing
    - Sediment traps
  - Stage Heights
    - Point gauges

Recent Projects

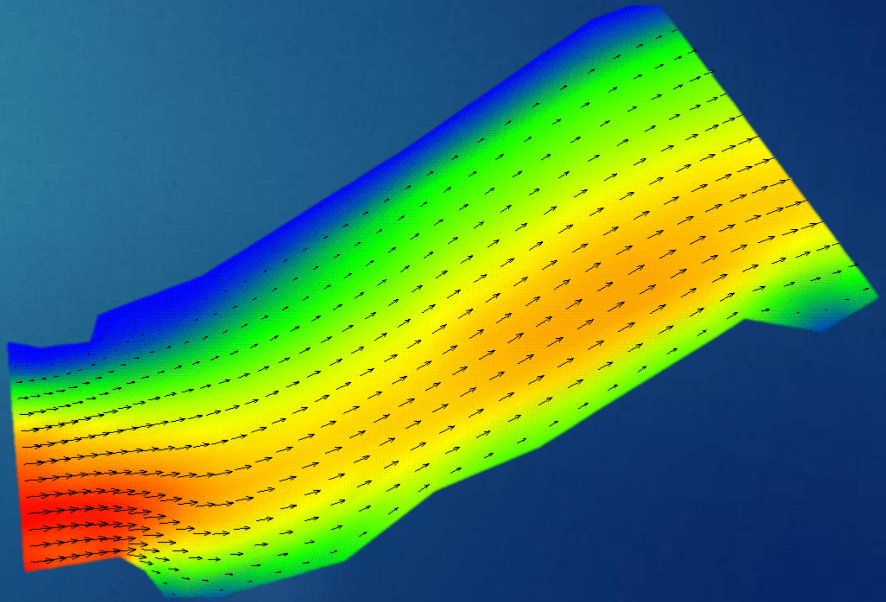
- Mount Saint Helens North Fort Toutle River
- Illinois River Model
- McLaughlin White Water Park Design

Illinois River-Physical Model

- Background
  - Legal case involving a between dam operators and towboat operators.
  - Led to damage of locks , towboats, flooding of city.
    - Billions of dollars in damages
  - Bad design of lock system, bad operation of lock system, or bad towboat driving?
  - Confidential Results

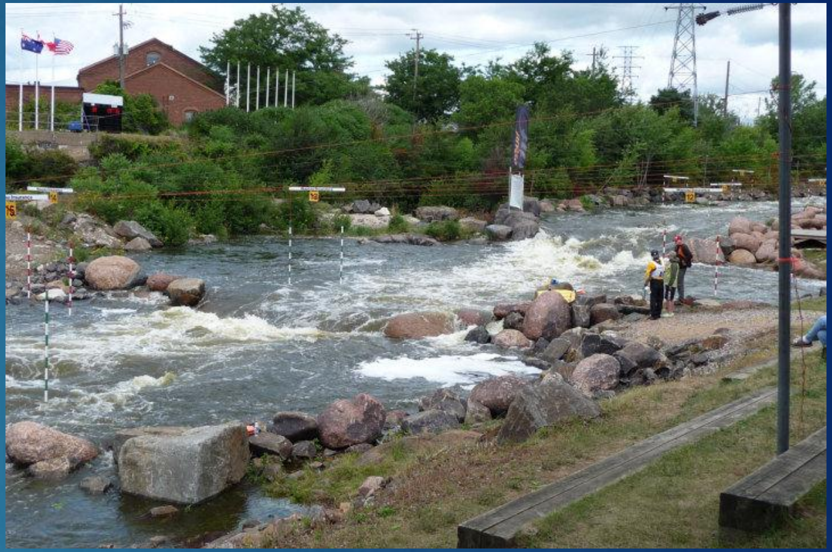
Illinois River-Physical Model

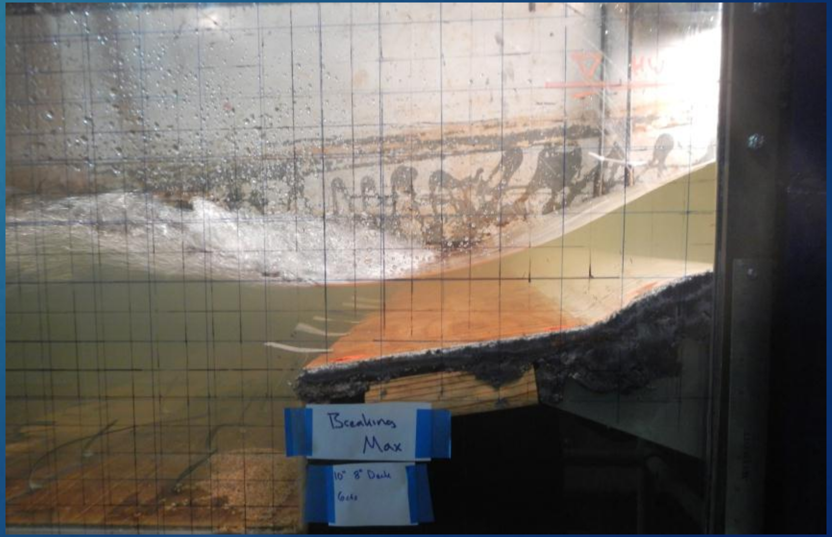
- Scaling of lock dimensions and calibration of flows based on stage height in model.
- Testing included a reconstruction of the lock system and recreation of the day of the accident.
  - The main testing was of the velocity fields in the model in and around the lock and pier system.
    - Lidar was used in compliance with LSPIV to map velocity field
    - Point velocities taken with Marsh McBirney



McLaughlin White Water Park Design

- Background
  - Recreational river play parks for kayaks and surfing are becoming increasingly popular in rivers around the nation
  - The goal is to create a hydraulic jump in the river or a standing wave
  - McLaughlin white water used CSUs hydraulics lab facilities for design of new white water park technology to be implemented in a new park in South Denver Region.
  - Flows scaled based on Froude Number.
- Testing included point velocities and water height for scaling of hydraulic information
- Confidential design and results



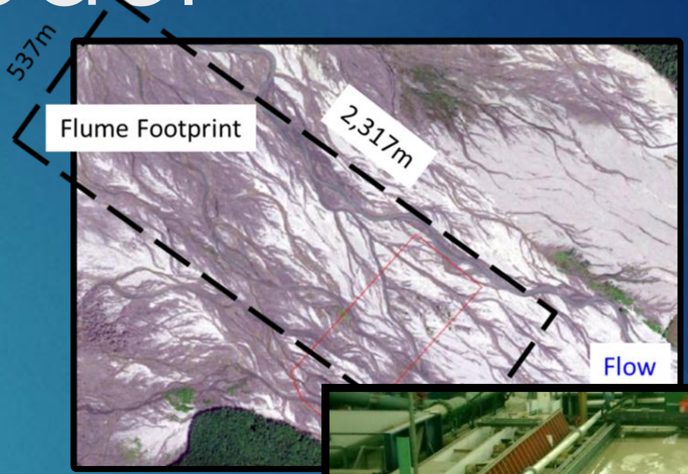


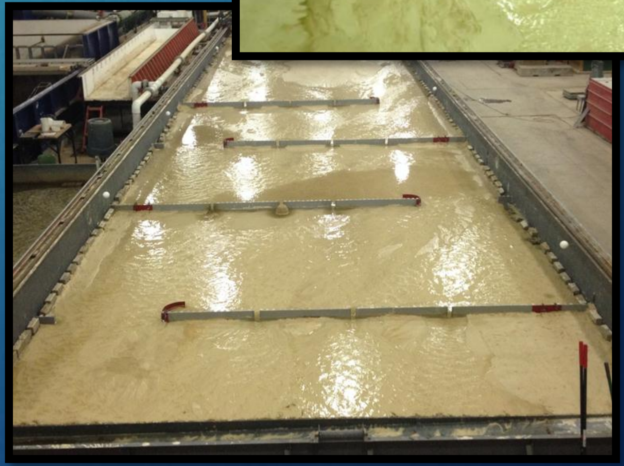
North Fort Toutle River-Model

- Background
  - When Mount Saint Helens Erupted all sediment was concentrated into the North Fork Toutle River.
  - Army Core of Engineers ongoing efforts to trap the sediment from propagating further downstream while being ecologically more sound than a retention wall.
  - Testing contracted out to CSU

North Fort Toutle River-Model

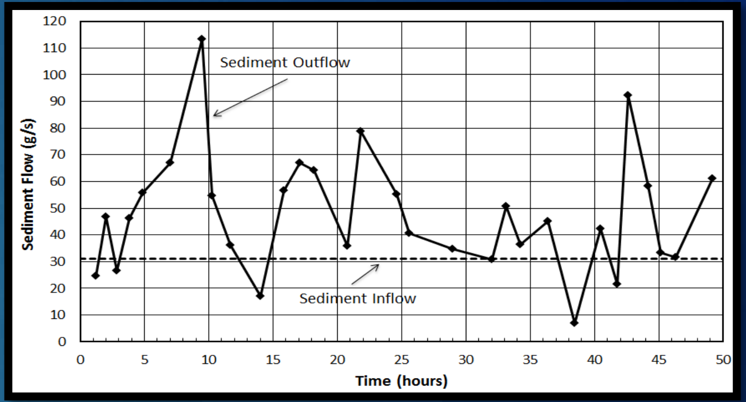
- Modeling outline
  - The biggest model of its kind
  - Braided river channel network to be recreated
  - 0.2mm silica sand used (very fine sand) chosen based on field sediment analysis
  - Location of interest determined the length scale of flume
  - Due to the difficulty of the model itself and lack of field sediment transport data the braided network was established first in the model and some scaling parameters were calibrated based of the physical model settings
  - Structures designed and installed
    - 6 different structure configurations tested for optimal design.

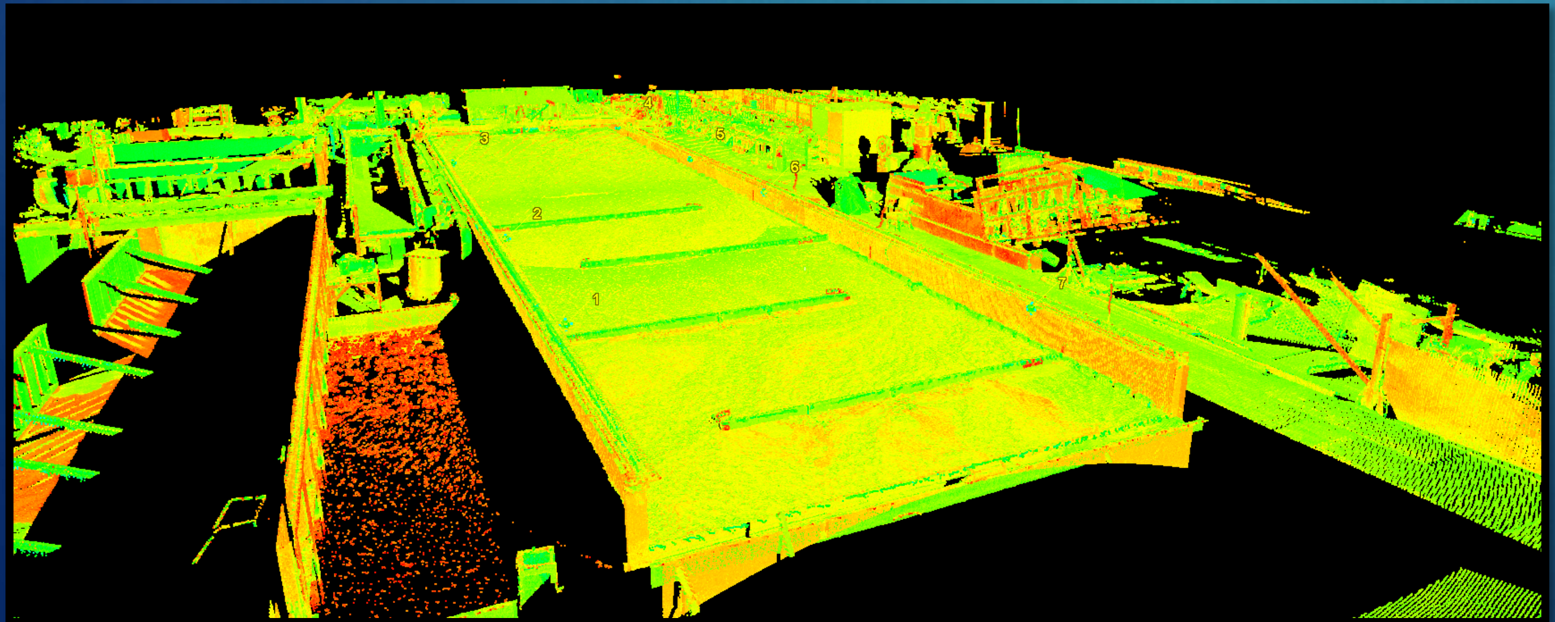


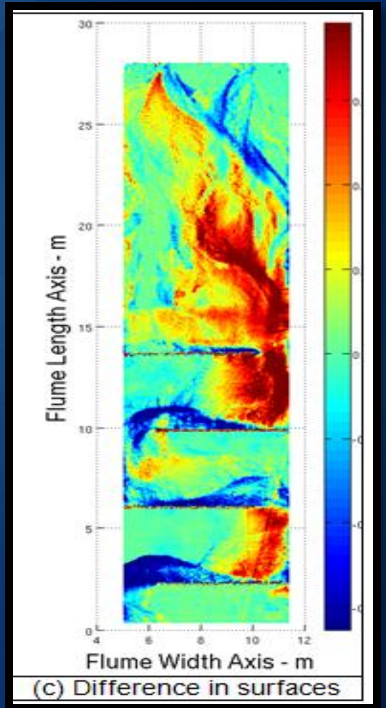


North Fort Toutle River-Model

- Data collection in the model
  - Sediment outflow data was periodically collected in custom sediment trap baskets and measured for depth and time averaged to get outflow data.
  - Lidar was used in the model to acquire surface differencing and volume estimates of local aggradation/degradation







Conclusion

- Similitude
  - For rivers, gravitational effects dominate = Froude similitude
- Rigid-bed vs. mobile-bed modeling
- Alternative, less dense sediment material
- CSU Hydraulics Lab
- Data collection
  - Velocity, survey, sediment analysis, stage heights
- Recent projects
  - Mount Saint Helens North Fort Toutle River, Illinois River Model, McLaughlin White Water Park Design