Estudio del resalto hidráulico y su aplicación en cuencos amortiguadores a través de modelación física y numérica

Juan Francisco Macián Pérez

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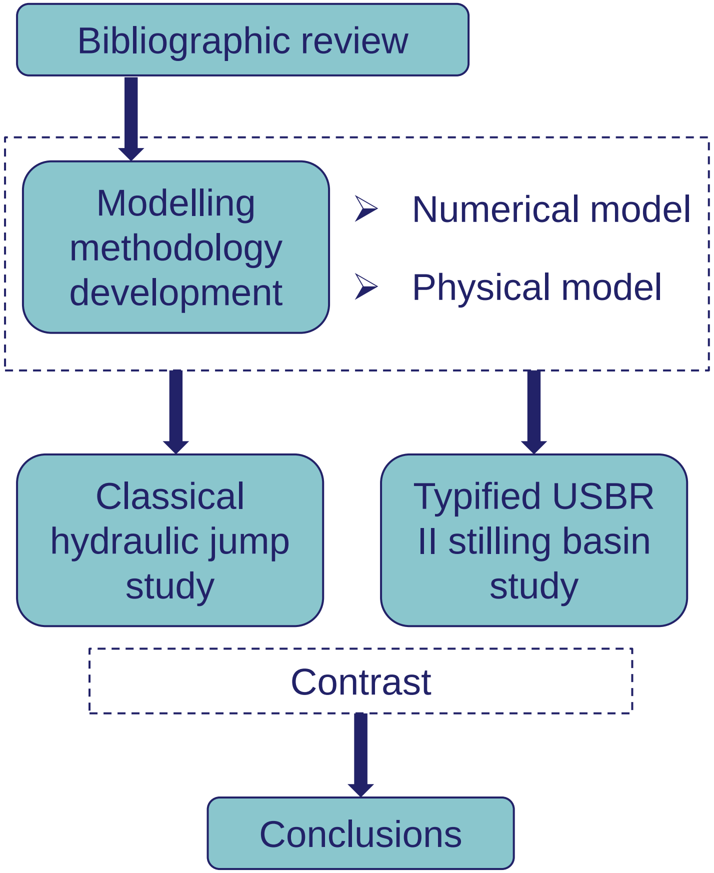


Bibliographic review

Modelling methodology development

- ➢ Numerical model
- ➢ Physical model

Classical hydraulic jump study

Typified USBR II stilling basin study

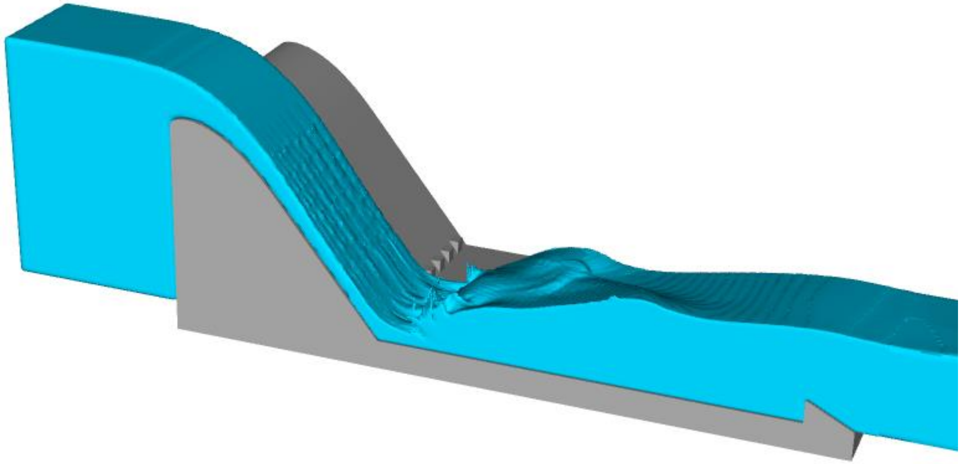
Contrast

Conclusions

1. INTRODUCTION

Background

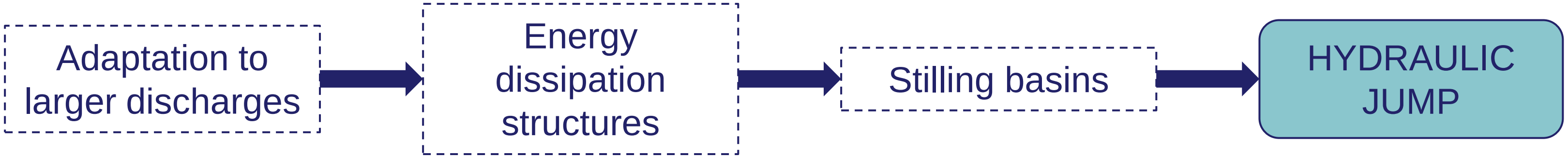
Large-Dams importance



- Key civil engineering structures
- Economic and social interest
- Critical consequences derived from failure
- Climate change effects leading to new scenarios
- Increasing society demands regarding flood protection

Existing dams must deal with larger discharges than those considered in their original design

Background

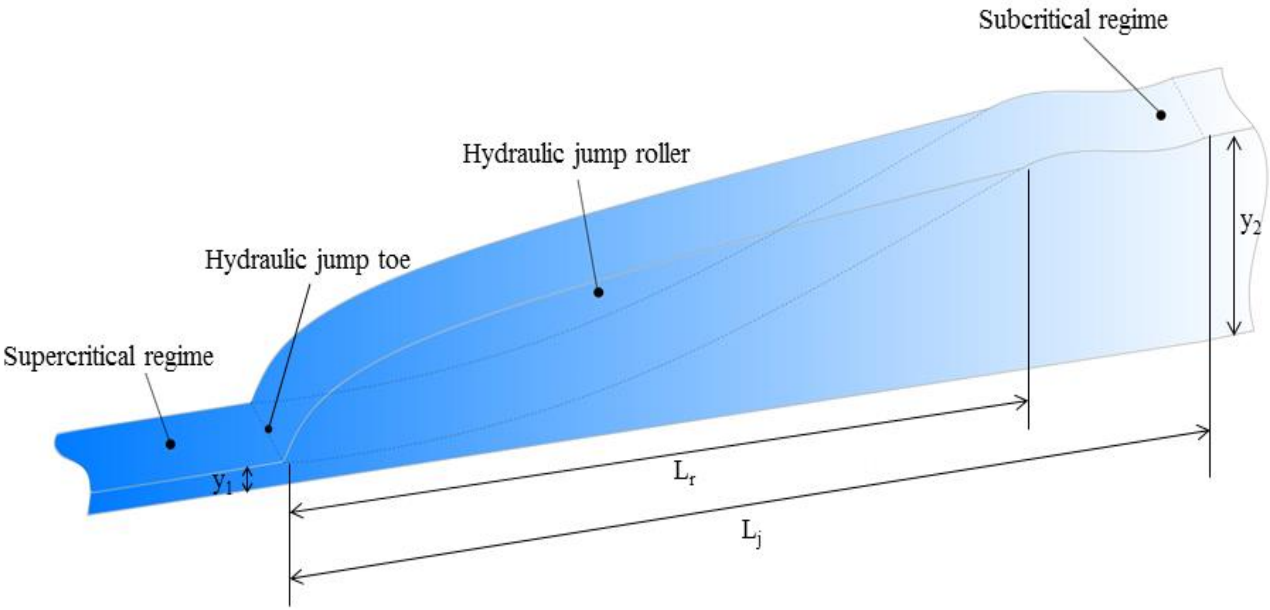


Adaptation to larger discharges

Energy dissipation structures

Stilling basins

HYDRAULIC JUMP



Background

Hydraulic Jump Characterisation

Dimensionless inflow numbers

- Froude number: $Fr_1 = \frac{u_1}{\sqrt{gy_1}}$

- Reynolds number: $Re_1 = \frac{u_1 y_1}{\nu}$
- Weber number: $We_1 = \frac{u_1^2 y_1}{\sigma}$

Hydraulic Jump Modelling

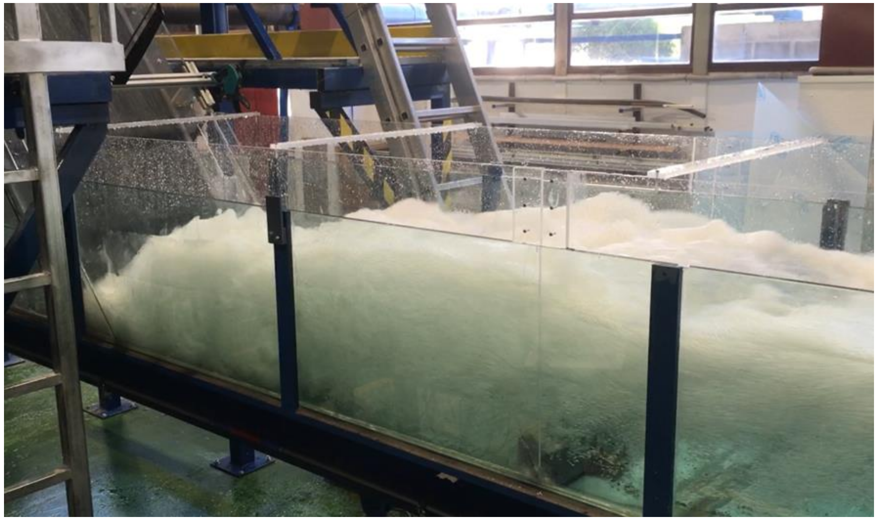
Double approach

- Physical Modelling: reduced scale
- Numerical modelling: CFD techniques

Modelling a representative case study with limited scale effects provides an adequate extrapolation to real-life applications

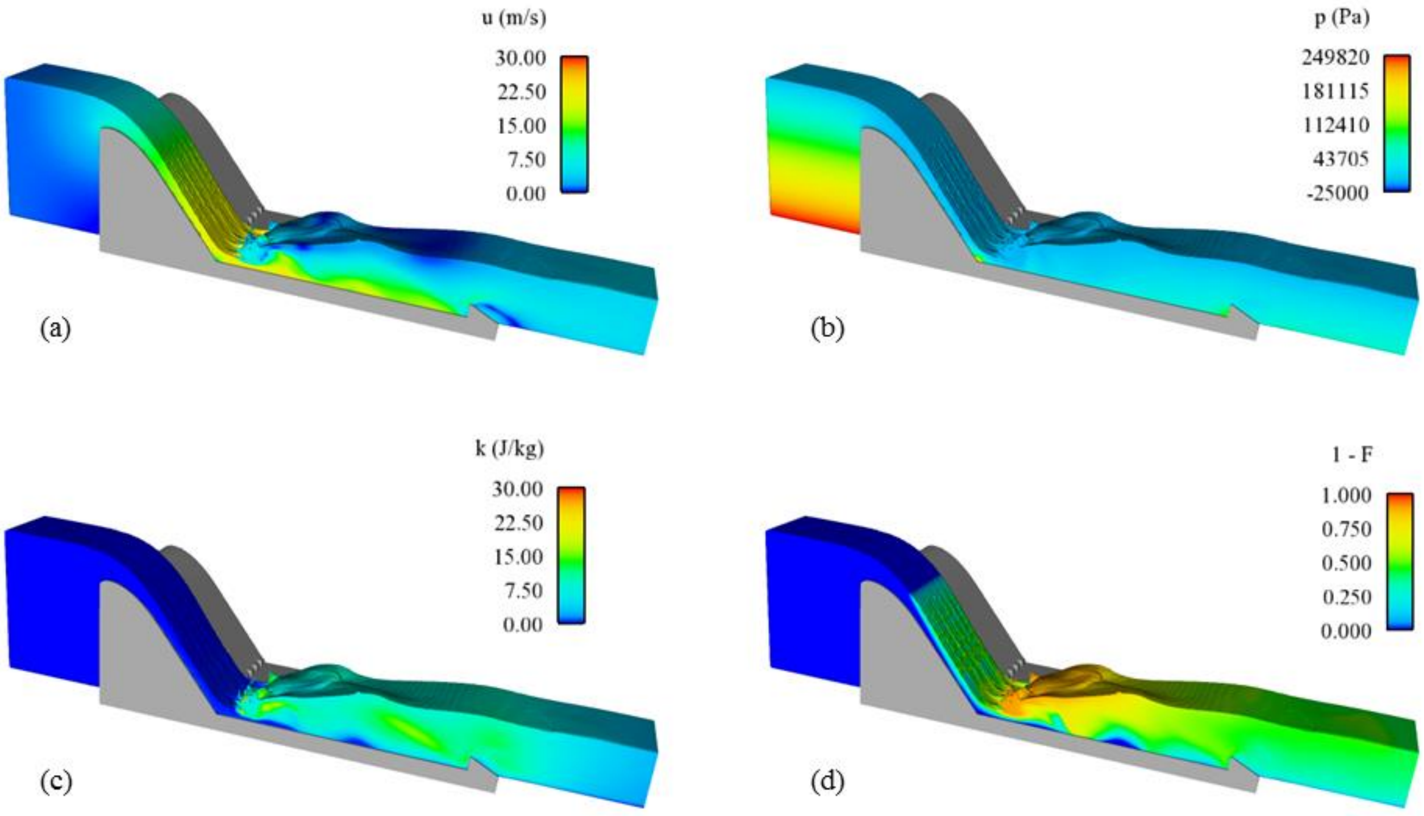
Objectives

- Develop a **state-of-the-art** of the hydraulic jump phenomenon
- Establish a **modelling methodology** based on a double approach
- Characterisation of the **classical hydraulic jump**
- Study of the typified **USBR II** stilling basin

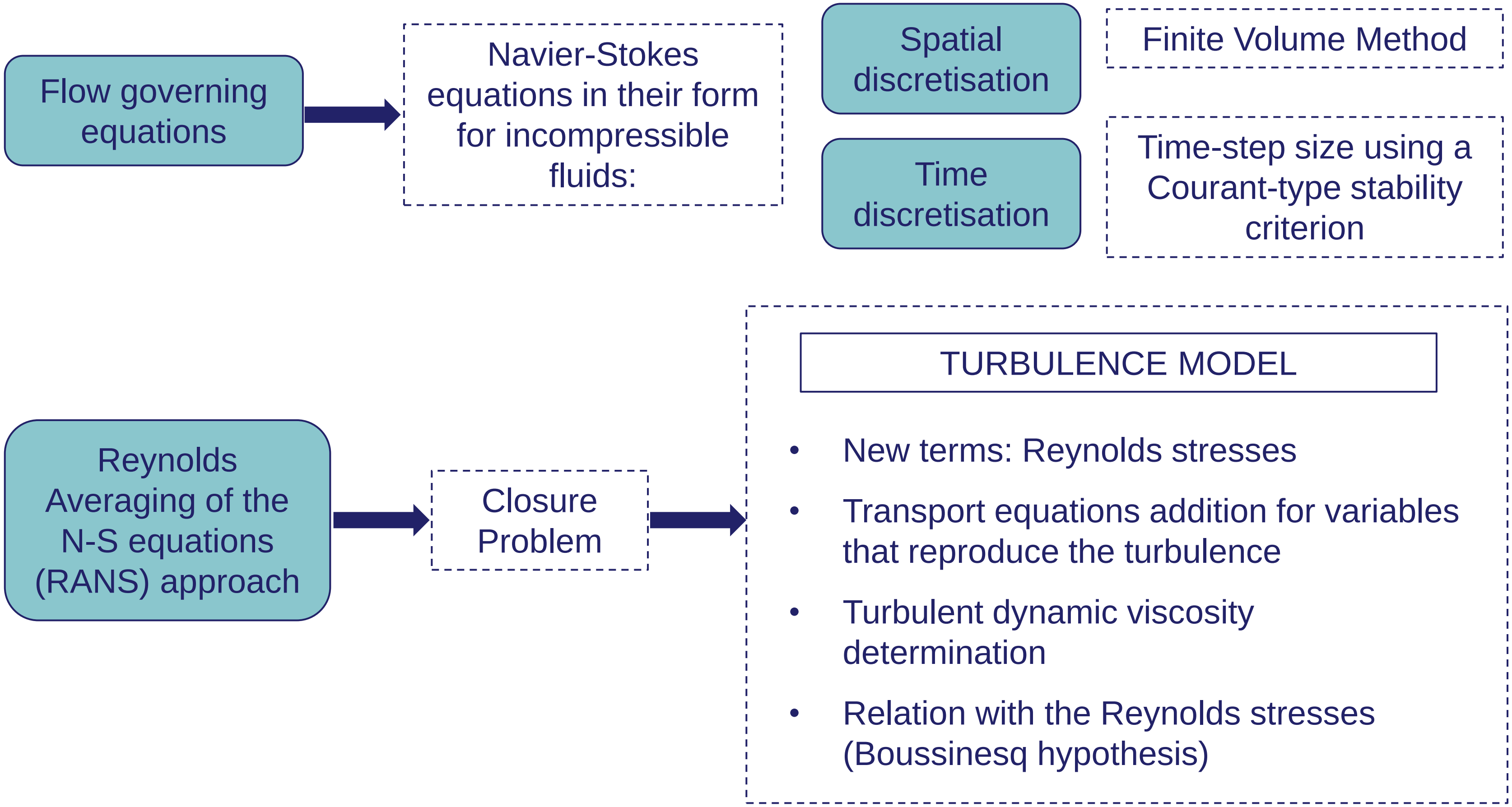


The research aims at contributing to the general knowledge of the hydraulic jump phenomenon and its application for energy dissipation purposes in large-dam stilling basins

2. NUMERICAL MODELLING



General Settings



Flow governing equations

Navier-Stokes equations in their form for incompressible fluids:

Spatial discretisation

Finite Volume Method

Time discretisation

Time-step size using a Courant-type stability criterion

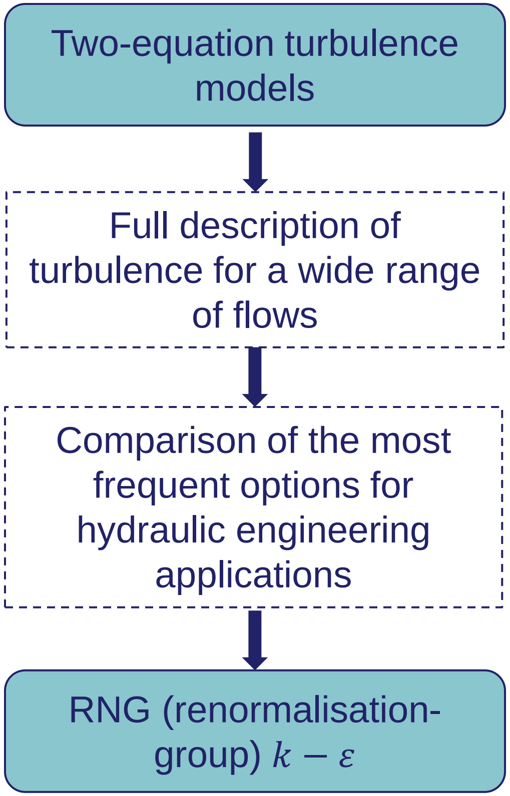
Reynolds Averaging of the N-S equations (RANS) approach

Closure Problem

TURBULENCE MODEL

- New terms: Reynolds stresses
- Transport equations addition for variables that reproduce the turbulence
- Turbulent dynamic viscosity determination
- Relation with the Reynolds stresses (Boussinesq hypothesis)

Turbulence Modelling

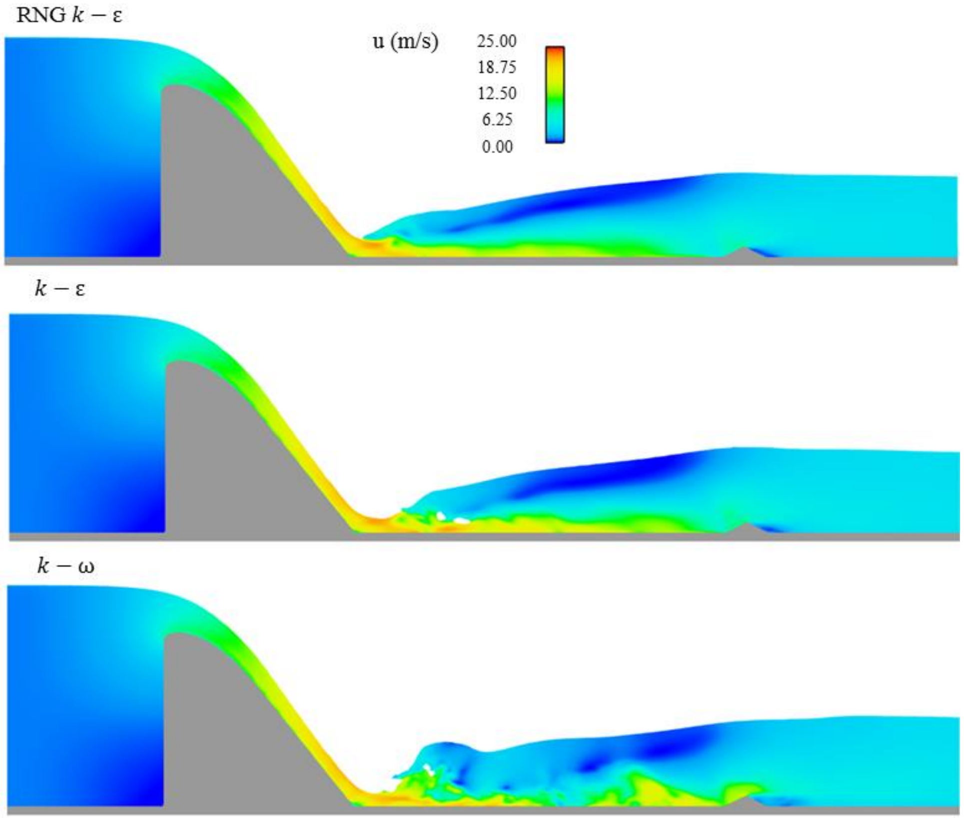


Two-equation turbulence models

Full description of turbulence for a wide range of flows

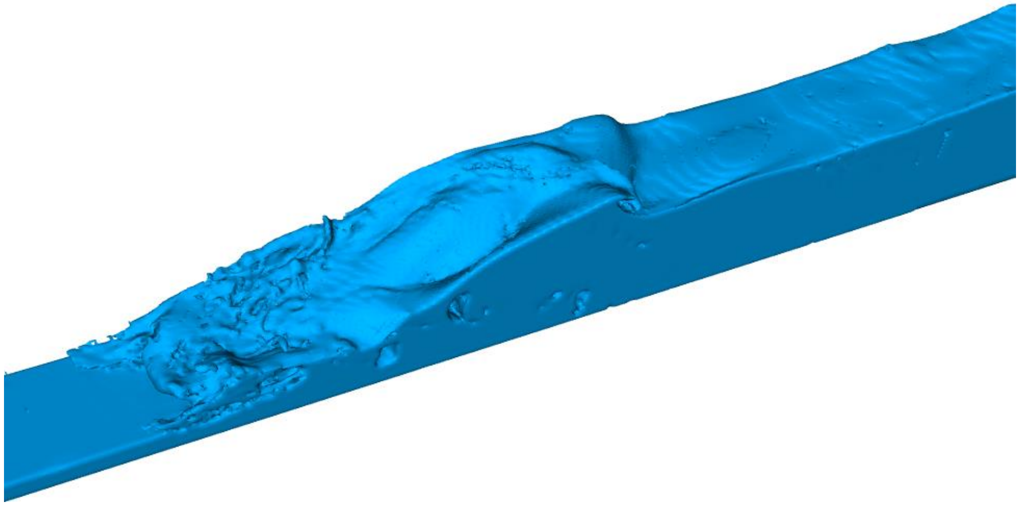
Comparison of the most frequent options for hydraulic engineering applications

RNG (renormalisation-group) $k-\varepsilon$



Free Surface Modelling

Volume Of Fluid (VOF) Method → Definition of a Fraction of Fluid function (F) for each cell



- F=1: Cell completely filled with water
- F=0: Empty cell
- Cells with F values between 0 and 1 contain free surface
- Advection method to track the evolution of the free surface
- Free surface refinement routines

Meshing Information

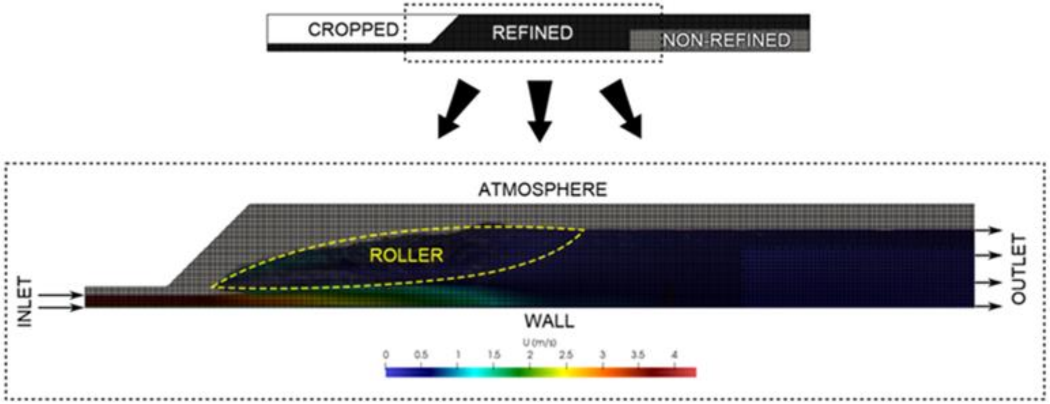
Structured rectangular 3D meshes → Hexahedral cells → Cell size

Mesh convergence analysis (ASME criterion)

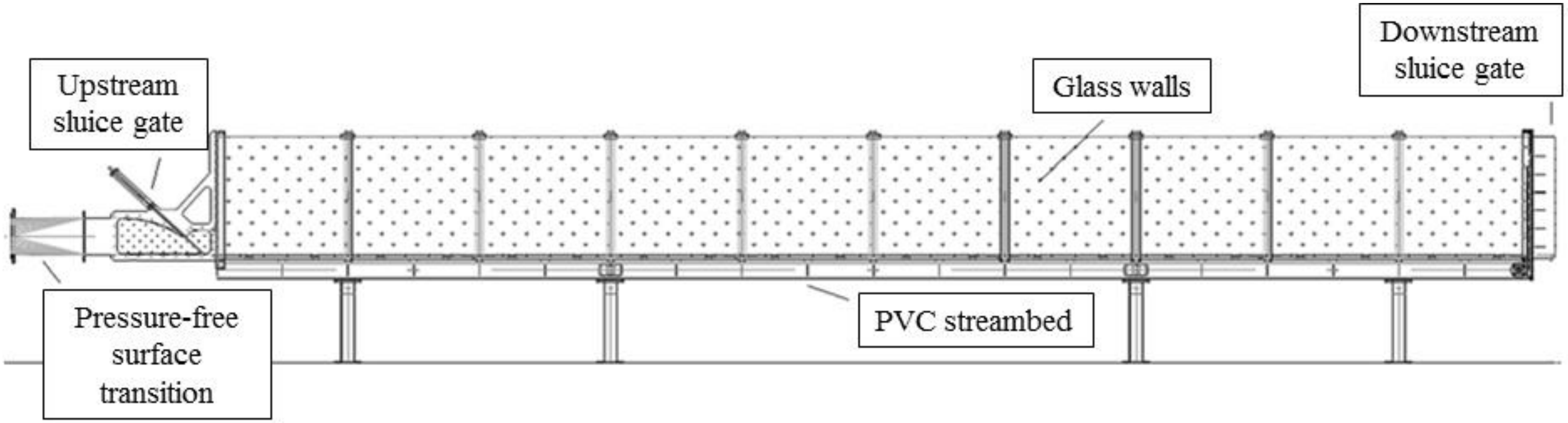
Independence of the results from the imposed cell size. Quantify the uncertainty

- Cropping of domain without flow
- Cell refinement of regions with complex geometry/potentially higher flow gradients

Increase efficiency without affecting the results



3. PHYSICAL MODELLING



Physical Models Design

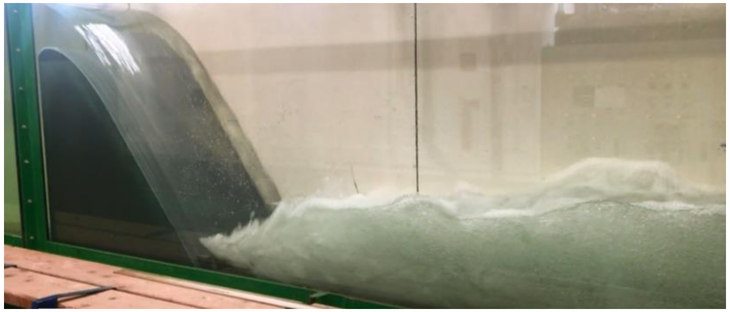
CHJ →

$Fr_1 = 6.0$
$Re_1 = 210{,}000$
$y_1/b = 0.17$

USBR II →

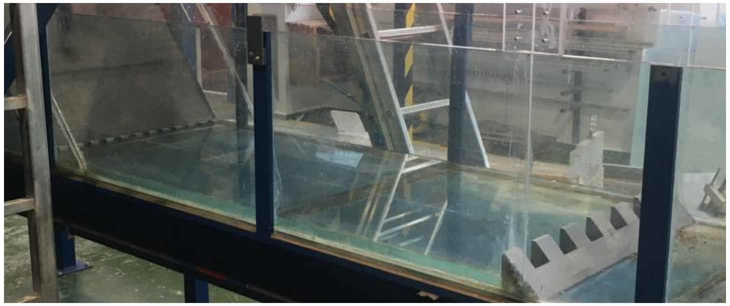
TUWien →

$Fr_1 = 5.0$
$Re_1 = 233{,}000$
$y_1/b = 0.12$



UPV →

$Fr_1 = 9.0$
$Re_1 = 147{,}000$
$y_1/b = 0.04$



Instrumentation

FREE SURFACE PROFILE

Digital Image Processing (DIP)

Time-of-flight Camera (LIDAR)

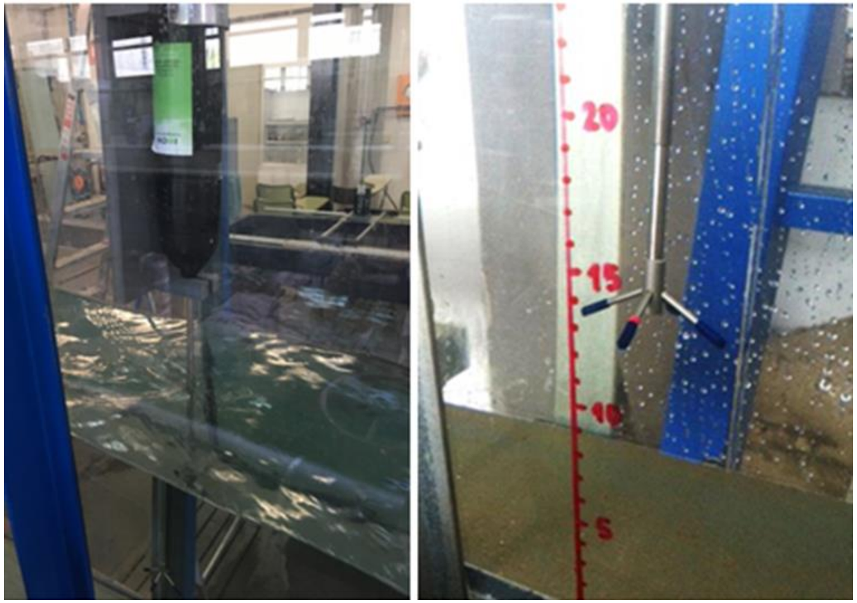
Instrumentation

VELOCITY DISTRIBUTION

Pitot Tube

Turbine Velocity Meter

Acoustic Doppler Velocimeter (ADV)



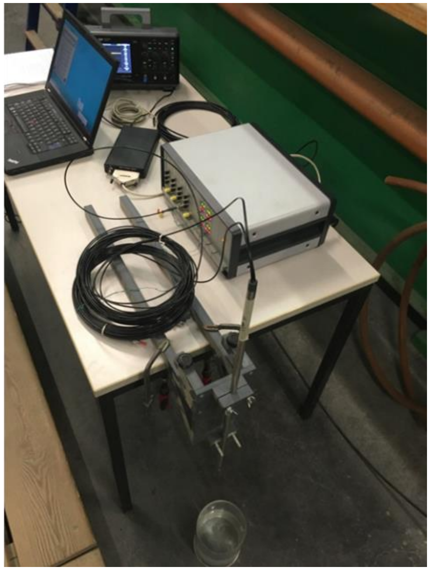
Instrumentation

PRESSURE DISTRIBUTION

Pressure Transmitters

VOID FRACTION DISTRIBUTION

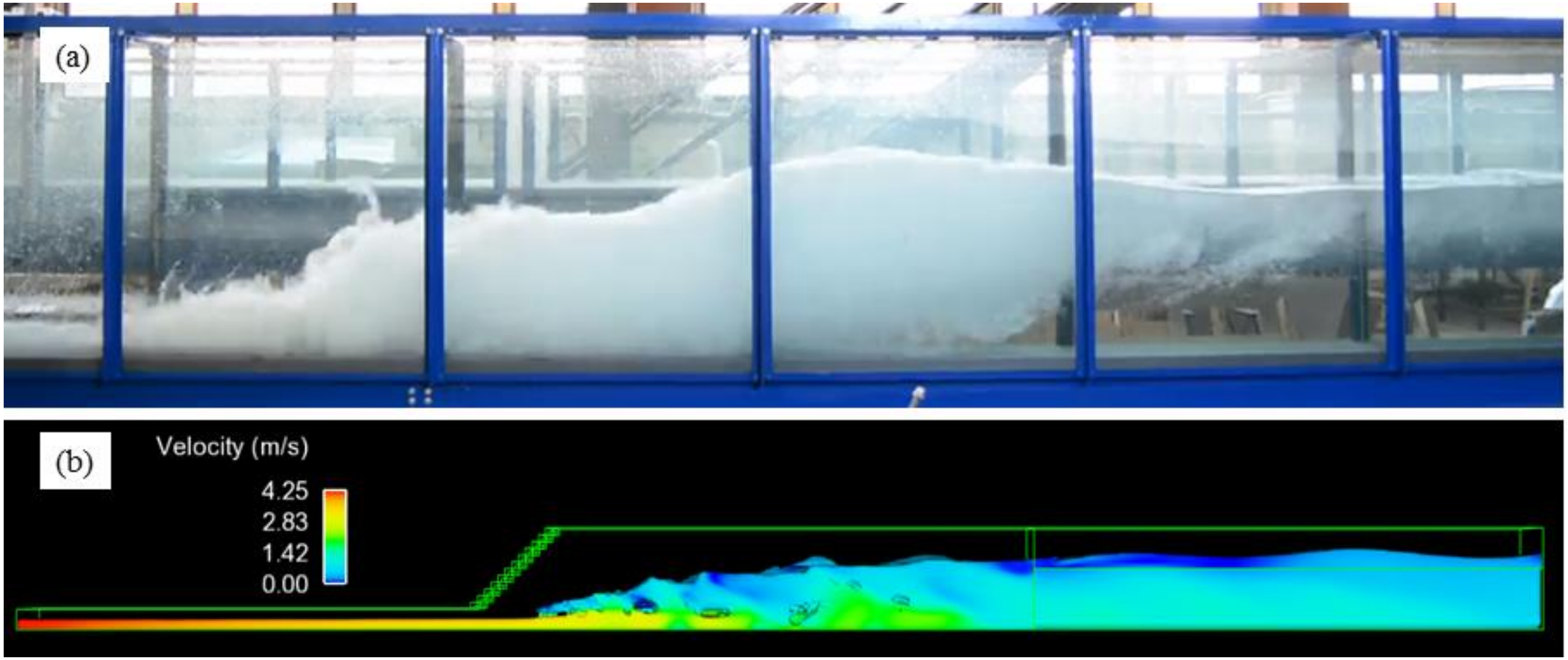
Optical Fibre Probe



Experimental Campaign

Hydraulic Jump Feature	Instrumentation	Classical Hydraulic Jump	USBR II stilling basin (TUWien)	USBR II stilling basin (UPV)
Free surface profile	Digital Image Processing	x	x	
	Ultrasound distance meter	x		
	Limnimeters	x	x	x
	LIDAR			x
Velocity distribution	Pitot tube	x		x
	Acoustic Doppler Velocimeter (ADV)	x		
	Turbine velocity meter		x	
Pressure distribution	Pressure transmitters	x	x	
Void fraction distribution	Optical fibre probe		x	

4. CLASSICAL HYDRAULIC JUMP

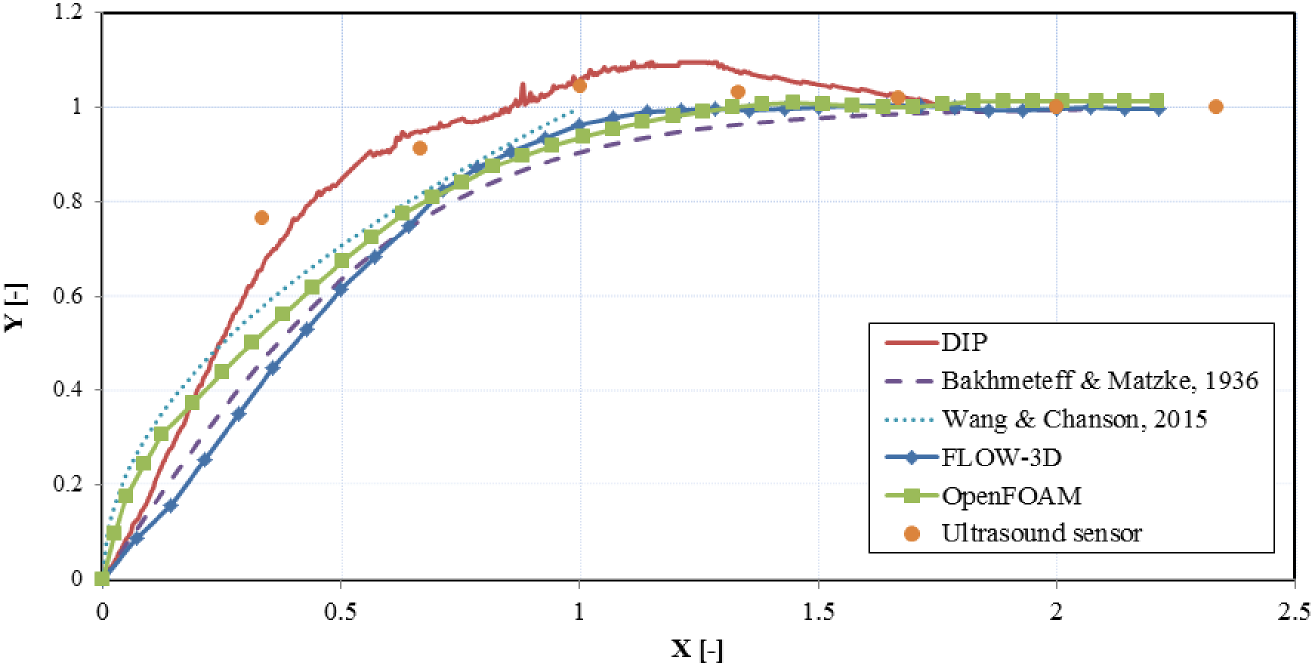


Free Surface Profile

Dimensionless Free Surface Profile

$$X = \frac{x - x_0}{L_r}$$

$$Y = \frac{y - y_1}{y_2 - y_1}$$



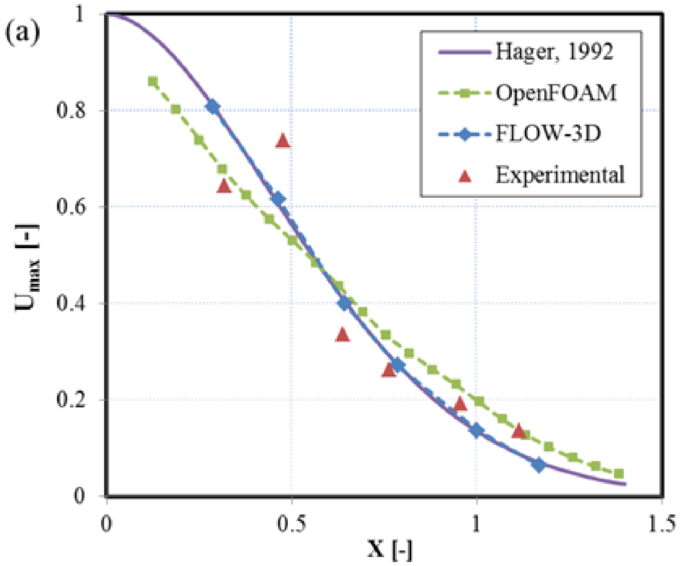
R^2

	DIP	**Bakhmeteff & Matzke** [39]	**Wang & Chanson** [8]
FLOW-3D®	0.943	0.991	0.956
OpenFOAM	0.961	0.996	0.996

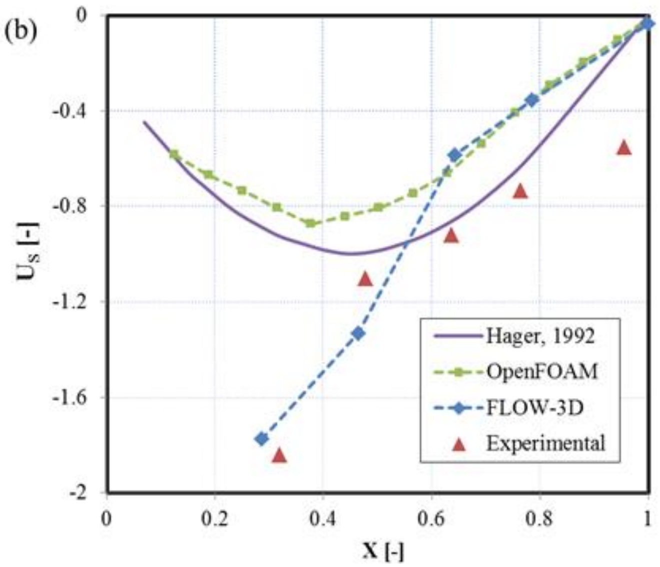
Velocity Profiles

Velocity Distribution in the Roller Region

Maximum Forward Velocity Decay



Maximum Backwards Velocity



$$U_{max} = \frac{u_{max} - u_2}{u_1 - u_2}$$

$$U_S = \frac{u_S}{u_2}$$

R^2

	Hager, 1992
FLOW-3D®	0.999
OpenFOAM	0.992

	Hager, 1992
FLOW-3D®	0.618
OpenFOAM	0.928

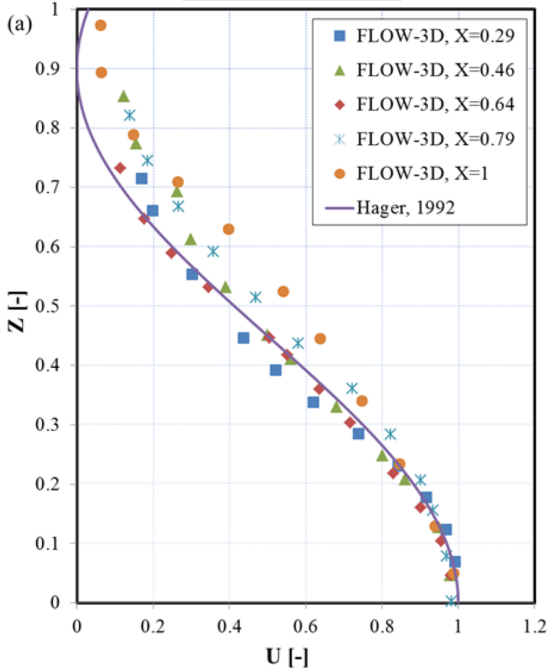
Velocity Profiles

Velocity Distribution in the Roller Region

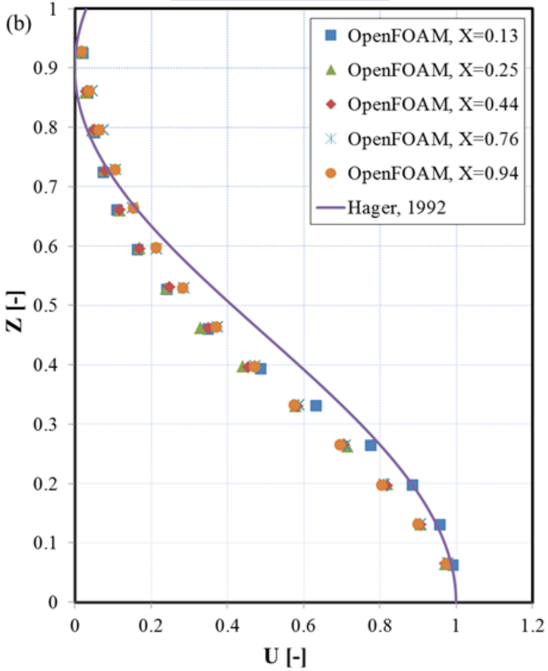
Streamwise Velocity Vertical Profiles

R^2	Hager, 1992
FLOW-3D®	0.988
OpenFOAM	0.978
Experimental	0.962

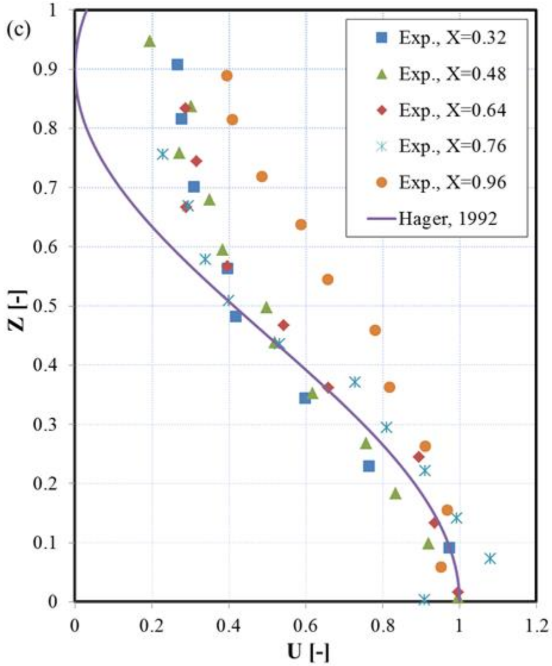
FLOW-3D



OpenFOAM

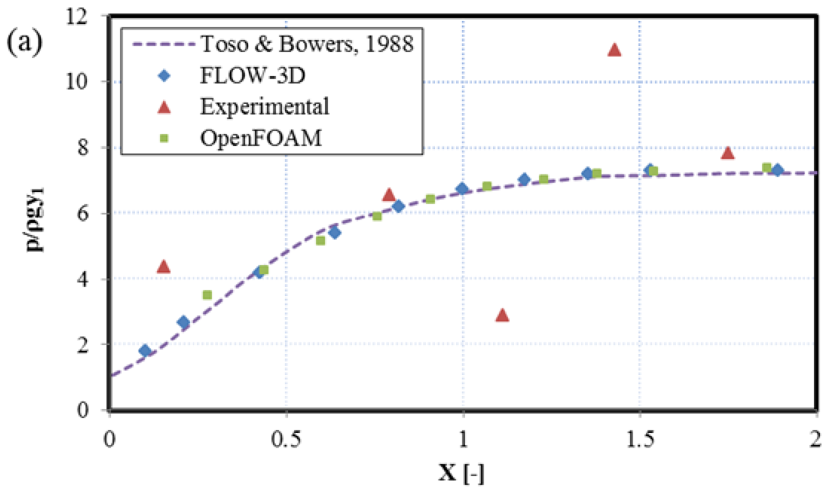


Experimental

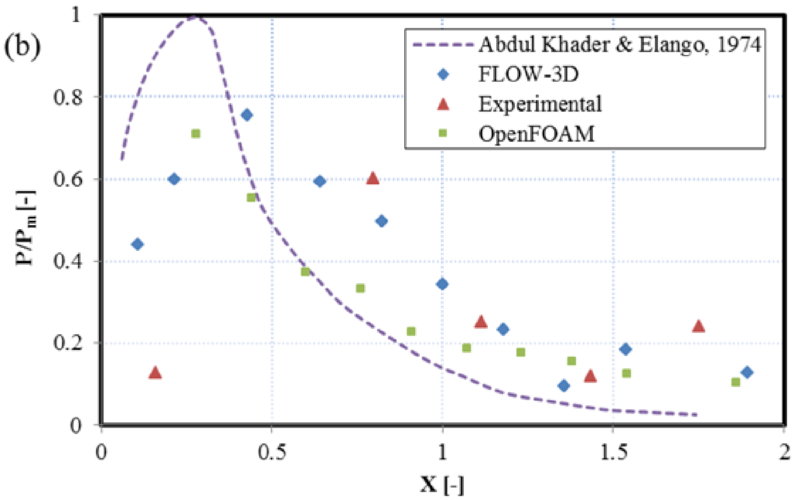


Streambed Pressures

Average relative pressures along the longitudinal axis



Pressure Fluctuations

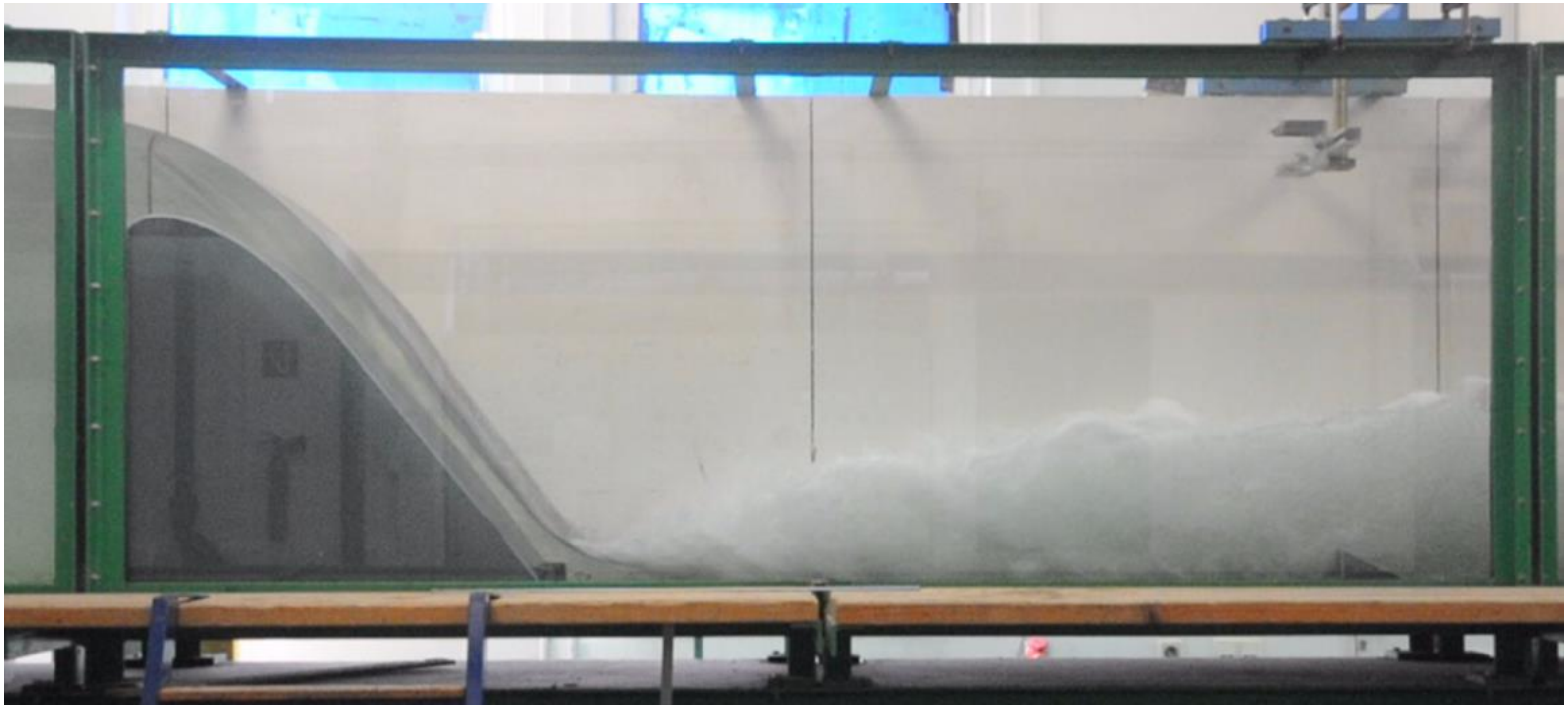


R^2

	Toso & Bowers, 1988
FLOW-3D®	0.995
OpenFOAM	0.958

	Peak location
Toso & Bowers, 1988	0.40
Abdul Khader & Elango, 1974	0.30-0.35

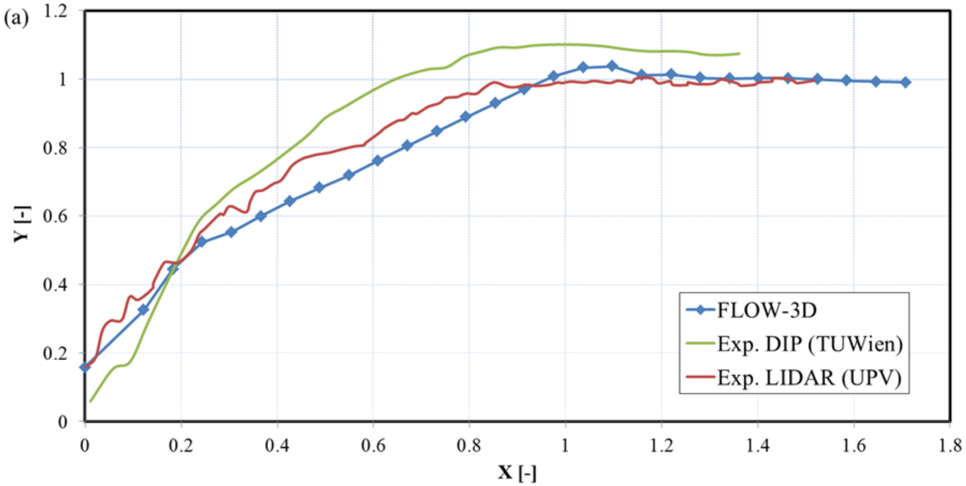
5. USBR II STILLING BASIN

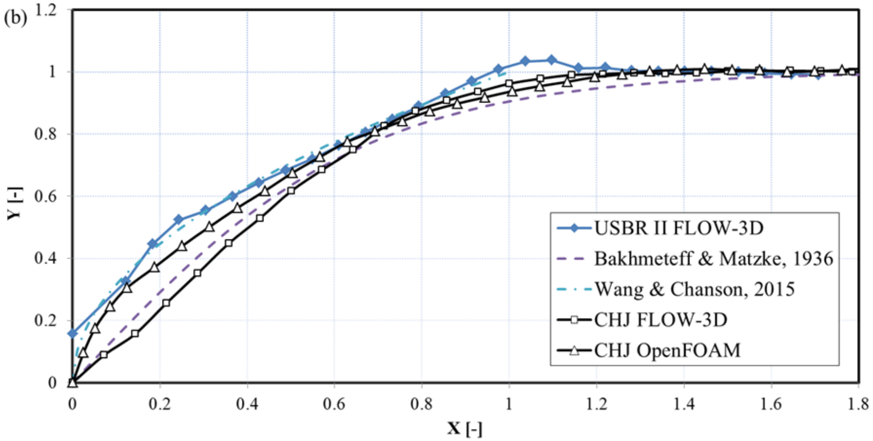


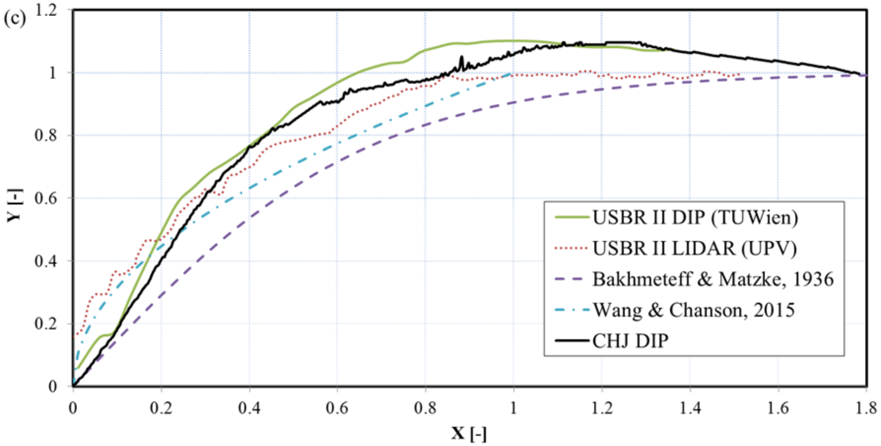
Free Surface Profile

Dimensionless Free Surface Profile

$$X = \frac{x - x_0}{L_r} \qquad Y = \frac{y - y_1}{y_2 - y_1}$$







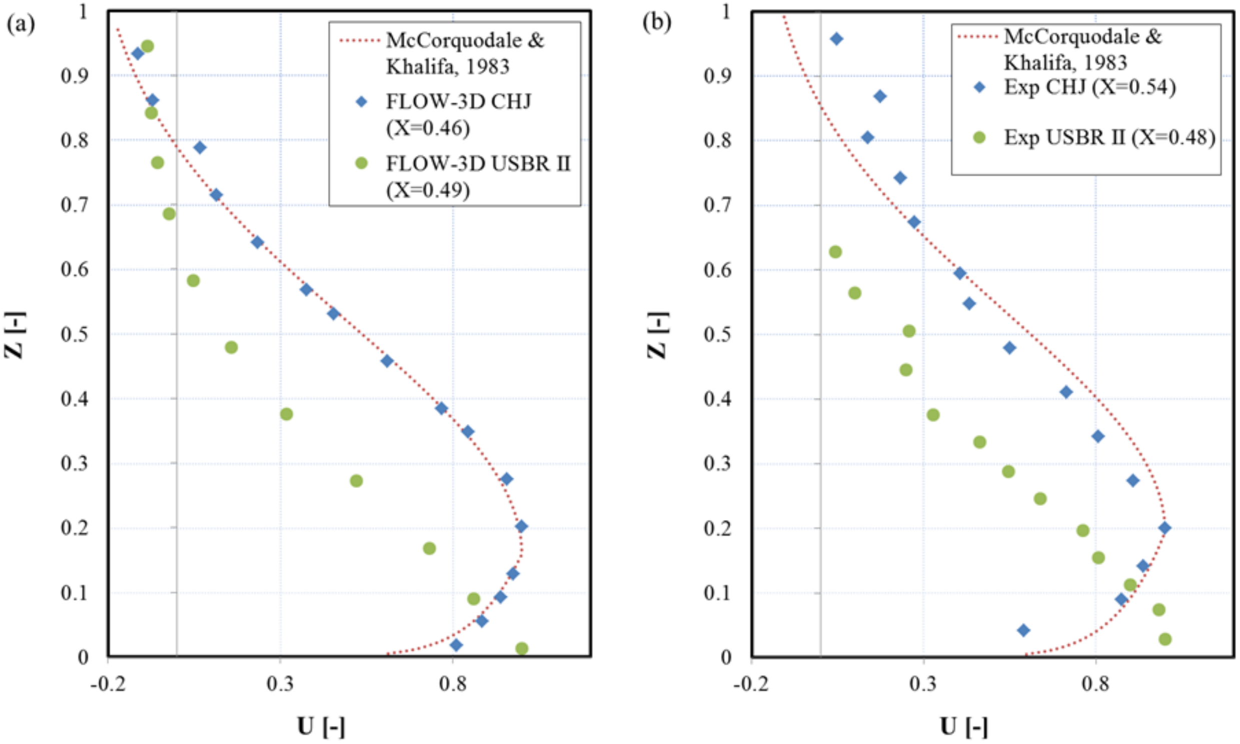
Velocity Profiles

Velocity Distribution in the Roller Region

Numerical and physical model profiles comparison with the analytical expression by McCorquodale & Khalifa (1983) for the mean velocity distribution within a classical hydraulic jump roller

Significant differences

Streamwise velocity vertical profiles along the CHJ longitudinal axis

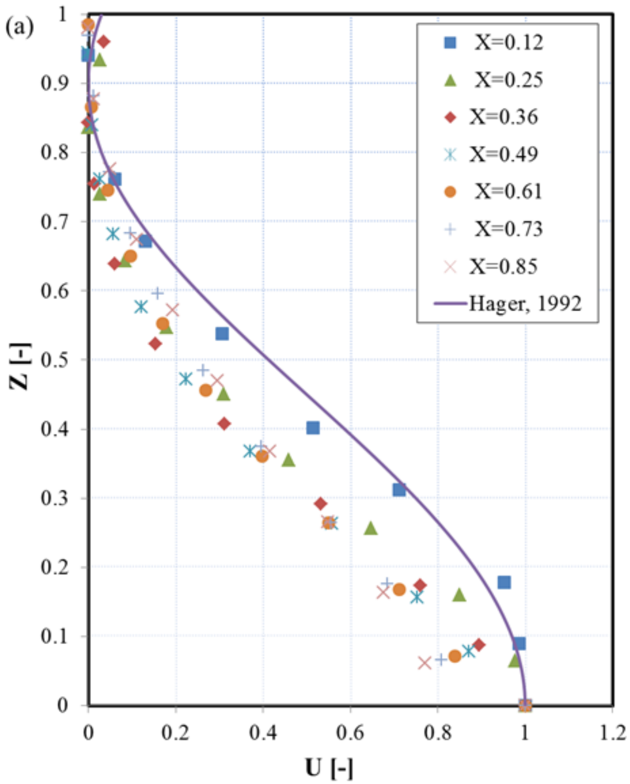


Velocity Profiles

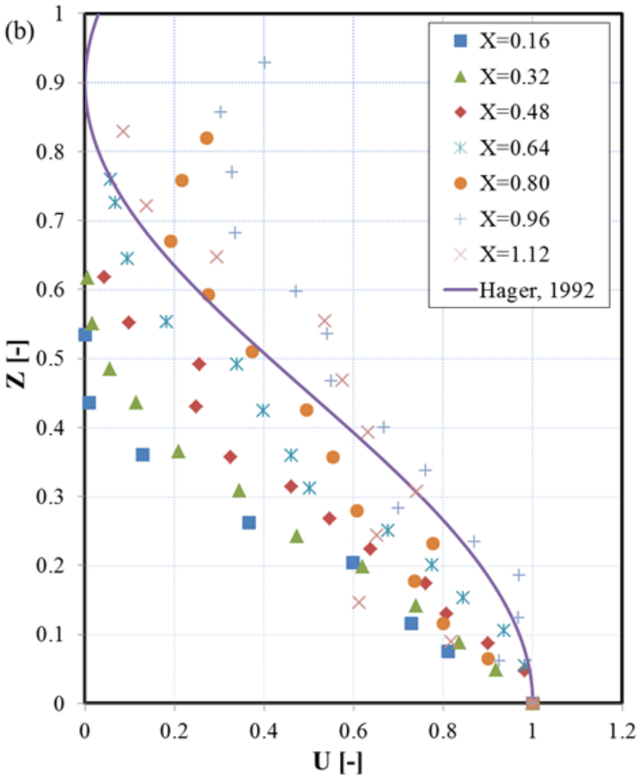
Velocity Distribution in the Roller Region

Streamwise Velocity Vertical Profiles

Numerical



Experimental



General good agreement in the numerical model

Instrumentation limitations in the aerated region for the physical model

Influence of the energy dissipation devices: Steeper velocity decay than in the CHJ for both models

Void Fraction Distribution

Formulation

Murzyn et al., 2005

Lower Region:

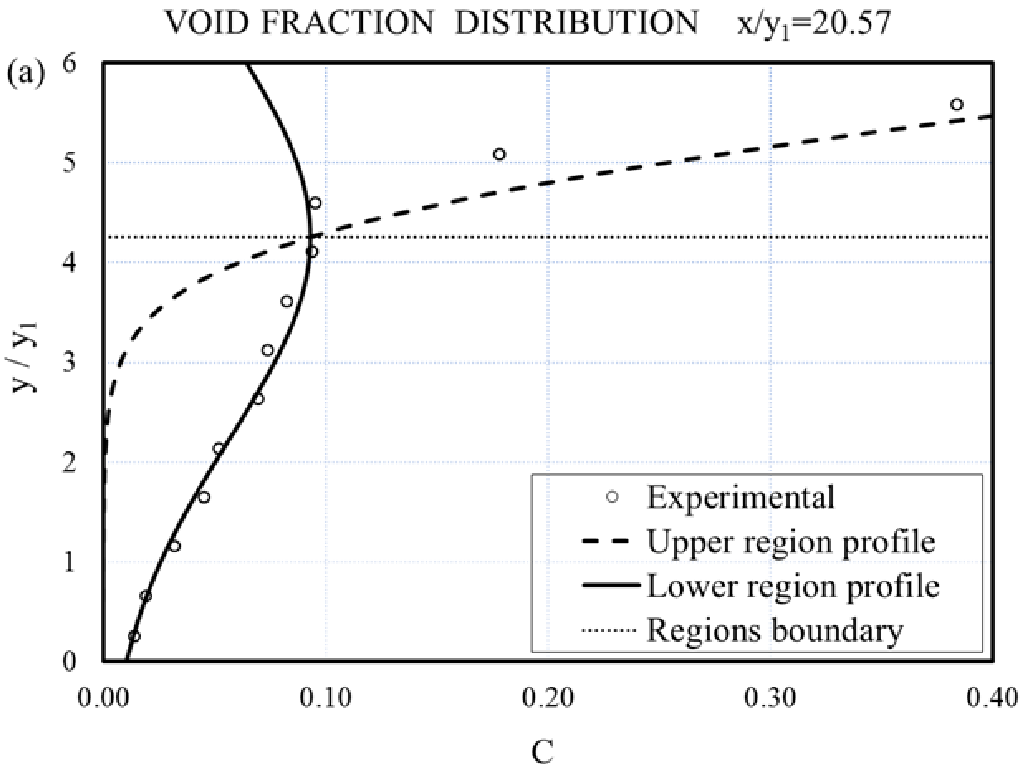
$$C = C_{max} exp\left[-\frac{1}{4}\frac{u_1}{D}\frac{(\xi - \xi_{Cmax})^2}{x}\right]$$

Upper Region:

$$C = \frac{1}{2}\left[1 + erf\left(\frac{\xi - \xi_{C50}}{2\sqrt{Dx/u_1}}\right)\right]$$

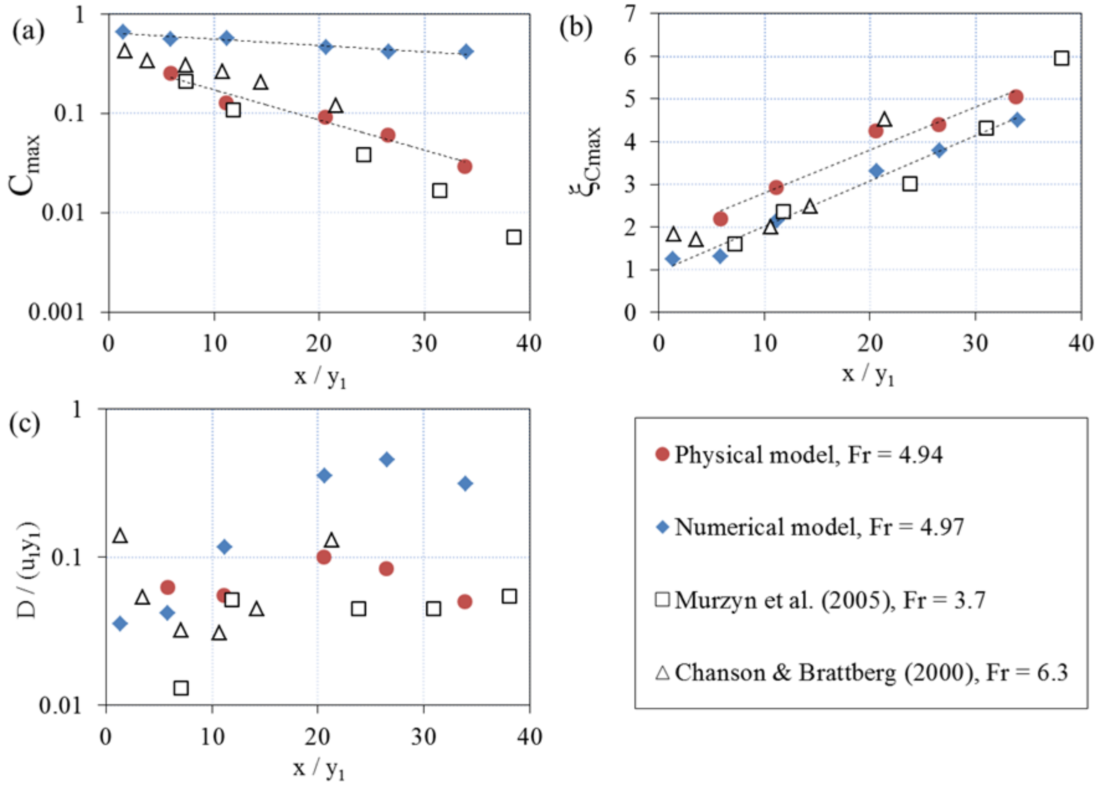
Additional condition

$$\xi_{Cmax} = \xi_*$$



Void Fraction Distribution

Lower Region Analysis



Adjustment proposed in the bibliography:

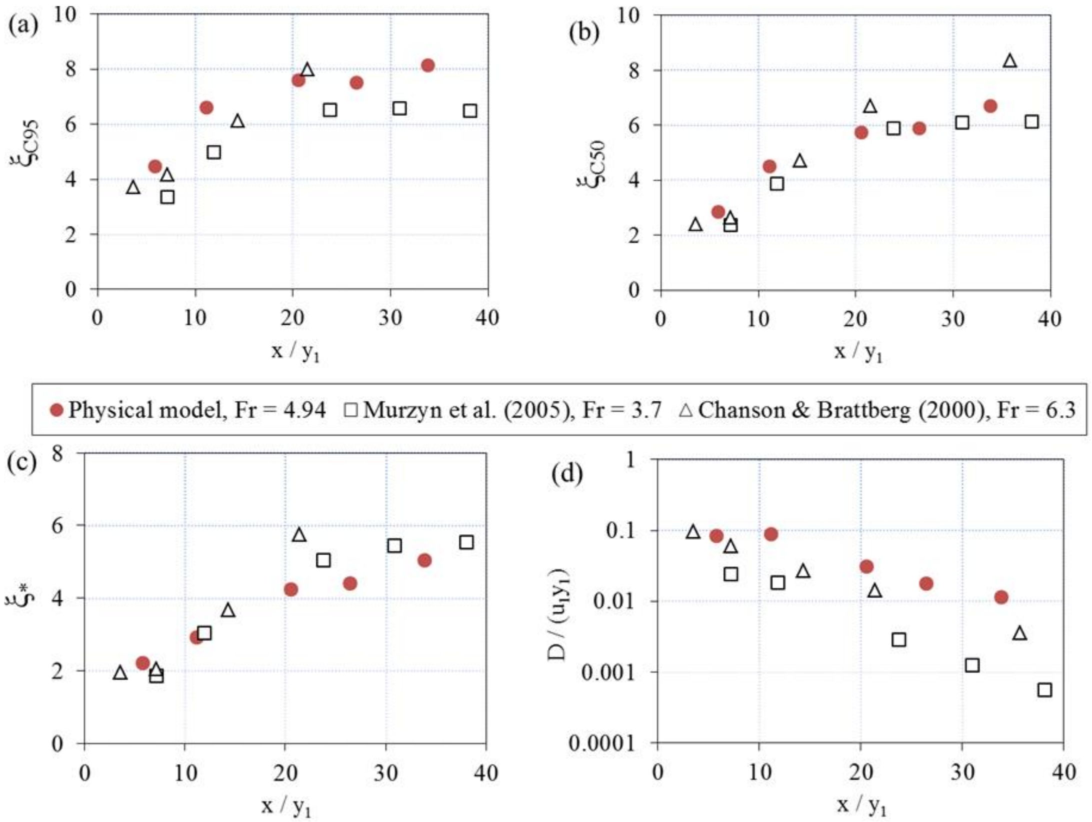
$$C_{max} = \alpha \times exp(-Ax/y_1)$$

Larger ξ_{Cmax} values with increasing distances to the hydraulic jump toe. Estimated gradient in good agreement with bibliographic information

Significant dispersion of the diffusion coefficient values in accordance with the bibliography

Void Fraction Distribution

Upper Region Analysis



Increasing ξ_*, ξ_{C95}, and ξ_{C50}values from the hydraulic jump toe position. Rate of increase higher in sections closer to the toe

Widening of the upper region along the hydraulic jump longitudinal axis

Decreasing trend of the diffusion coefficient values in accordance with the bibliography

6. CONCLUSIONS

Conclusions

Double Modelling Approach

Complementary nature

Numerical modelling

- Model **different configurations** and measure **complex variables** in hydraulic phenomena
- **Calibration and validation** through physical modelling. **Limitations** to accurately reproduce some internal features
- Codes **benchmarking** importance

Physical modelling

- Crucial to model **complex hydraulic phenomena**
- Performance of **traditional instrumentation** and potential of **innovative techniques**
- Available **resources** and appropriate **extrapolation** to prototype scale

Classical Hydraulic Jump

- Complexity of the phenomenon. **Contributions** to current knowledge
- **Complete study** of the hydraulic jump. Interaction of the different processes involved
- Multiple features and techniques approached under a **unique study**

Typified USBR II Stilling Basin

- Relatively **reduced bibliographic information** despite its practical interest
- Step forward to build an **extended database** for the study of typified stilling basins
- Influence of the **energy dissipation devices** on the hydraulic jump properties

Numerical and Physical Modelling Approaches to the Study of the Hydraulic Jump and its Application in Large-Dam Stilling Basins

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