Dam/Levee Breach and Flood Modeling

Weiming Wu, PhD
Professor
Dept. of Civil and Environmental Eng.
Clarkson University
Potsdam, NY 13699, USA

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Causes of Dam Failures

Overtopping - 34%

Inadequate Spillway Design
Debris Blockage of Spillway
Settlement of Dam Crest

Foundation Defects - 30%

Differential Settlement
Sliding and Slope Instability
High Uplift Pressures
Uncontrolled Foundation Seepage

Piping and Seepage - 20%

Internal Erosion Through Dam Caused by Seepage-"Piping"
Seepage and Erosion along Hydraulic Structures Such as Outlet Conduits or Spillways, or Leakage through Animal Burrows
Cracks in Dam

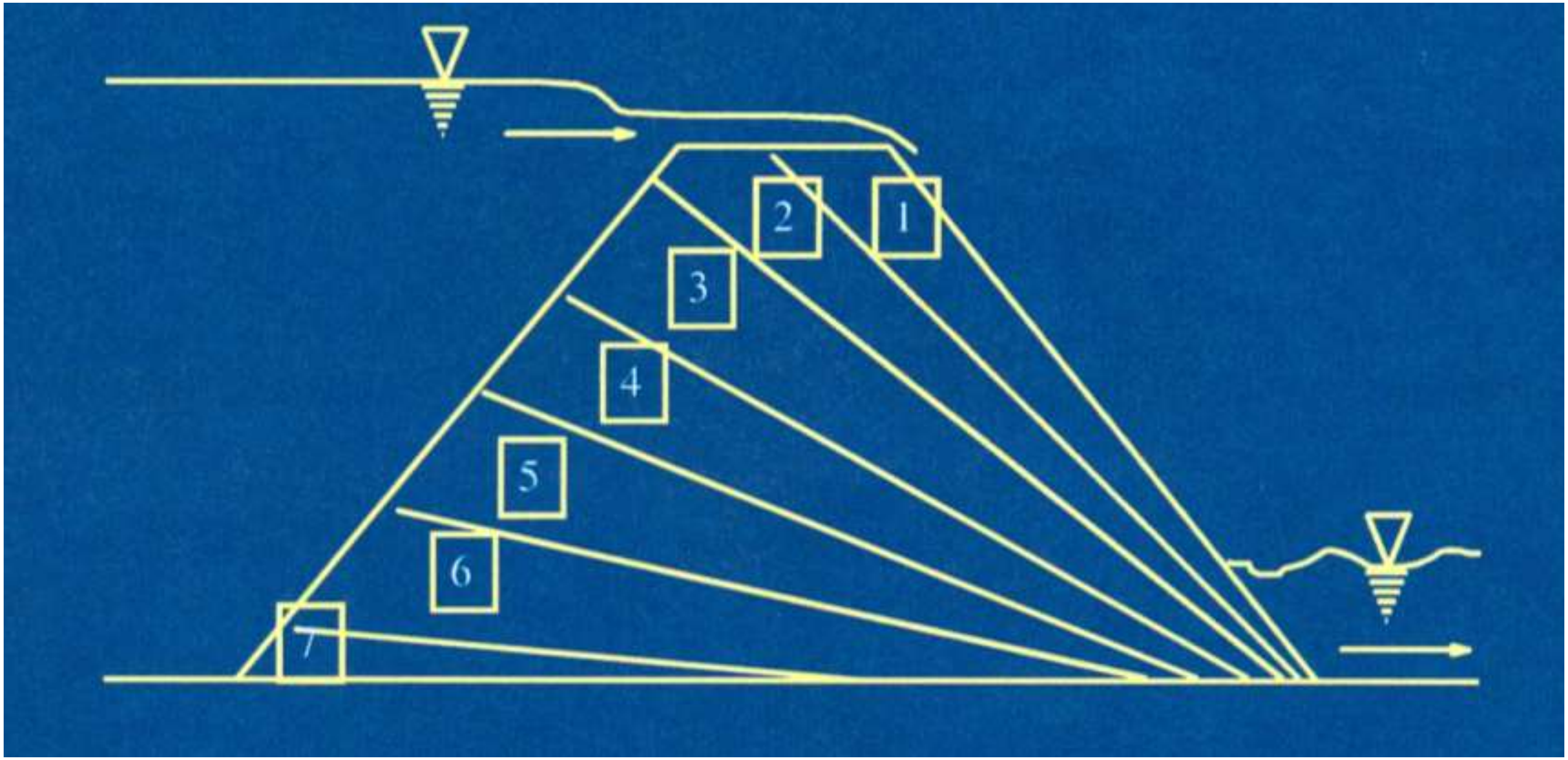
Conduits and Valves - 10%

Piping of Embankment Material into Conduit through Joints or Cracks

Other - 6%

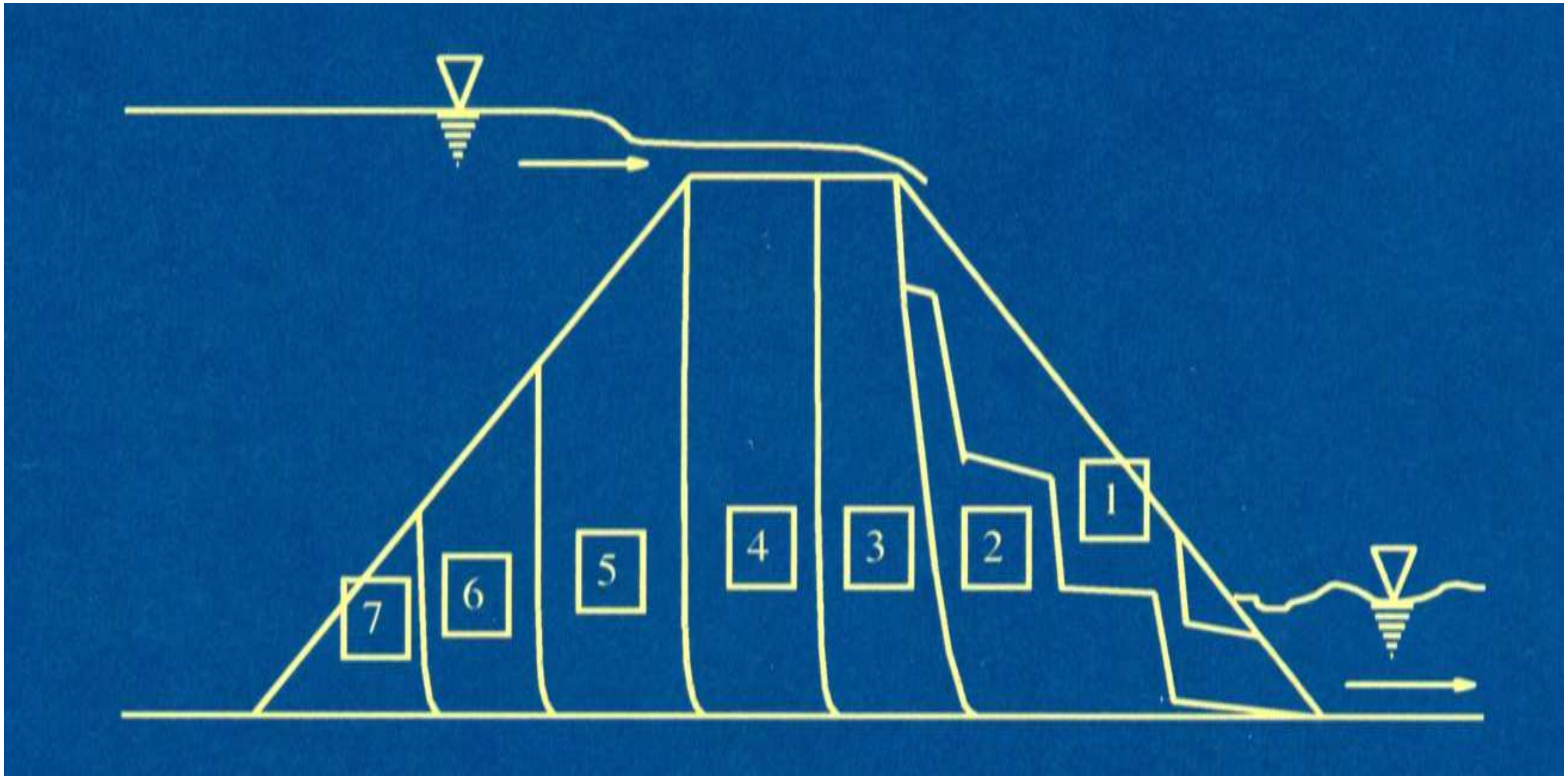
http://www.ecy.wa.gov/PROGRAMS/wr/dams/failure.html

Non-cohesive or Loose Embankment



(Hanson, 2007)

Cohesive or Compacted Embankment



(Hanson, 2007)

Dam/Levee Breach Experiment Data (ASCE/EWRI Task Committee, 2011)

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Performing Organization	Test Description	Literature Citation	No. of Tests
			> 726
Washington State Univ., US	Fuse plug breach –lab and field scales	Tinney and Hsu (1961)	13
Univ. of Windsor, Canada	Fuse plug breach –lab scale	Chee (1984)	Unknown
China	Fuse plug breach –field scale	Pan et al. (1993)	>50
Bureau of Reclamation, US	Fuse plug breach –lab scale	Pugh (1985)	8
Technical University of Graz	Rockfill dam breach –Overtopping	Simmler and Samet (1982)	22
China	Rockfill dam breach – lab scale	Pan et al. (1993)	Approx. 6-8
Simons, Li & Assoc. for USDOT FHWA	Highway embankment –overtopping	Chen and Anderson (1986)	35
Simons, Li & Assoc. for USDOT FHWA	Highway embankment –protection	Clopper and Chen (1988), Clopper (1989)	74
Bureau of Reclamation, US	Embankment dam –overtopping;	Dodge (1988)	9
University of Colorado, US	Embankment erosion –overtopping	Powledge et al. (1989)	3
Colorado State University, US	Overtopping breach	AlQaser and Ruff (1993)	2
USDA-ARS-HERU	Erosion in cohesive bare-earth and vegetated steep channels	Hanson and Temple (2002)	4
USDA-ARS-HERU	Overtopping breach –cohesive	Hanson et al. (2005), Hunt et al. (2005)	10
USDA-ARS-HERU	Internal erosion breach –cohesive	Hanson et al. (2010)	4
IMPACT - HR Wallingford, UK	Lab-scale overtopping and piping –various configurations	Morris and Hassan (2005)	22
Norway - IMPACT	Large-scale overtopping and piping breach –various configurations	Morris and Hassan (2005), Vaskinn et al. (2004), EBL_Kompetanse (2006)	5
Norway - Other field tests	Rockfill dams –through-flow and breach	Vaskinn et al. (2004), EBL_Kompetanse (2006)	2
Norway - Lab tests	Rockfill dams –through-flow and overtopping	EBL_Kompetanse (2006)	23
Delft Univ. of Technology, The Netherlands	Overtopping – sand dikes	Visser (1998)	5
University of Birmingham, UK	Overtopping –sand embankments	Lecointe (1998)	2

Performing Organization	Test Description	Literature Citation	No. of Tests
Brno Univ. of Technology , Switzerland	Overtopping –noncohesive	Jandora and Riha (2009)	>1
Univ. of Auckland, New Zealand	Overtopping –noncohesive	Coleman et al. (2002)	9
Technical University of Lisbon, Portugal	Overtopping –rockfill	Franca and Almeida (2004)	22
St. Petersburg State Technical Univ., Russia	Overtopping –noncohesive	Rozov (2003)	4
Asian Institute of Technology, Thailand	Overtopping –noncohesive, full/partial-width breach	Tingsanchali and Chinnarasri (2001), Chinnarasri et al. (2004)	16
South Africa	Overtopping –noncohesive	Parkinson and Stretch (2007)	24
École Polytechnique de Montréal, Canada	Overtopping –moraine	Zerrouk and Marche (2005)	1
University of Ottawa, Canada	Overtopping –effects of compaction and initial breach	Al-Riffai et al. (2009), Orendorff (2009)	14
New Zealand /Switzerland	Overtopping –replicate landslide dam	Davies et al. (2007)	2
VAW, Switzerland	Overtopping –noncohesive, lab scale	Schmocker and Hager (2009)	approx. 60
Germany-FLOODsite	Overtopping –coastal dike (small and large scales)	Geisenheiner and Kortenhaus (2006), Geisenhainer and Oumeraci (2008)	approx. 11
Japan	Levee breach –lab scale	Fujita and Tamura (1987)	32
Federal Armed Forces Univ., Germany	Overtopping –noncohesive, lab scale	Kulisch (1994)	approx. 7
Wuhan University, China	Overtopping –landslide dams, lab scale	Cao et al. (2011)	Approx. 50
Nanjing Hydraulic Research Institute, China	Overtopping –cohesive, layered, field scale	Zhang et al. (2009)	5
Universitá di Padova, Italy	Criteria for overtopping failure –landslide dames, small scale	Gregoretti et al. (2010)	168

Field Case Studies

- Justin (1932) – 29 cases
- Singh (1996) – 63 cases
- Wahl (2007) – 108 cases
- Xu and Zhang (2009) – 182 cases
  - 75 cases were used for parametric breach model
- Pierce et al. (2010) – 87 cases
  - Including lab and field cases
  - Tested Q_p parametric breach model
- Wu (2013) – 50 cases
  - Including lab and field cases
  - Tested Wu's simplified breach model

Summary of Lab and Field Data

- A lot of data are for dam breaching, whereas levee breach data are needed
- Most lab data are small-scale, whereas large-scale experiments are needed.
- Most data are for homogeneous dams, whereas composite embankments are needed to investigate.
- Most data are related to overtopping, whereas piping needs to be studied.
- Erosion of cohesive soil and headcut need to be further investigated.
- Quality of field case study needs to be improved.

Classification of Breach Models

- Parametric models
  - Regression equations derived from limited field case studies of dam breach
- Simplified physically-based breach models
  - Analytical solutions
  - Numerical solutions
- Detailed physically-based breach models
  - 1-D numerical models
  - Depth-averaged 2-D numerical models
  - 3-D numerical models

Parametric Breach Models

Reference	Relations Proposed	No. of Case Studies	Remarks
Kirkpatrick (1977)	$Q_p=1.268(h_w+0.3)^{2.5}$	16 (plus 5 hypothetical failures)	
SCS (1981)	$Q_p=16.6(h_w)^{1.85}$	13	
Hagen (1982)	$Q_p=0.54(h_dS)^{0.5}$	6	
Singh and Snorrason (1984)	Guidance for B, z, t_f $Q_p=1.776S^{0.47}$, $Q_p=13.4(h_d)^{1.89}$	20 real failures and 8 simulated failures	Q_p relations based on simulations
MacDonald & Langridge-Monopolis (1984)	$V_{er}=0.0261(V_wh_w)^{0.769}$ (earthfill) $V_{er}=0.00348(V_wh_w)^{0.852}$ (nonearthfills) $t_f=0.0179(V_{er})^{0.364}$ $Q_p= 1.154(V_wh_w)^{0.41}$	42	
Costa (1985)	$Q_p=0.981(h_dS)^{0.42}$	31 constructed dams	
Evans (1986)	$Q_p= 0.72(V_w)^{0.53}$		
USBR (1988)	$B_{avg}=3h_w$, $t_f=0.011B_{avg}$ $Q_p=19.1(h_w)^{1.85}$ (envelope eq.)	21	
Von Thun and Gillette (1990)	Guidance for z $B_{avg}=2.5h_w+C_b$ $t_f=B_{avg}/(4h_w)$ erosion resistant, $t_f=B_{avg}/(4h_w+61)$ highly erodible	57	Including erodibility
Froehlich (1995a)	$Q_p=0.607(V_w)^{0.295}(h_w)^{1.24}$	22	
Froehlich (1995b)	Guidance for z $B_{avg}=0.1803K_o(V_w)^{0.32}(h_b)^{0.19}$ $t_f=0.00254(V_w)^{0.53}(h_b)^{-0.9}$	63	Including overtopping/piping in K_o
Walder & O'Connor (1997)	$Q_p= f(V_w$, relative erodibility)		Including erodibility
Xu and Zhang (2009)	B, Q_p, t_f =f(V_w, h_w, erodibility, etc.)	75	Considering overtopping and piping; low, medium and high erodibility
Pierce et al. (2010)	$Q_p=0.0176(Vh)^{0.606}$ or $Q_p=0.038V^{0.475}h^{1.09}$	87	

(ASCE/ EWRI Task Committee, 2011)

Simplified Breach Models (ASCE/EWRI Task Committee, 2011)

Model	Breach Morphology		Flow over the Breach	Sediment Transport	Geomechanics	Solution Method	Remarks
	Cross-section	Longitudinal section					
Singh and Scarlatos (1988)	Triangular, trapezoidal, rectangular		Broad-crested weir formula	Erosion rate as function of flow velocity		Analytical solution	simplified reservoir storage curve
Rezov (2003)	Rectangular with initial bottom at the dam base	Exner equation	Weir formula	Sediment transport as function of flow velocity and depth		Analytical solution	simplified reservoir storage curve
Franca and Almeida (2004)	Breach shape observed by experiments		Weir formula	Sediment transport as function of flow velocity		Analytical solution	simplified reservoir storage curve, rockfill dams
Macchione (2008)	Triangular to Trapezoidal		Weir formula	Sediment transport as function of bed shear stress		Analytical solution	simplified reservoir storage curve
Cristofano (1965)	Trapezoidal with constant bottom width	Constant d/s slope	Broad-crested weir formula	Cristofano's formula	No lateral collapse	Iterative	No downstream submergence
BRDAM (Brown & Rodgers, 1981; based on Harris &Wagner, 1967)	Constant Parabolic Shape		Weir formula for overtopping and orifice for piping	Schoklitsch's formula	Top wedge failure; no lateral collapse	Numerical	No downstream submergence
Ponce & Tsivoglou (1981)	Relation between the top-width and discharge	Exner equation	Unsteady Saint-Venant equations	Meyer-Peter and Mueller's formula	No lateral collapse	Preissmann's finite difference	
Lou (1981)	Most efficient stable section	Exner equation	Unsteady Saint-Venant equations	Duboy's and Einstein's formulas	No lateral collapse	Preissmann's finite difference	
Nogueira (1984)	Determined by effective shear stress	Exner equation	Unsteady Saint-Venant equations	Meyer-Petr and Mueller's formula	No lateral collapse	Preismann's finite difference	
DAMBRK (Fread, 1984; similar one used by HEC-RAS)	Trapezoidal or rectangular	Constant d/s slope	Weir formula	Assumed linear erosion	None	Numerical iterative	
BEED (Singh and Scarlatos, 1985)	Trapezoidal	Constant d/s slope and erosion of the crest	Weir formula	Einstein and Brown; Meyer-Peter-Mueller	Breach side slope stability	Numerical iterative	

Simplified Breach Models (cont'd)

Model	Breach Morphology		Flow over the Breach	Sediment Transport	Geomechanics	Solution Method	Remarks
	Cross-section	Longitudinal section					
EMBANK (Chen & Anderson, 1986)	Erosion in horizontal layers; breach width undetermined		Broad-crested weir velocity profile	Duboys formula, Shields diagram		Iterative nomogram s	Road embankment failure
NWS BREACH (Fread, 1988)	Rectangular and trapezoidal	Constant d/s slope	Weir formula for overtopping and orifice for piping	Meyer-Peter-Mueller modified by Smart	Breach side slope stability; top wedge failure during piping	Numerical-Iterative	With downstream submergence effects
DEICH_A (Broich, 1998)	Trapezoidal	Horizontal channel	Weir formula	Meyer-Peter-Mueller			
BRES (Visser, 1998; Zhu et al., 2006)	Trapezoidal	Rotation up to a constant d/s slope	Weir formula	Various equations; Noncohesive and cohesive	Simple slope stability mechanism	Numerical iterative	Sea dike breach
HR BREACH (Mohamed et al., 2002; Morris et al., 2009a)	Effective shear stress dependent	Soil erosion/wasting	Variable weir plus 1D steady non-uniform equation	Various equations; noncohesive and cohesive	Slope stability; core stability; multiple zones of variable erodibility	Numerical iterative	Uncertainties in material properties and full Monte Carlo
Kraus and Hayashi (2005)	Rectangular	Horizontal channel	1D Keulegan equation	Empirical formula, plus longshore sediment source	None	Numerical iterative	Coastal barrier breach
FIREBIRD (Wang et al., 2006)	Variable trapezoidal	Exner equation	Unsteady St. Venant equations	Sediment transport formulas or erosion rate equations	Side stability	Numerical finite differences	Limited testing on Norweigian data and two prototype cases
D'Eliso (2007)	Rectangular to trapezoidal	Headcut development and migration	Wave overtopping and/or overflow - Bernoulli equation	Formulas erosion rate and headcut advance	Grass cover, clay cover, sand core; breach slope stability	Numerical iterative	Composite sea dike failure
WinDAM/SIMBA (Hanson et al., 2005&2010; Temple et al., 2005 &2006)	Rectangular trapezoidal	Headcut development and migration	Weir formula	Parametric relations for headcut advance, bottom and lateral erosion	Breach side slope erosion	Numerical iterative	
Wu (2013)	Trapezoidal	Variable slope and erosion of the crest	Weir formula for overtopping and orifice for piping	Noneq. sediment transport, noncoh. and cohesive erosion, headcut advance	Lateral erosion, headcut stability, clay core stability, pipe top failure	Numerical iterative	With downstream submergence, dam and levee

Detailed Breach Models (selected)

Model	Breach Morphology	Flow	Sediment Transport Capacity	Geomechanics	Solution Method	Remarks
Tingsanchali and Chinnarasri (2001)	1-D Exner equation	1-D St. Venant Equations	Multiple formulas	Longitudinal slope stability	Finite difference, uncoupled	Cohesive, overtopping, no lateral erosion
DEICH_N1 & DEICH_N2 (Broich, 1998)	Evolution from 1-D/2-D Exner equation	shallow water equations	Nine different formulas available		1-D/2-D numerical model, uncoupled	
Dave_F (Froehlich, 2004)	2-D Exner equation	2-D shallow water equations	Erosion formula from WEPP, USDA		2-D numerical model, uncoupled	Validated on Norweigian field tests
Wang and Bowles (2006)	Clear water scour	2-D shallow water equations	Chen and Anderson's formula for erosion rate	3-D slope stability	2-D TVD finite difference, uncoupled	Noncohesive dam, overtopping
Faeh (2007)	2-D Exner equation	2-D shallow water equations	Formulas for bed load and Suspended load	Lateral erosion, vertical erosion, slope stability	2-D finite volume (Roe and HLL), uncoupled	Noncohesive levee, overtopping
Wang et al. (2008)	2-D non-equilibrium sediment transport equation	2-D shallow water equations	Formula for bed load	Lateral erosion, vertical erosion, slope stability	2-D finite volume (Roe's Riemann solver), coupled	Noncohesive, overtopping
Roelvink et al. (2009)	2-D non-equilibrium sediment transport equation	2-D shallow water equations with wave-action	Soulsby formula	Bed avalanching	2-D finite difference, uncoupled	Noncohesive dune and barrier, overtopping
Wu and Wang (2007), Wu et al. (2012)	1-D/2-D non-equilibrium total-load transport equations	Generalized shallow water equations	Wu et al. total-load capacity formula	Lateral erosion, slope stability (repose angle)	1-D/2-D finite volume (HLL) scheme, coupled	Noncohesive dam and levee, overtopping
Cao et al. (2011)	2-D non-equilibrium sediment transport	Generalized shallow water equations	Modified Meyer-Peter & Mueller bed-load	slope stability (repose angle)	finite volume (HLLC) scheme, coupled	Landslide dam, overtopping

DLBreach Model Series

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- DLBreach - Dam/Levee/Barrier Breach
- DLBreach (Wu 2013, JHE)
  - Simplified physically-based breach model
- DLBreach1D (Wu and Wang 2007, JHE)
  - 1-D numerical model
- DLBreach2D (Wu et al., 2012, JHE)
  - 2-D numerical model
- DLBreach3D (Marsooli and Wu 2014, JHE)
  - 3-D numerical model

1-D and Depth-averaged 2-D Models

DLBreach1D/2D

By Wu and Wang (2007, 2008) and Wu et al. (2012)

DLBreach1D/2D Models

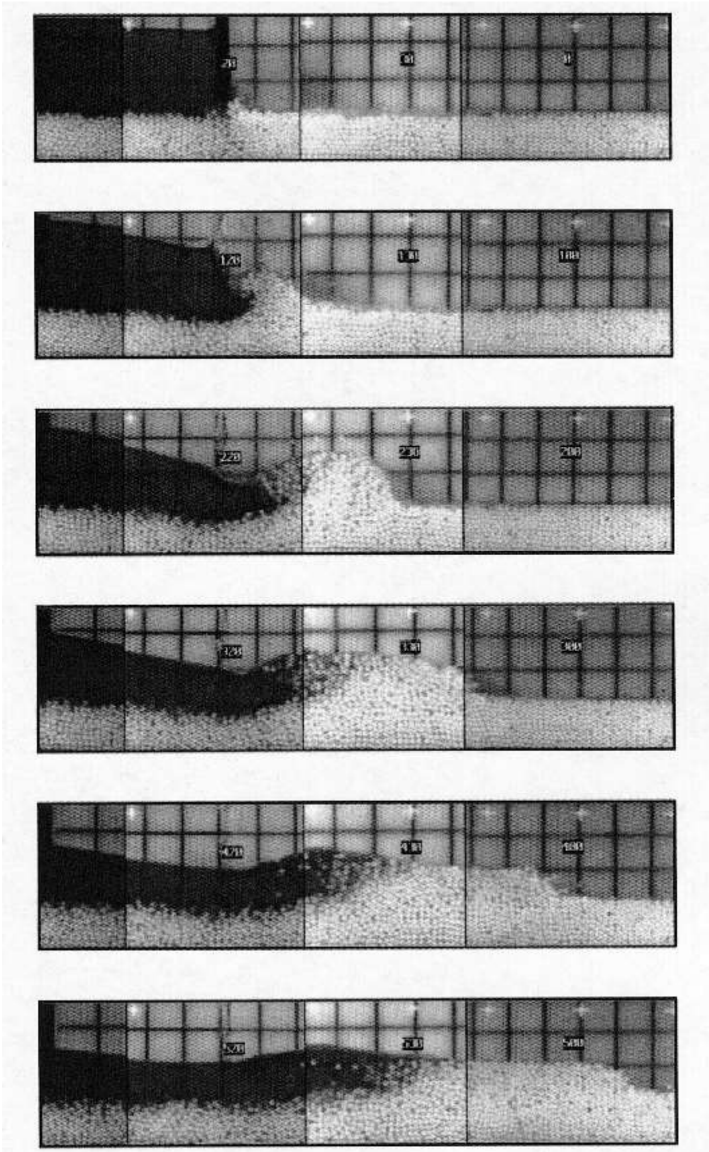
- Based on hydrodynamic and sediment transport equations
- Explicit finite volume method
- 1-D/2-D approximate Riemann solvers
- Mixed supercritical/subcritical flows
- Considering effect of sediment transport and bed change on the flow
- Non-equilibrium total-load sediment transport model

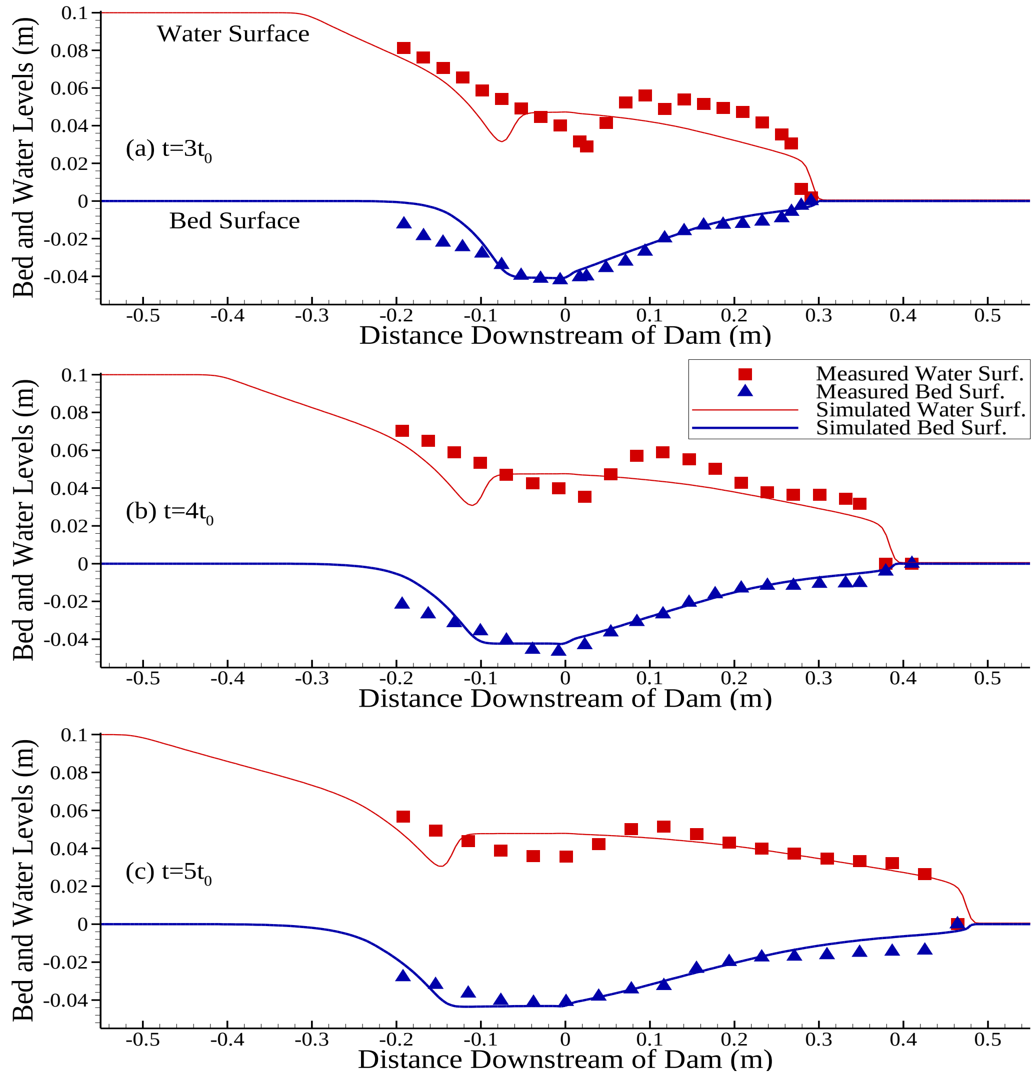
1-D Dam-Break Flow Model

$$\frac{\partial(\rho A)}{\partial t} + \frac{\partial(\rho Q)}{\partial x} + \frac{\partial(\rho_b A_b)}{\partial t} = \rho_w q_w + \rho_s q_s$$

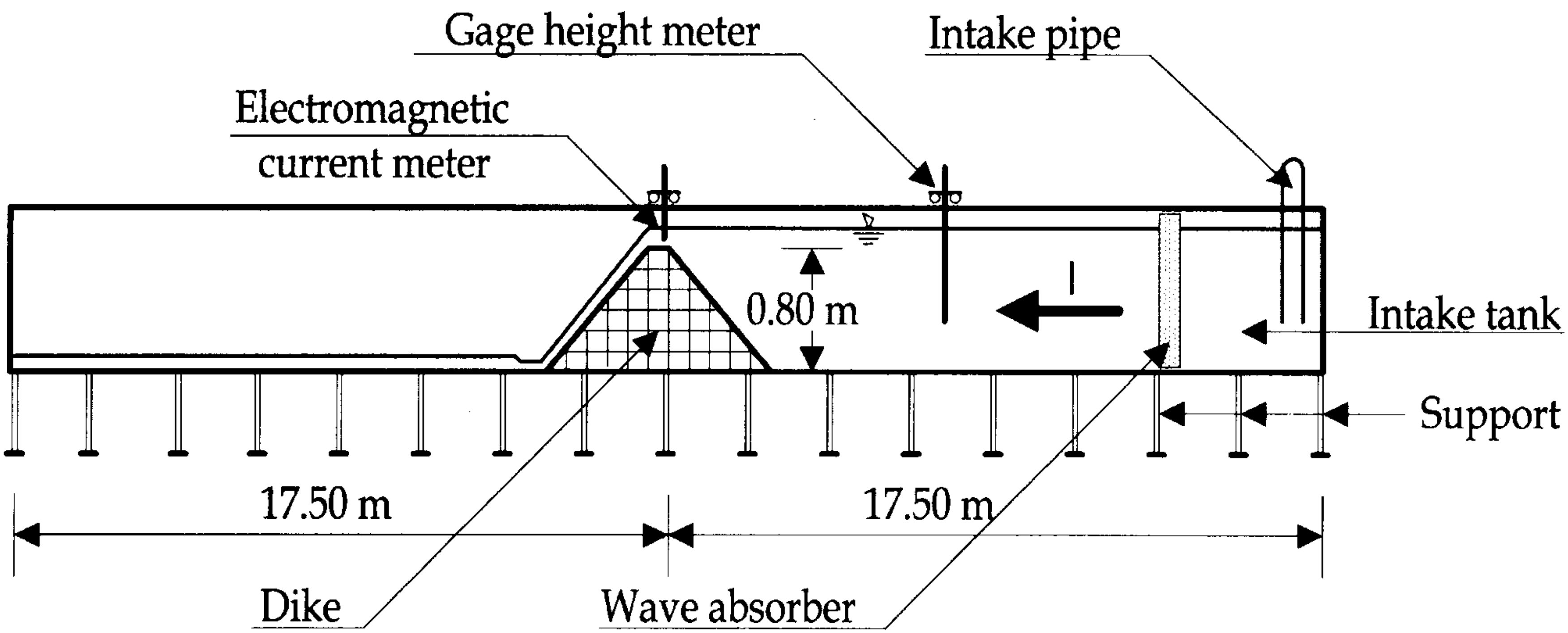
$$\frac{\partial}{\partial t}(\rho Q) + \frac{\partial}{\partial x}\left(\frac{\rho \beta Q^2}{A}\right) + \rho g A \frac{\partial z_s}{\partial x} + \frac{1}{2} g A h_p \frac{\partial \rho}{\partial x} + \rho g \frac{n^2 Q|Q|}{A R^{4/3}} = 0$$

Dam-Break Flow over Movable Beds



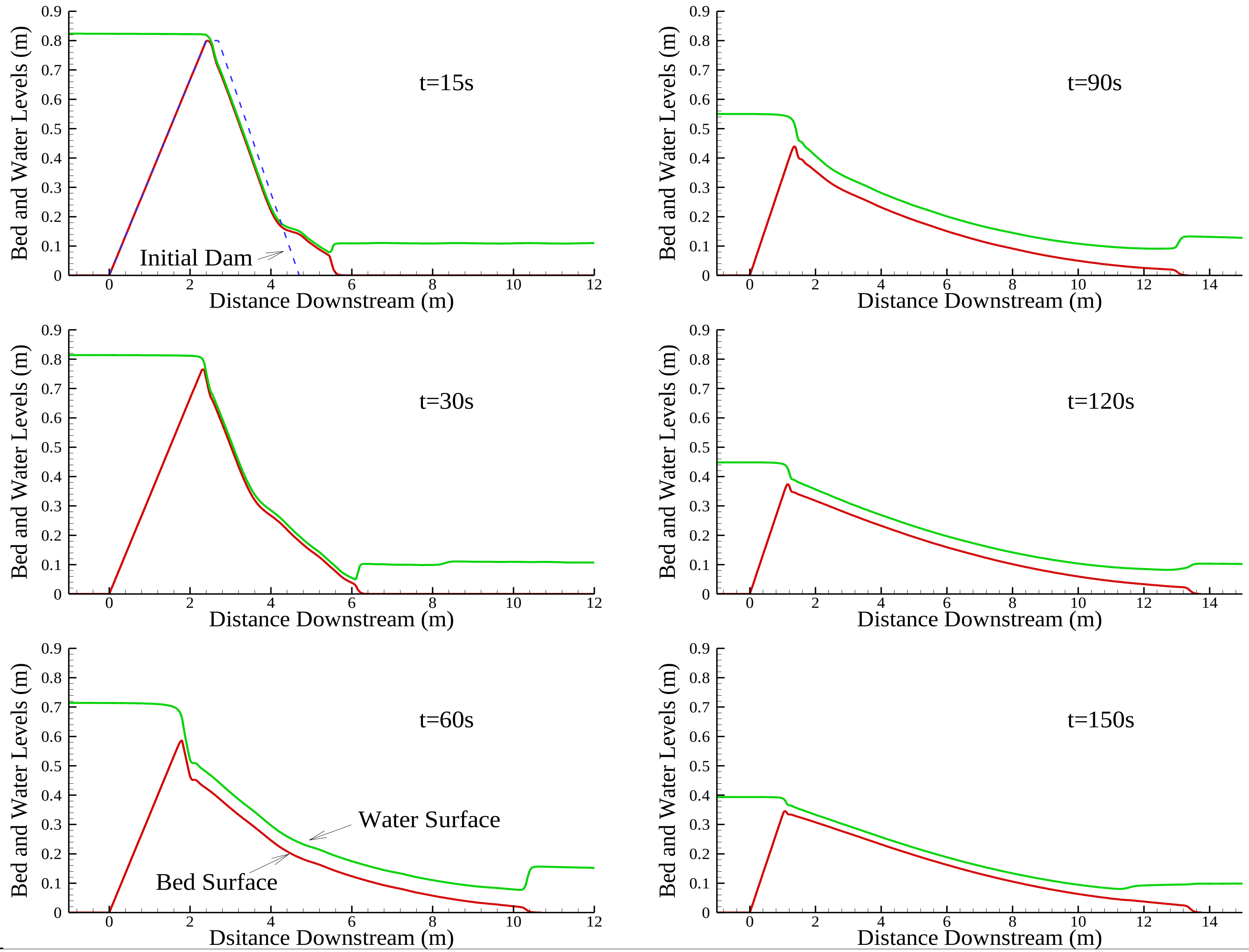


Dam Erosion Due to Overtopping Flow



Longitudinal section

Chinnarasri et al. (2003) at AIT, Thailand


t=15s
Initial Dam
Distance Downstream (m)
Bed and Water Levels (m)
t=90s
t=30s
t=120s
t=60s
Water Surface
Bed Surface
Dsitance Downstream (m)
t=150s

2-D Shallow Water Equations

$$\frac{\partial\left(\rho h\right)}{\partial t}+\frac{\partial\left(\rho hu\right)}{\partial x}+\frac{\partial\left(\rho hv\right)}{\partial y}+\rho_b\frac{\partial z_b}{\partial t}=0$$

$$\frac{\partial(\rho hu)}{\partial t}+\frac{\partial(\rho hu^2)}{\partial x}+\frac{\partial(\rho huv)}{\partial y}=-\rho gh\frac{\partial z_s}{\partial x}-\frac{1}{2}gh^2\frac{\partial\rho}{\partial x}-\rho g\frac{n^2u|\overline{u}|}{h^{1/3}}$$

$$\frac{\partial(\rho hv)}{\partial t}+\frac{\partial(\rho huv)}{\partial x}+\frac{\partial(\rho hv^2)}{\partial y}=-\rho gh\frac{\partial z_s}{\partial y}-\frac{1}{2}gh^2\frac{\partial\rho}{\partial y}-\rho g\frac{n^2v|\overline{u}|}{h^{1/3}}$$

2-D Sediment Transport Model

Sediment Transport

$$\frac{\partial(hC_t)}{\partial t}+\frac{\partial(huC_t)}{\partial x}+\frac{\partial(hvC_t)}{\partial y}=-\frac{h\bar{u}}{L_s}(C_t-C_{t*})$$

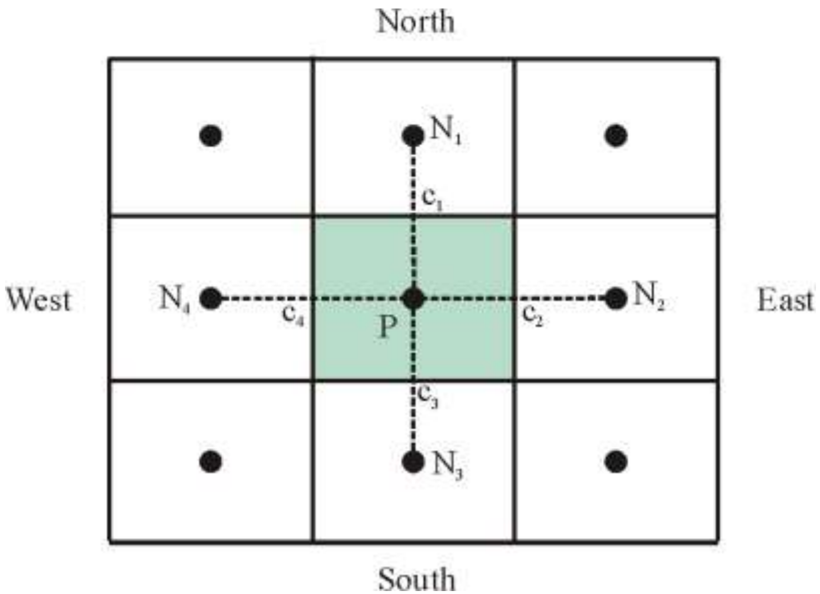
Bed Change

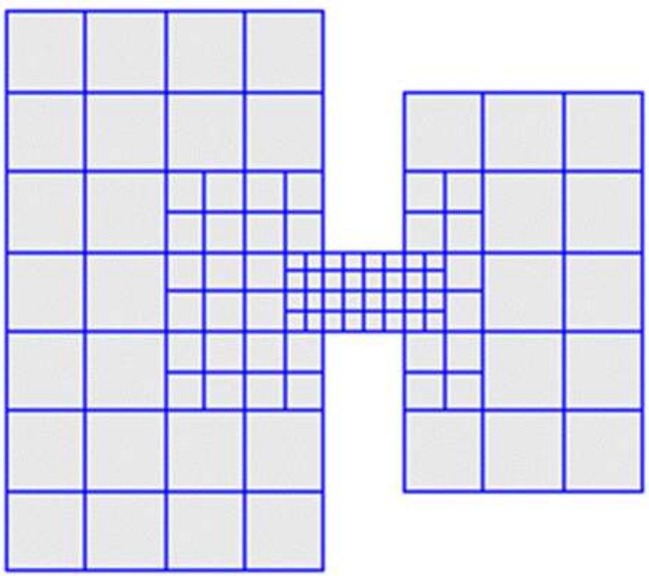
$$(1-p'_m)\frac{\partial z_b}{\partial t}=\frac{h\bar{u}}{L_s}(C_t-C_{t*})$$

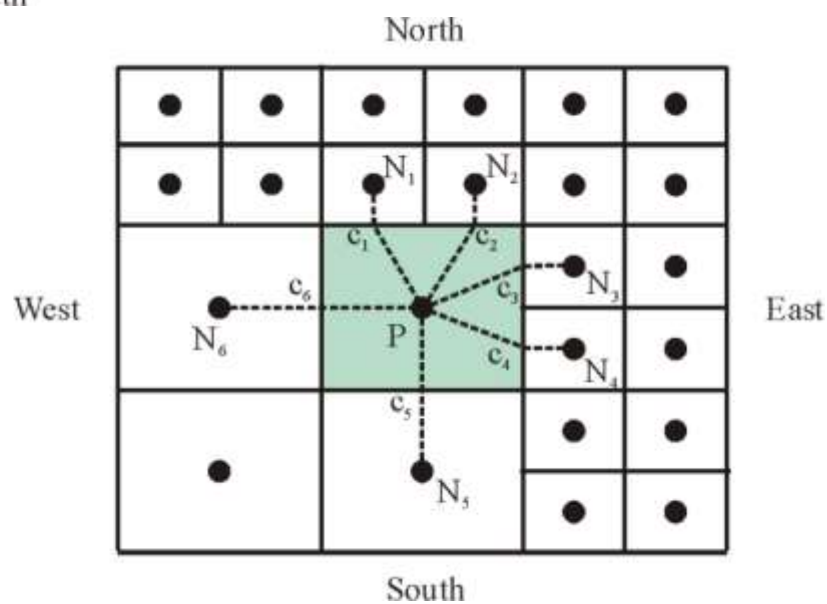
Sediment Transport Capacity

by Wu et al. (2000) Formula

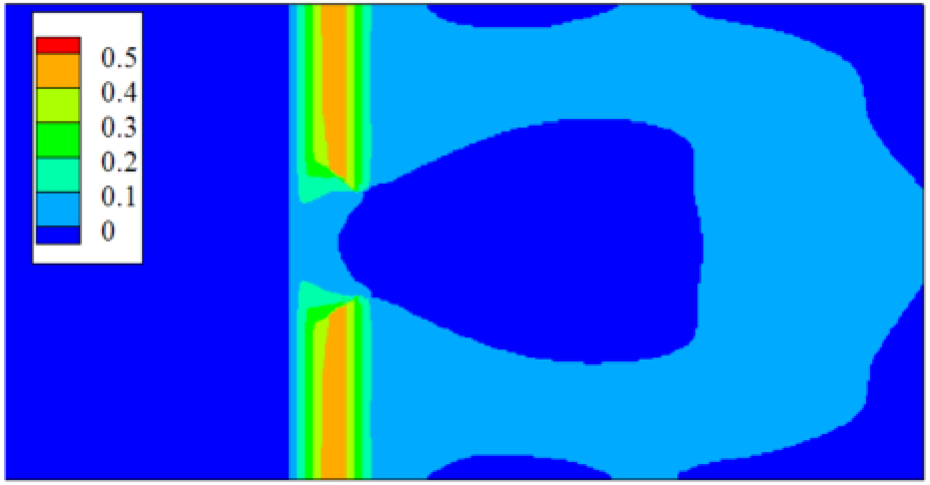
2-D Rectangular Mesh

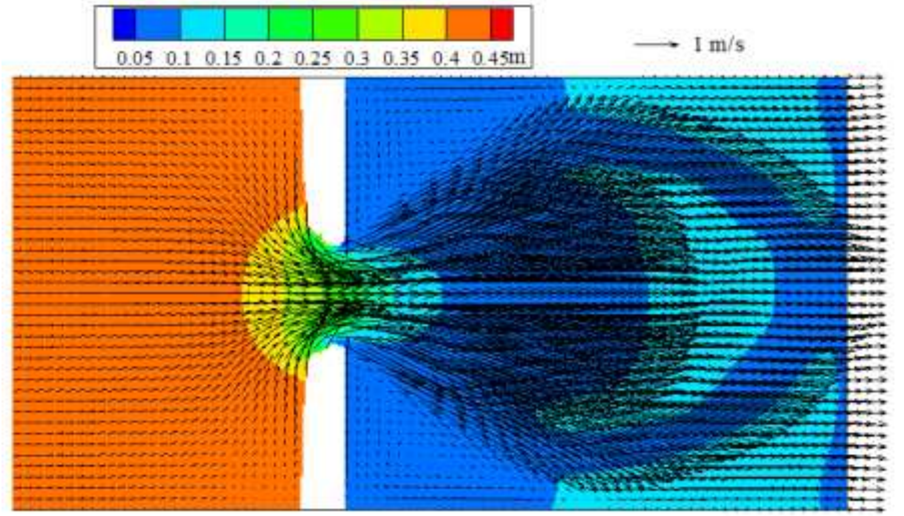


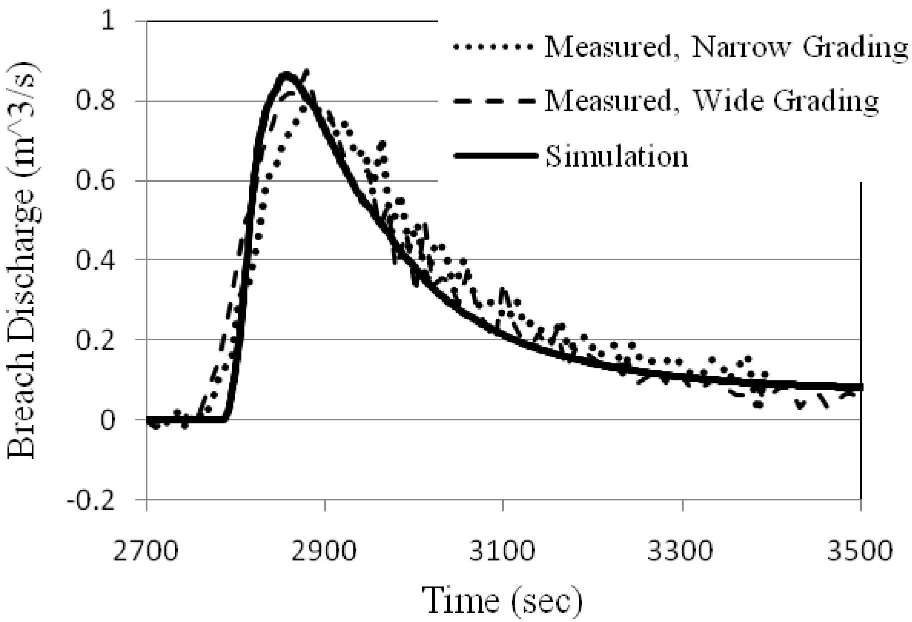


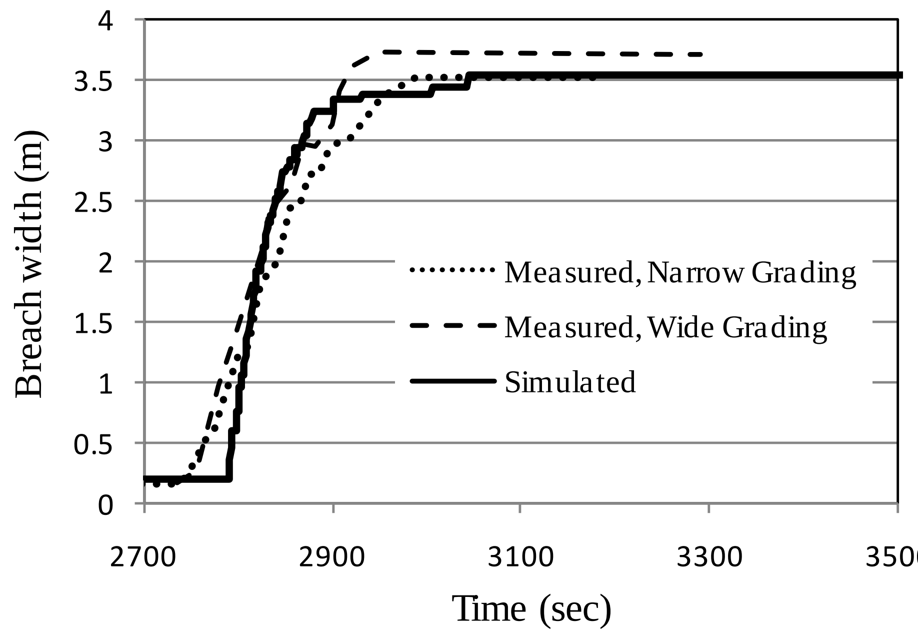


IMPACT Lab Test (No. 2)

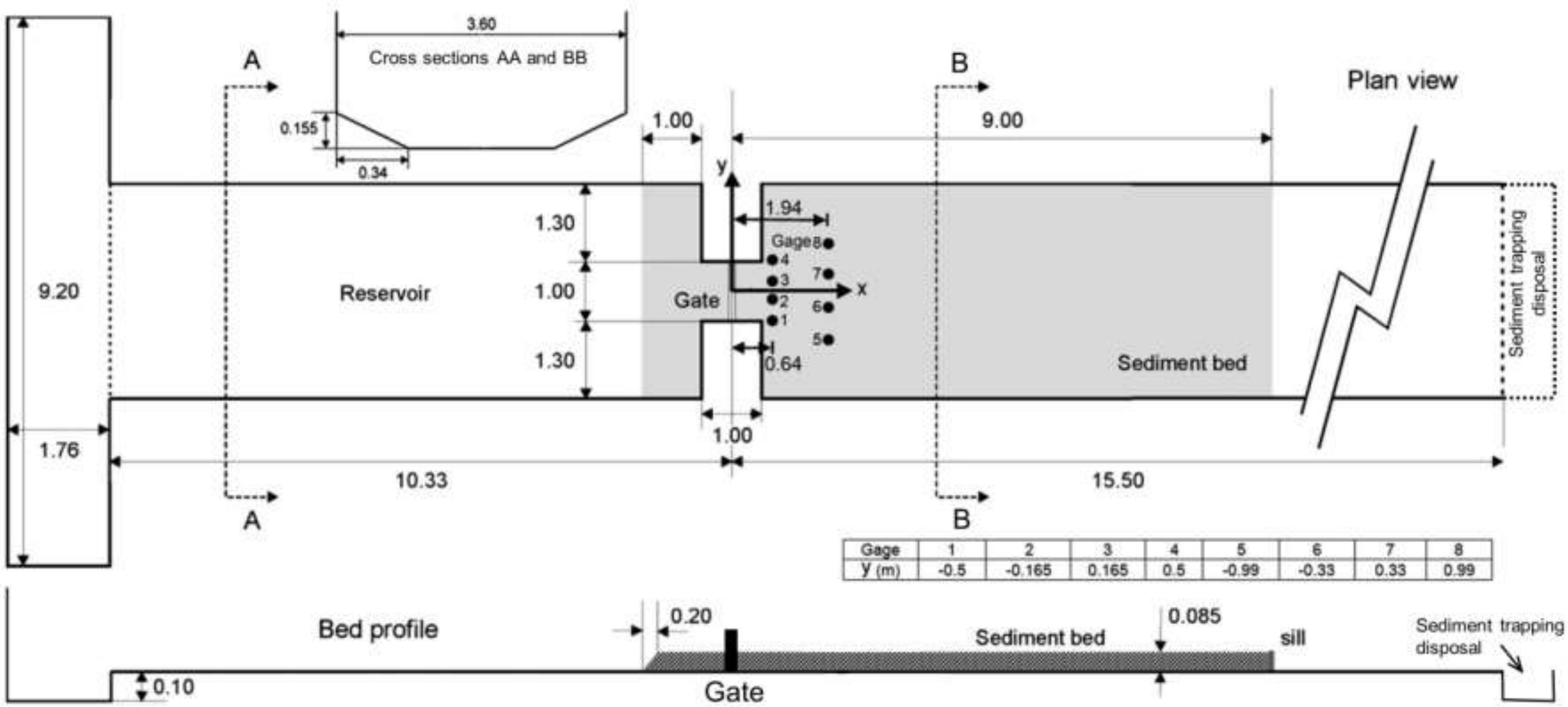






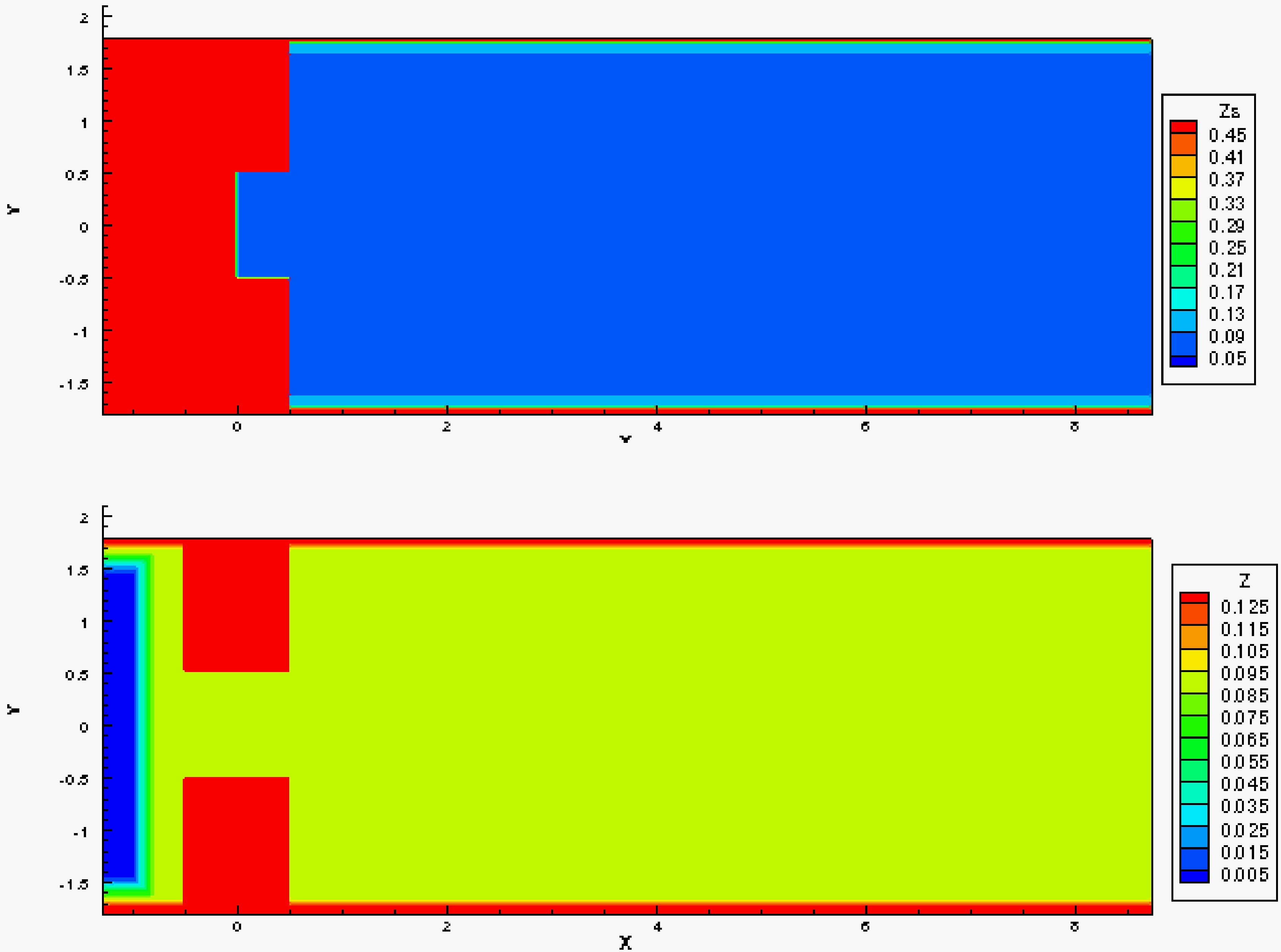


Partial Dam-Break Flow over Movable Bed (Université catholique de Louvain, Belgium)

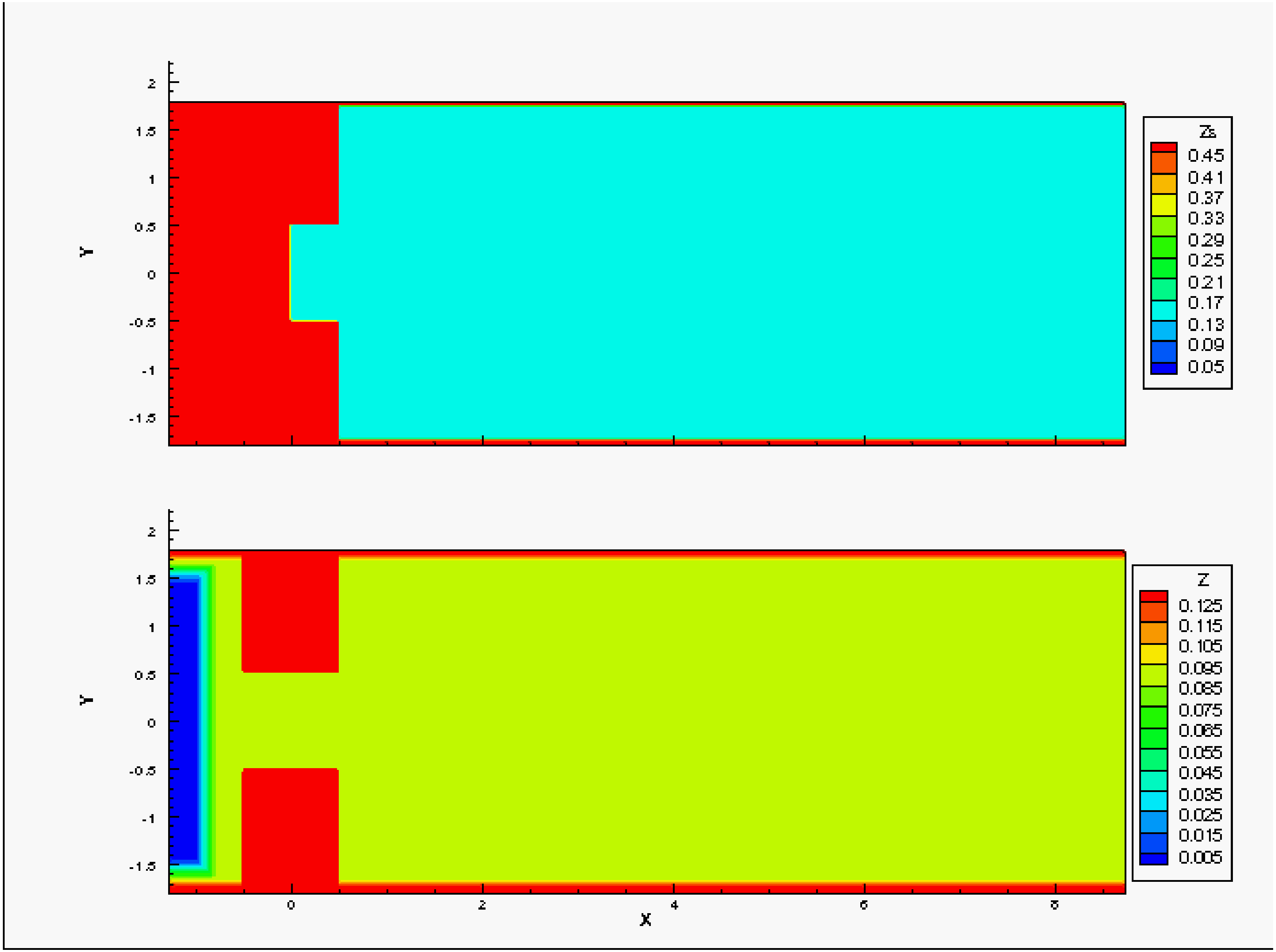


Gage	1	2	3	4	5	6	7	8
y (m)	-0.5	-0.165	0.165	0.5	-0.99	-0.33	0.33	0.99

2-D Results: Partial Dam-Break Flow over Movable Bed (Dry D/S)



2-D Results: Partial Dam-Break Flow over Movable Bed (Wet D/S)



Water Levels for the Partial Dam Break Case

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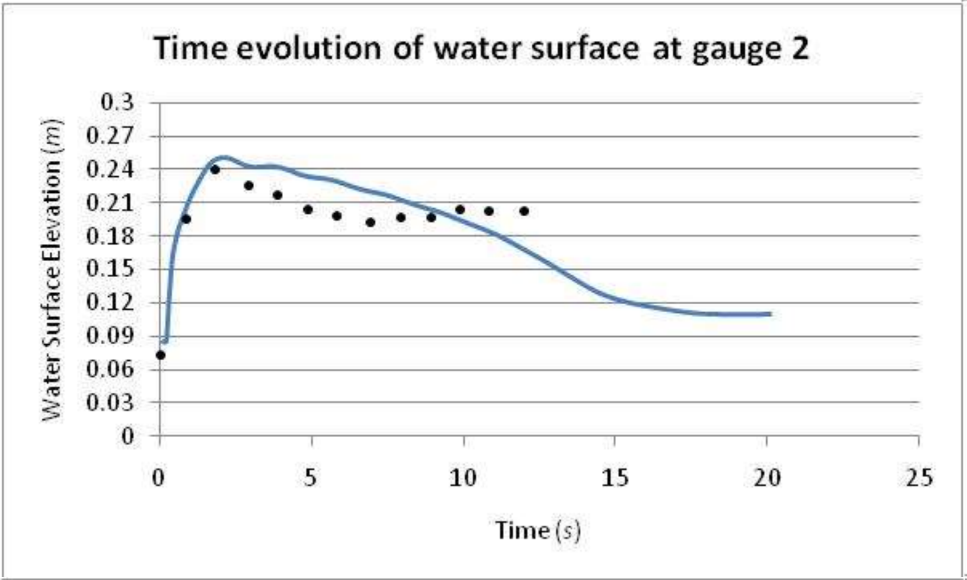
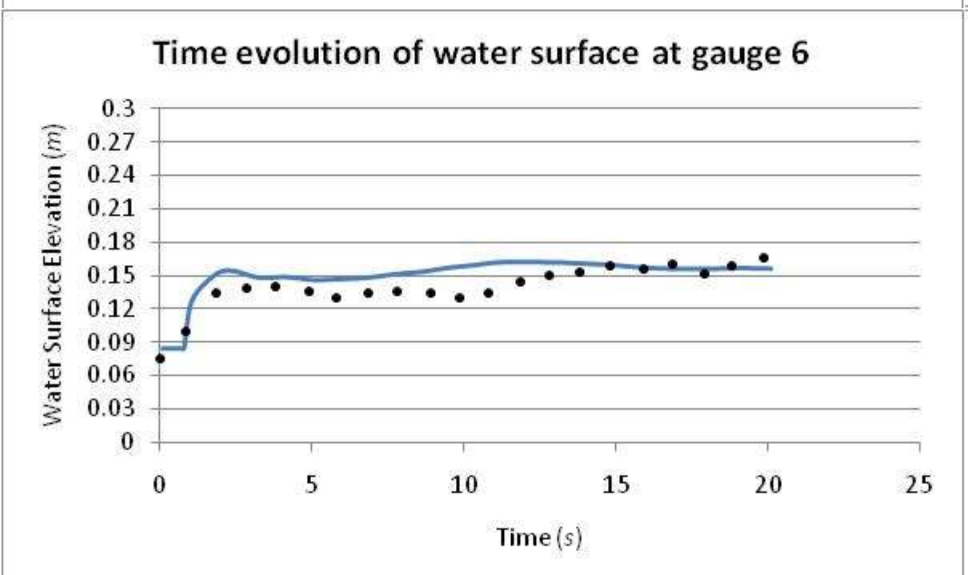
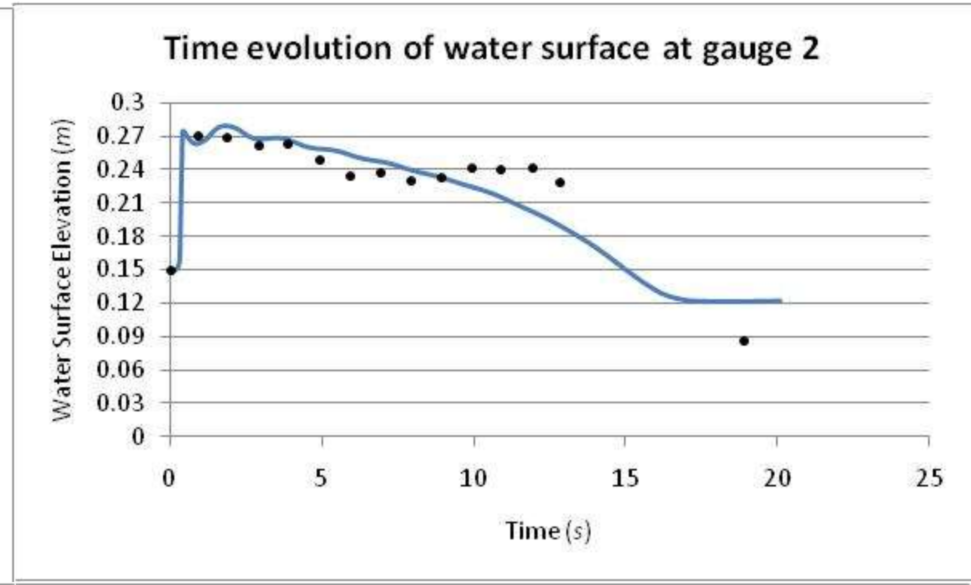
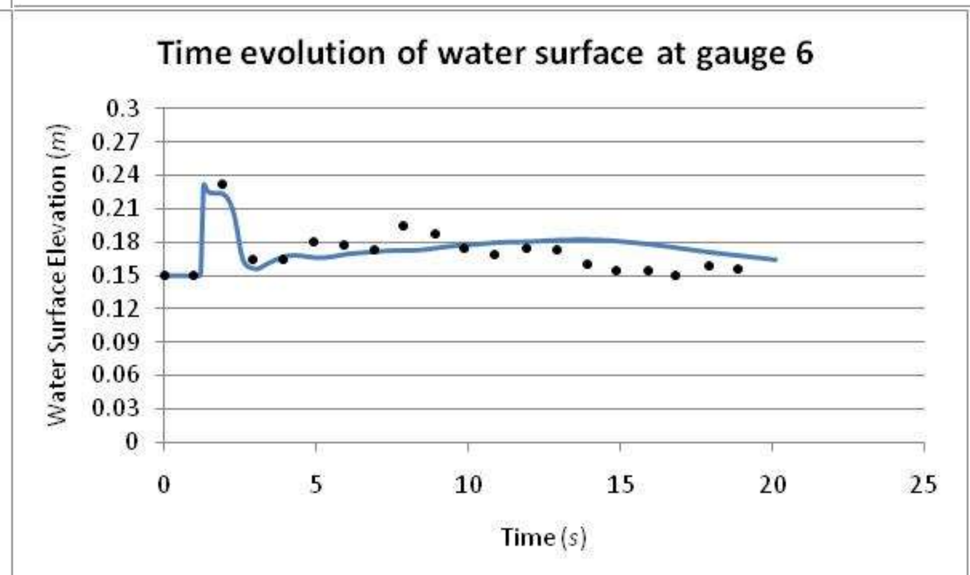
Case 1 – Dry bed



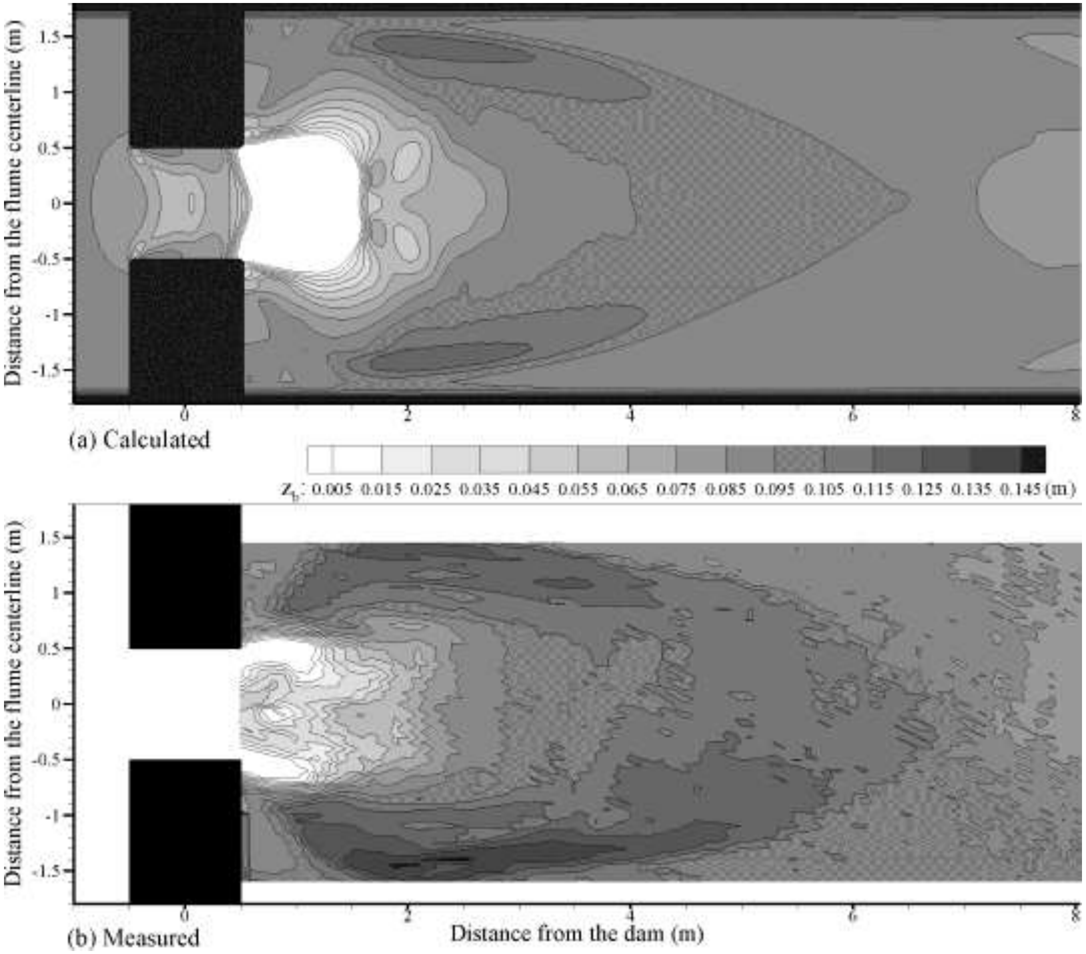


Case 2 – Wet bed

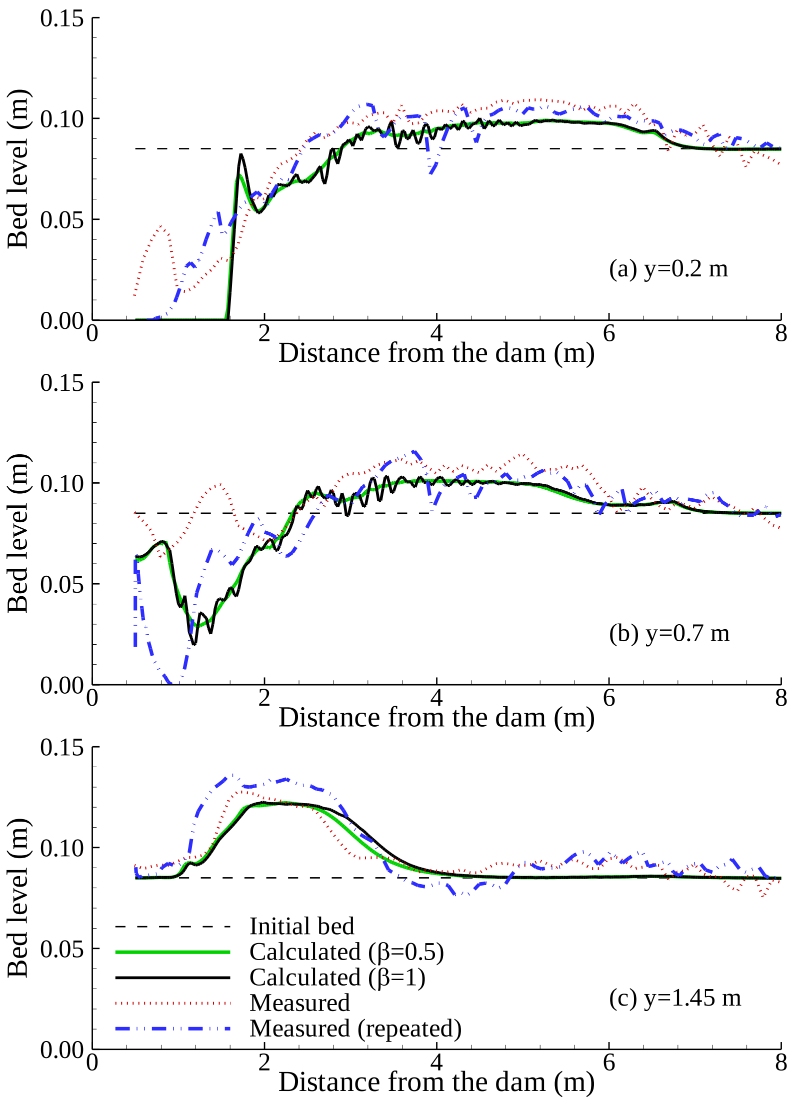




2-D Results of Partial Dam-Break



Final bed topography (in m)



Final longitudinal profiles of bed

Sea Dike Breach Test at Zwin Channel (1994)

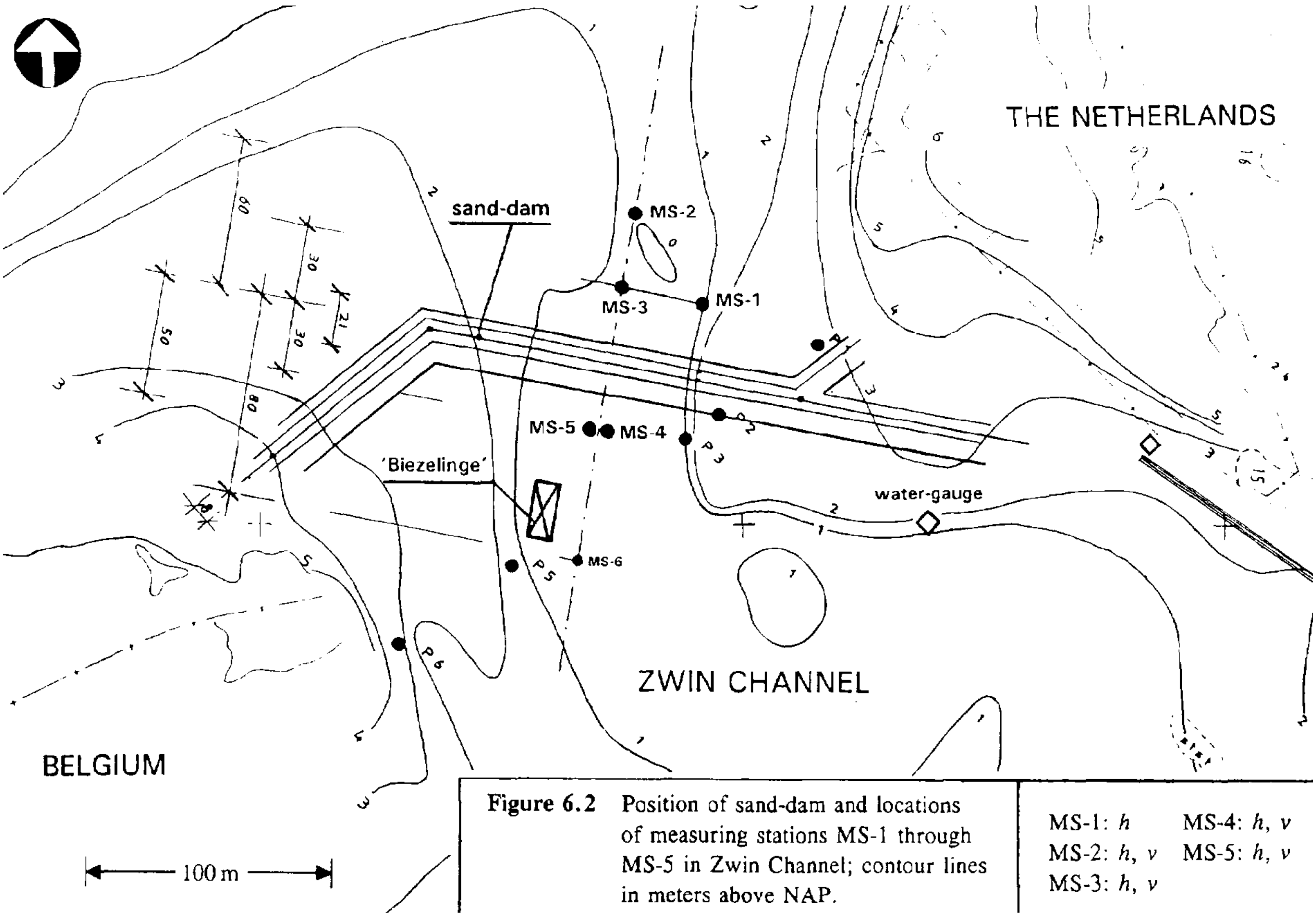
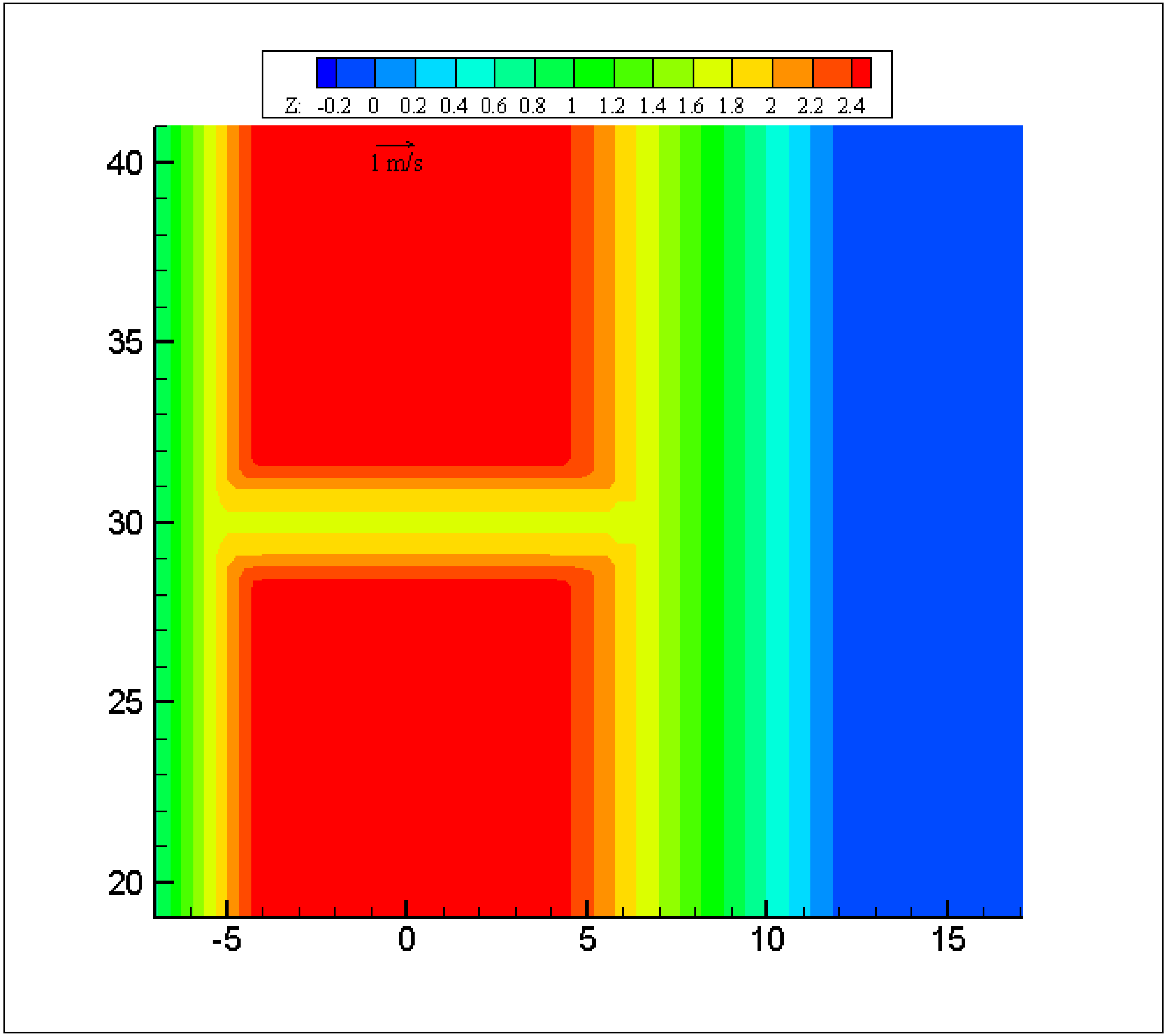


Figure 6.2 Position of sand-dam and locations of measuring stations MS-1 through MS-5 in Zwin Channel; contour lines in meters above NAP.

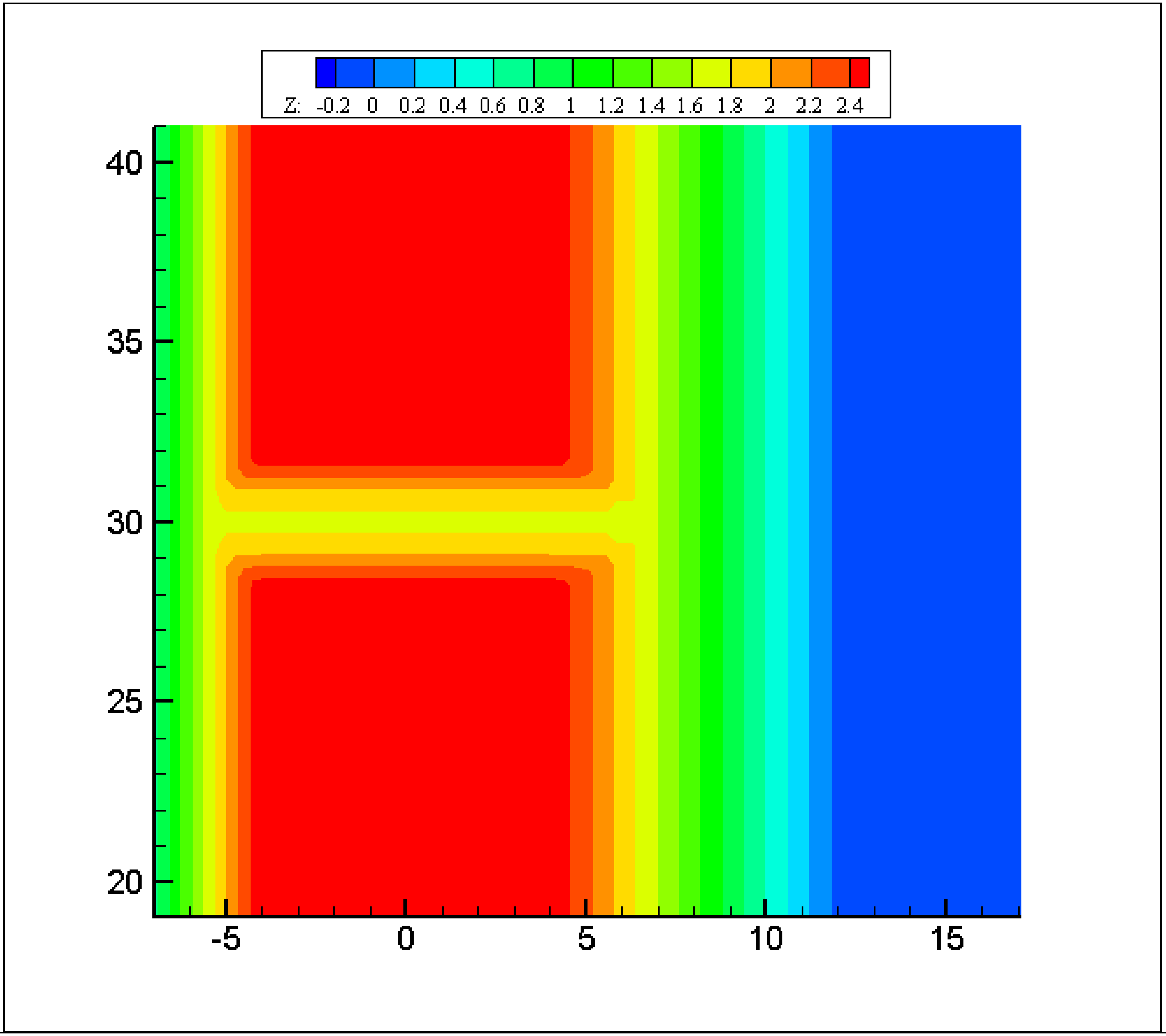
MS-1: h
MS-2: h, v
MS-3: h, v
MS-4: h, v
MS-5: h, v

2-D Results of Dike Breaching

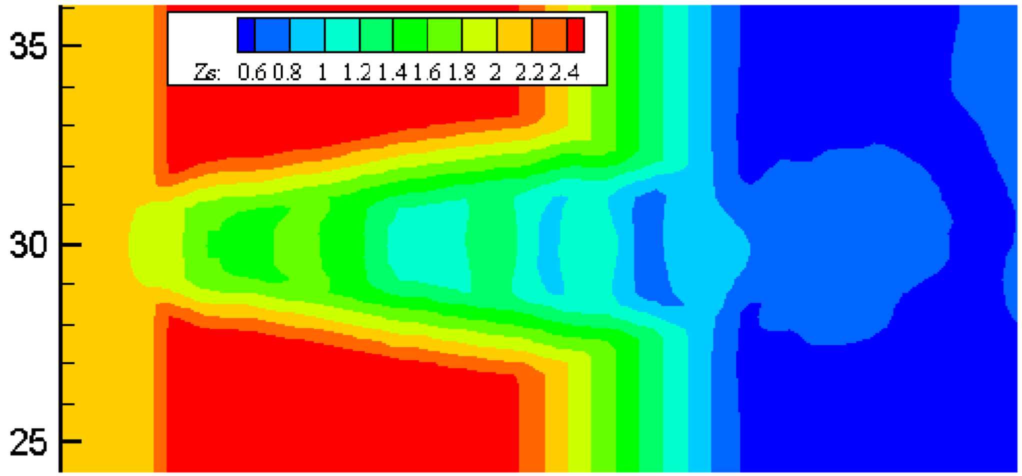
Clarkson UNIVERSITY defy convention

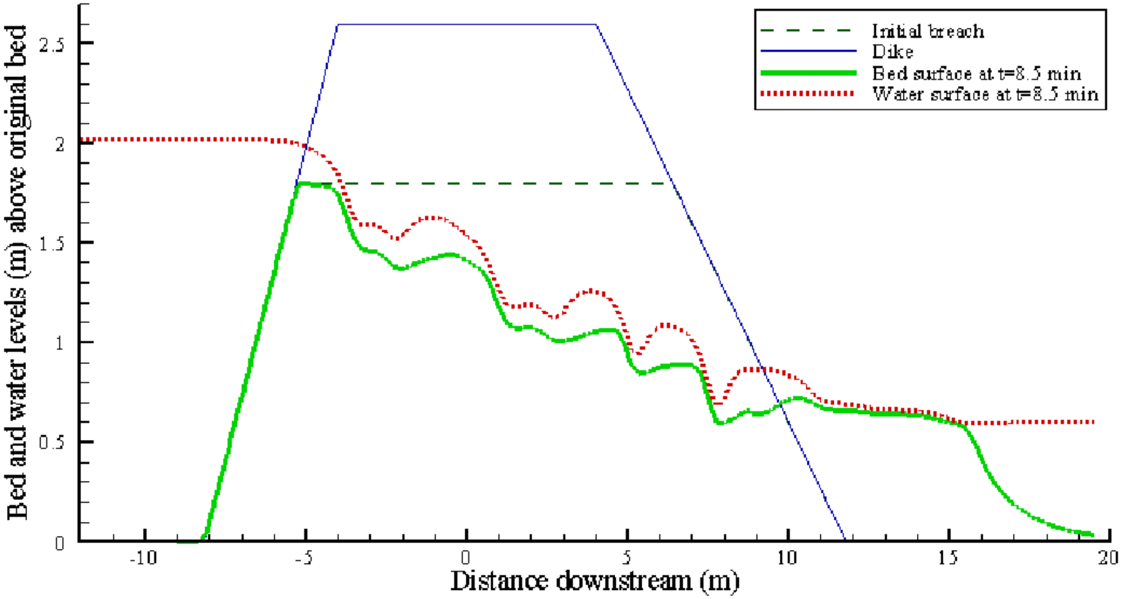


2-D Results of Dike Breaching

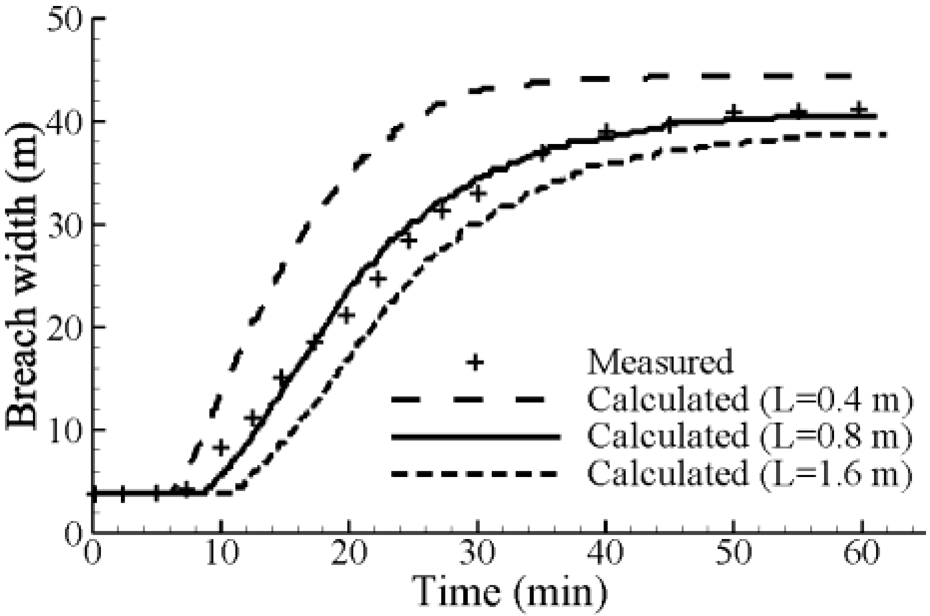


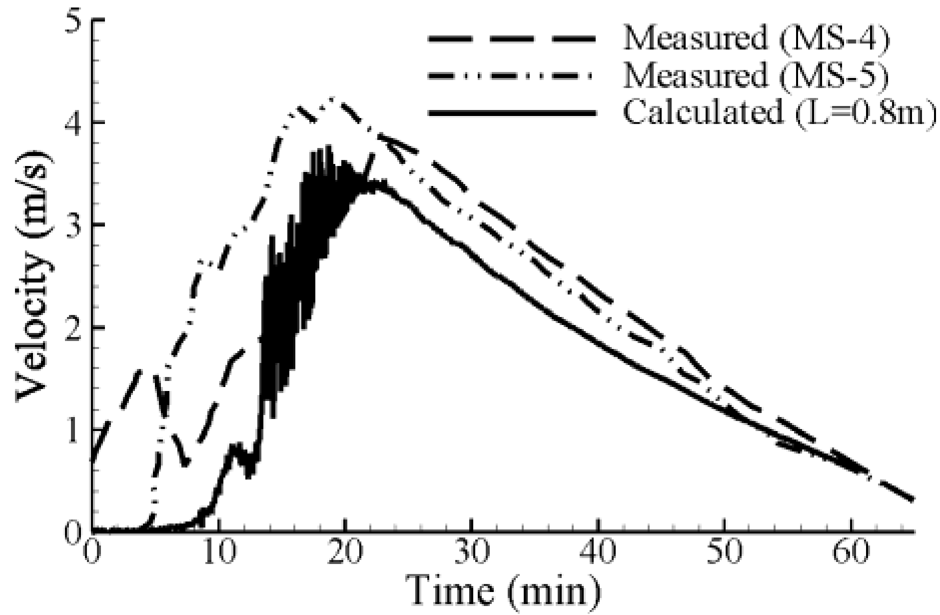
Dike Breaching





2-D Results of Dike Breaching





3-D Model of Dam-Break Flow over Movable Beds

Reza Marsooli's Dissertation Topic (2013)

Supervised by Weiming Wu

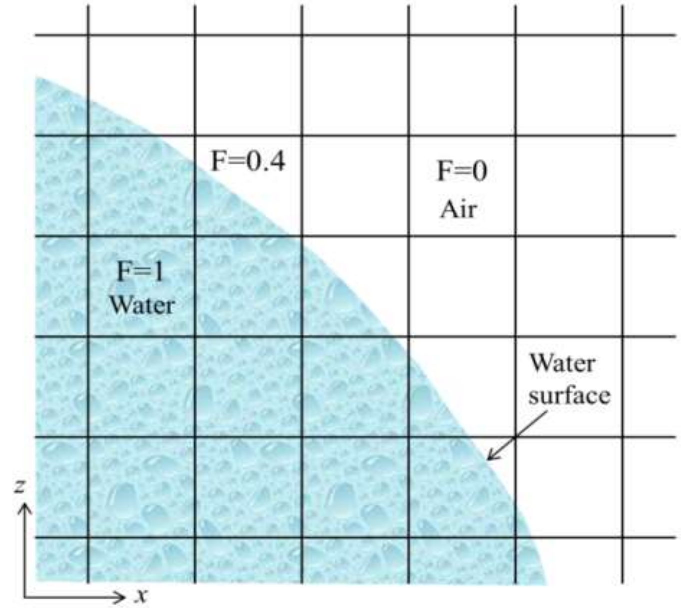
3-D Dam-Break Flow Model over Movable Bed

- Continuity equation

$$\nabla \bullet \mathbf{u} = 0$$

- Momentum equation

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \bullet (\mathbf{u}\mathbf{u}) = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\mathbf{f} + \frac{1}{\rho}\nabla \bullet (\mu \nabla \mathbf{u})$$

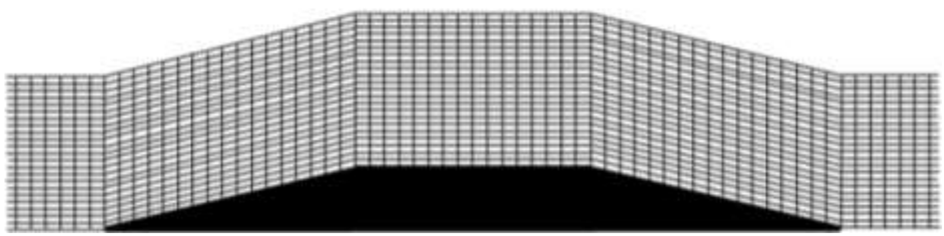


- Collocated (non-staggered) mesh
- VOF technique for free surface

$$\frac{\partial F}{\partial t} + \nabla \bullet (F\mathbf{u}) = 0$$

- Empty cell: F=0
- Fluid cell: F=1
- Surface cell: 0<F<1

- Hexahedral cells that fits on irregular bed
- Moving mesh vertically to follow bed changes



Numerical Discretization

- Temporal terms: Explicit Euler scheme
- Convection terms: Exponential scheme
- Diffusion terms: Central scheme
- Pressure-velocity coupling method: Pressure Implicit solution by Split Operator (PISO) method proposed by Issa (1986)
- VOF advection equation: Compressive Interface Capturing Scheme for Arbitrary Meshes (CICSAM)

- Consider mesh moving velocity and cell volume change

$$\sum_{f=1}^{n}\left(\mathbf{A}_f \bullet \mathbf{u}_f\right)\mathbf{u}_f = \sum_{f=1}^{n}\left(\mathbf{A}_f \bullet (\mathbf{u}_{\mathrm{flow},f} - \mathbf{u}_{\mathrm{mesh},f})\right)\mathbf{u}_f = \sum_{f=1}^{n} Flux_f \mathbf{u}_f$$

$$\frac{\partial V_P \mathbf{u}}{\partial t} = \frac{V_P^{t+\Delta t}\mathbf{u}_P^{t+\Delta t} - V_P^t \mathbf{u}_P^t}{\Delta t}$$

3-D Sed. Transport Model under Dam Break

- Suspended load

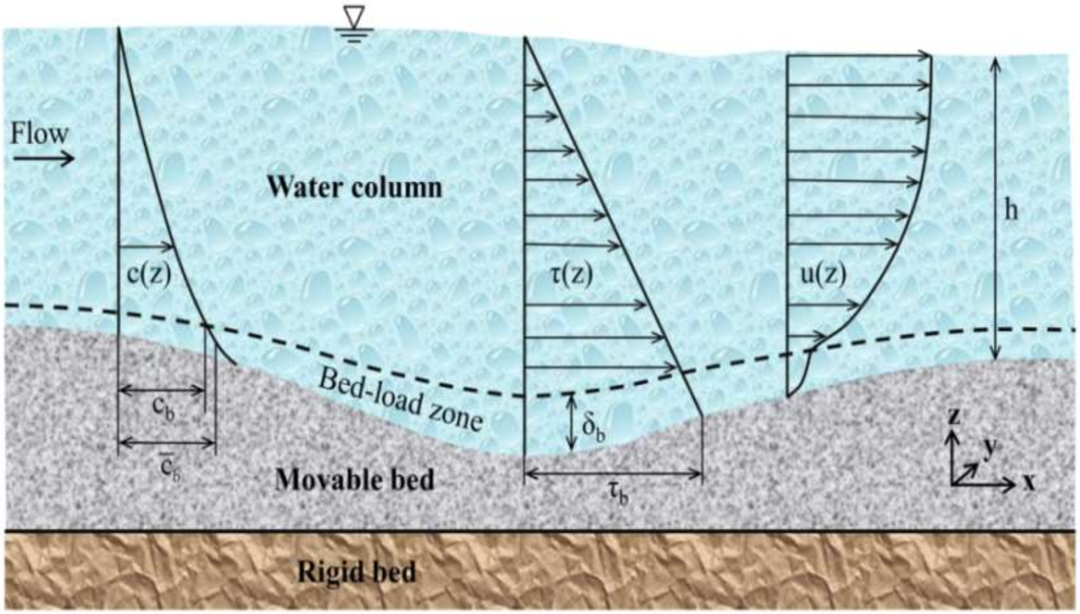
$$\frac{\partial c}{\partial t} + \frac{\partial\left[\left(u_j - \omega_s \delta_{j3}\right)c\right]}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\varepsilon_s \frac{\partial c}{\partial x_j}\right)$$

- Bed-load

$$\frac{\partial\left(q_b / u_b\right)}{\partial t} + \frac{\partial\left(\alpha_{bx} q_b\right)}{\partial x} + \frac{\partial\left(\alpha_{by} q_b\right)}{\partial y} = \frac{1}{L}\left(q_{b*} - q_b\right)$$

- Bed change

$$\left(1 - p'_m\right)\frac{\partial z_b}{\partial t} = D_b - E_b + \frac{1}{L}\left(q_b - q_{b*}\right)$$



Model Parameters

- **Equilibrium Transport Rate of Bed Load**

$$q_{b*} = 0.0053\sqrt{(\gamma_s/\gamma - 1)gd^3}\,T^{2.2} \quad \text{with} \quad T = \frac{\tau_b}{\tau_{cr}} - 1$$

- **Near-Bed Equilibrium Concentration of Suspended Load**

$$c_{b*} = \frac{q_{b*}}{u_b \delta_b} \quad \text{where} \quad u_b = 1.64T^{0.5}\sqrt{\left(\frac{\rho_s}{\rho} - 1\right)gd}$$

$$\Rightarrow \quad c_{b*} = \frac{0.0053}{1.64\delta_b} T^{1.7} d$$

- **Sediment Settling Velocity**

$$\omega_{sm} = (1-c)^4 \omega_s \quad \text{with} \quad \omega_s = \frac{M\nu_m}{Nd}\left[\sqrt{\frac{1}{4} + \left(\frac{4N}{3M^2}D_*^3\right)^{1/n}} - \frac{1}{2}\right]^n$$

Effective Shear Stress

$$\tau_b = \sqrt{\tau_{b,x}^2 + \tau_{b,y}^2}$$

$$\tau_{b,x} = k_t C_{fb} \rho u_b U_b + \tau_{cr} \frac{\sin\varphi_x}{\sin\varphi_r} - \frac{a\pi}{6} d \frac{\partial p_d}{\partial x}$$

$$\tau_{b,y} = k_t C_{fb} \rho v_b U_b + \tau_{cr} \frac{\sin\varphi_y}{\sin\varphi_r} - \frac{a\pi}{6} d \frac{\partial p_d}{\partial y}$$

$$k_t = 1 + \frac{c_b \rho_s}{(1 - c_b)\rho_w}$$

Steep slope

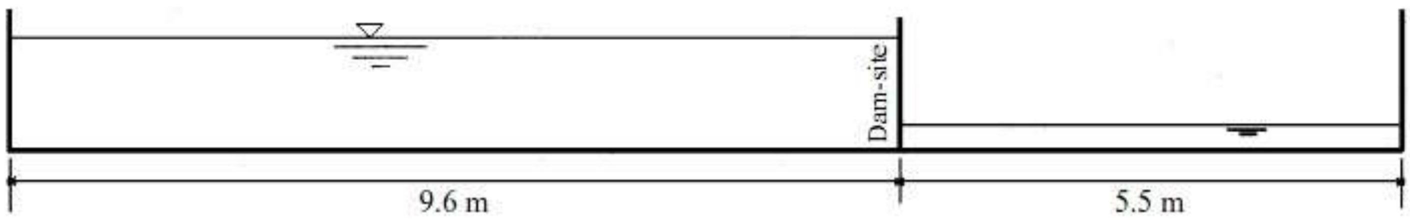
Streamwise dynamic pressure gradient

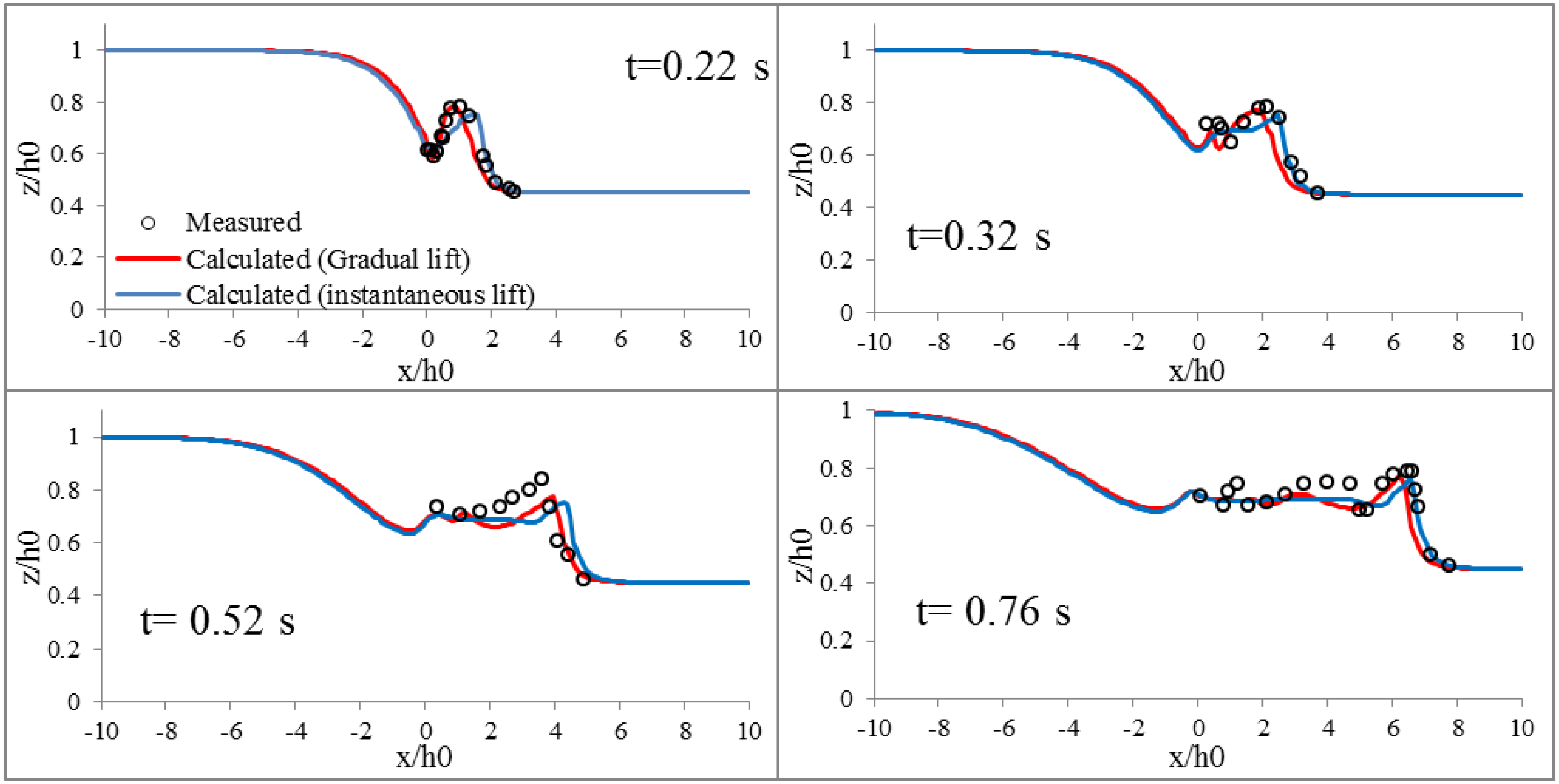
Critical Shear Stress

$$\tau_{cr} = K_p 0.03(\gamma_s - \gamma_w) d + (\rho_s - \rho_w) g H_s \tan\varphi_r$$

- Dynamic pressure gradient $K_p = 1 + \frac{1}{(\rho_s - \rho_w) g} \frac{\partial p_d}{\partial z}$
- Submerged weight of moving particles $H_s = q_b / u_b + \int_{z_b + \delta_b}^{z_s} c\,dz$

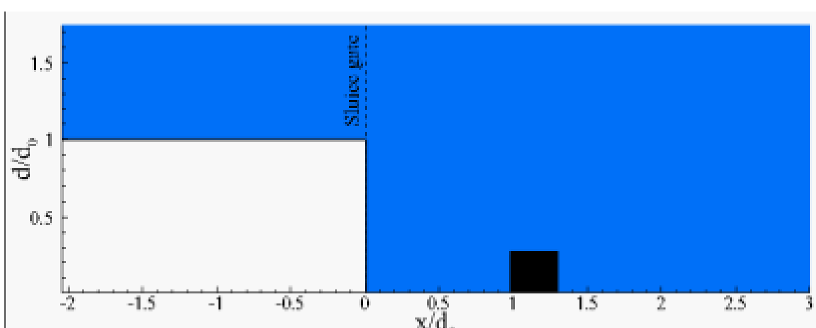
3-D Model Testing

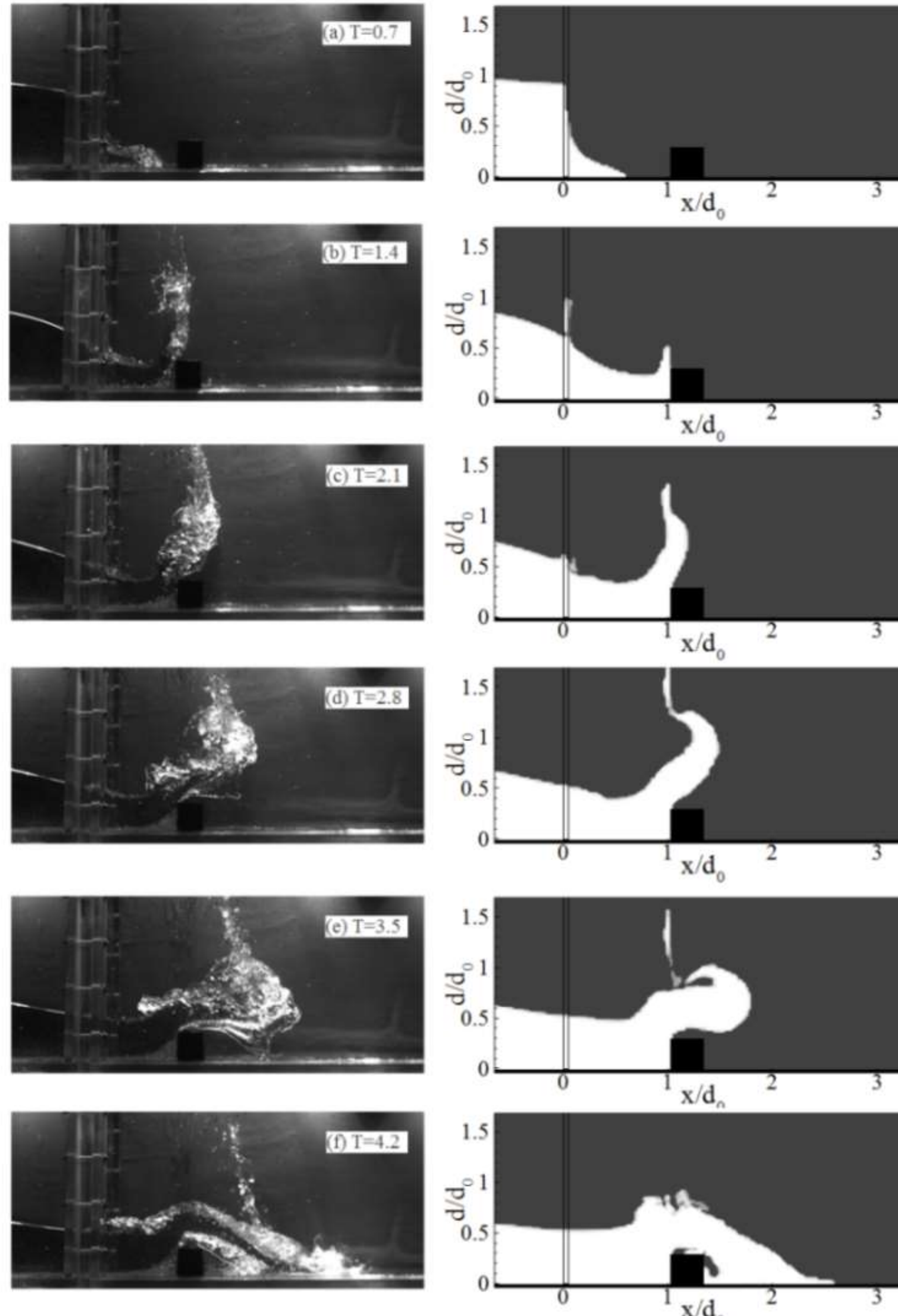




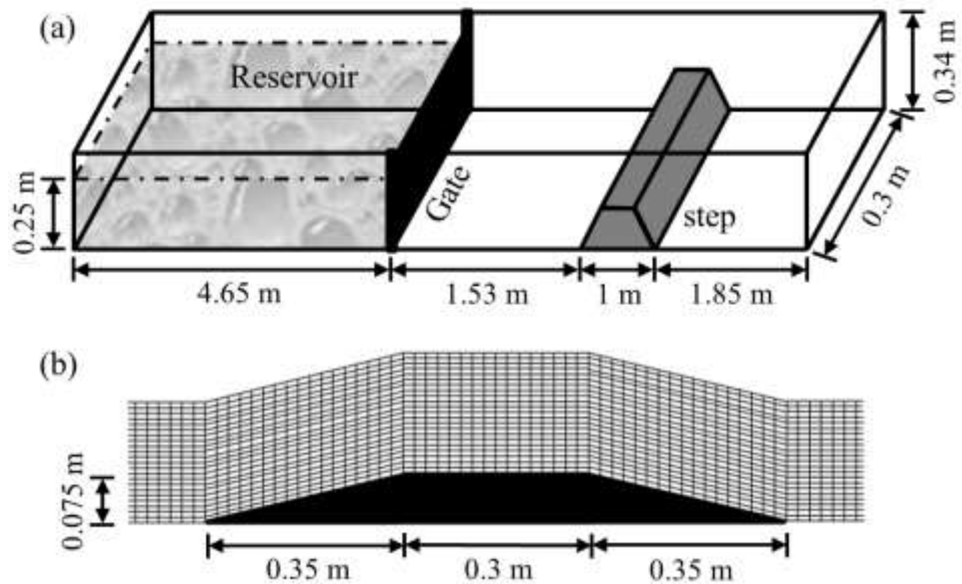
Initial stage of dam-break flow over a rectangular obstacle

- Experiment was carried out by Oertel and Bung (2012).
- Flume was 22 m long, 0.3 m wide, and 0.5 m high.
- A gate was located 13 m downstream of the upper flume end.
- An obstacle, 6 cm high, was placed 0.2 m downstream of the gate.
- Initial water depth in the reservoir, d_0=0.2 m
- Initial dry downstream.
- Grid spacing=0.5 cm.

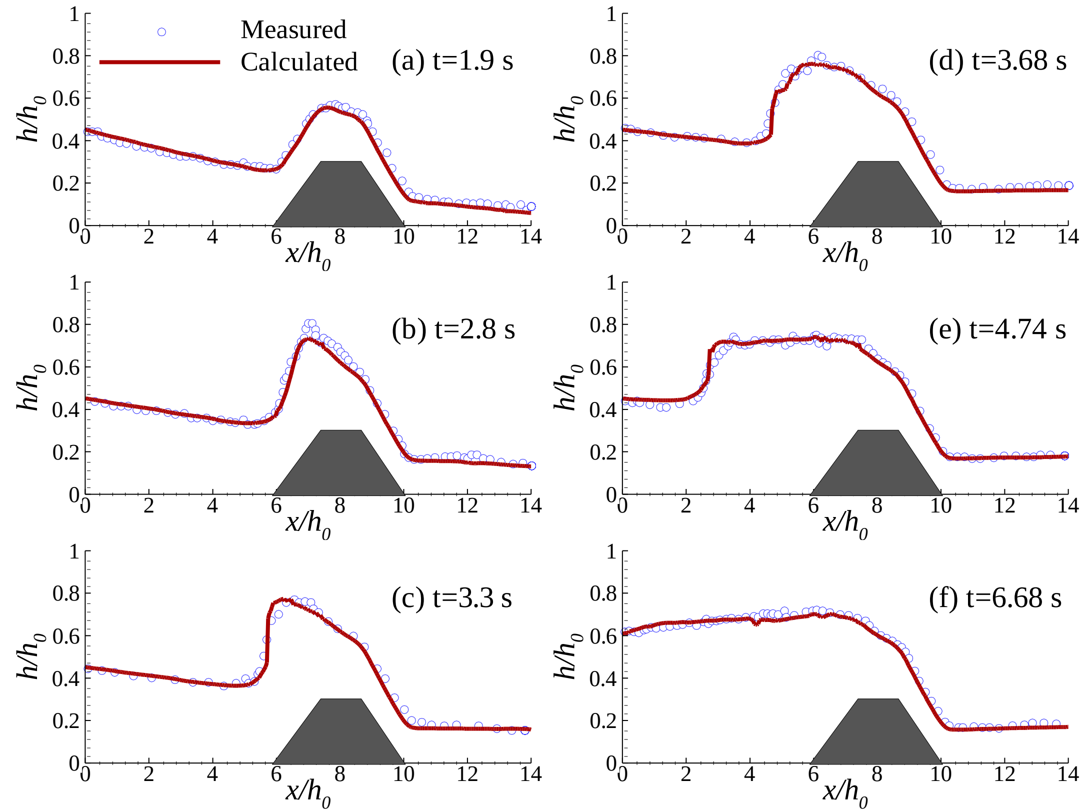




Dam-break flow over a trapezoidal step

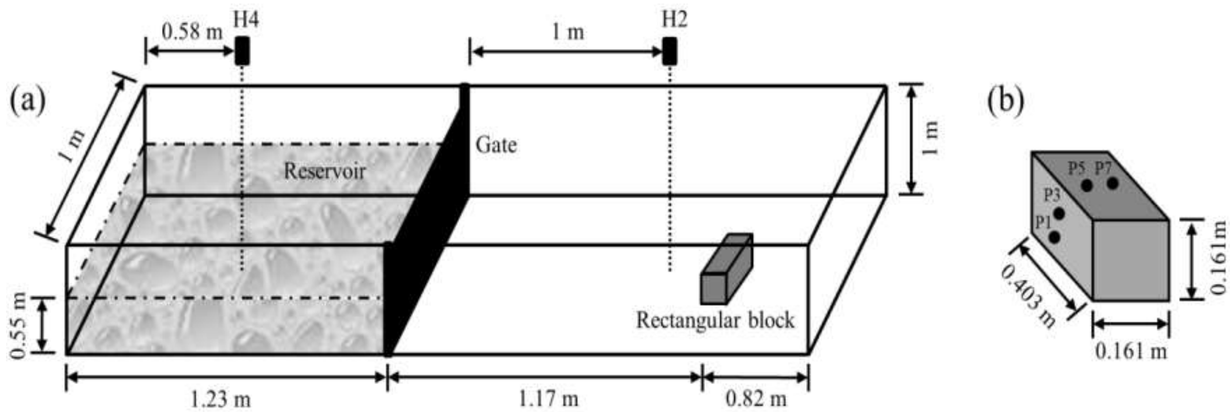


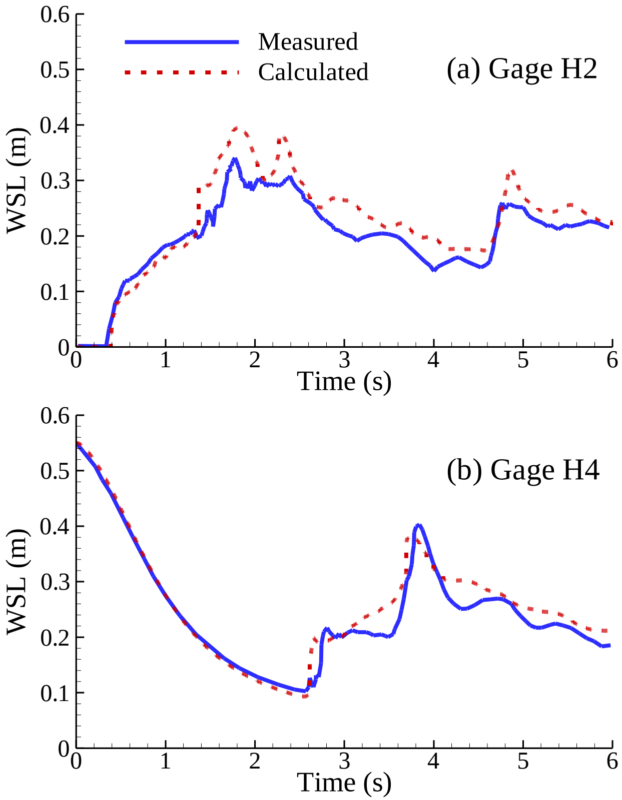
- Experiment by Kocaman (2007)
- Initial water depth in the tank, h_0=0.25 m
- Dry downstream
- Grid spacing=1 cm



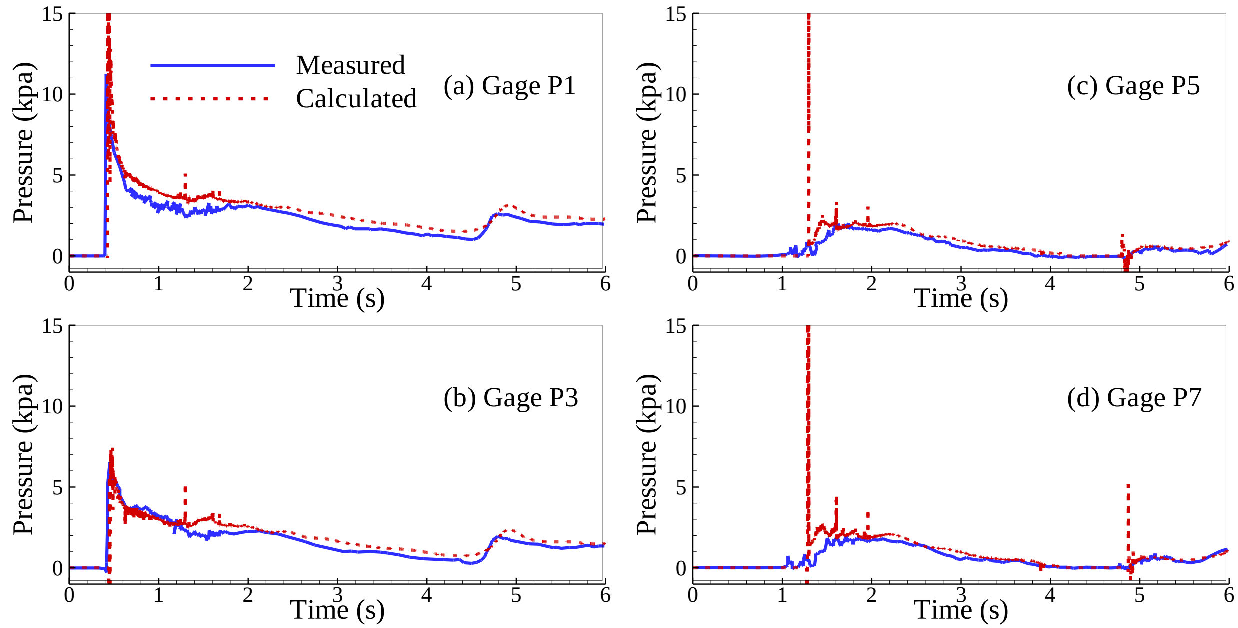
Dam-break flow over an isolated block

- By Kleefsman et al. (2005)
- Initial water depth in the tank, h_0=0.55 m
- Dry downstream
- grid spacing=2 cm





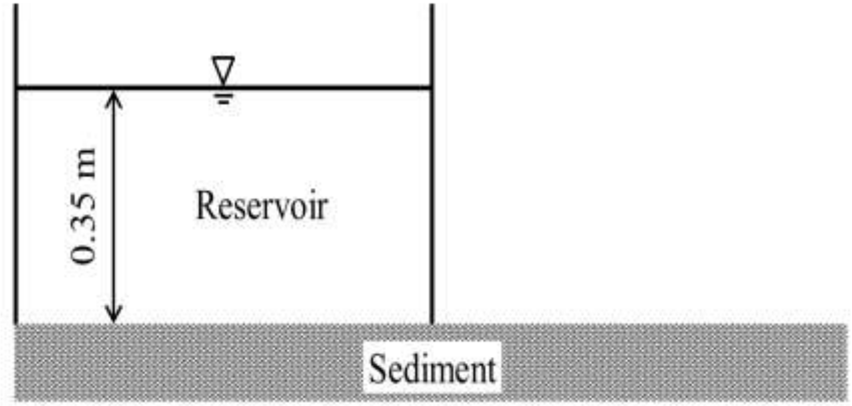
Water surface level (WSL)

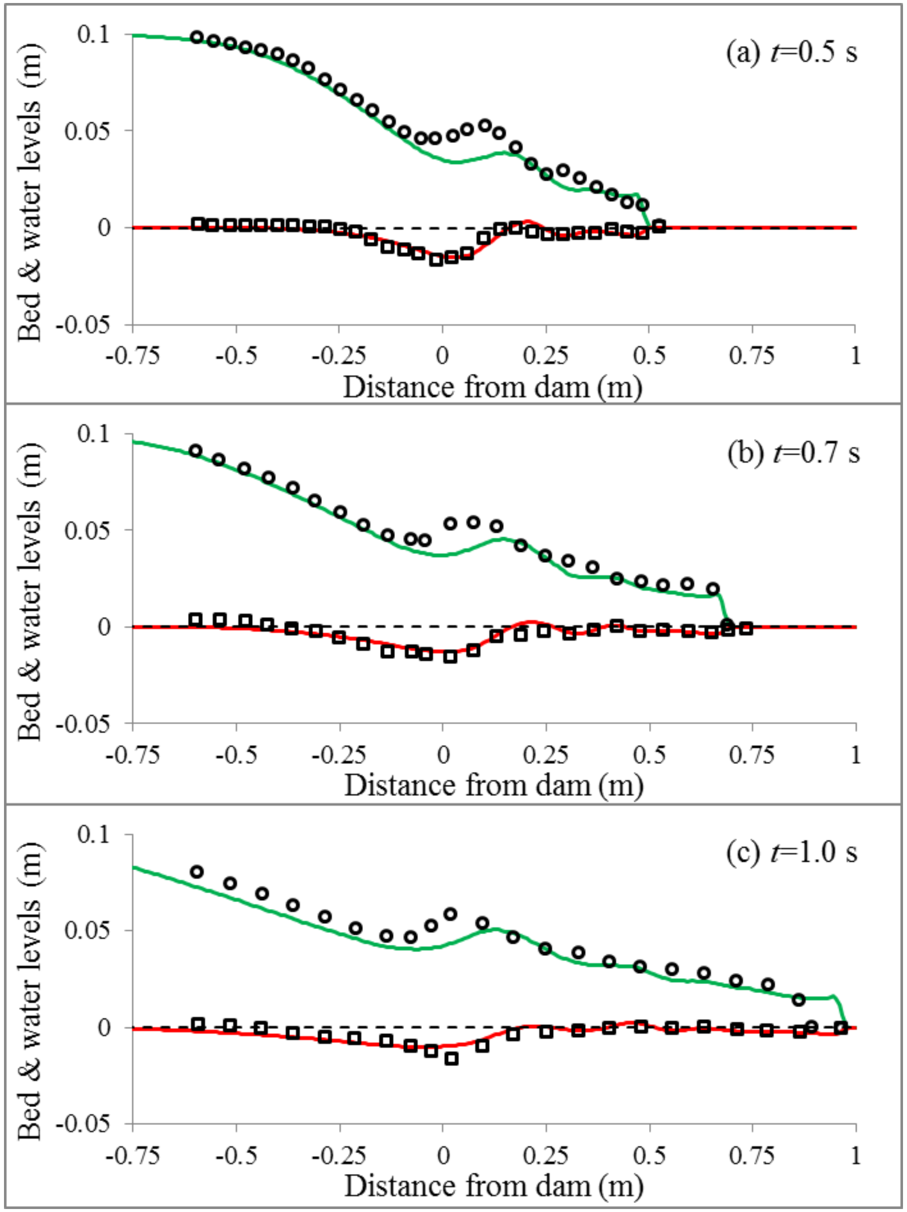


Pressure time series at gages P1, P3, P5, and P7

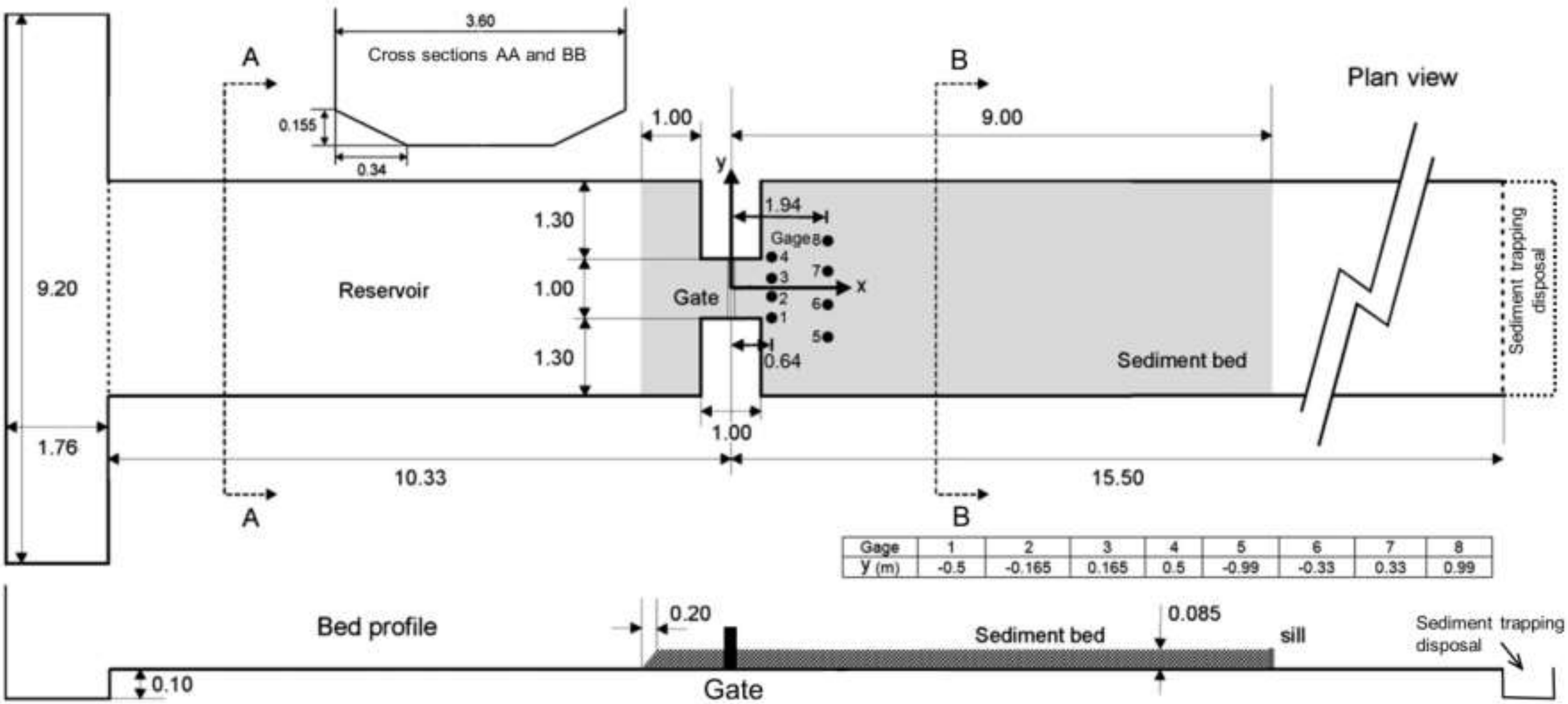
Initial stage of dam-break flow over movable beds

- Flume bed is covered by PVC pellets
- Experiment at UCL (Fraccarollo and Capart, 2002)
- Flume was 2.5 m long, 0.1 m wide and 0.35 m high
- d_{50}=3.5 mm, ρ_s=1540 kg/m^3.



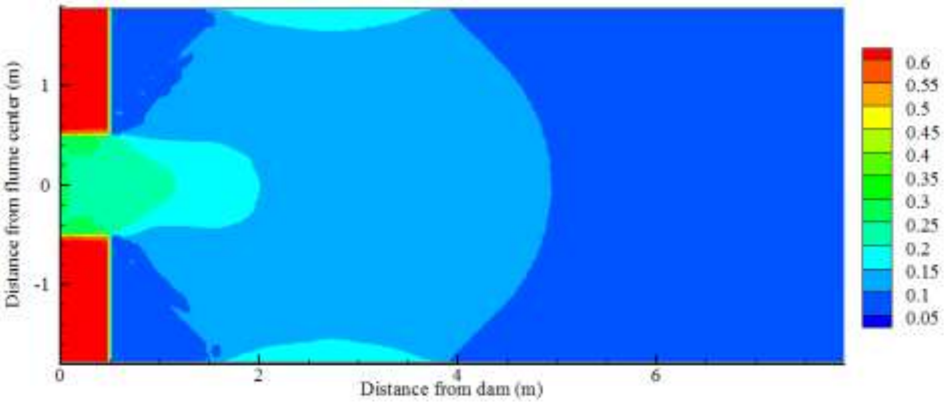


Partial Dam-Break Flow over Movable Bed
(Université catholique de Louvain, Belgium)

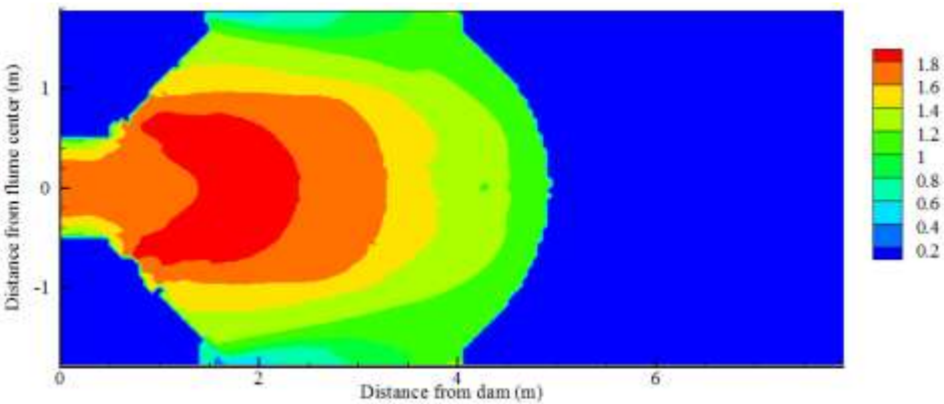


Gage	1	2	3	4	5	6	7	8
y (m)	-0.5	-0.165	0.165	0.5	-0.99	-0.33	0.33	0.99

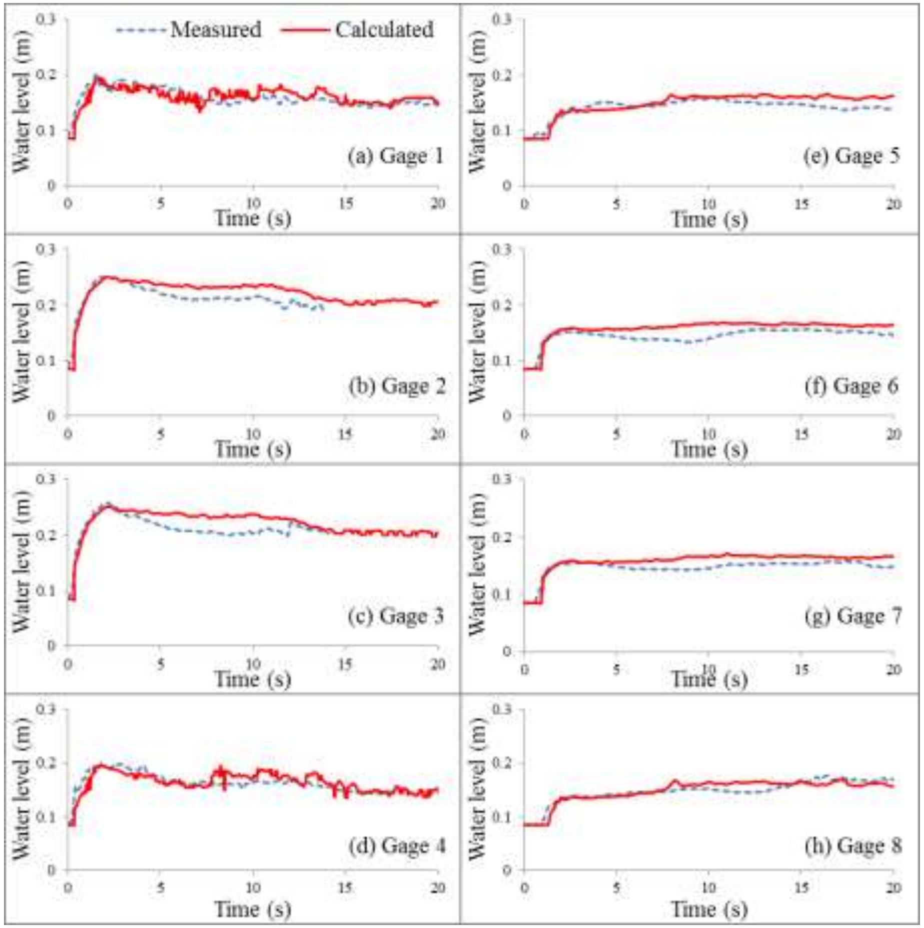
3-D Model Results of Partial Dam-Break Case



Calculated water surface level (in m) t=3 s

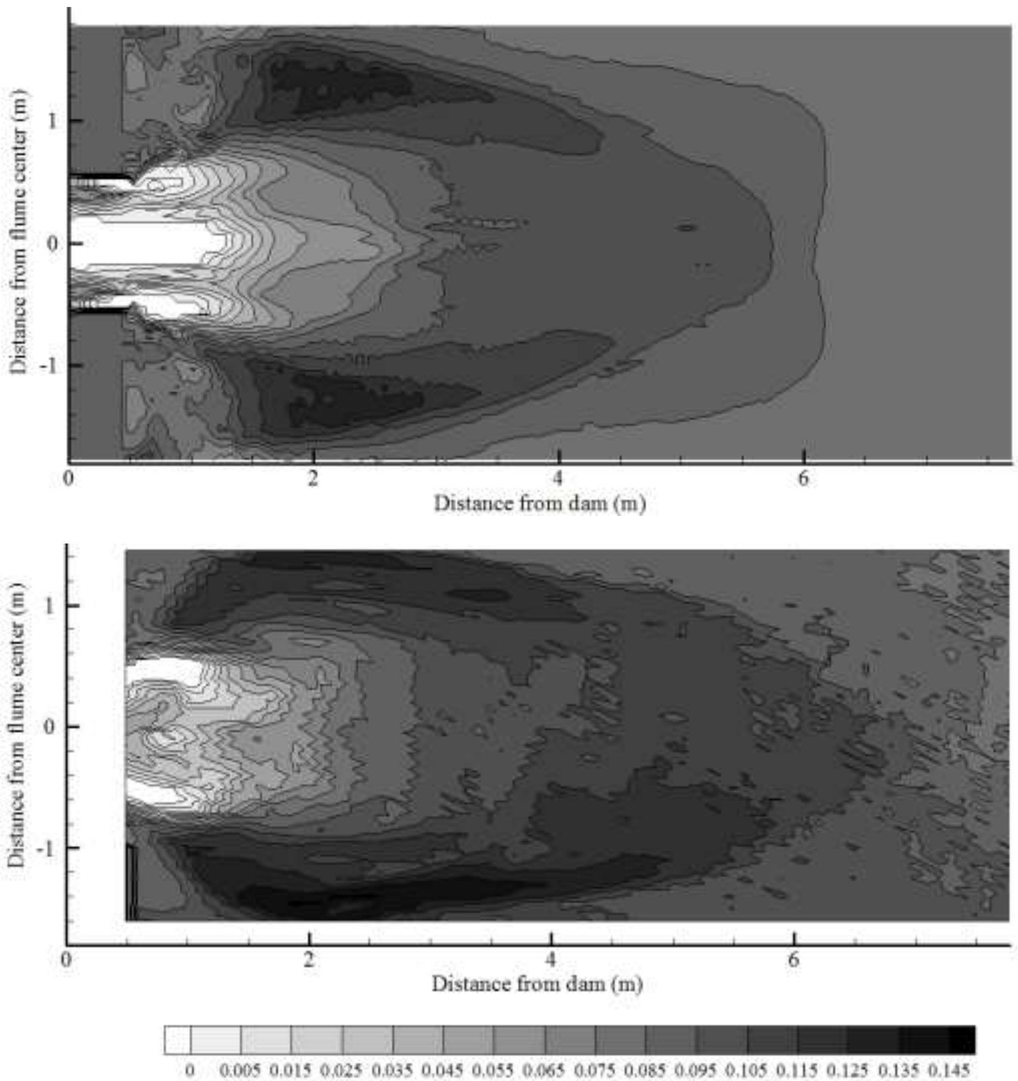


Calculated resultant velocity (in m/s) near the bed t=3 s (C_{fb}=0.2 and L=0.025 m)

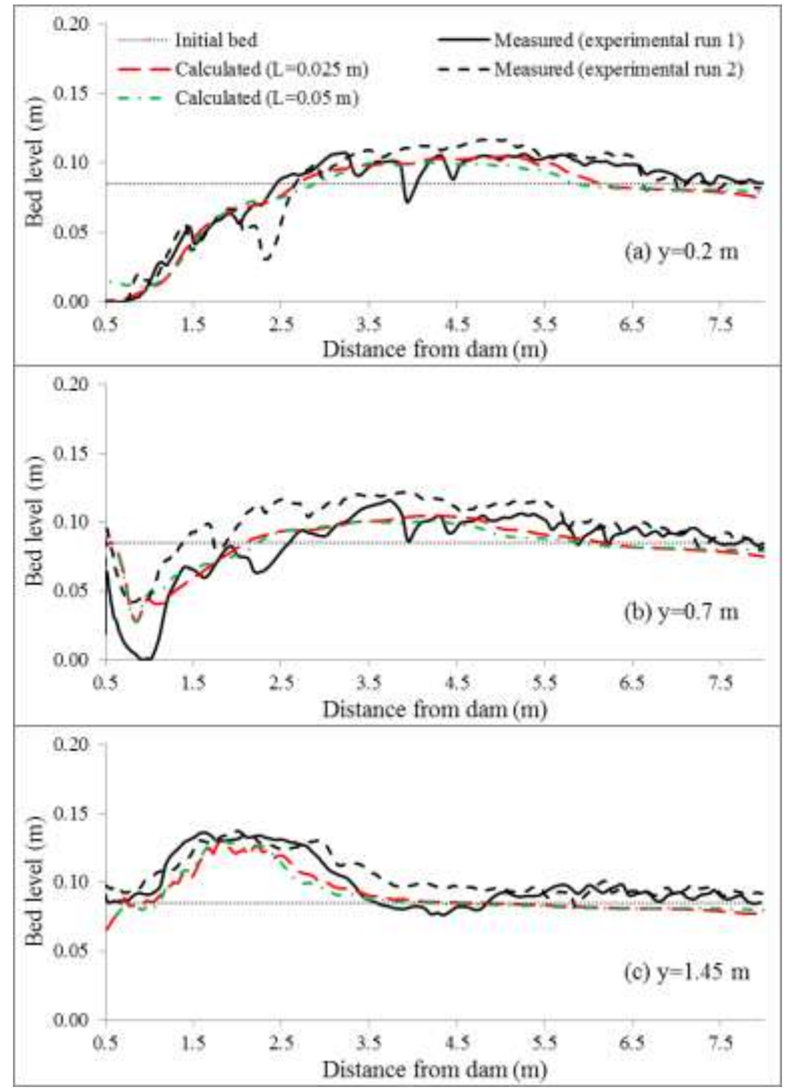


Water surface level time series (C_{fb}=0.2 and L=0.025 m)

3-D Model Results of Partial Dam-Break Case



Final bed topography (in m, C_{fb}=0.2, L=0.025 m)



Final longitudinal profiles of bed (C_{fb}=0.2)

Summary of the Detailed Models

- Applicable to both dam and levee.
- Consider only homogeneous embankments, not complex composite embankments.
- Only for overtopping, whereas piping is very difficult to simulate because many factors involved.
- Mainly in 1-D and depth-averaged 2-D models, whereas 3-D model is just in early development stage.
- Erosion rate of cohesive soil is the biggest challenge.

Simplified Physically-Based Breach Model

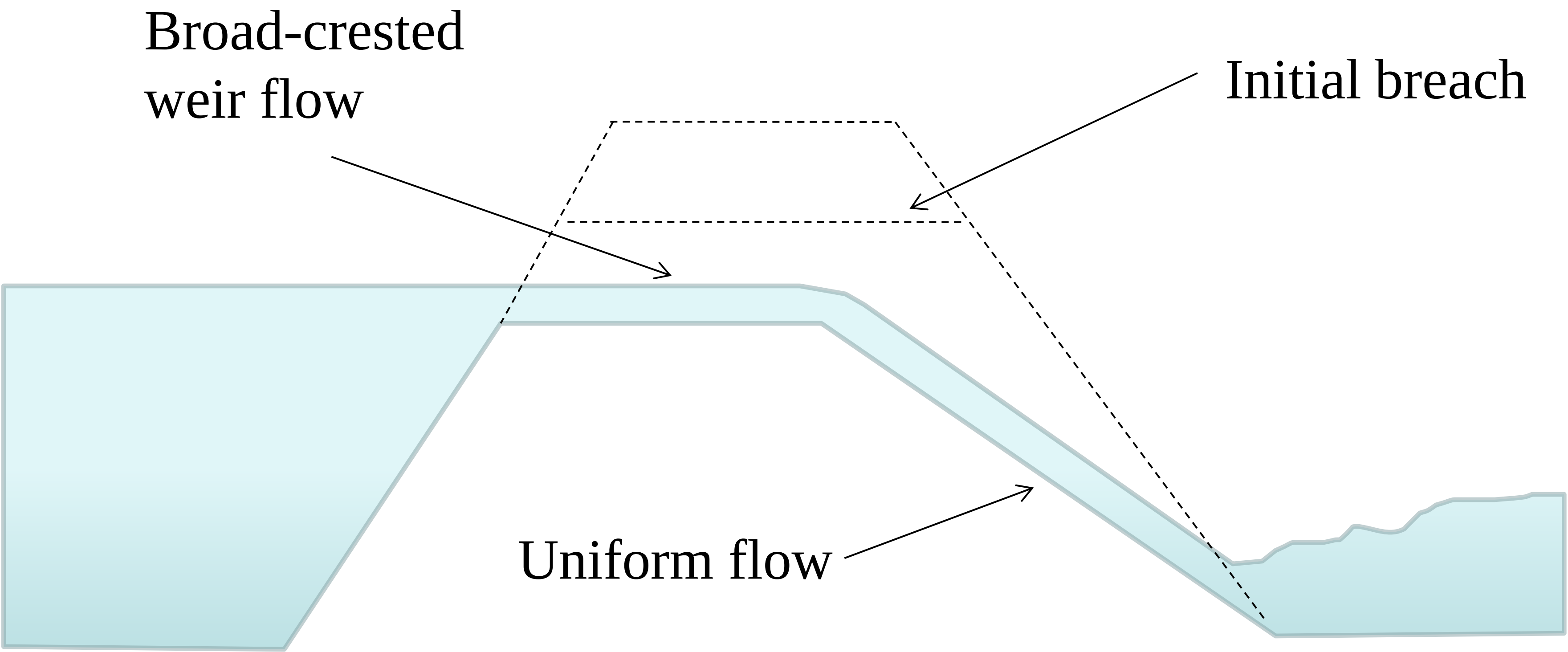
DLBreach

by Wu (2013)

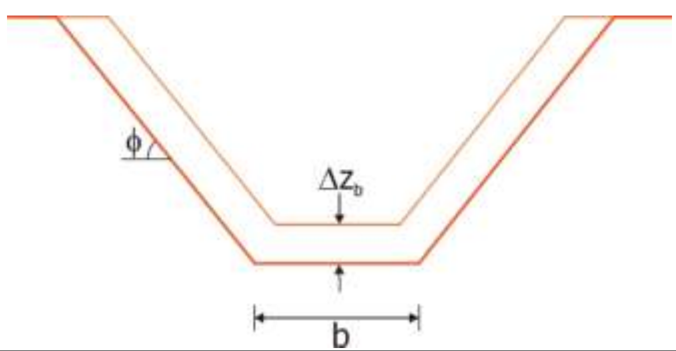
DLBreach Simplified Model

- **Why is the simplified model needed?**
- **Due to the weakness of the detailed models**
  - Detailed models are still in development stage
  - Only consider overtopping, and difficult to handle piping
  - Headcut erosion is not well modeled
  - Difficult to handle composite embankments
  - Too expensive to run

Failure by Overtopping, Surface Erosion



Breach cross-section



Flow Calculations

Clarkson UNIVERSITY defy convention

Head and tail water levels can be given by measured time series or determined by using water balance in the reservoir or bay:

$$\frac{dV}{dt} = A_s \frac{dz_s}{dt} = Q_{inflow} - Q - Q_{spill} - Q_{sluice}$$

Breach flow – Broad-crested weir:

$$Q = k_{sm}\left(c_1 b h^{1.5} + c_2 m h^{2.5}\right)$$

Uniform flow on the downstream slope:

$$U = R^{2/3} S_0^{1/2} / n$$

Sediment Transport Model

Non-cohesive sediment transport

$$\frac{\partial C_t}{\partial x} = -\frac{1}{L_s}\left(C_t - C_{t*}\right)$$

$$\left(1 - p'_m\right)\frac{\partial V_b}{\partial t} = Q\left(C_{t,in} - C_{t,out}\right)$$

Non-cohesive transport capacity

by Wu et al. (2000) and Zhang (1961) Formulas

Cohesive sediment erosion rate is determined by the USDA SITES model

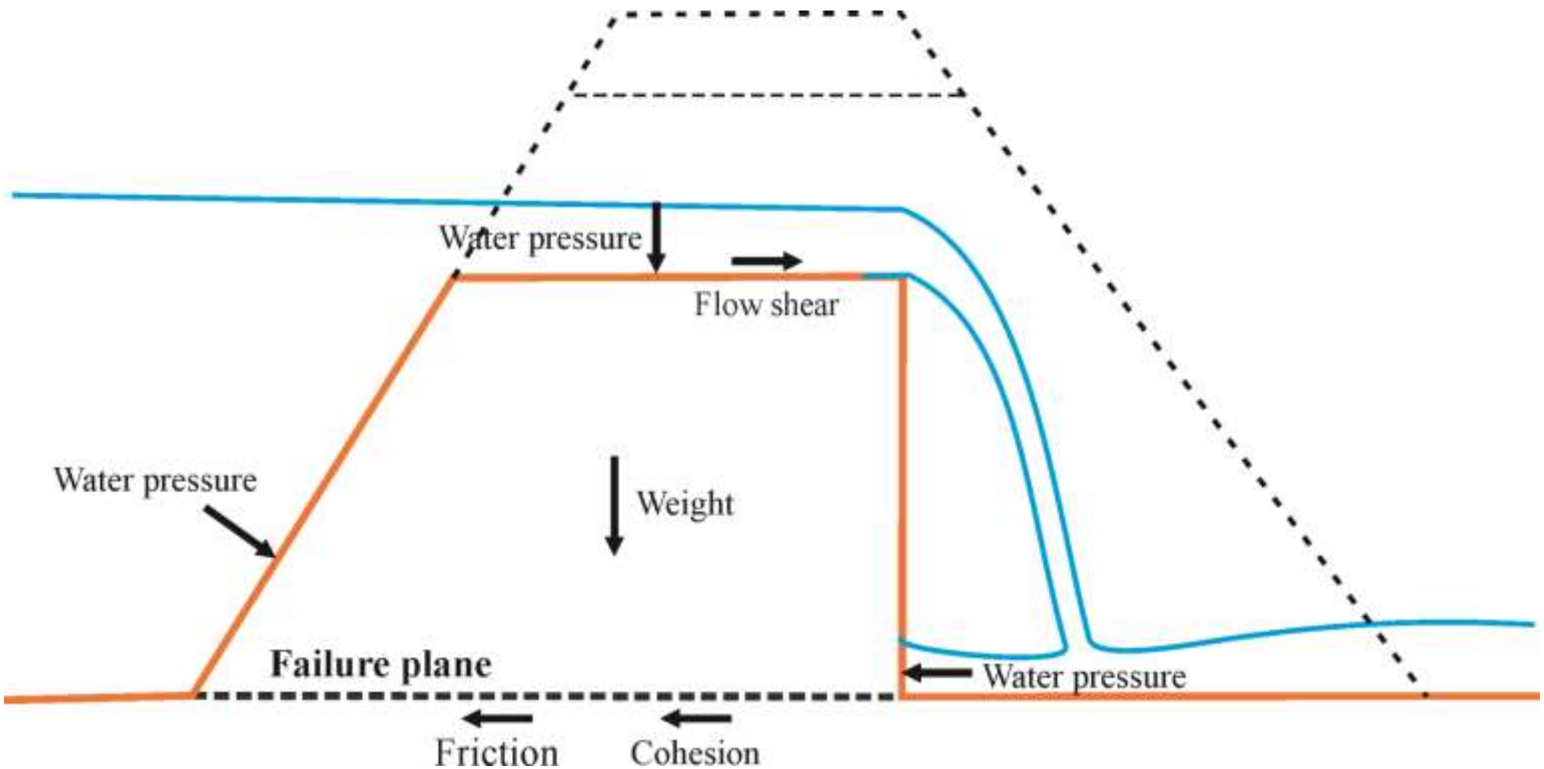
$$\frac{d\varepsilon}{dt} = k_d\left(\tau_e - \tau_c\right)$$

$$k_d = \frac{0.0564\gamma}{\gamma_d}\exp\left[-0.121 c_{\%}^{0.406}\left(\frac{\gamma_d}{\gamma}\right)^{3.1}\right] \quad \text{(m/hr - Pa)}$$

τ_e : Effective bed shear stress

τ_c : Critical shear stress by Shields criteria

Headcut Migration



Headcut migration rate by Temple (1992)

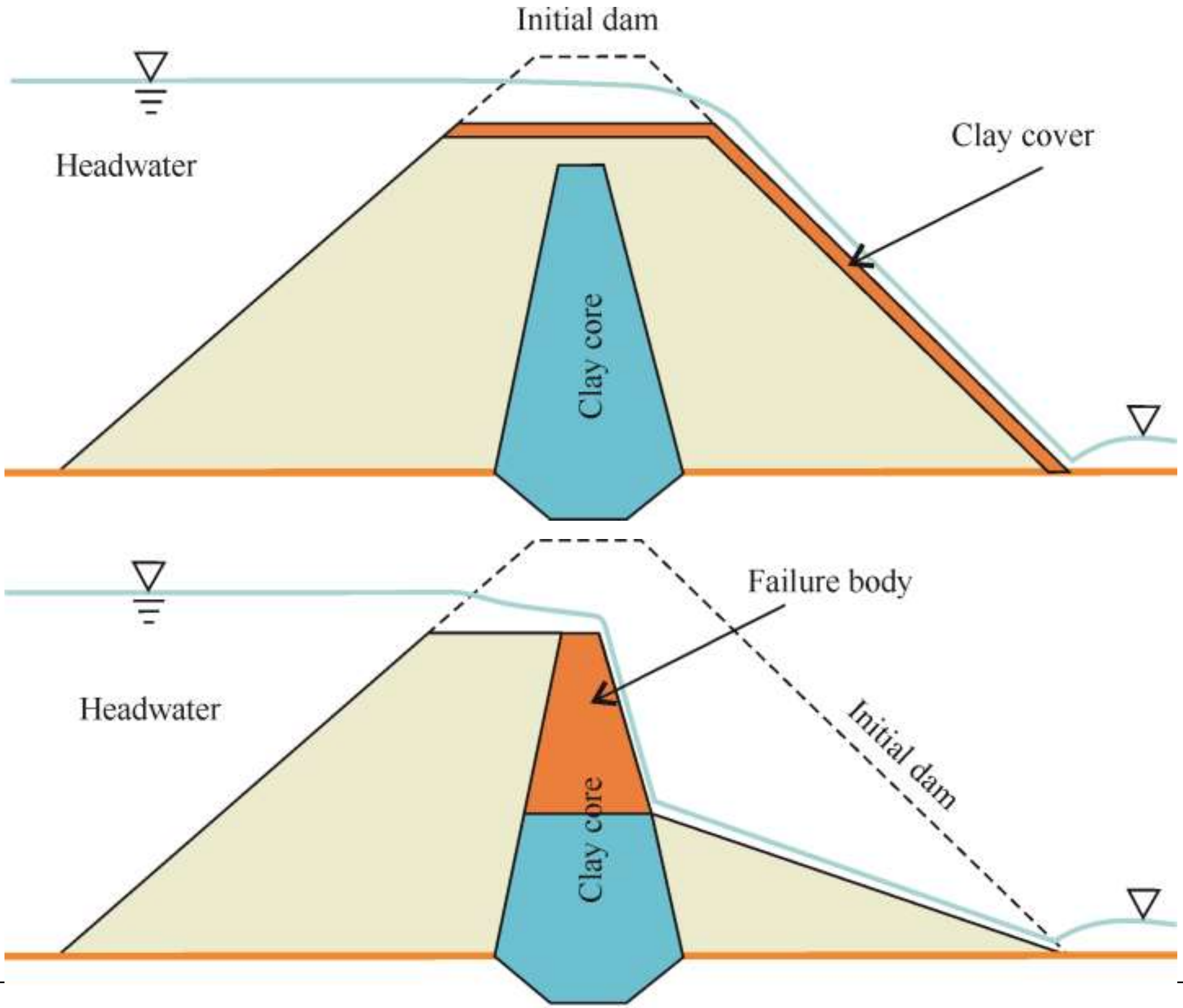
$$\frac{dx}{dt} = C_T q^{1/3} H_e^{1/2}$$

$q =$ unit discharge at headcut

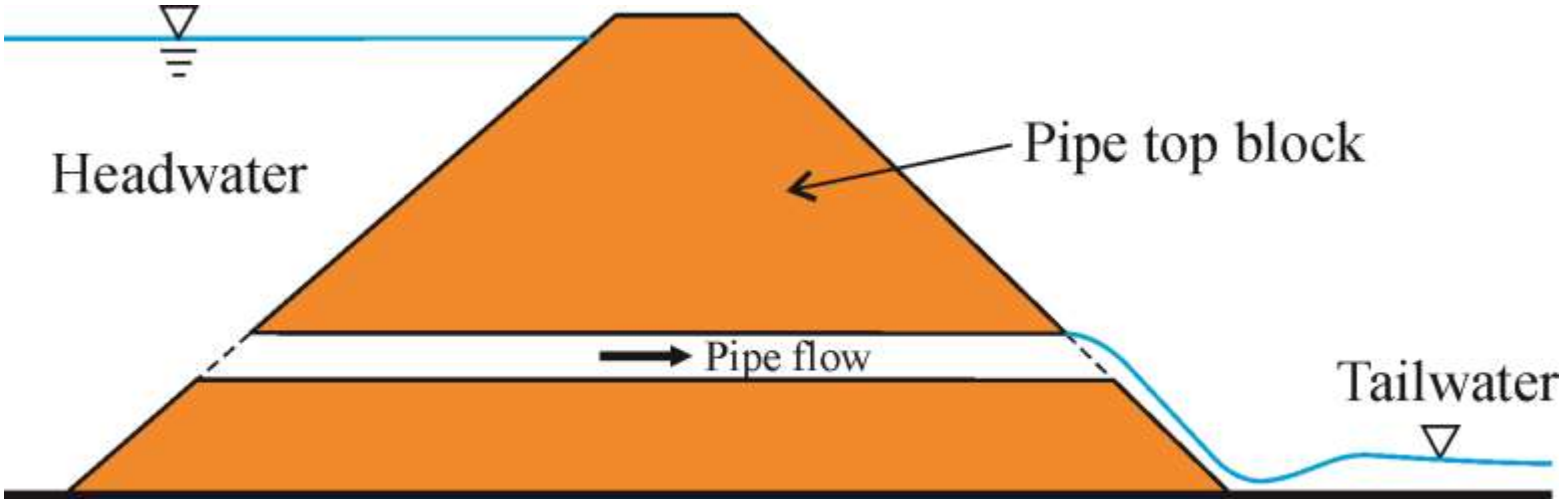
$H_e =$ headcut height or energy head change

$C_T =$ coefficients related to soil properties

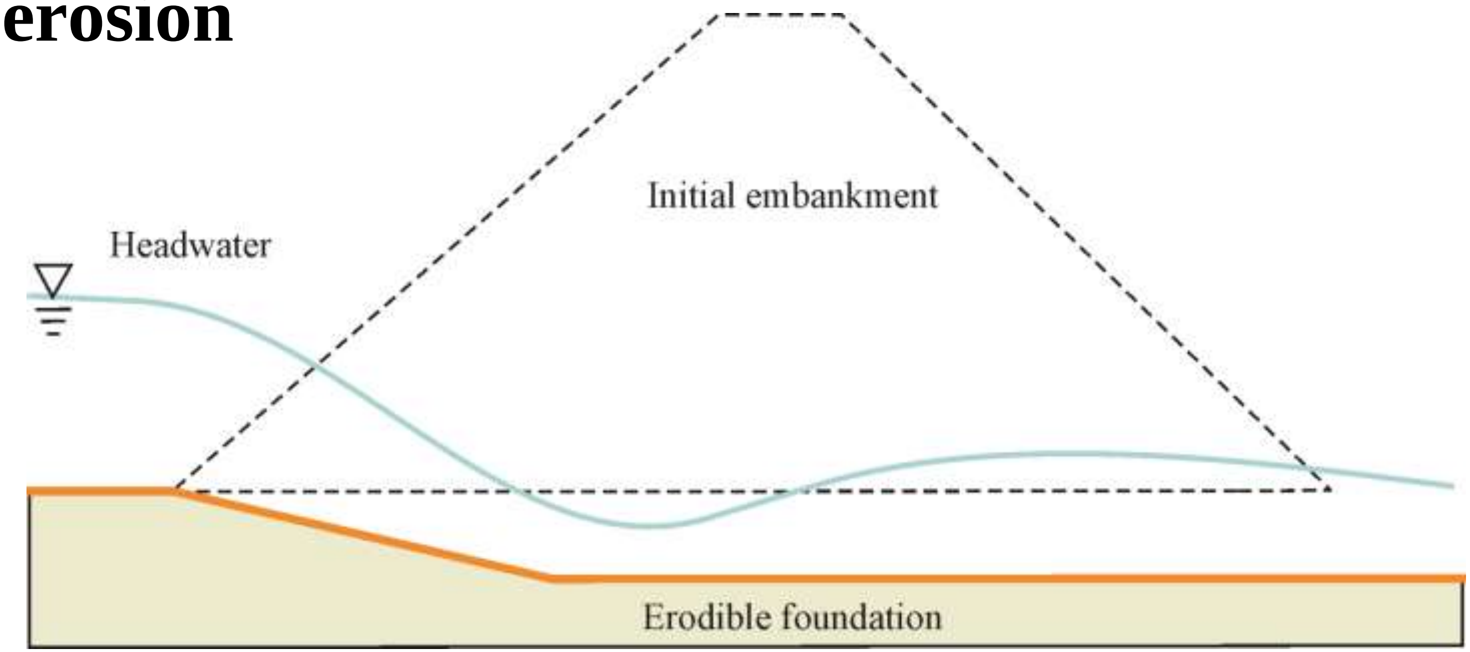
Composite Embankment with Clay Cover/Core



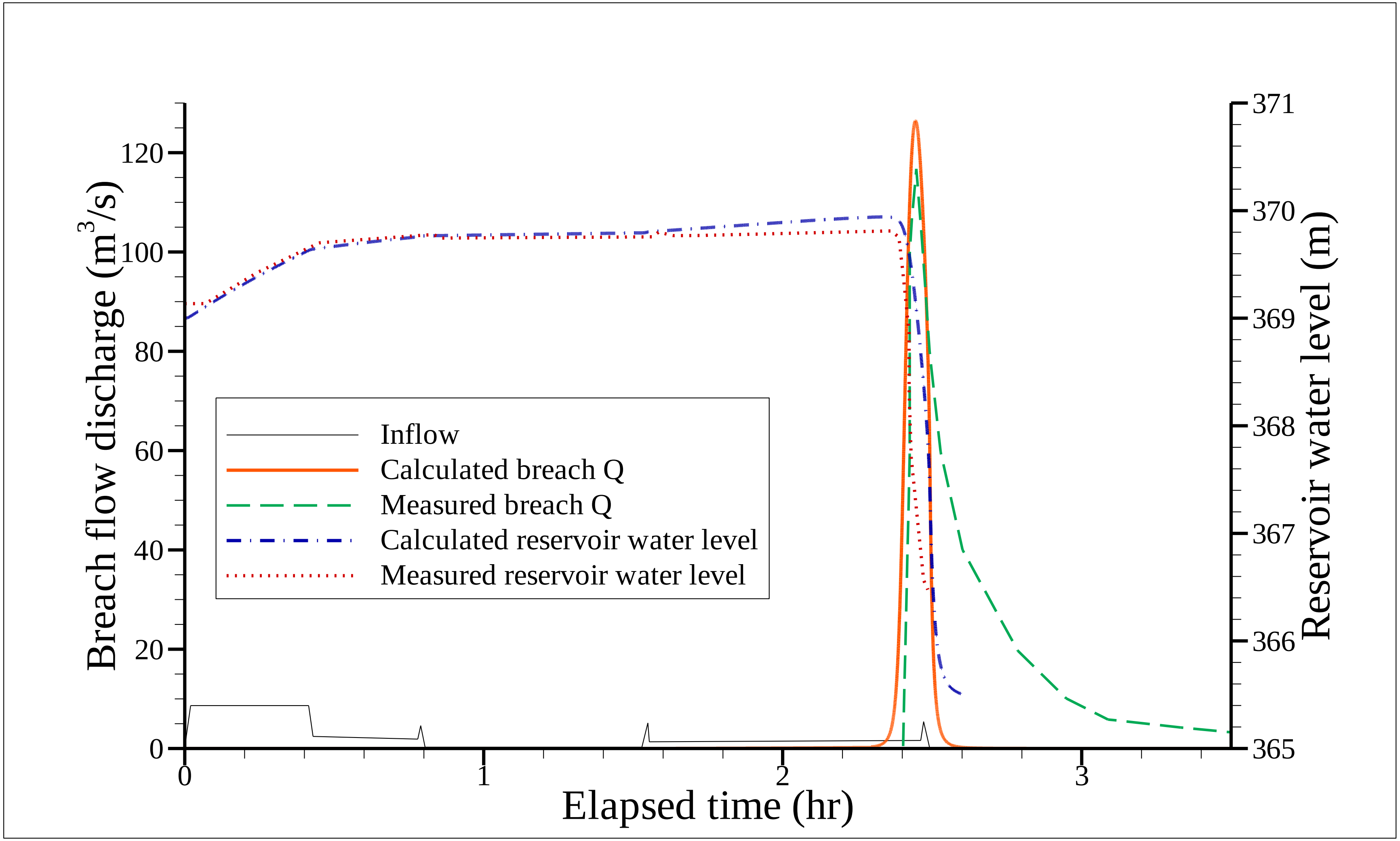
Piping



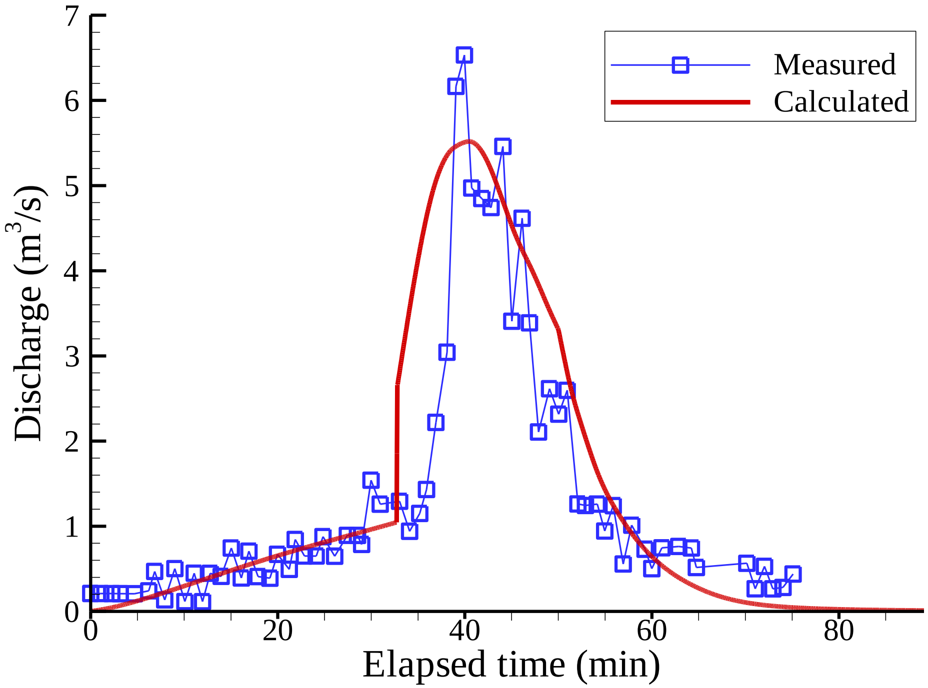
Base erosion

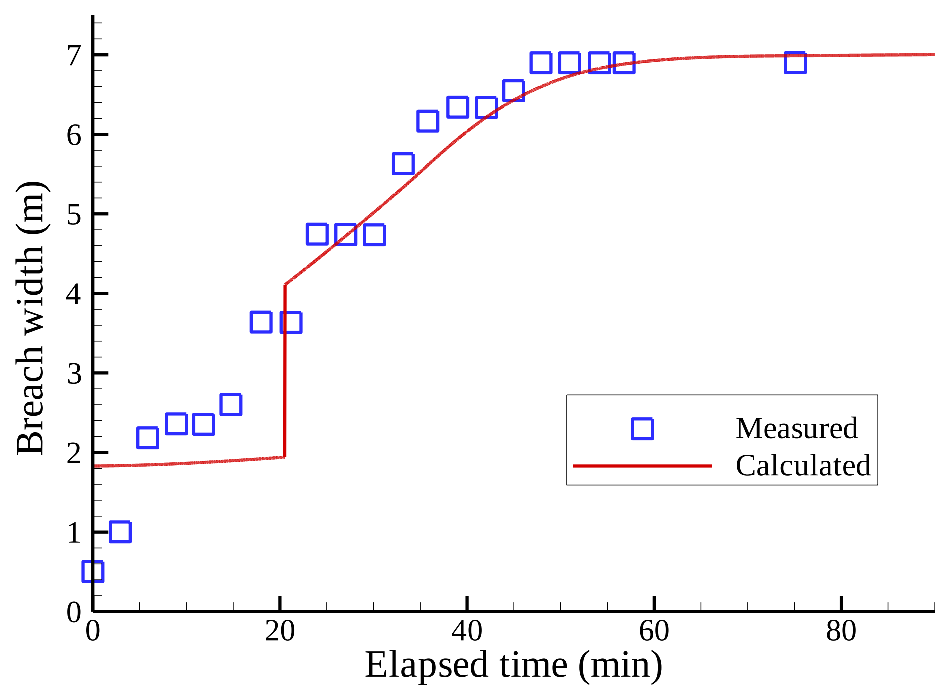


IMPACT Field #2 Results



Model Test using USDA ARS HERU Experiments





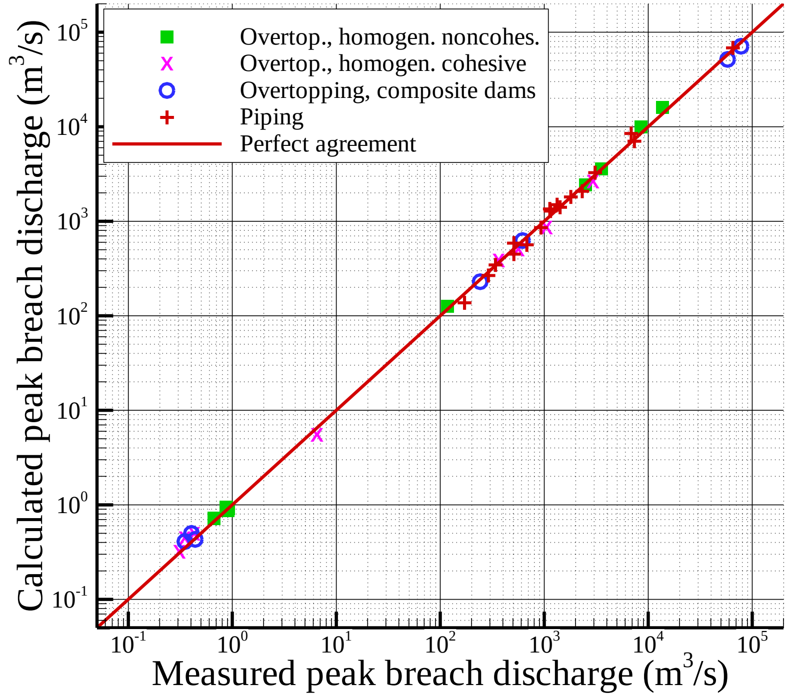
Test #1 of Hanson et al. (2005)

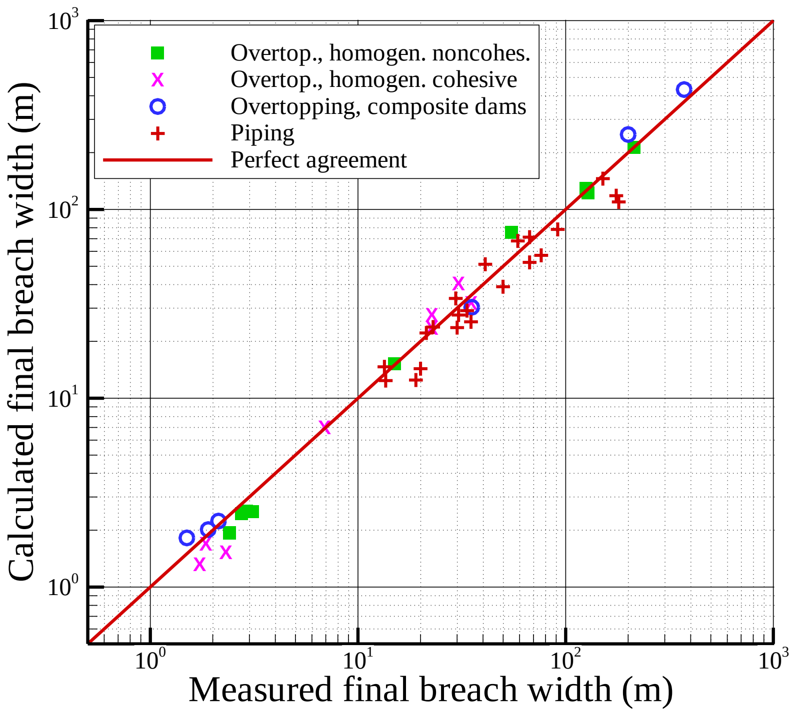
Test of the Simplified Model

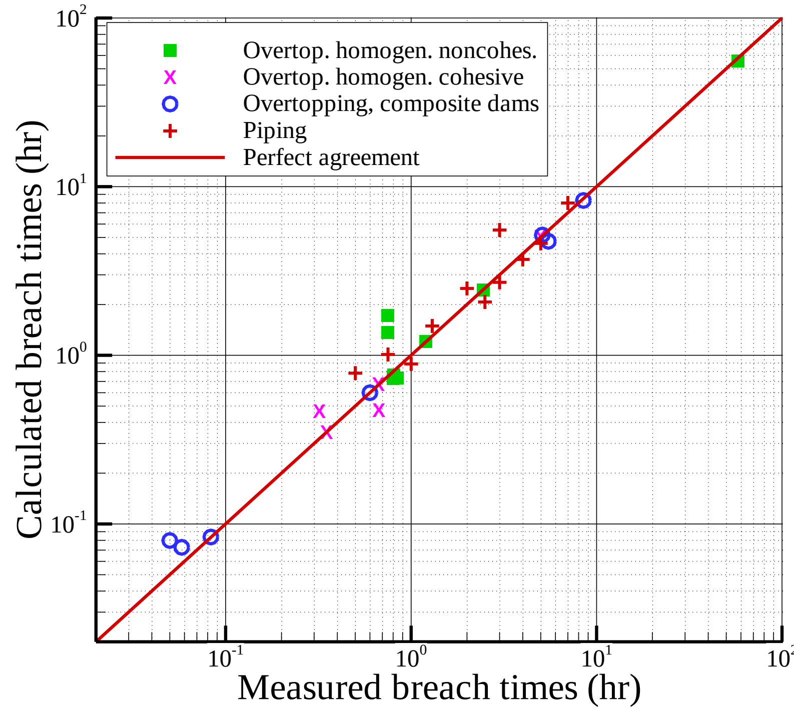
25 Overtopping Cases

- 10 for Non-cohesive Homogeneous
- 8 for Cohesive Homogeneous
- 7 for Composite Dams

25 Piping Cases







Summary of Simplified Physically-Based Breach Models

- Simplified hydrodynamic and sediment transport equations
- Overtopping, piping
- Cohesive, non-cohesive soils
- Homogenous, composite structures
- Surface erosion, headcut migration, mass failure, and base erosion
- Dams, levees, dikes, and barriers

Publications Related

W. Wu and S. S.Y. Wang (2007). "One-dimensional modeling of dam-break flow over movable beds," J. Hydraulic Eng., ASCE, 133(1), 48–58.

W. Wu and S. S.Y. Wang (2008). "One-dimensional explicit finite-volume model for sediment transport with transient flows over movable beds," J. Hydraulic Research, IAHR, 46(1), 87–98.

ASCE/EWRI Task Committee on Dam/Levee Breaching (Weiming Wu as the Committee Chair and corresponding author) (2011). "Earthen embankment breaching," Journal of Hydraulic Engineering, ASCE, 137(12), 1549–1564.

M. Zhang and W. Wu (2011). "A two dimensional hydrodynamic and sediment transport model for dam break based on finite volume method with quadtree grid," Applied Ocean Research, Elsevier, 33, 297–308.

W. Wu, R. Marsooli and Z. He (2012). "A depth-averaged two-dimensional model of unsteady flow and sediment transport due to non-cohesive embankment break/breaching." Journal of Hydraulic Engineering, ASCE, 138(6), 503–516.

W. Wu (2013). "Simplified physically based model of earthen embankment breaching." J. Hydraul. Eng., 139(8), 837-851.

R. Marsooli (2013). "3-D numerical simulation of dam-break flows over movable beds." PhD Dissertation, the University of Mississippi, USA.

R. Marsooli and W. Wu (2014a). "3-D finite-volume model of dam-break flow over uneven beds based on VOF method." Advances in Water Resources, 70, 104–117, http://dx.doi.org/10.1016/j.advwatres.2014.04.020 0309-1708.

R. Marsooli and W. Wu (2014b). "3-D finite-volume model of dam-break flow over movable beds." Journal of Hydraulic Engineering, ASCE, in press.