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OpenFoam applications in hydraulic structures at University of Coimbra

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Introduction Applications: 2D Gully 3DGully GullyReverseFlow Channel withCrossBeams Manhole SteppedSpillway Multifunctional Artificial Reef Conclusions

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Numerical simulations in hydraulic structures using VOFOR-2DV (Carvalho 2002 and Carvalho et al., 2008)

- ➔ code constructed based on Nasa-VOF2D (Torrey et al., 1985)
- ➔ 2DV Navier-Stokes equations solved by explicit methods like **NWSF** (Normalized Variable and Space Formulation) (Darwish & Moukalled 1994),
- ➔ a refined Volume-Of-Fluid (**VOF**) (Hirt & Nichols 1981),
- ➔ the Fractional Area-Volume Obstacle Representation (**FAVOR**) method (Hirt & Sicilian 1985)

IN-HOUSE
Carvalho & Amador, 2008

PIV

IN-HOUSE and PHOTO
Carvalho 2002

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using **VOFOR-2DV** (Carvalho 2002 and Carvalho et al., 2008)

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Discharge coefficient
 Teoretical $\mu_v = 0,385$.
 Lencastre $\mu_v = 0,393$.
 Calculated from simulation:
 $h = 0,1 \text{ m} = 0,15 - 0,05$
 $q = 0,099 \text{ m}^3/\text{s}/\text{m}$ de largura
 $q = \mu_v \sqrt{2g} h^{3/2}$. $\mu_v = 0,3886$

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→ **OpenFOAM™ Toolbox** (OpenFOAM 2011) with unstructured meshes using “blockMesh” and the “solver” **interFOAM**, considering VOF method with two fluids and the solvers **PISO** (Pressure Implicit Splitting of Operators) or **PIMPLE** which results from merging PISO and SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) (OpenFOAM 2011).

```

graph TD
    A["Initial Setup:  
- Geometry  
- Boundary Conditions  
- Initial Conditions  
- Mesh Size"] --> B[InterFoam]
    B --> C["Results :  
- Free Surface Level  
- Stream Lines  
- Velocity and Pressure profiles"]
  
```

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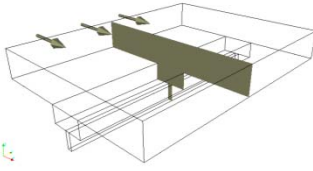
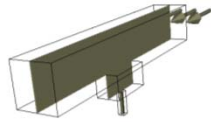
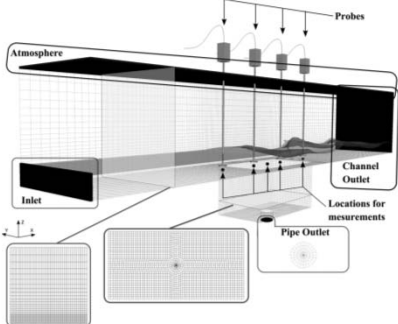
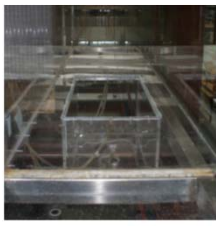
Starting with OpenFOAM

1. *Gully 2D (Martins et al. 2012)*
2. *Gully 3D (Martins et al. 2014)*
3. *Gully with reverse flow (Lopes et al. 2012) and both (Carvalho et al. 2012; Lopes et al. 2014, Leandro et al. 2014)*
4. *Channel with cross beams (Gogolin et al. 2013)*
5. *(Multifunctional artificial reef*
6. *Manhole* Not yet published
7. *Stepped spillway)*
8. *Jet Plunge Pools (Lopes et al. 2015)*

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2D Gully, DEC-UC 2011 **3D Gully, DEC-UC 2011/2**

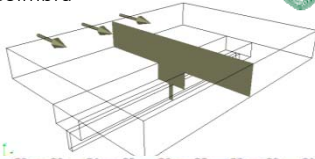
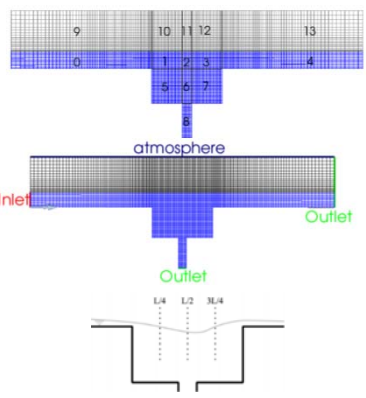
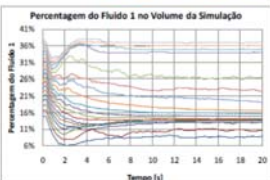
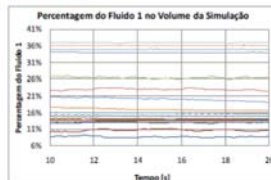
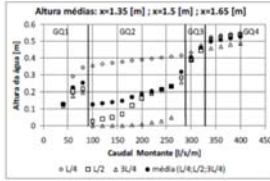
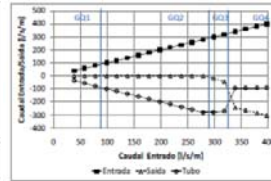






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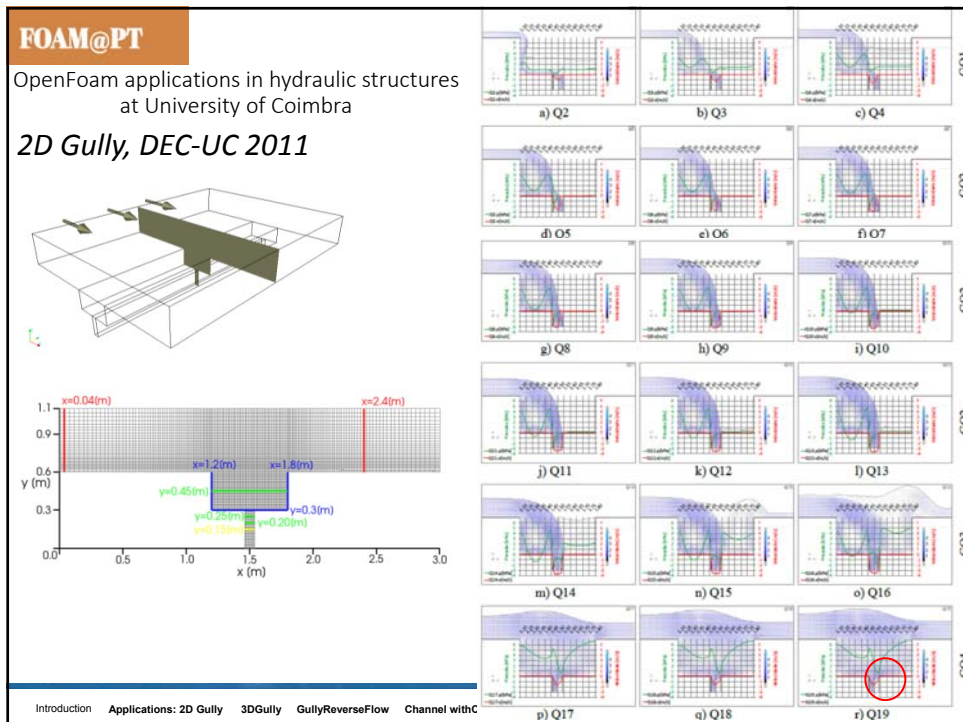
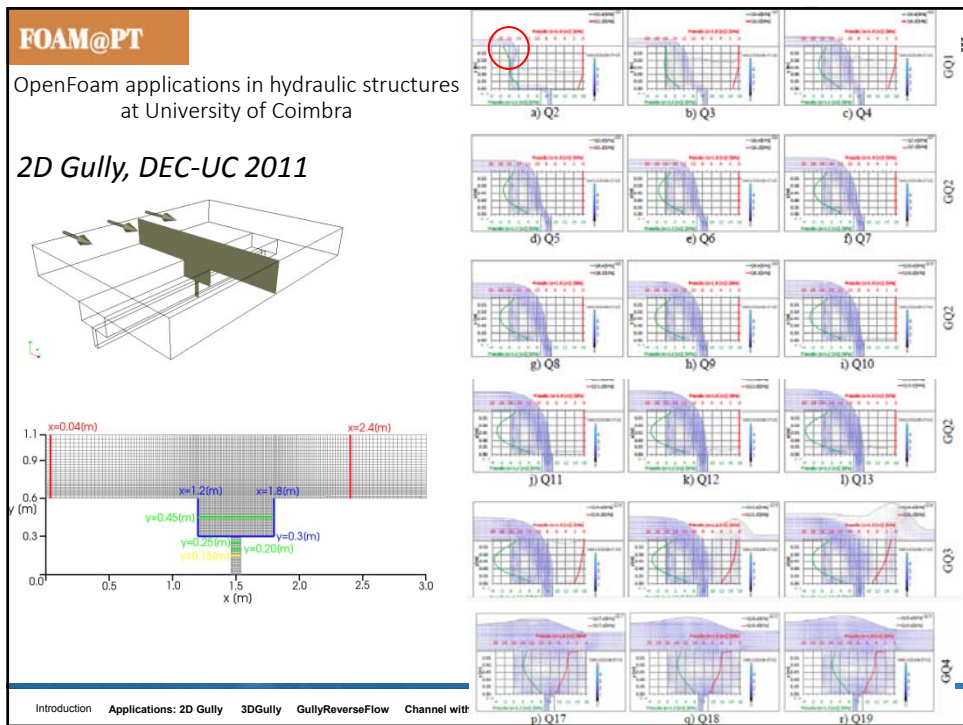
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2D Gully, DEC-UC 2011

OpenFOAM Toolbox simulations
 (un)structured mesh with 180 x 60 x 1 cells defined by 70 vertices and 9 blocks in blockMeshDict file

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2D Gully, DEC-UC 2011

Perfis de velocidade em $x=0.04$ [m], $x=2.4$ [m] e $y=0.15$ [m]

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3D Gully, DEC-UC 2011/2

Units	Discharge [m³/s]	L/4 [m]	L/2 [m]	3L/4 [m]
Experimental	0.005 0.01 0.02 0.05	0.390 0.471 0.631 0.649	0.393 0.475 0.624 0.645	0.392 0.478 0.636 0.672
Numerical	0.005 0.01 0.02 0.05	0.376 0.569 0.629 0.634	0.368 0.568 0.606 0.623	0.372 0.568 0.614 0.646
Error	0.005 0.01 0.02 0.05	2.1% 20.8% 5.5% 2.5%	5.5% 19.5% 2.8% 3.5%	6.2% 19.0% 3.5% 3.6%
RMSD				0.050
NRMSD				18%
CV(RMSD)				9%

$$RMSD = \sqrt{\frac{\sum_{i=1}^n (x_i - y_i)^2}{n}}$$

$$NRMSD = \frac{RMSD}{|\max(x_i) - \min(x_i)|}$$

$$CV(RMSD) = \frac{RMSD}{\bar{x}}$$

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3D Gully, DEC-UC 2011/2

Label	Q0.5	Q1	Q2	Q3	Q4	Q5	Q6	Discharge	Q6	Q5	Q4	Q3	Q2	Q1	Q0.5	
Q_{in} [m ³ /s]	0.005	0.010	0.020	0.030	0.040	0.050	0.060	Numerical Data	C_{in}	0.16	0.19	0.23	0.33	0.50	0.95	0.90
h_{in} [m]	0.017	0.027	0.041	0.053	0.065	0.075	0.083	Experimental Data	C_{in}	1.36	1.45	1.51	1.77	2.04	2.50	1.53
u_{in} [m/s]	0.58	0.75	0.97	1.12	1.24	1.34	1.42		C_{in}	0.22	0.25	0.29	0.4	0.56	1.00	0.99
									C_{in}	1.81	1.86	1.91	2.08	2.27	2.68	1.67

$C = a h_{in}^b$

Variable	C_{in}	C_{on}	C_{we}	C_{an}	
Power Law	a	0.75	0.35	0.0075	-1.35
Coefficients	b	-0.35	-0.55	0.0035	-1.55
Fitness	R^2	0.99	1.00	1.00	1.00

(a)

(b)

Legend:

- Numerical Inlet
- Numerical Pipe Outlet
- ▲— Numerical Channel Outlet
- Experimental Inlet
- Experimental Pipe Outlet
- ▲— Experimental Channel Outlet
- Error Inlet
- Error Pipe Outlet
- ▲ Error Channel Outlet

Introduction

Applications: 2D Gully
3DGully
GullyReverseFlow
Channel withCrossBeams
Manhole
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3D Gully, DEC-UC 2011/2

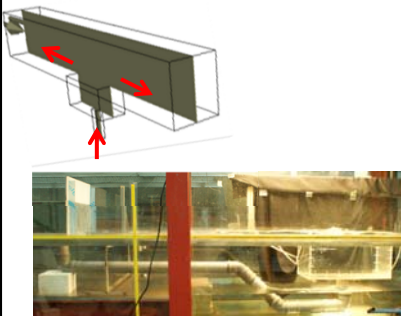
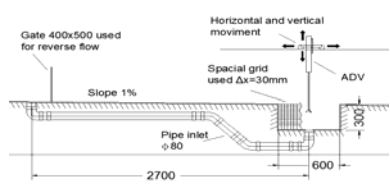
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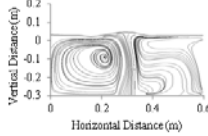
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3D Gully-reverse flow, DEC-UC

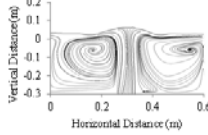



Introduction Applications: 2D Gully 3DGully GullyReverseFlow Chann

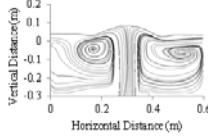
Q4



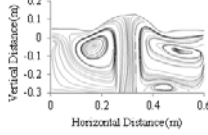
Q5



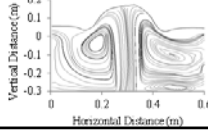
Q6

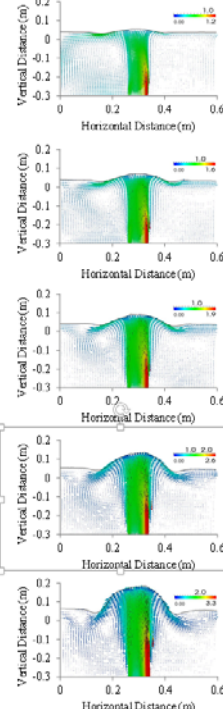


Q8*



Q10*

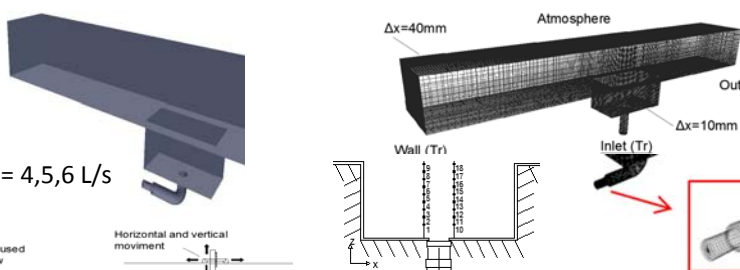
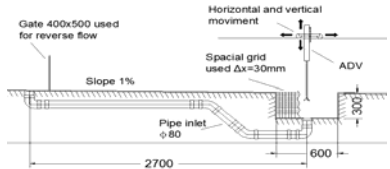




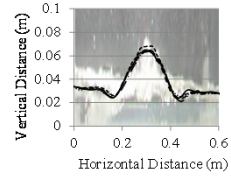
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3D Gully-reverse flow, DEC-UC 2011/2

$Q_{inlet} = 4,5,6 \text{ L/s}$

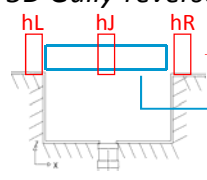
Q5 - different set of LES parameters (C_ϵ and C_k)
Calculating water depth by films using Roque (2011)



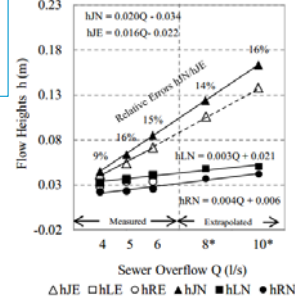
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3D Gully-reverse flow, DEC-UC 2011/2



H-Q relations



Flow Heights h (m)

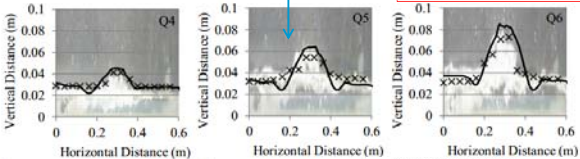
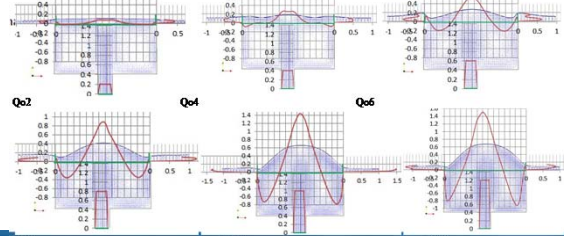
Sewer Overflow Q (l/s)

$h_{LN} = 0.020Q - 0.034$
 $h_{JE} = 0.016Q - 0.025$
 $h_{LN} = 0.003Q + 0.021$
 $h_{RN} = 0.004Q + 0.006$

Δh_{JE} $\square h_{LE}$ $\square h_{RE}$ $\blacktriangle h_{LN}$ $\blacksquare h_{LN}$ $\bullet h_{RN}$

FLOW OUT OFF THE BDS
 To map the flow, velocity and pressure /several locations

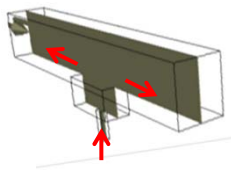
- symmetry was verified in all flow discharges from BDS
- For larger flows $Q > Q_{o6}$ negative velocities occurs near the top of the left and right walls

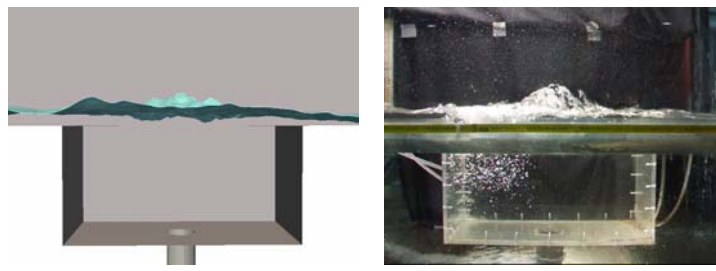
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3D Gully-reverse flow, DEC-UC 2011/2



Air-Entrainment - What is missing to model it?



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3D Gully-reverse flow, DEC-UC 2011/2

The figure illustrates the 3D gully-reverse flow simulation. On the left, three vertical velocity profiles are shown for flow rates Q4, Q16, and Q18. Below them, a plan view shows the gully layout with regions R1, R2, and R3. On the right, two side-view diagrams show the flow path and velocity profiles. The left diagram shows a single profile with velocity V_0 and height s . The right diagram shows multiple profiles with velocities V_0 , V^* , and V^{**} , and heights s , h_m , h_0 , and h_1 . The horizontal distance is labeled DM, and the vertical axis is y.

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Channel with Cross beams DEC-UC 2012/3

The figure shows the channel with cross beams simulation. On the left, a photograph of the physical model is shown. Below it, a 3D mesh of the channel with cross beams is displayed. In the center, a graph titled "Image data analysis" shows a plot of velocity u versus distance x . On the right, the "OpenFOAM™ Toolbox" is listed, including "blockMesh", "interFOAM", and "swak4Foam". Below that, "Numerical simulations" are detailed with a list of parameters and conditions.

OpenFOAM™ Toolbox,
 "blockMesh",
 "interFOAM" - VOF method with two fluids
 "swak4Foam" - groovyBC

Numerical simulations

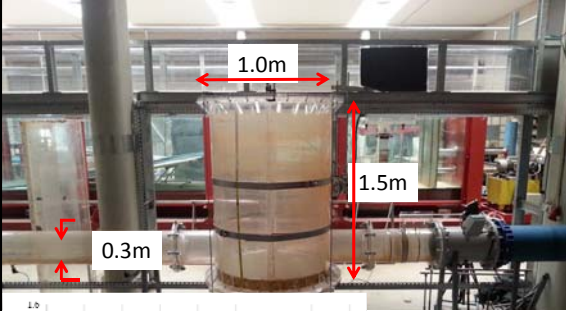
- mesh defined by 160 vertices and 45 blocks in blockMeshDict file;
- horizontal mesh $/g = (0.4905\ 0\ -9.3195)$;
- seven important patches were defined: inlet, outlet and atmosphere (patch type) and lateralWall, leftWall, lowerWall, baffleWall (Wall type) ;
- $u_{in} = Q_{in} / (0.5h_{in})$;
- initial condition imposed was the presence of water under $z < h$, $t = 0$ s;
- water depth in function of time was extracted on the same places also by an in-house Matlab® code.

b1) Configuration 2: $a = 0.05$ m, $L = 1.0$ m;
 $Q = 84$ l/s, $t = 20$ s and b2): Configuration 4
 $a = 0.1$ m, $L = 2.0$ m for $Q = 59$ l/s $t = 20$ s)
 b3): Configuration $a = 0.1$ m, $L = 1.0$ m for
 $Q = 59$ l/s $t = 20$ s).

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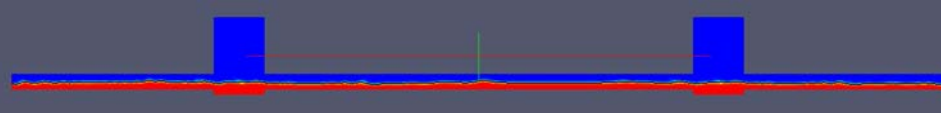
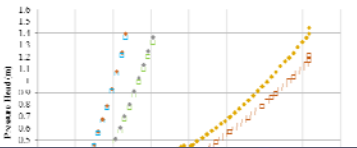
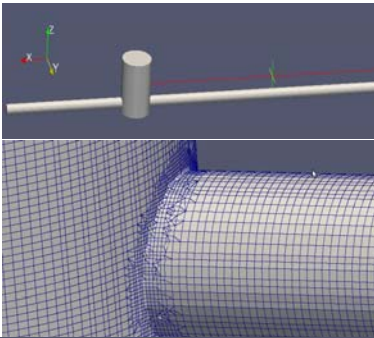
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ManholeDEC-UC 2015



OpenFOAM™ Toolbox,

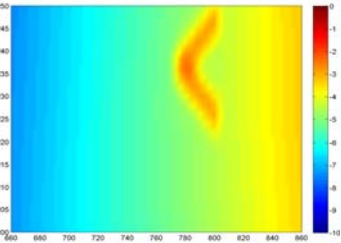
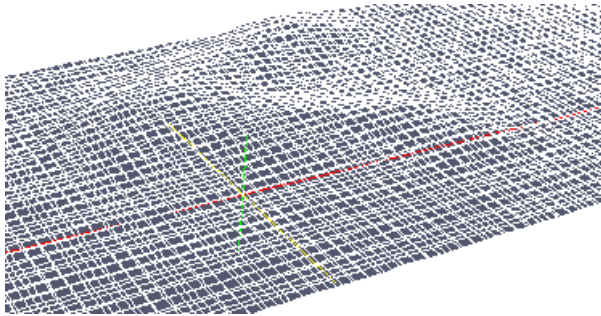
- SnappyHexMesh
- "interFOAM" - VOF method with two fluids
- "swak4Foam" - groovyBC



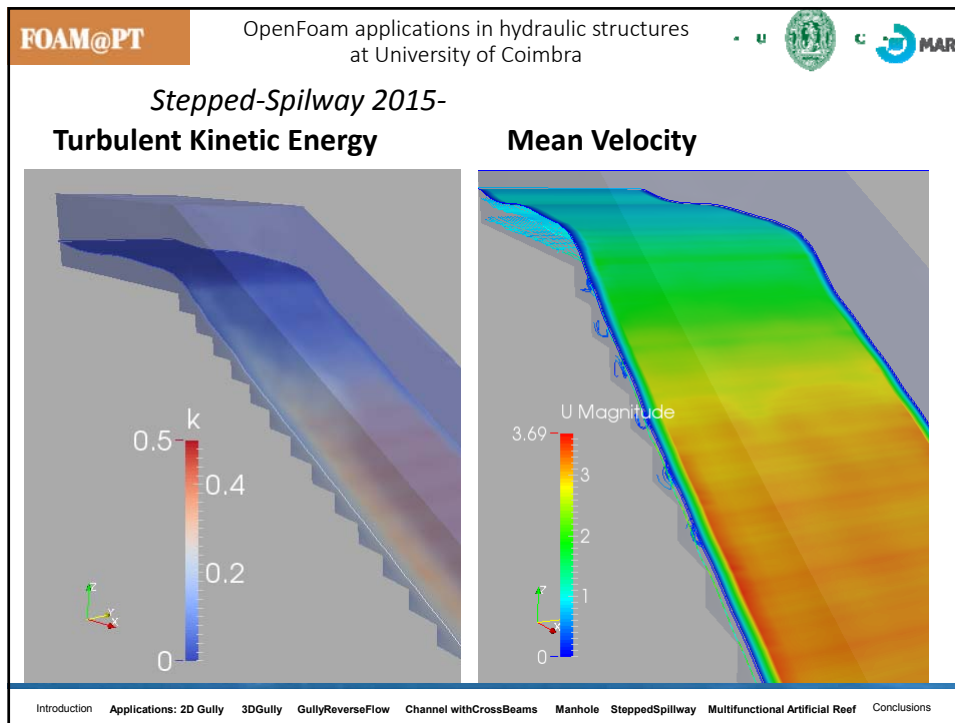
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Multi-functional Reef 2012-



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Conclusions:

We are using OpenFoam since 2011 in several successful cases in the aim of hydraulic structures applications

We are interested in implement a code for air-entrainment treatment

We are interested in developing tools or cooperate to be able to model water quality and sediment suspension as well as morphology very important in civil engineering applications

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