R&D Forum, Drainage Services Department
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Design Review of Tai Po River by Advanced Hydraulic Modelling

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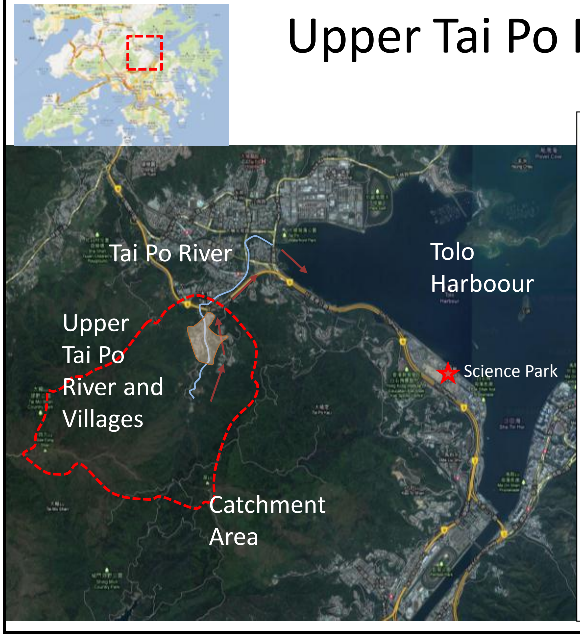
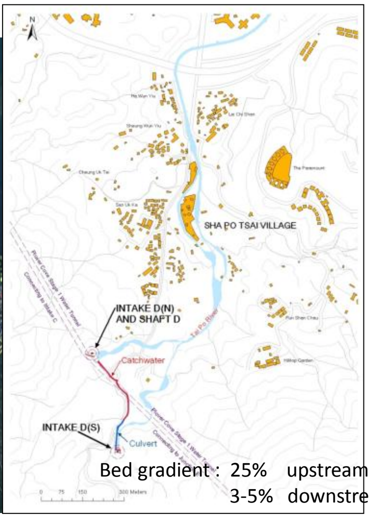
Outline

- Introduction
- Tai Po River Restoration Scheme
  - Debris flood of July 22, 2010
- Schematic physical model study for review of river training design
- Numerical (CFD) modelling issues for supercritical open channel flow
- Physical model study of Upper Taipo River
- Conclusions

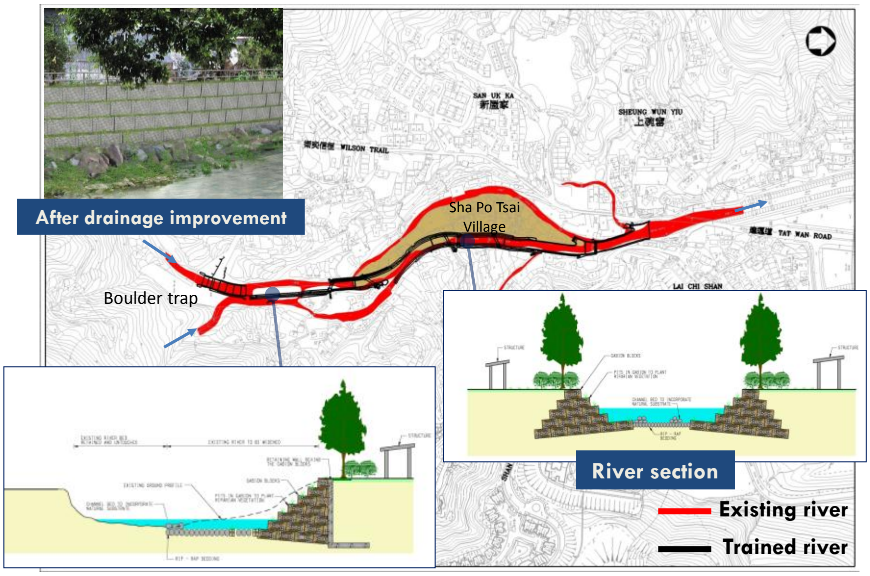
River Improvement Work for Upper Tai Po River





Bed gradient : 25% upstream
3-5% downstrea

Training of Upper Tai Po River



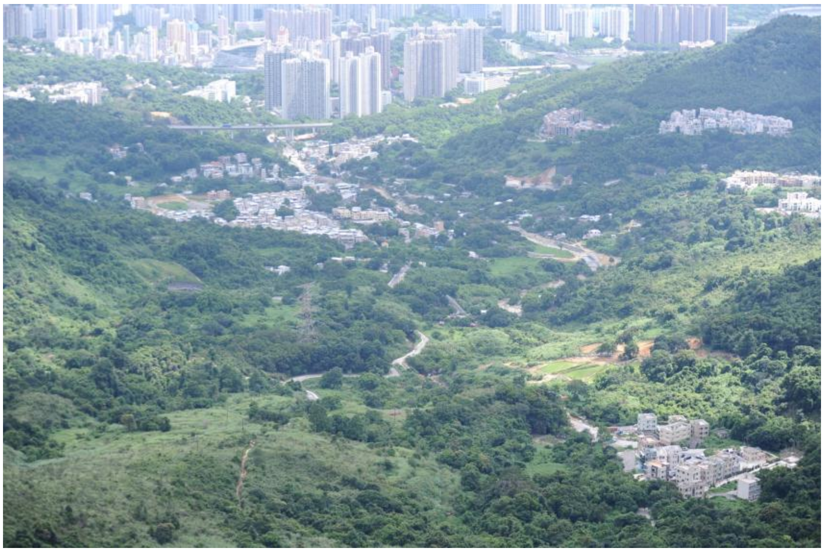
After drainage improvement

River section

Existing river

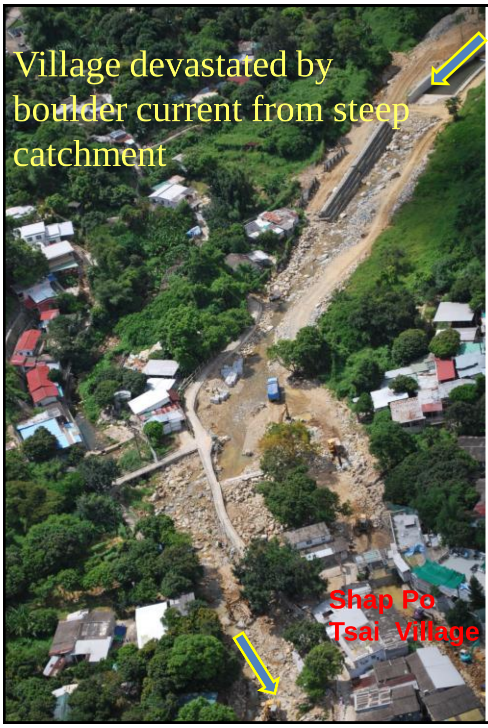
Trained river

Challenges of Urbanisation
Flooding in Sha Po Tsai Village,
Tai Po, 22 July 2010

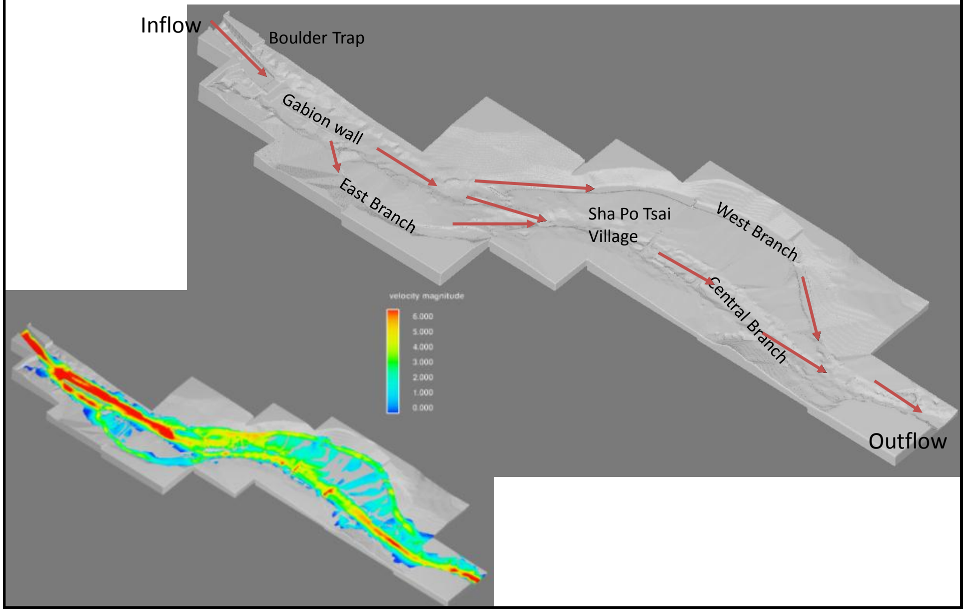


Debris flood and boulder current in Tai Po River

Rainfall on 22/7/2010
(225 mm/d)
114.5 mm/hr
(record maximum)



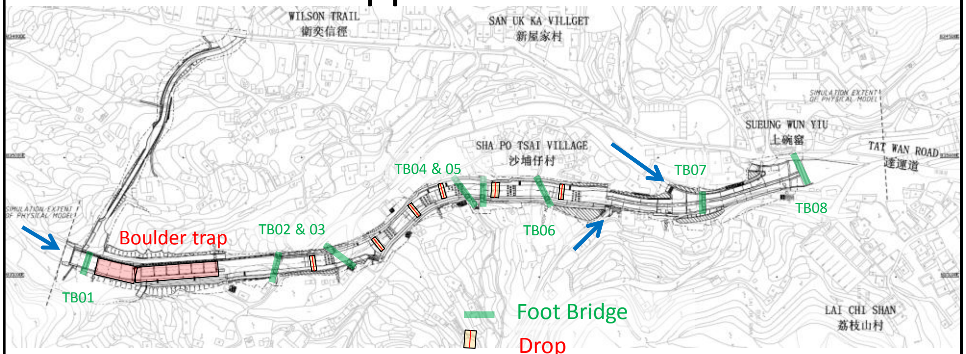
CFD simulation of 22/7/2010 flood
Without downstream river training



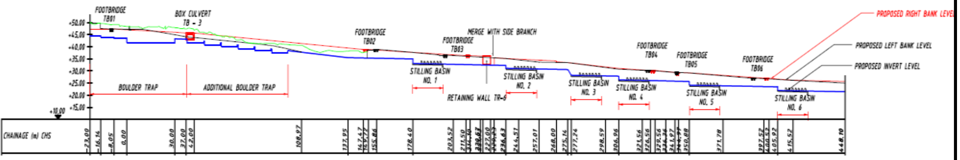
Review of 2010 Tai Po Debris Flood

- Flash flood caused by a combination of unlikely events: rapid black rainstorm, saturated catchment, flood flows in excess of vortex intake design capacity, stream bed erosion and boulder current
- Review of Tai Po River Improvement Works design using advanced hydrodynamic models and/or physical models to optimise hydraulic performance is recommended.

General Layout of River Training for Upper Tai Po River



Layout Plan of Upper Tai Po River



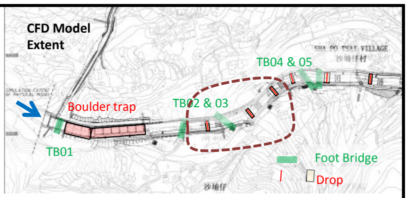
Longitudinal Profile of Upper Tai Po River

Detailed 3D Computational Fluid Dynamics (CFD) Study by AECOM

- Review flow features in the high speed flow
- Assess the suitability of the proposed design relative to overtopping of river banks and flow velocities (CH150-CH320)
- Super-elevation at river bends in supercritical flow
- FLOW3D - VOF (free surface model)
- 20 million cells (0.1 m cells size)
- Various block height and roughness tested
- Only representative reach of the River modelled

	Manning's n
Concrete	0.016
Gabion	0.035

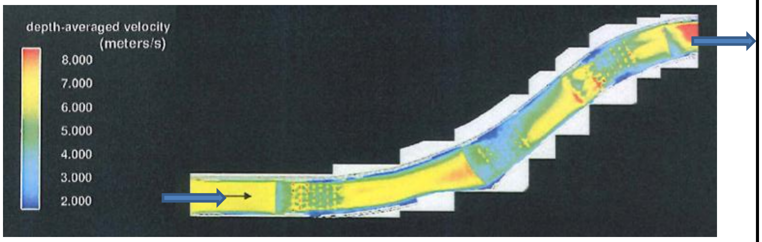
Numerical Model Result



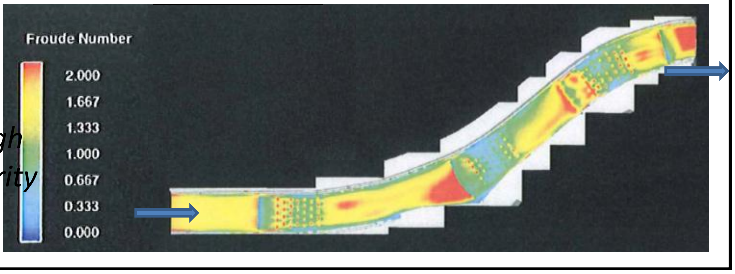
Parameters	Values
Flow	94.4 m3/s
Gradient	1 : 75
Manning's n	0.035
Arrangement of baffle block for each step	7 rows, 1m (H) baffle blocks

Depth Averaged Velocity > 5 m/s

Vmax = 8 m/s



Froude No > 1



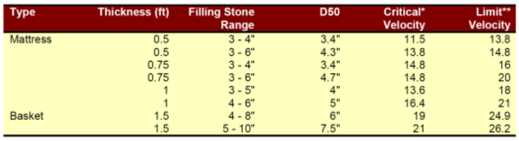
Velocities too high for gabion integrity

Computed velocities (Vmax = 7.5 – 8 m/s) in trained river too high for gabion integrity

Critical Velocity of Gabion Mattress

US Army Corps of Engineers – Gabions for Streambank Erosion Control

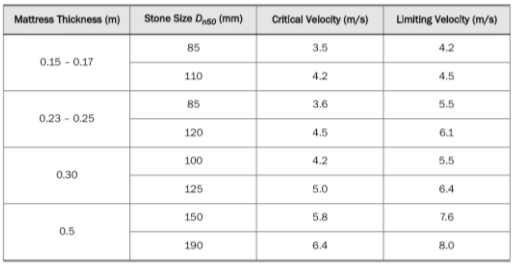
Table 2. Stone Sizes and Allowable Velocities for Gabions (courtesy of and adapted from Maccaferri Gabions)



Type	Thickness (ft)	Filling Stone Range	D50	Critical* Velocity	Limit** Velocity
Mattress	0.5	3 - 4"	3.4"	11.5	13.8
	0.5	3 - 6"	4.3"	13.8	14.8
	0.75	3 - 4"	3.4"	14.8	16
	0.75	3 - 6"	4.7"	14.8	20
	1	3 - 5"	4"	13.6	18
	1	4 - 6"	5"	16.4	21
Basket	1.5	4 - 8"	6"	19	24.9
	1.5	5 - 10"	7.5"	21	26.2

CIRIA - The Rock Manual
- use of rock in hydraulic engineering (2007)

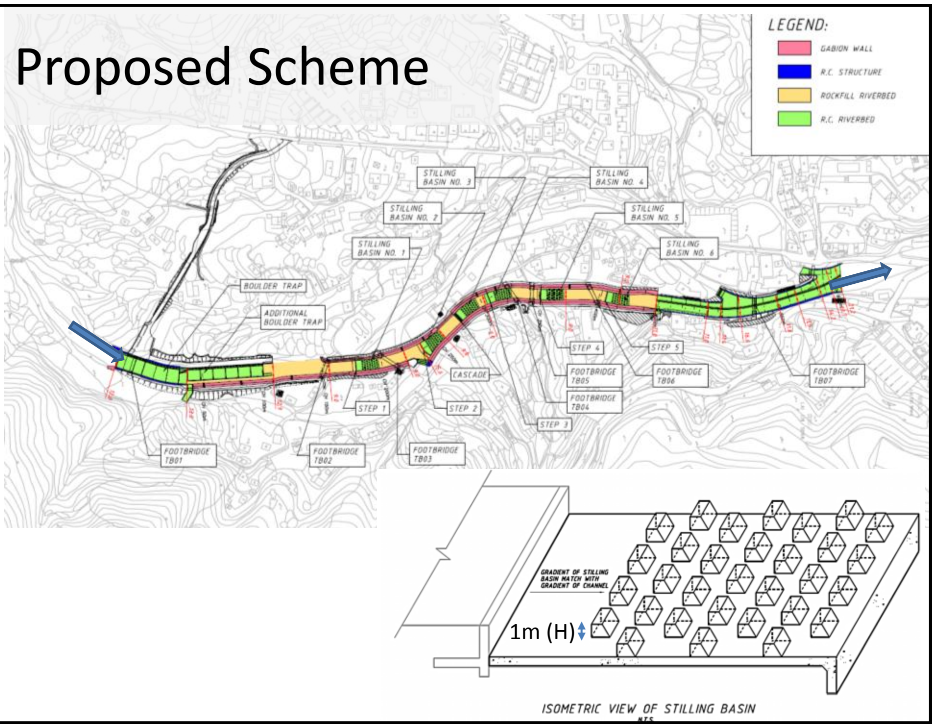
Table 8.11 *Indicative values of critical and limiting velocities for mattresses*



Mattress Thickness (m)	Stone Size D_{n50} (mm)	Critical Velocity (m/s)	Limiting Velocity (m/s)
0.15 – 0.17	85	3.5	4.2
	110	4.2	4.5
0.23 – 0.25	85	3.6	5.5
	120	4.5	6.1
0.30	100	4.2	5.5
	125	5.0	6.4
0.5	150	5.8	7.6
	190	6.4	8.0

Critical velocity ~ 6.4 m/s
Limiting velocity ~ 7.9 m/s

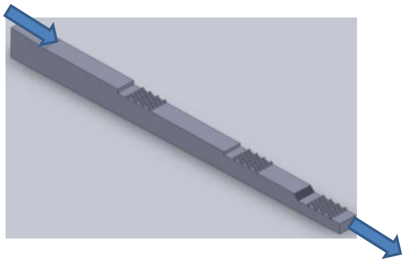
Proposed Scheme



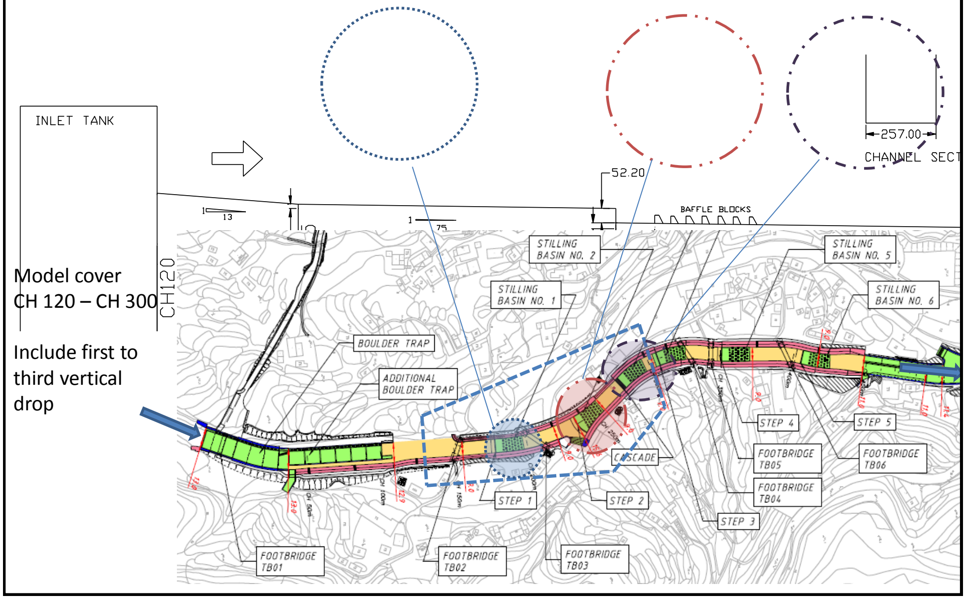
ISOMETRIC VIEW OF STILLING BASIN
NTS

Schematic Physical Model Study of Upper Tai Po River

- Limited information on energy dissipation and hydraulic interaction in short supercritical channel flow
- Robustness and accuracy of CFD calculations have to be demonstrated
- Construction works have to be completed in dry season of 2011 prior to the wet season (April 2012); need to arrive at satisfactory design within a short time frame
- Aesthetics of stilling blocks
- Develop simple energy dissipation design to meet design constraints
- Special emphasis: first three drops



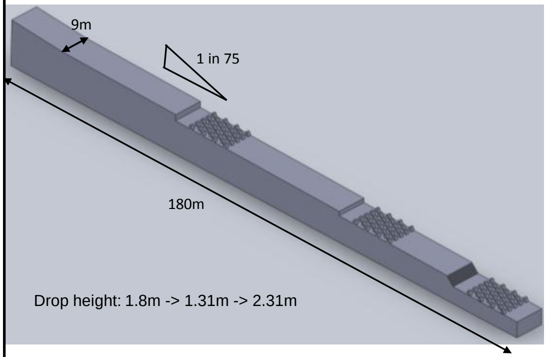
Schematic Physical Model Dimension (CH120 – CH300)



Model cover CH 120 – CH 300

Include first to third vertical drop

Schematic Physical Model of representative river reach (CH120 – CH300)



Scale	Prototype : Model
Length	1: 35
Velocity	1: 5.92
Flow	1 : 7247
Reynolds no.	$5 \times 10^6 : 2.4 \times 10^4$
Manning's n	1 : 1.808

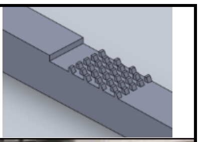
Simulated Scenario	Q (m3/s)
Historical Event	120
Design Flow	90
Medium Flow	60
Low Flow	30

	Manning's n
Perspex bed (Concrete bed)	0.015
LEGO Mat (Gabion Bed)	0.0205

Design considerations

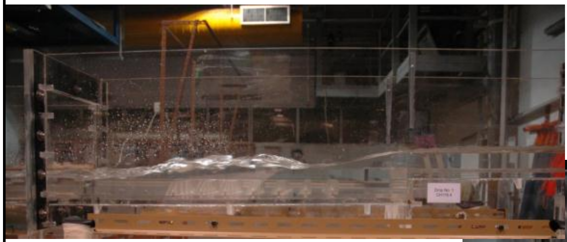
- Flood level below embankment or bridge level
- Velocities below 7-8 m/s to avoid bed erosion
- Robust and natural looking; minimize the use of artificial stilling blocks
- Optimize the energy dissipation by a series of supercritical weirs (raised drop or flow humping over the weirs) and weak jumps at the right locations; make use of local freeboard
- Lower the water level before the villages

Generic Design 1:
7- Row Baffle Block after Drop (Q = 90m3/s)

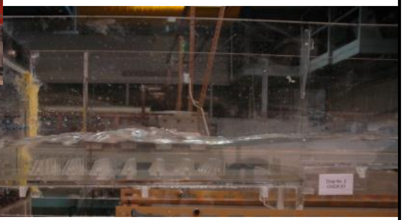


7- Row Baffle Block after Drop (Q = 90 m3/s)

- High speed supercritical flow
- No hydraulic Jump can be formed
- As the flow does not impinge directly on the baffle block, a skimming flow above the block is formed, with local rise in water level

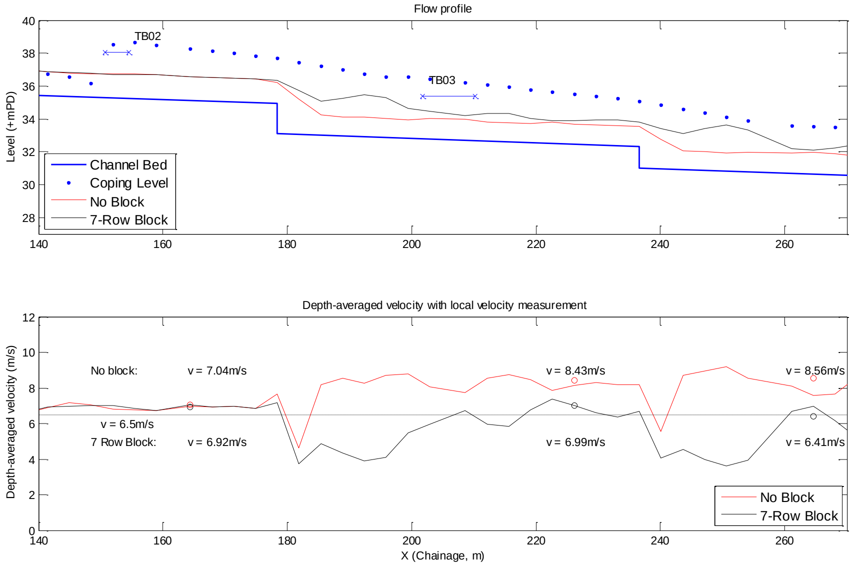


Drop 1

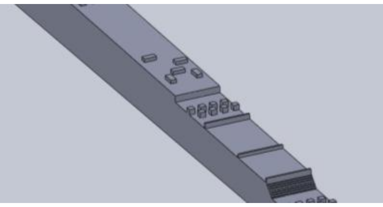


Drop 2

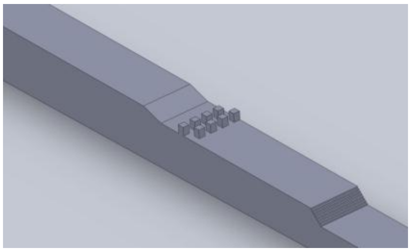
Measured level and velocity with and without 7- Row baffle block (smooth channel; Q = 90 m3/s)



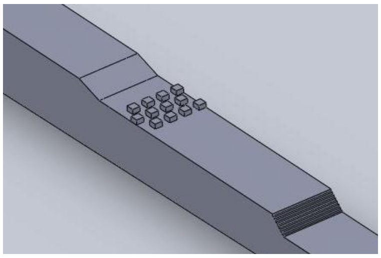
Alternative designs for energy dissipation



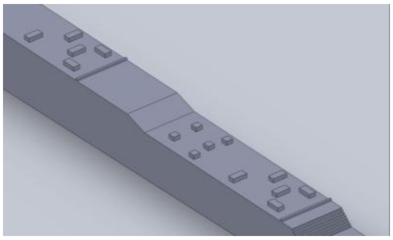
Distributed blocks and weir and vertical drop



2 Rows x 1.4 m (H) (sloping drop)

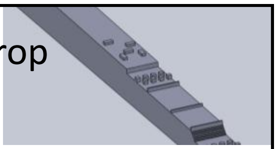


3 Rows x 0.7 m (H) (sloping drop)

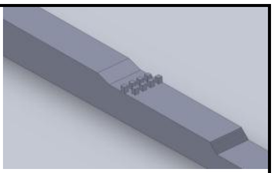


0.7 m (H) Distributed blocks and weir (sloping drop)

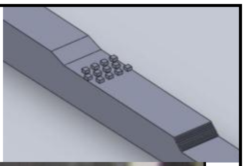
Distributed blocks and weir and vertical drop (Q = 90m3/s)



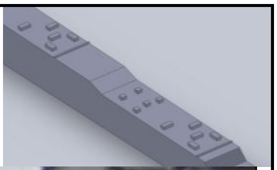
2 Rows x 1.4m (H) (Sloping Drop) (Q = 90m3/s)



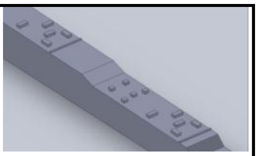
3 Rows x 0.7m (H) (Sloping Drop)
(Q = 90m3/s)

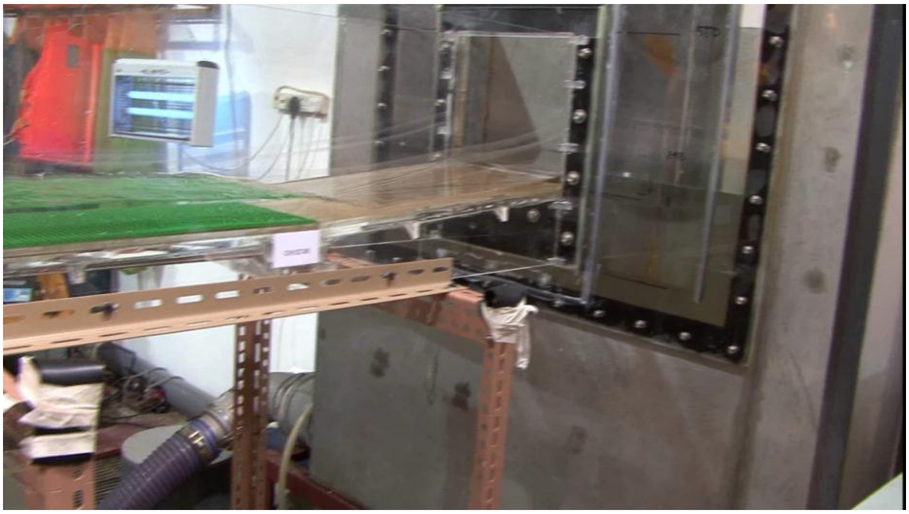


0.7m (H) Distributed Blocks and Weir (Sloping Drop) (Q = 90m3/s)

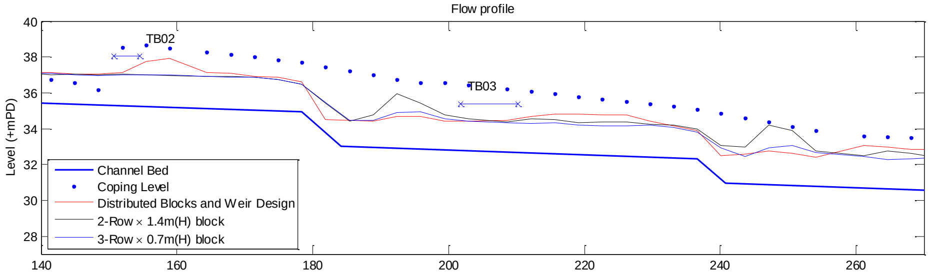


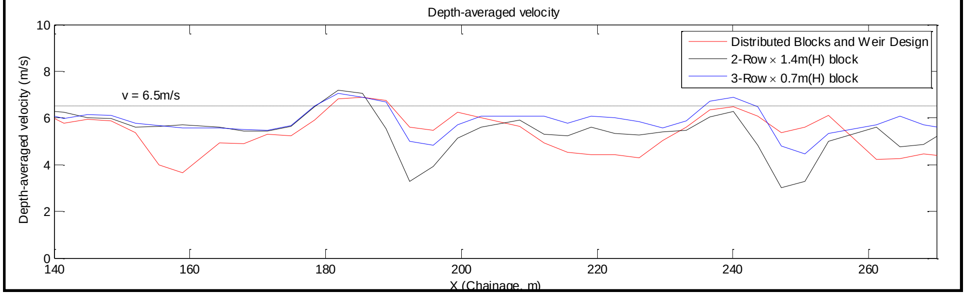
0.7m (H) Distributed Blocks and Weir (Sloping Drop) (Q = 10m3/s)





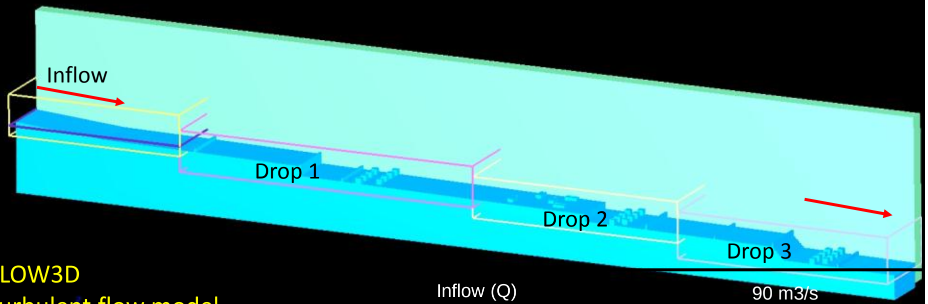
Measured level and velocity for 2 row x 1.4 m(H), 3 row x 0.7m(H) baffle block and Distributed Blocks and Weir (Rough bed; Q = 90 m3/s) (CH 140 - CH270)





Numerical Model Study

NUMERICAL STUDY: FLOW3D computation (Distributed blocks w/ vertical drop)



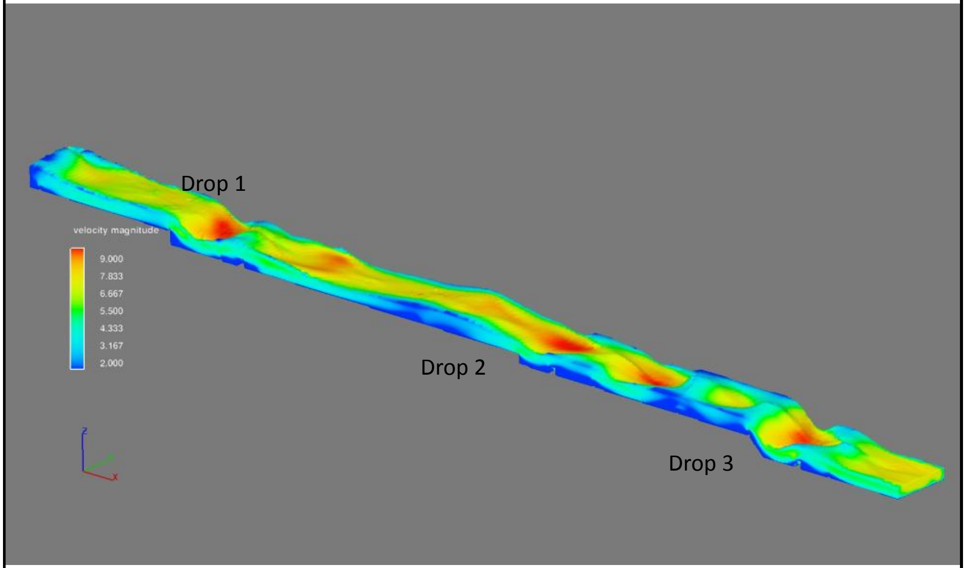
FLOW3D

Turbulent flow model
- Reynolds-Averaged Navier-Stokes (RANS) equation
- k–ε two-equation model

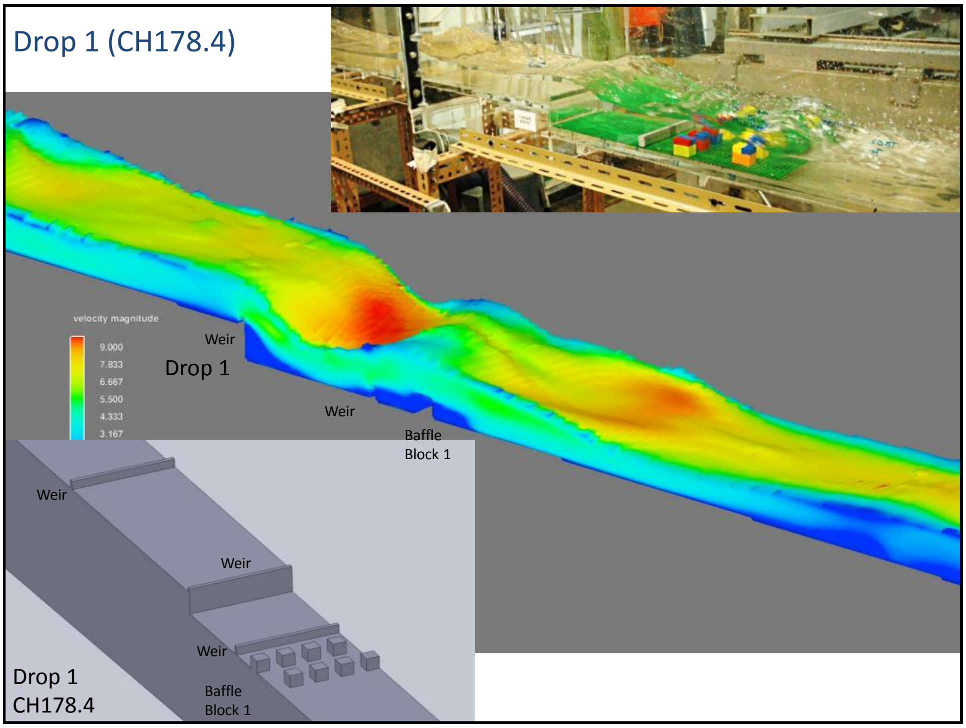
Free surface flow model
- Volume of Fluid (VOF)

Inflow (Q)	90 m3/s
Delta x – y – z (m)	0.1 x 0.5 x 0.16
Number of Cell	2.5×10^6
Mesh Blocks	4
Inflow Boundary	Discharge with Flow Depth
Outflow Boundary	Outflow
Surface Roughness	Manning's n = 0.035 ; ks = 0.368

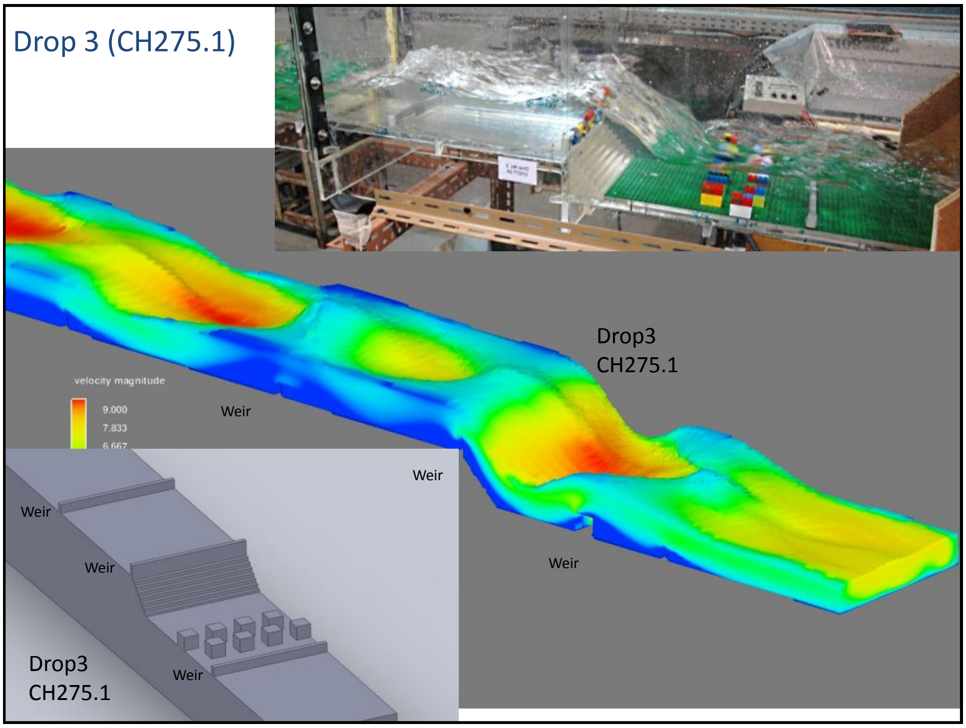
Computed Velocity Field (Distributed blocks with vertical drop)



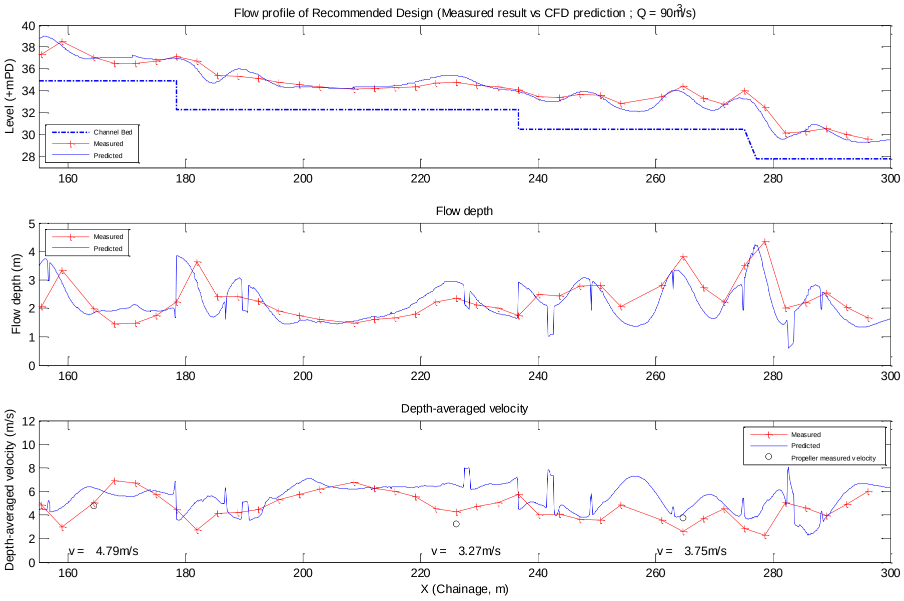
Drop 1 (CH178.4)



Drop 3 (CH275.1)



Comparison of computed and measured level and velocity (Distributed blocks and weir with vertical drops; smooth channel)


Flow profile of Recommended Design (Measured result vs CFD prediction ; Q = 90m³/s)

Flow depth

Depth-averaged velocity

Numerical Modelling Issues

- Accuracy of depth-averaged velocities computed by FLOW3d
- Can the numerical model provide meaningful results for our project?
- Quantification of bottom roughness for supercritical flow – consistency between FLOW3d and the one-dimensional field-tested Mannings Equation for uniform open channel flow

Manning’s n for Gabion surface

Blodgett (1986) proposed the relationship between Manning’s n and flow depth (d) and riprap size (D50) :

$$n = \frac{0.319\, d_a^{1/6}}{2.25 + 5.23 \log\left(\frac{d_a}{D_{50}}\right)}$$

Where

n = Manning's n
d_a = average flow depth in the channel, m
D_{50} = median riprap/gravel size, m

Thus, in this case:-

d_a = 1 m
D_{50} = 48.8 mm – 76.2 mm
n = 0.035 – 0.0394

Surface Roughness Input in FLOW3D

FLOW3D TN60
Modeling Roughness Effects in Open Channel Flows
(D.T. Souders and C.W. Hirt) (http://www.flow3d.com/pdfs/tn/FloSci-TN60.pdf)

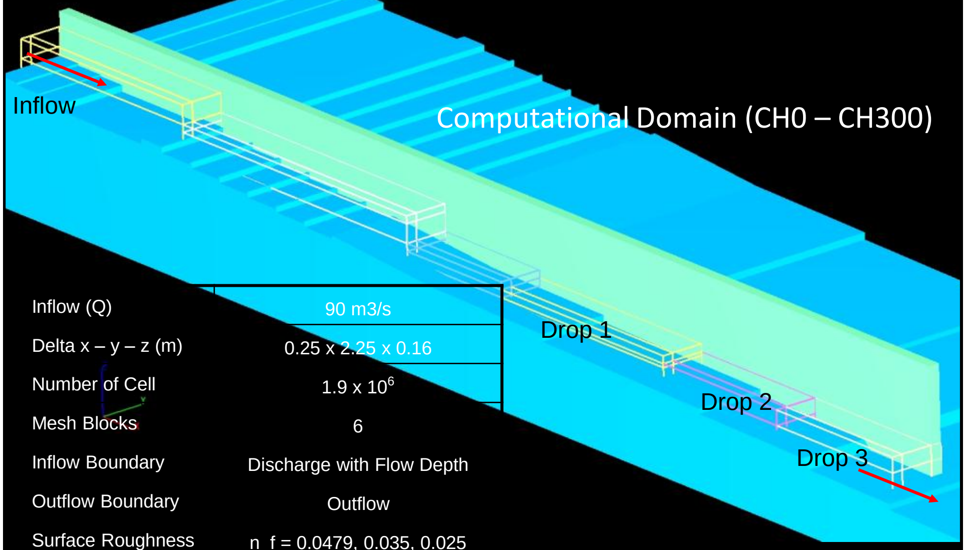
Extrapolation of Darcy-Weisbach friction factor in turbulent pipe flow to steady uniform open channel flow

$$\ln \frac{R_h}{k_s} = \frac{0.128}{n} R_h^{1/6} - 2.5$$

where

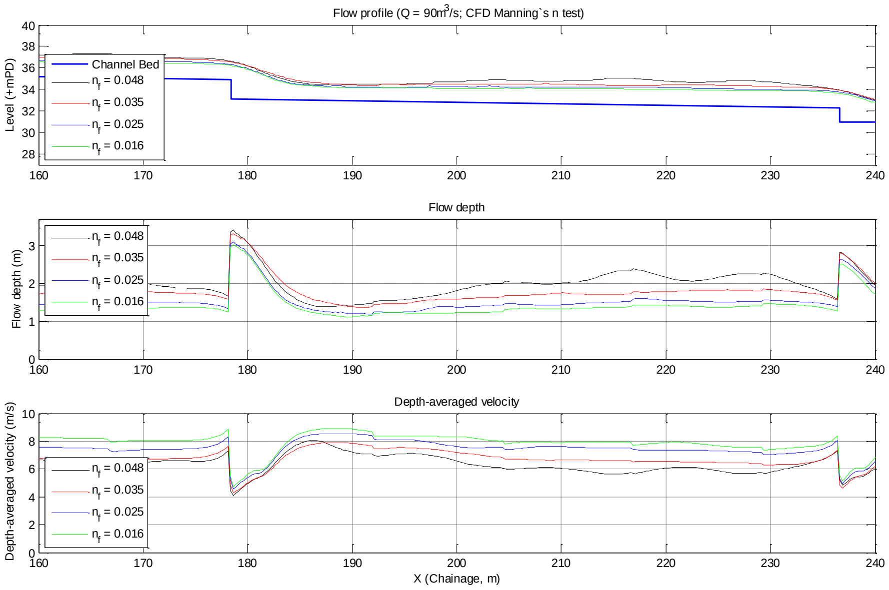
R_h = Hydraulic Radius (m)
K_s = Surface Roughness (m)
n = Manning's n

CFD study of supercritical flow in uniform open channel with vertical drops



Inflow (Q)	90 m3/s
Delta x – y – z (m)	0.25 x 2.25 x 0.16
Number of Cell	1.9 x 10^6
Mesh Blocks	6
Inflow Boundary	Discharge with Flow Depth
Outflow Boundary	Outflow
Surface Roughness	n_f = 0.0479, 0.035, 0.025 and 0.016

Computed centerline level and velocity (CH160 - CH240)



FLOW3d computed velocities/depths for a uniform open channel flow correspond to lower Mannings roughness of well-established 1D model

	FLOW3D Calculation				
Manning's n $n = \frac{0.319\, d_a^{1/6}}{2.25 + 5.23 \log\left(\frac{d_a}{D_{50}}\right)}$	Surface Roughness ks (m) $\ln \frac{R_h}{k_s} = \frac{0.128}{n} R_h^{1/6} - 2.5$	Averaged depth/velocity along centerline of channel at CH200 - CH230			Correspond. Manning's n $n = \frac{1}{V} R_h^{2/3} S_o^{1/2}$ $S_o = 1/75$
		$\overline{Y}$ (m)	$\overline{V}$ (m/s)	Fr	
0.0479	1.1	2.12	4.72	1.03	0.0312
0.035 (gabion)	0.368	1.74	5.75	1.39	0.0233
0.030					
0.025	0.073	1.49	6.71	1.76	0.0186
0.023					
0.02	0.0198	1.35	7.41	2.04	0.016
0.016 (concrete)	0.0040				

For a given Mannings roughness n, FLOW3d gives higher velocities/lower depth than that given by the field-tested Mannings Equation

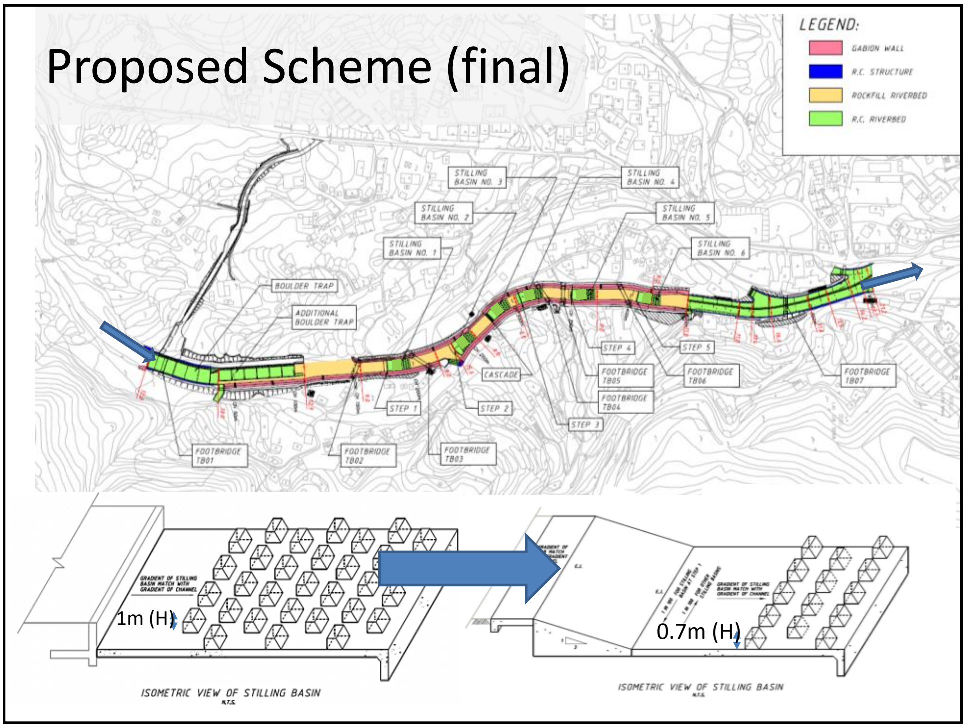
	FLOW3D Calculation				1D Open Channel Flow $V = \frac{1}{n} R_h^{2/3} S_o^{1/2}$		
Manning's n $n = \frac{0.319\, d_a^{1/6}}{2.25 + 5.23 \log\left(\frac{d_a}{D_{50}}\right)}$	Surface Roughness ks (m) $\ln \frac{R_h}{k_s} = \frac{0.128}{n} R_h^{1/6} - 2.5$	Averaged depth/velocity along centerline of channel at CH200 - CH230			Normal Depth	Velocity	Froude no
		$\overline{Y}$ (m)	$\overline{V}$ (m/s)	Fr	Y (m)	V (m/s)	Fr
0.0479	1.1	2.12	4.72	1.03	2.86	3.50	0.66
0.035 (gabion)	0.368	1.74	5.75	1.39	2.30	4.36	0.92
0.030					2.06	4.85	1.08
0.025	0.073	1.49	6.71	1.76	1.82	5.49	1.30
0.023					1.72	5.81	1.41
0.02	0.0198	1.35	7.41	2.04	1.57	6.38	1.63
0.016 (concrete)	0.0040				1.35	7.40	2.03

FLOW3D TN60
Modeling Roughness Effects in Open Channel Flows
(D.T. Souders and C.W. Hirt)

" The computed results are within the scatter of empirical data and, as Chow points out, there are many physical factors in a real channel that affect its flow rate.

Users are encouraged to use the new model, which simply means defining a roughness for the boundaries of the channel. If the value of roughness is unknown it can be computed from Mannings n… Be aware, however, that computed results for flow rates can be no more accurate than the data on which the above formulae are based – i.e. accepting the values as a decent approximation but not the absolute truth. "

Proposed Scheme (final)

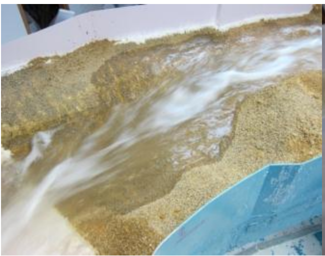


Physical Model of Full Upper Tai Po River

Local flow features

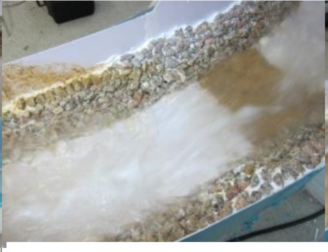
1 – Upstream end

2 – Immediate upstream (natural stream)



3 – TB01

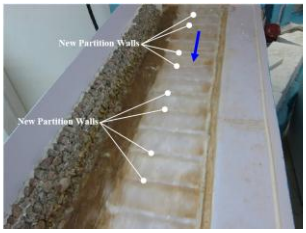
4 – TB03



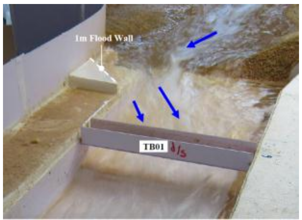
5 – Inclined Slope 3

6 - TB04 & TB05

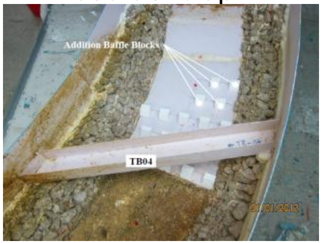
Summary of Recommendations



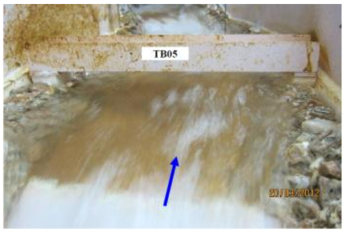
Partition of additional boulder trap



Construction of guide wall at upstream



Additional baffle blocks in stilling basin no. 4



Raising footbridges

On-site Implementation

Raised Footbridge TB04

Additional baffle blocks: stilling basin of Step 3 is modified by adding 4 baffle blocks in 2 rows to minimize the hydraulic jump

Additional partitions in boulder trap

Conclusions

- A robust design of Upper Tai Po River drainage improvement scheme has been developed from heuristic reasoning, experiments on a schematic physical model, and CFD study
- A design of sloping drops with 3-row x 0.7 m H stilling baffle blocks would achieve flood protection without excessive supercritical velocities (<6.5 m/s)
- Alternative design with distributed blocks and weirs can meet design constraints; it also provides a more diverse river habitat for low and normal flow conditions
- The design has been fine-tuned on a physical model of the full Upper Tai Po River with additional design modifications and refinements
- Experiments suggest that the CFD predictions of velocity in the complex 3D supercritical flow need to be further validated by detailed velocity measurements