Numerical modelling of air entrainment

In hydraulic engineering

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Numerical modelling of air entrainment

- Develop a sub-grid model for air entrainment based on `interFoam`

(a) Stepped Spillway[1]

(b) Hydraulic Jump[2]

[1] Photo taken from [2]

[2] Photo taken from [1]

Numerical modelling of air entrainment

- Develop a sub-grid model for air entrainment based on `interFoam`
- Testing `airInterFoam`[4]

(a) Stepped Spillway[3]

(b) Hydraulic Jump[4]

[3] Photo taken from [2]

[4] Photo taken from [1]

Air entrainment in free surface flow

Turbulent forces > surface forces + buoyancy forces

$U_{jet,fs} > U_c$

$k > k_c$

State of the art

- Euler-Euler two fluid model

  `twoPhaseEulerFoam`
  - Numerical diffusion at the interface for stratified flow
- Interface capturing methods

  `interFoam`
  - Challenging to capture the processes at the surface
- Hybrid models

Subgrid models based on VoF

- Existing subgrid models based on VoF

Hirt (2003)[3] ⇒ FLOW-3D

Lopes (2017)[4] ⇒ `airInterFoam`

Due to lack of grid resolution, the amount of entrained air will be underestimated by the VoF method

https://openfoamwiki.net/index.php/Contrib/airInterFoam

interFoam

- Solves a single set of mass- and momentum equations

$$\nabla \boldsymbol{U} = 0$$

$$\frac{\partial \rho \boldsymbol{U}}{\partial t} + \nabla \cdot (\rho \boldsymbol{U}\boldsymbol{U}) = -\nabla p^* + \mathbf{g} \cdot \mathbf{x} \nabla \rho + \nabla \cdot \boldsymbol{\tau} + \mathbf{f}$$

- interFoam uses a VOF method with a compression term to capture the interface

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \boldsymbol{U}) + \nabla \cdot [\boldsymbol{U}_r \alpha (1-\alpha)] = 0$$

where $\boldsymbol{U}_r = \boldsymbol{U}_1 - \boldsymbol{U}_2$ is the relative velocity

airInterFoam

$$\frac{\partial \alpha_g}{\partial t} + \nabla \cdot (\mathbf{u}_g \alpha_g) - b \cdot \nabla \cdot (\nu_t \nabla \alpha_g) = S_g$$

airInterFoam

$$\frac{\partial \alpha_g}{\partial t} + \nabla \cdot (\mathbf{u}_g \alpha_g) - b \cdot \nabla \cdot (\nu_t \nabla \alpha_g) = S_g$$

$$S_g = \frac{a}{\phi_{ent}} \left\langle \frac{\partial \mathbf{u}_n}{\partial \mathbf{n}} \right\rangle \delta_{fs}$$

airInterFoam

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$$k > k_c, u > u_c$$

airInterFoam

$$\frac{\partial \alpha_g}{\partial t} + \nabla \cdot (\mathbf{u}_g \alpha_g) - b \cdot \nabla \cdot (\nu_t \nabla \alpha_g) = S_g$$

$$S_g = \frac{a}{\phi_{ent}} \left\langle \frac{\partial \mathbf{u}_n}{\partial \mathbf{n}} \right\rangle \delta_{fs}$$

$$k > k_c, u > u_c$$

$$\mathbf{u}_g = \mathbf{u}_l + \mathbf{u}_r$$

airInterFoam

- α_g is calculated
- α_l is calculated independent of α_g

$$\alpha_2 = 1 - \alpha_l - \alpha_g$$

airInterFoam

- Interacts with the α_l-equation by reducing the compression

```
fvc::flux
(
-fvc::flux(-phir, alpha2, alpharScheme),
alpha1,
alpharScheme
)
```

Test cases

- Stepped spillway
- Hydraulic jump

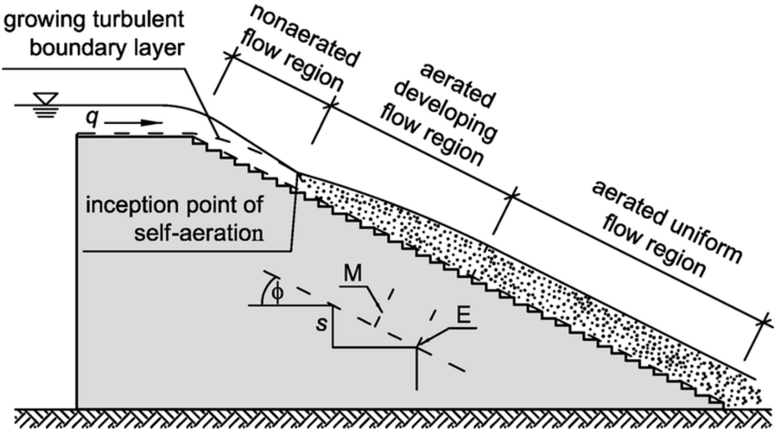
(a) Stepped Spillway[5]

(b) Hydraulic Jump[6]

[5] Photo taken from [2]

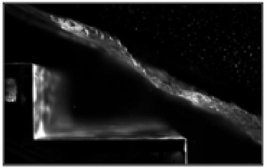
[6] Photo taken from [1]

Stepped Spillway

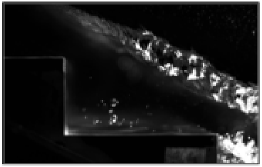


Sketch taken from [6]

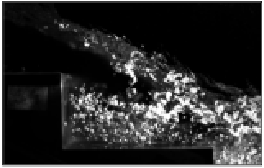
Stepped Spillway



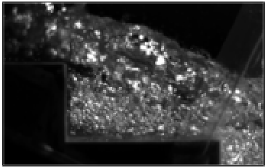
(a) Step 3



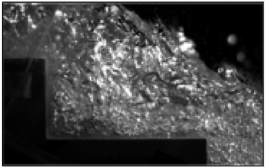
(b) Step 4



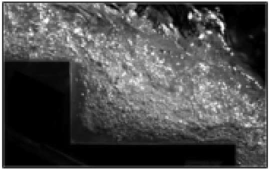
(c) Step 5 (IP)



(d) Step 6



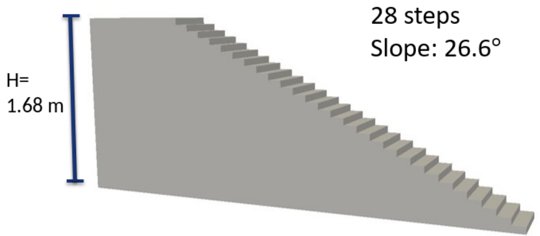
(e) Step 7



(f) Step 8

Photos taken from [6]

Stepped Spillway

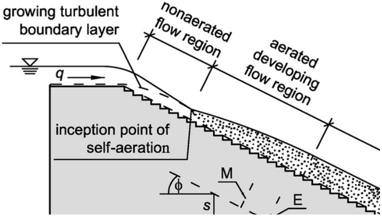


Inception point found experimentally at 5th step edge

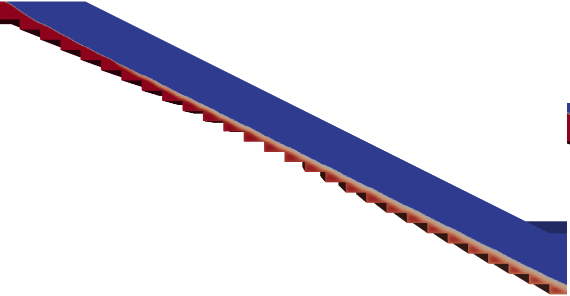
`airInterFoam` and the Flow3D-model has been verified for this stepped spillway

- Inception point
- Surface elevation curve

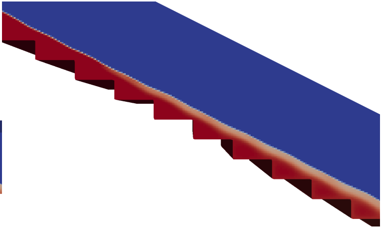
Inception point and surface elevation



[a]

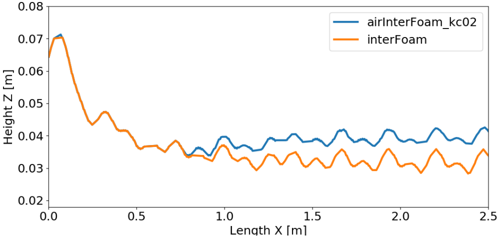


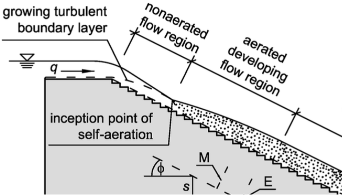
airInterFoam, $k_c = 0.2$



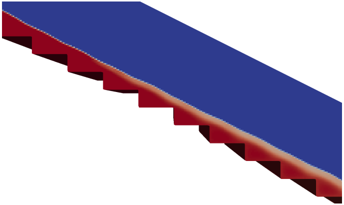
[a] Sketch taken from [6]

Inception point and surface elevation





a



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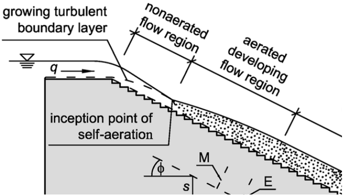
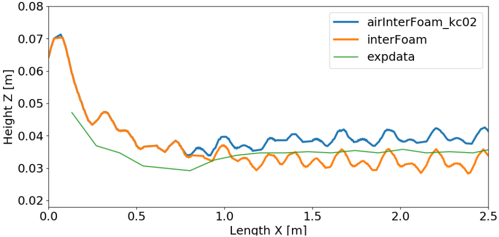
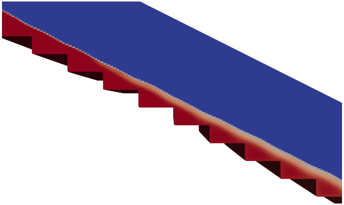
[a] Sketch taken from [6]

Inception point and surface elevation



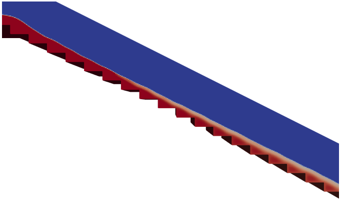
a



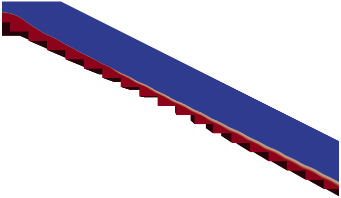


[a] Sketch taken from [6]

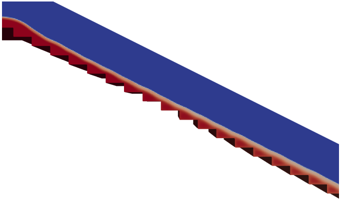
Dependent on inputvariables



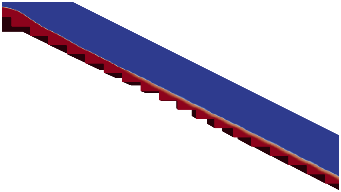
(a) $k_c = 0.2,\ \Delta x = 0.005$



(b) $k_c = 0.2,\ \Delta x = 0.0025$

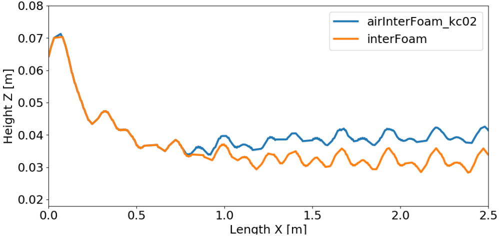


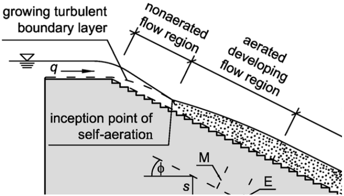
(c) $k_c = 0,\ \Delta x = 0.005$



(d) $\Delta x = 0.005,\ u_g = u_l + u_r$

Inception point and surface elevation





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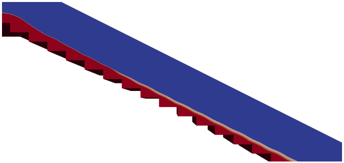
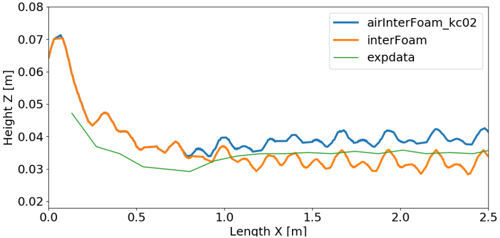
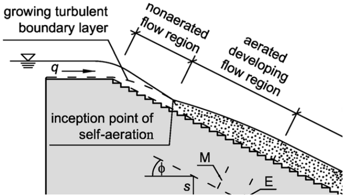


[a] Sketch taken from [6]

Inception point and surface elevation





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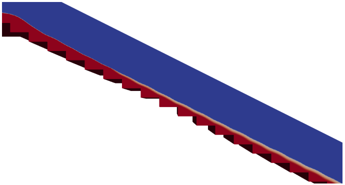
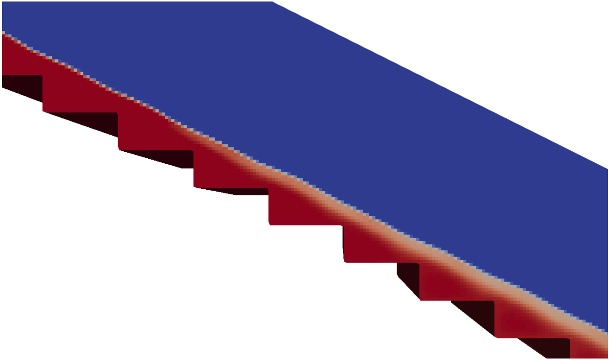
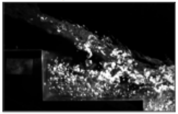


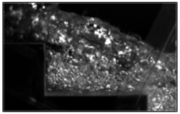
[a] Sketch taken from [6]

Void fraction

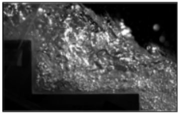




(a) Step 5



(b) Step 6



(c) Step 7

Photos taken from [6]

Hydraulic Jump

- Froude number, $Fr = \frac{u}{\sqrt{gh}}$

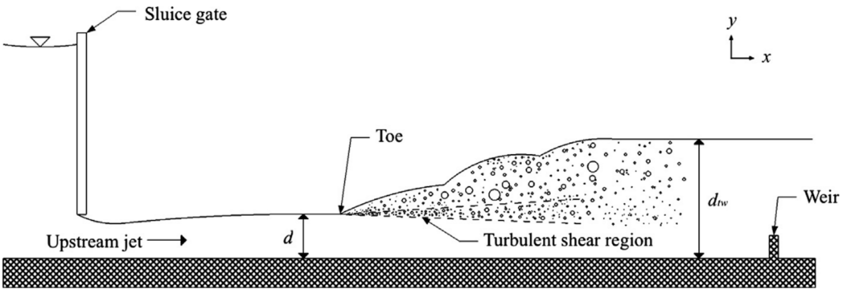


Figure: Hydraulic jump

Sketch taken from [7]

Hydraulic Jump

- Void fraction profiles
- Velocity profiles
- Free surface contour

Hydraulic Jump

- Void fraction profiles
- Velocity profiles
- Free surface contour

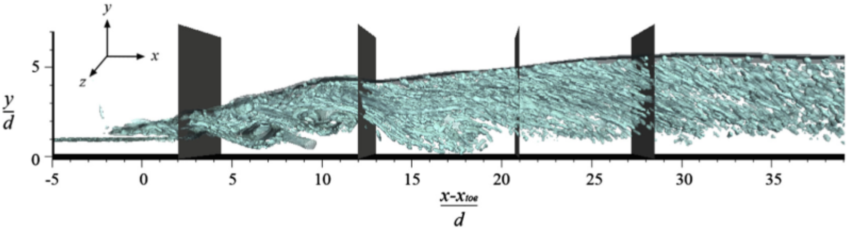


Figure: Hydraulic jump

Sketch taken from [7]

Test Case

- Froude number 4.8
- Physical experiments by Murzyn[5], reproduced by Witt[7] using `interFoam`

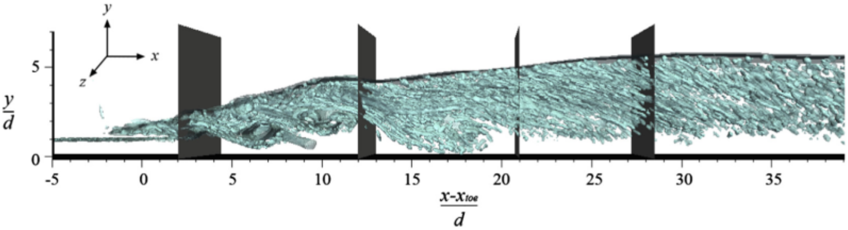
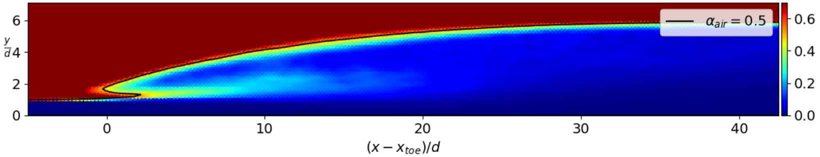


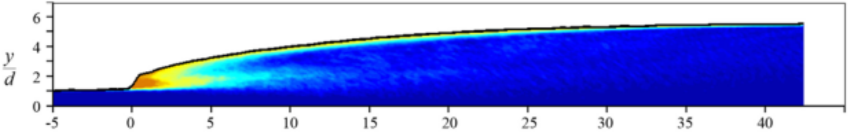
Figure: Hydraulic jump

Sketch taken from [7]

interFoam – reproduction



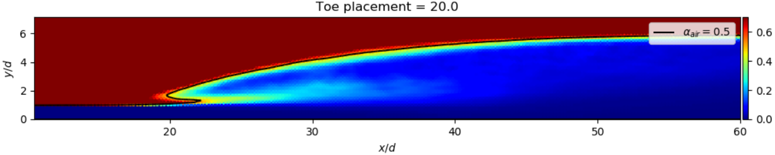
(a) Current work , realizableKE



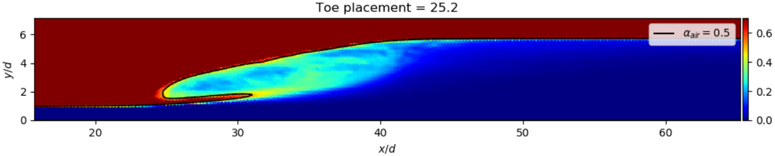
(b) Witt (2015)[7]

Figure: Mean flow field for $\overline{\alpha_{air}}$.

`interFoam` – realizableKE vs k-ϵ

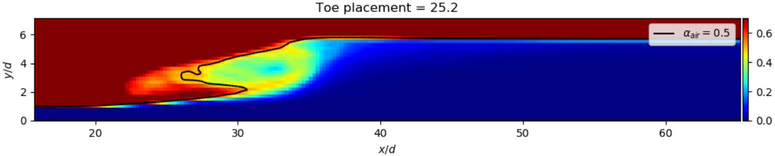


realizableKE

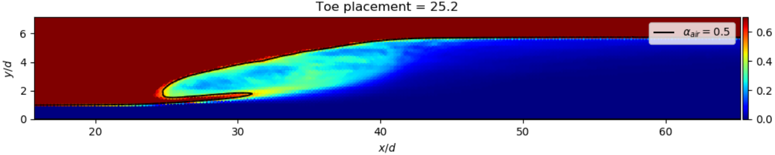


k-ϵ

interFoam – k-ϵ

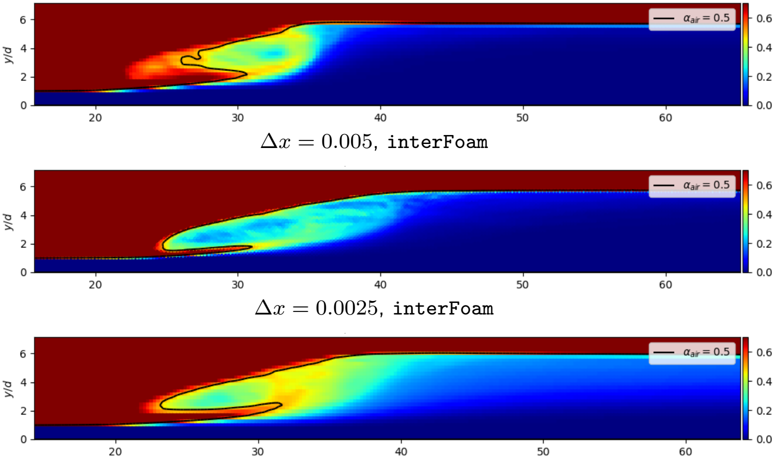


$$\Delta x = 0.005$$



$$\Delta x = 0.0025$$

interFoam – airInterFoam – k-ϵ

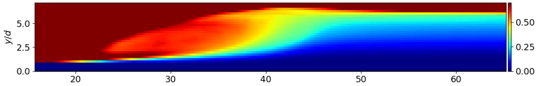


$\Delta x = 0.005$, interFoam

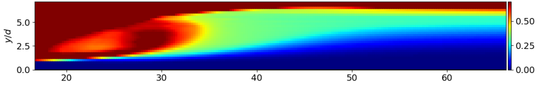
$\Delta x = 0.0025$, interFoam

$\Delta x = 0.005$, airInterFoam

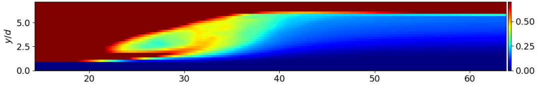
Dependence on parameters



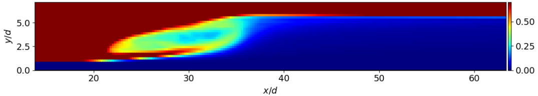
$u_g = u_l + u_r,\ k_c = 0.2$



$u_g = u_l,\ k_c = 0.2$



$u_g = u_l,\ k_c = 0.8$



$u_g = u_l,\ k_c = 2$

Conclusion

- Using a local reduction in interface compression gave some air entrained into the flow
- Gave results close to the experimental for prediction of
  - Inception point
  - Surface elevation curve
  - Void fraction (at lower parts of the spillway)
- Sensitive to
  - Grid refinement
  - Input parameters
- Behavior of hydraulic jump sensitive to choice of turbulence model
  - too little air transported in lower parts and towards the end of the jump

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