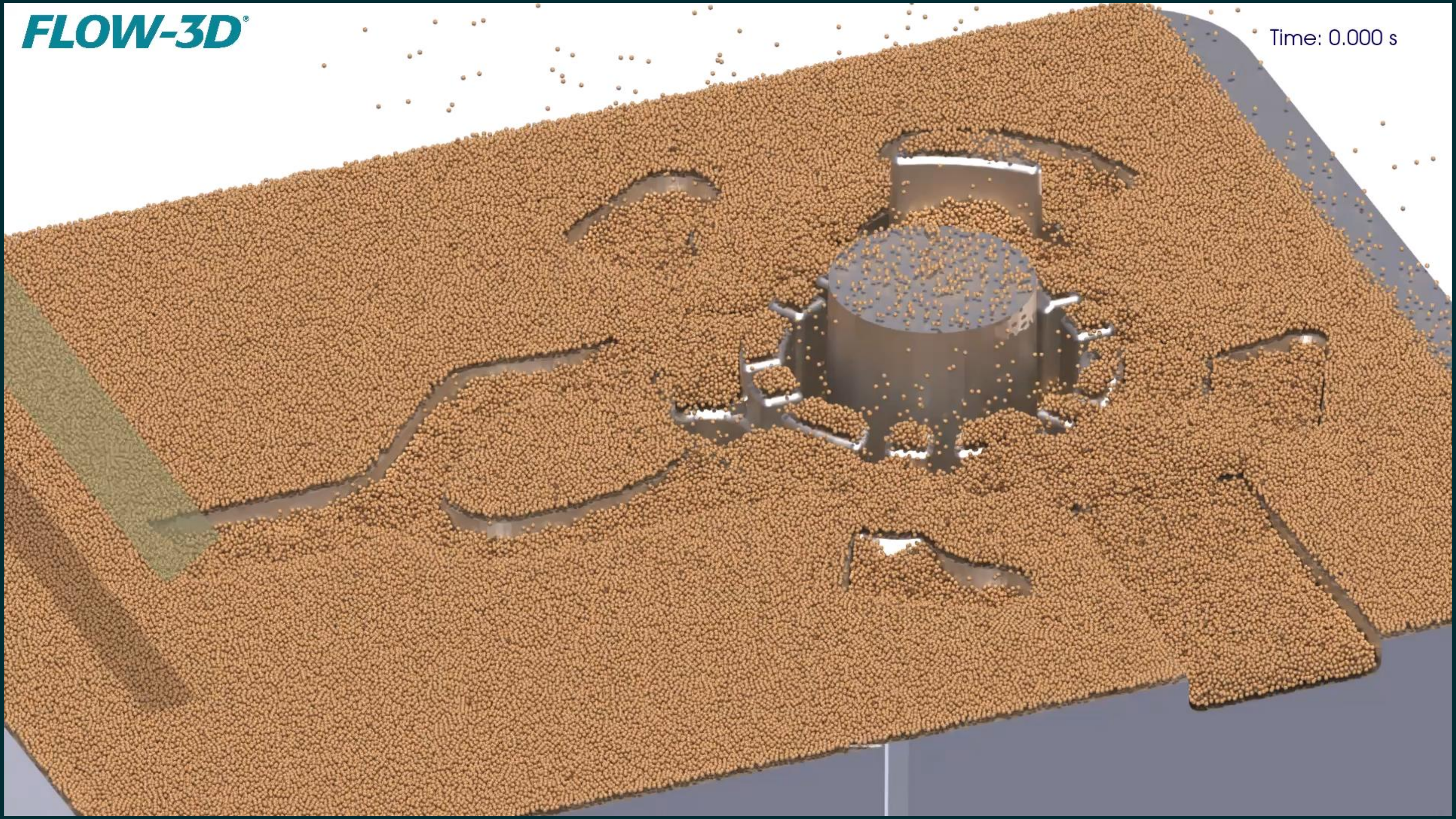
FLOW-3D

ParaSolS
Particulate Solids Simulations

CCC-ParaSolS Network Event 5

1 – 3 September | Manchester, UK



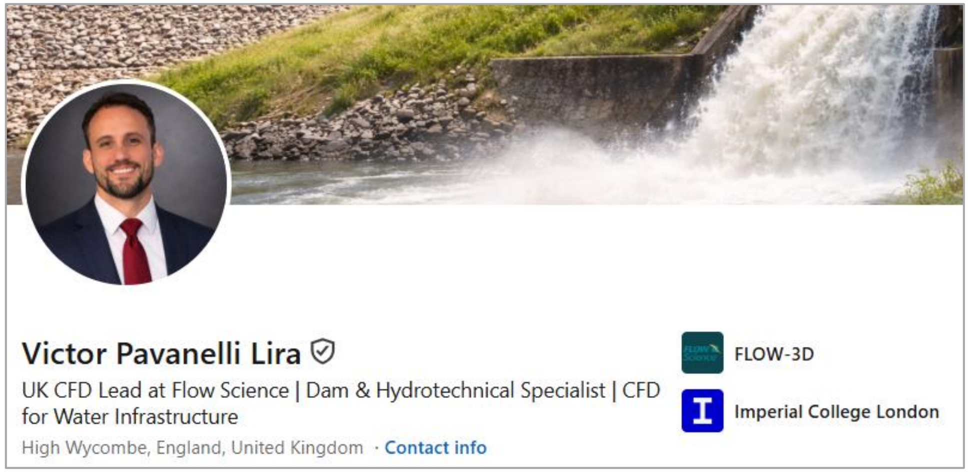
A Commercial Perspective on CFD-DEM

Victor Pavanelli Lira
MSc, CEng MICE
UK CFD Lead
FLOW Science

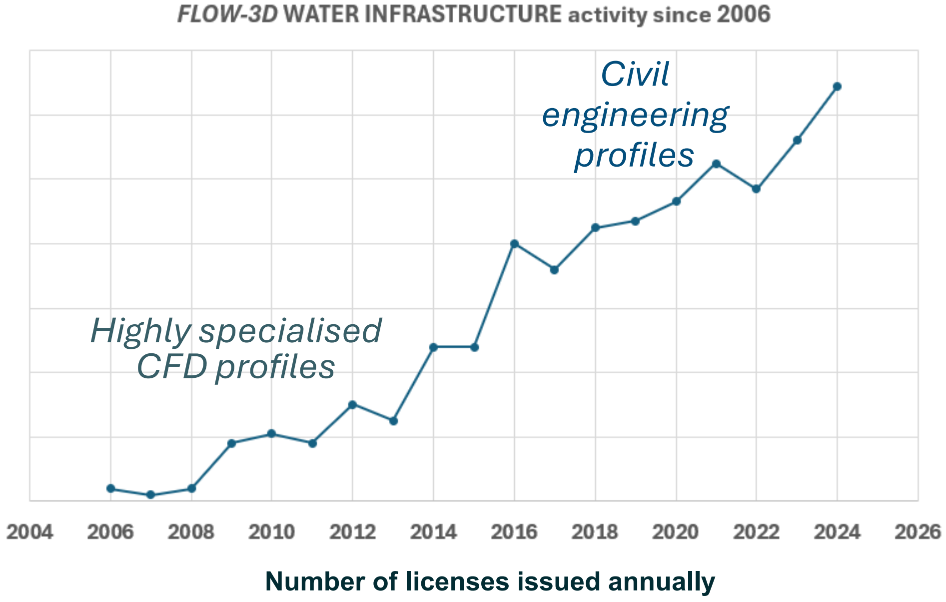
Victor Pavanelli Lira

UK CFD Lead, Flow Science Inc

- Chartered Civil Engineer (MICE)
- 16 years of experience in dam hydraulics, hydropower, drainage and water infrastructure
- Academic background
  - **BSc in Civil Engineering (2010)**
    Federal University of Minas Gerais (Brazil)
    + Erasmus at Lulea University of Technology (Sweden)
  - **MSc in Water Engineering (2014)**
    Federal University of Minas Gerais (Brazil)
    + Erasmus at Ghent University (Belgium)
    Research on CFD (*OpenFOAM*)
  - **MSc in Geotechnical Engineering (ongoing)**
    Imperial College London
    Research on DEM (*FLOW-3D*)
- History being repeated? CFD then, DEM now!



linkedin.com/in/victor-pavanelli-lira/
victor.lira@flow3d.com



About ***FLOW-3D***...

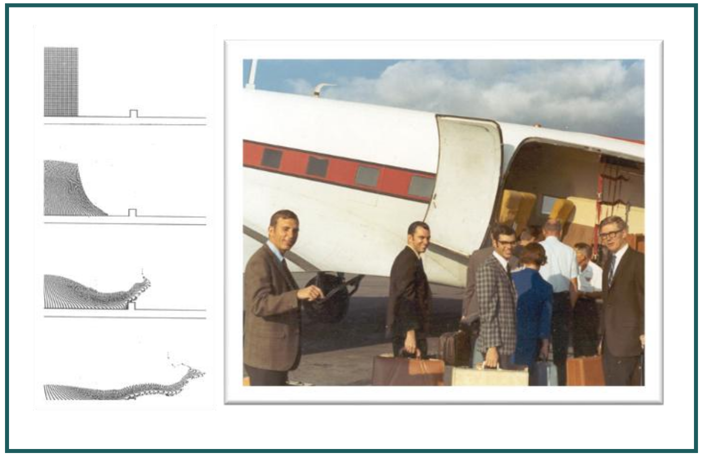
45 years of development of a general-purpose 3D CFD solver

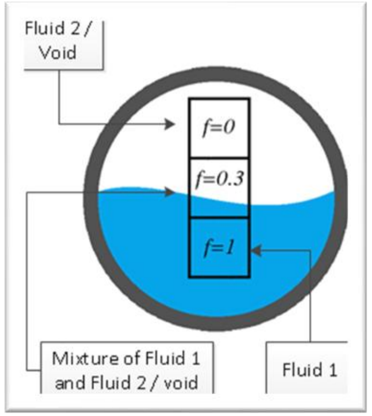
Focus on free surface flows

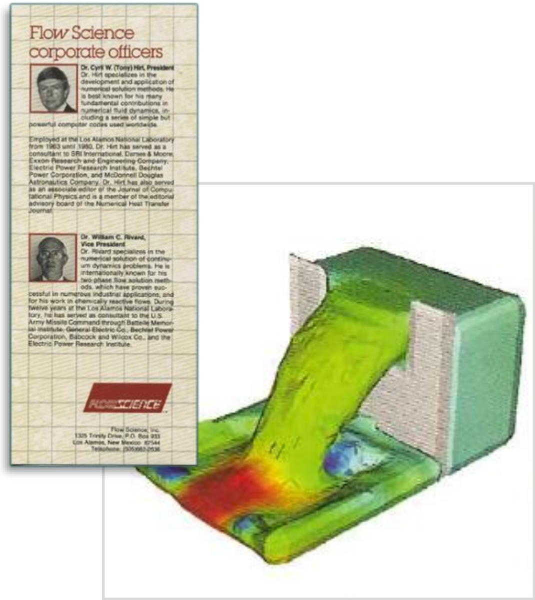
Dr C.W. “Tony” Hirt

Origins: **Los Alamos National Labs**

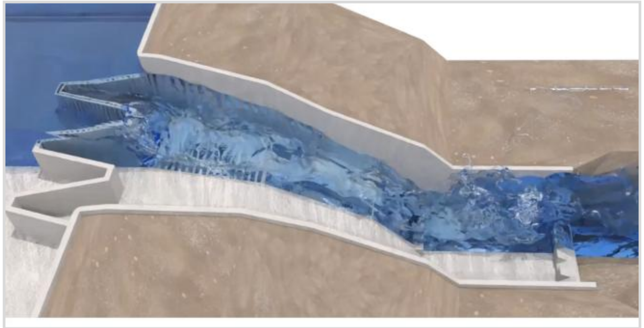
(T-3 Group Fluid Dynamics and Solid Mechanics)







Release of ***FLOW-3D*** version 1.0

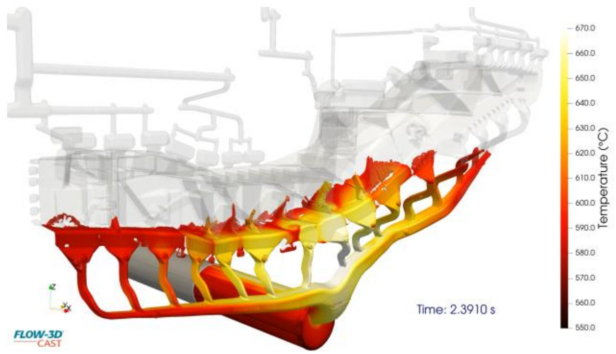


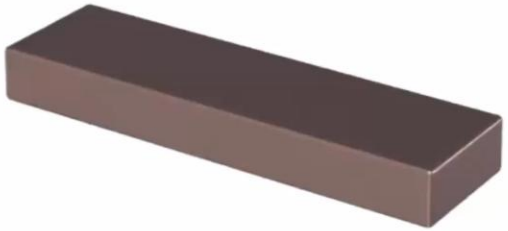
Continuous development of CFD solutions with a focus on free surface flows and multi-physics

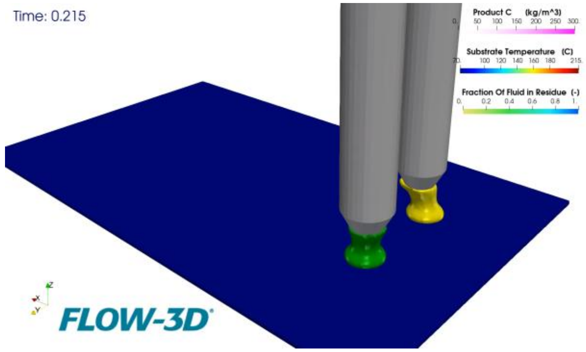
1960’s → **1981** → **1985** → **TODAY**

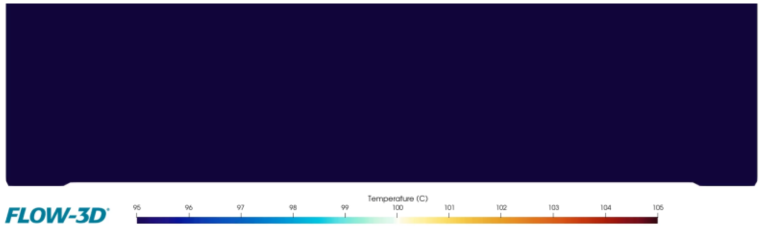
About ***FLOW-3D*...**

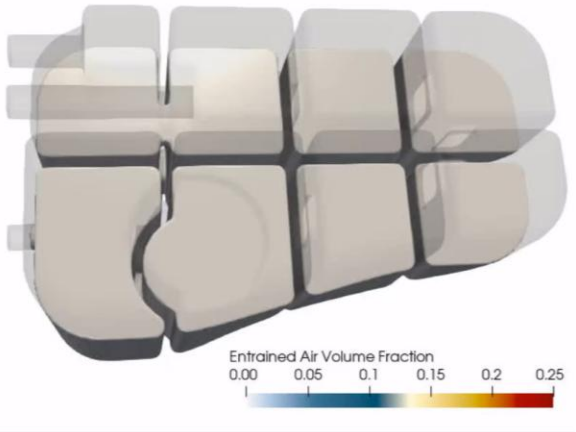
- Family of products:
  - FLOW-3D
  - FLOW-3D CAST
  - FLOW-3D WELD
  - FLOW-3D AM
  - FLOW-3D HYDRO





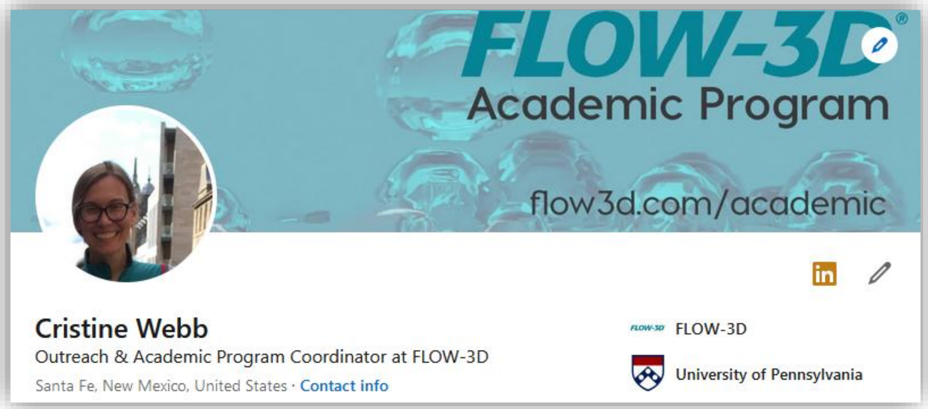


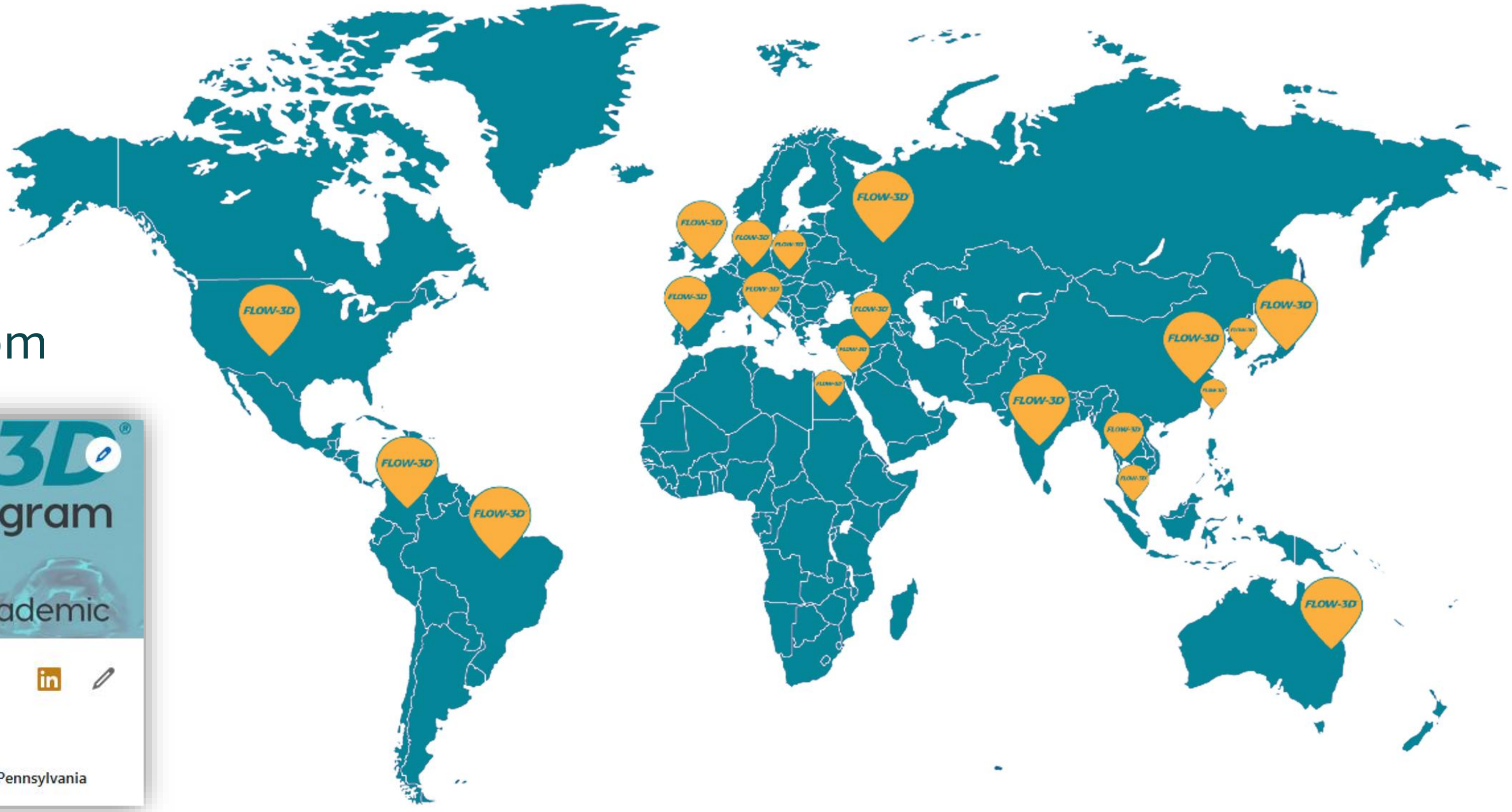




About *FLOW-3D*...

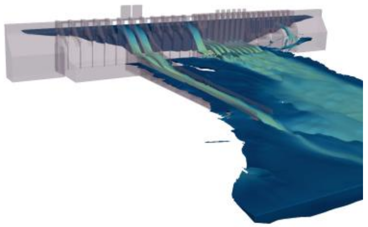
- World-wide adoption from:
  - Engineering consulting firms
  - Regulators and water authorities
  - Utilities
  - Academia
    - Free licenses for:
      research & teaching
      flow3d.com/academic
      cristine.webb@flow3d.com



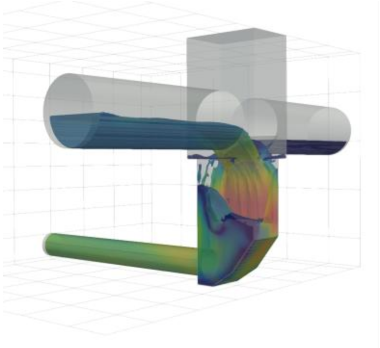


About *FLOW-3D* HYDRO...

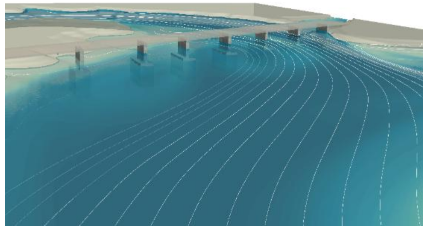
Dams & Spillways



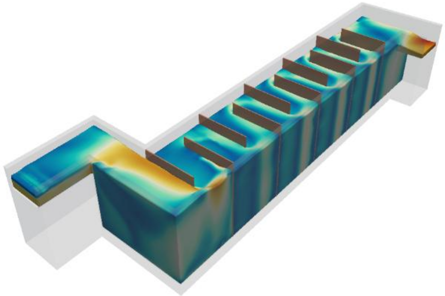
Conveyance Infrastructure



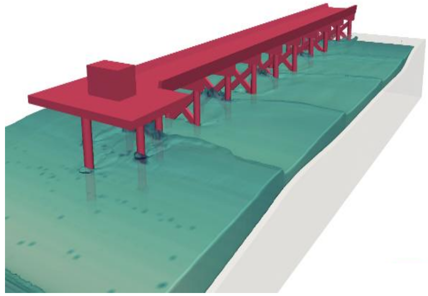
Rivers & Environmental



Water Treatment

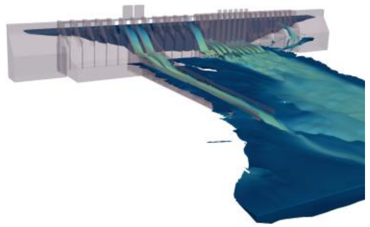


Ports & Coastal



About *FLOW-3D* HYDRO...

Dams & Spillways



Conveyance Infrastructure

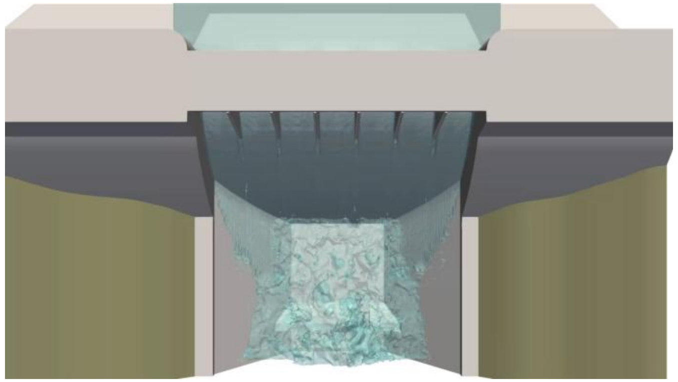
Rivers & Environmental

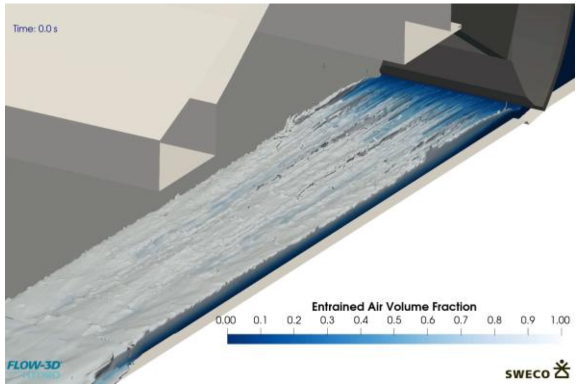
Water Treatment

Ports & Coastal

Main problems assessed:

- Spillway capacity & rating curves
- Energy dissipation
- Pressures
- Aerated flows
- Cavitation
- Scour
- Tailings (non-Newtonian) flow

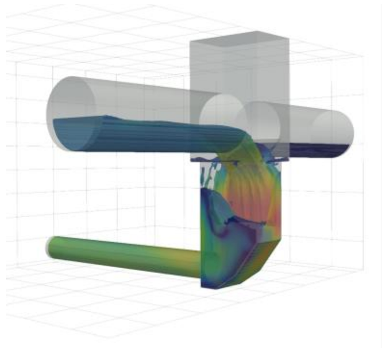




About *FLOW-3D* HYDRO...

Dams & Spillways

Conveyance Infrastructure



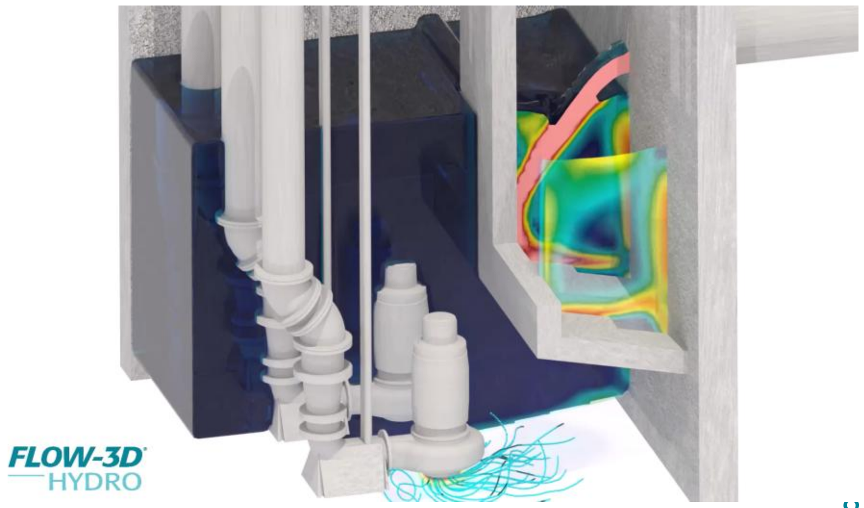
Rivers & Environmental

Water Treatment

Ports & Coastal

Main problems assessed:

- Flow capacity
- Flow splitting & overflows (CSO)
- Energy dissipation (drop structures)
- Intake vortex
- Sedimentation
- Air trapping & supply

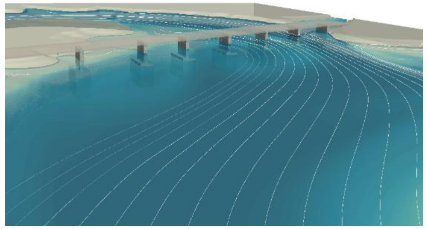


About *FLOW-3D* HYDRO...

Dams & Spillways

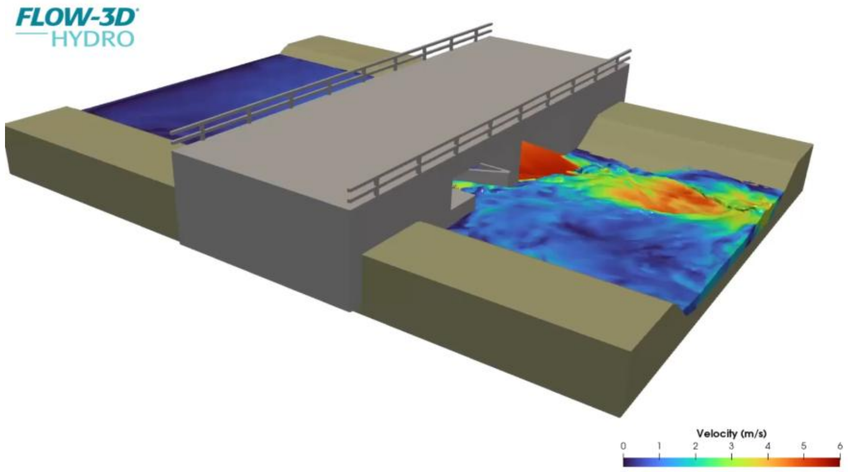
Conveyance Infrastructure

Rivers & Environmental



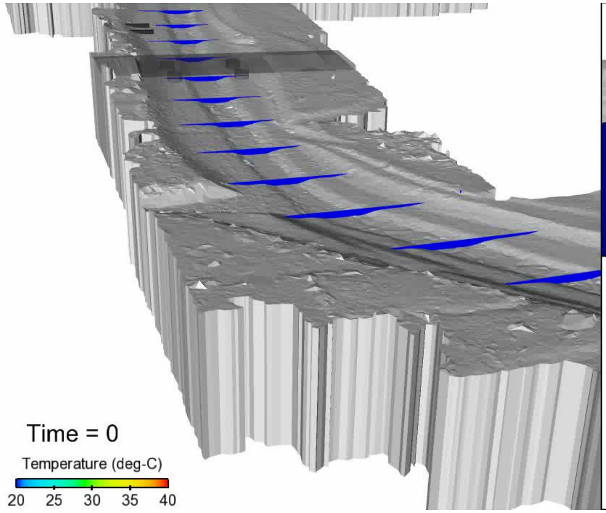
Water Treatment

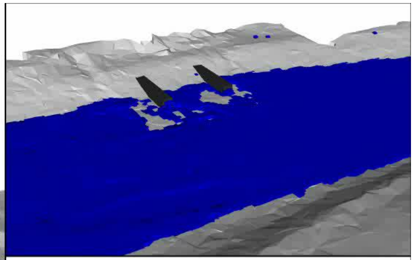
Ports & Coastal

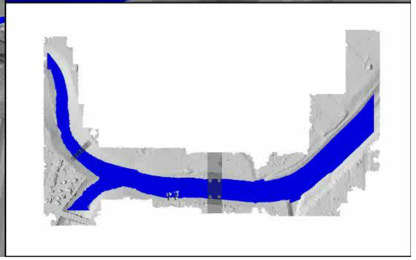


Main problems assessed:

- Bridge hydraulics
- Scour (bridge & outfalls)
- Fish protection (fishway & screens)
- Sedimentation
- Contaminants & plumes
- Large models (2D/3D)







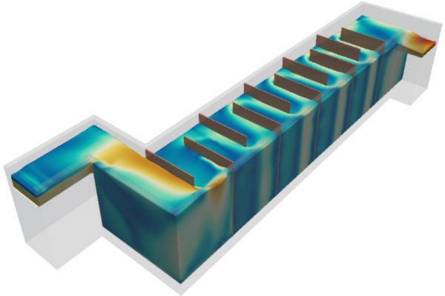
About *FLOW-3D* HYDRO...

Dams & Spillways

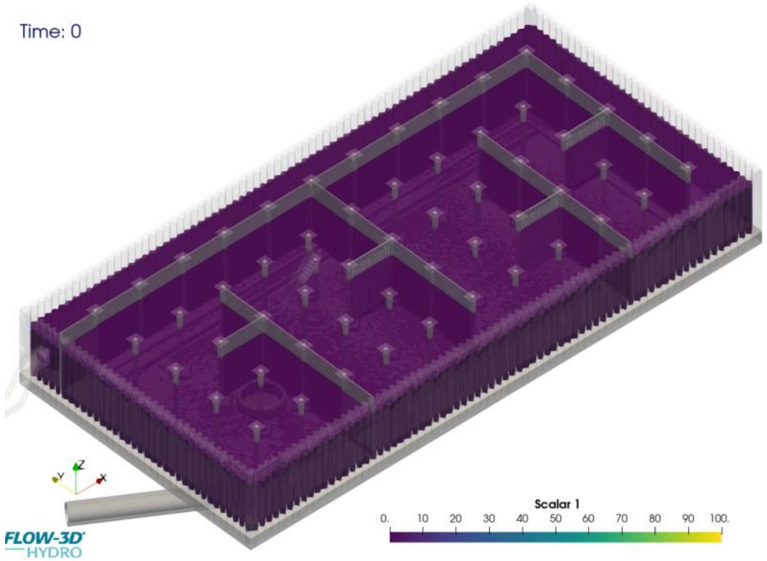
Conveyance Infrastructure

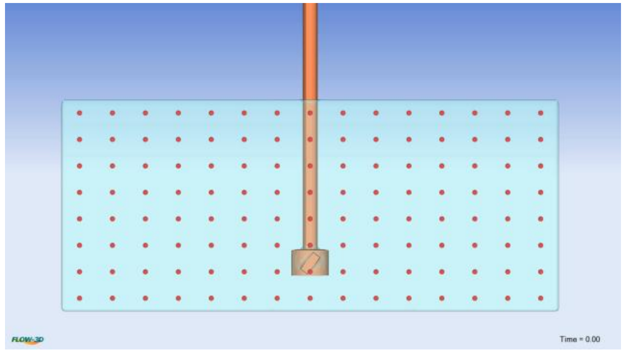
Rivers & Environmental

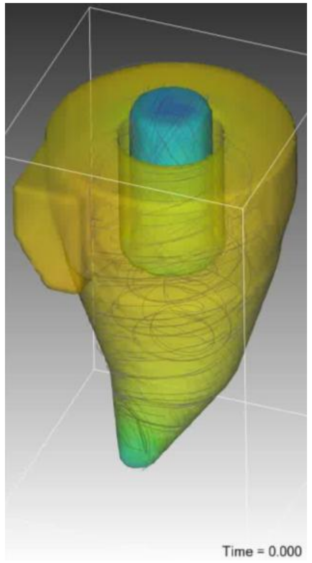
Water Treatment



Ports & Coastal







Main problems assessed:

- Flow splitting
- Contact tanks
- Mixing tanks
- Grit removal
- Clarifiers
- Aeration tanks
- Reaction kinetics

About *FLOW-3D* HYDRO...

Dams & Spillways

Conveyance Infrastructure

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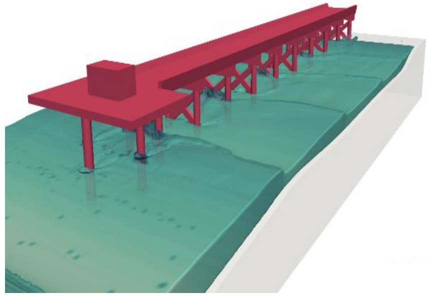
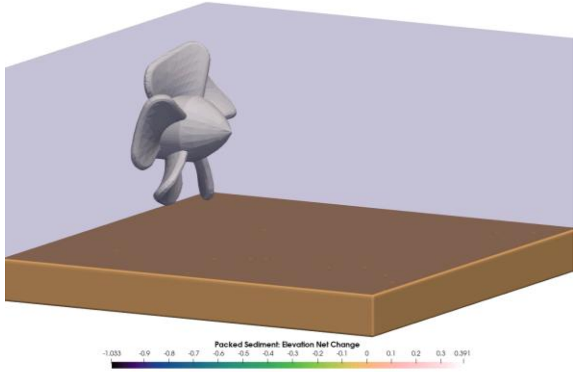
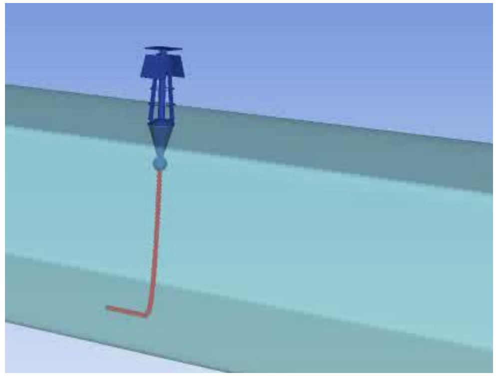
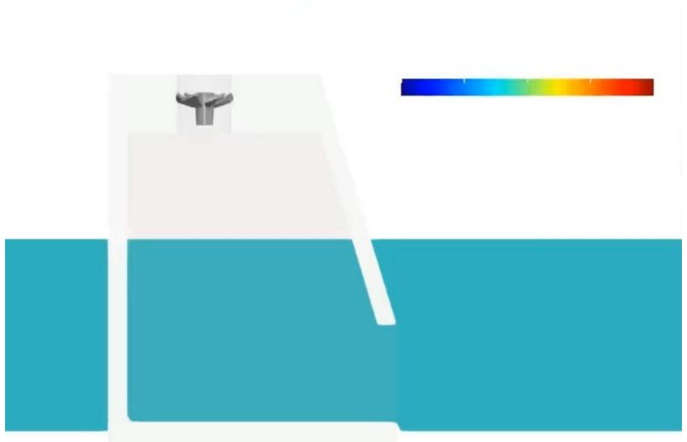
Ports & Coastal









Main problems assessed:

- Breakwaters
- Scour (waves & propeller)
- Ship launches
- Mooring lines
- Navigation locks
- Coastal outfalls
- Wave energy devices

Commercial perspective on CFD-DEM

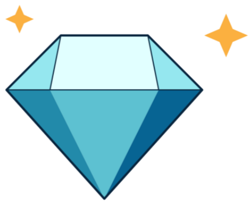
(vs. academic)

Commercial Perspective (vs. Academic)

What are the market requirements for the adoption of a new modelling method/tool?

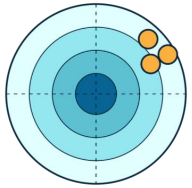
- Valuable

  = Academia
  The market is focused on the short-term benefits



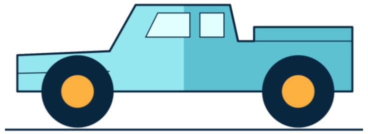
- Accurate

  < Academia
  The market prioritises other requirements



- Reliable

  > Academia
  The market is more risk averse



- Practical

  > Academia
  The market has shorter timelines

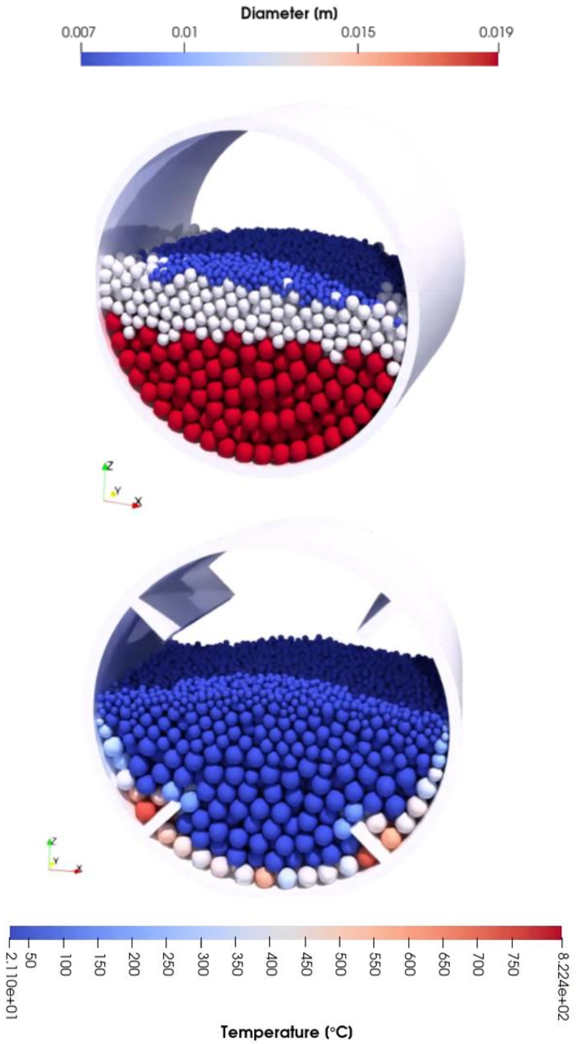
Outline

- Introduction & context ✓
- Commercial perspective on CFD-DEM ✓
- What is the value of DEM?
- Is DEM accurate?
- Is DEM reliable?
- How practical can DEM be?
- DEM challenges in the commercial environment

What is the value of DEM?

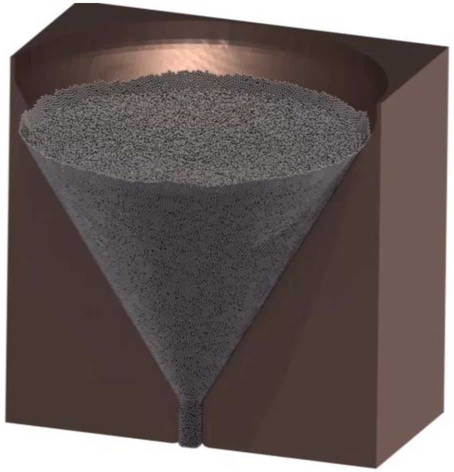
Industrial Applications

Screw Conveyor



Rotating Drums

Particle Sorting

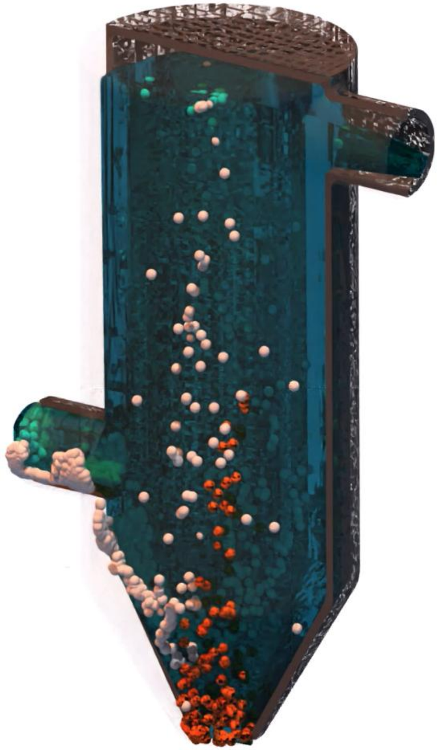


Silo Discharge of DRI Pellets

Metal Powder in MEX Printing

Industrial Applications

Slurry Settling in a Storage Tank



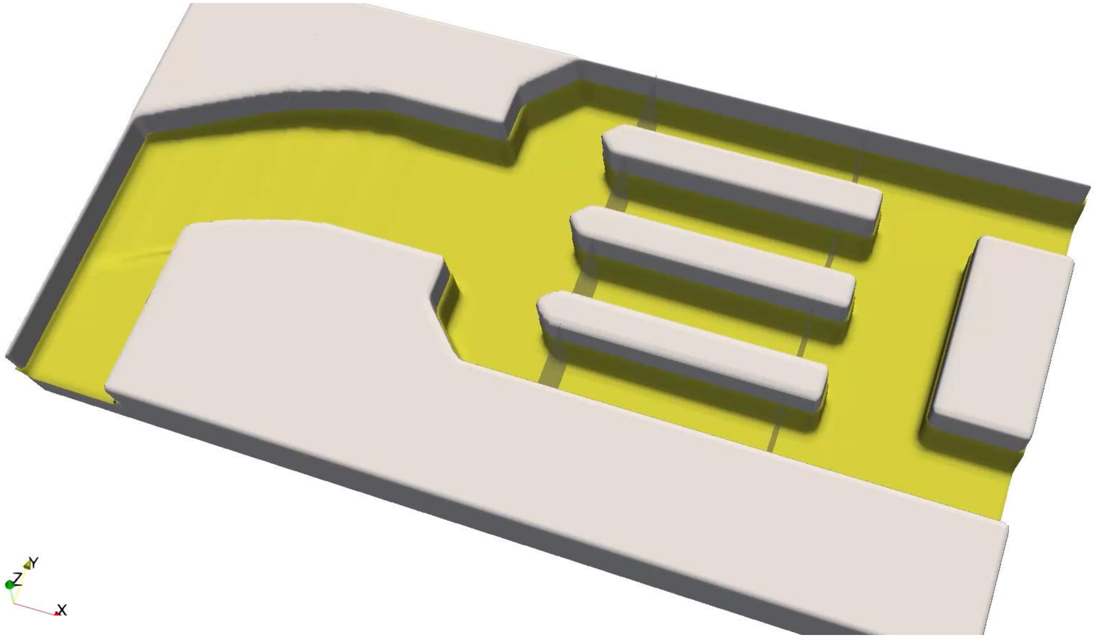
Particle classification by Elutriation

Slurry distribution line flow

Valve erosion in slurry lines

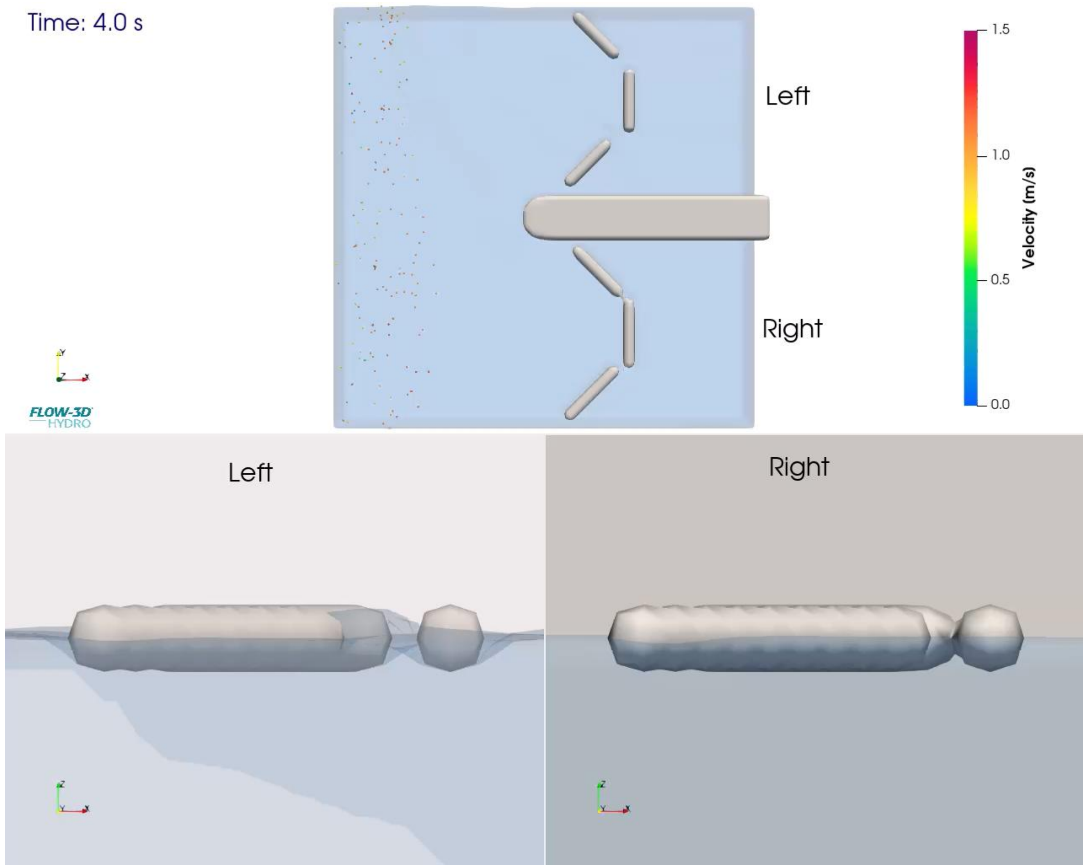
The value of DEM

Civil & Environmental Applications



Screening Channels

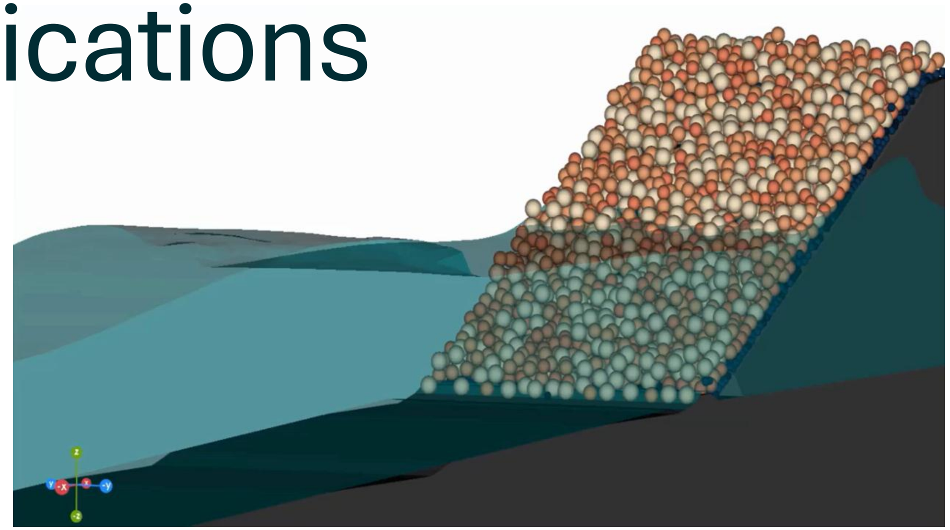
Sand Retention in
SAGD Wells



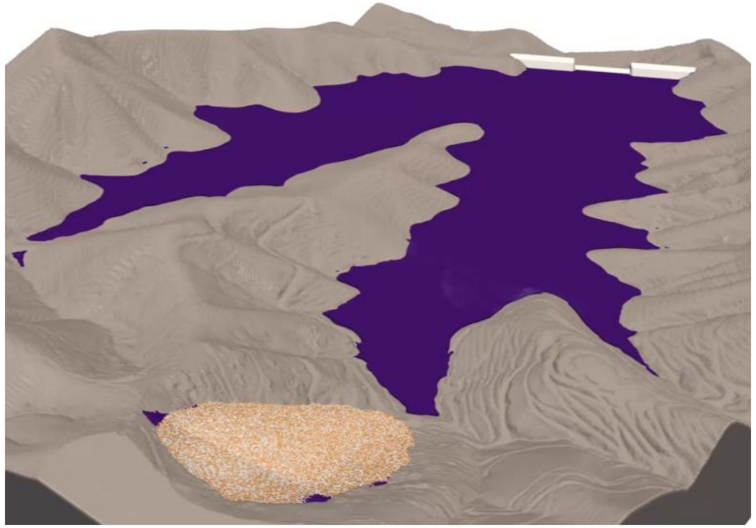
Debris Mitigation

Civil & Environmental Applications

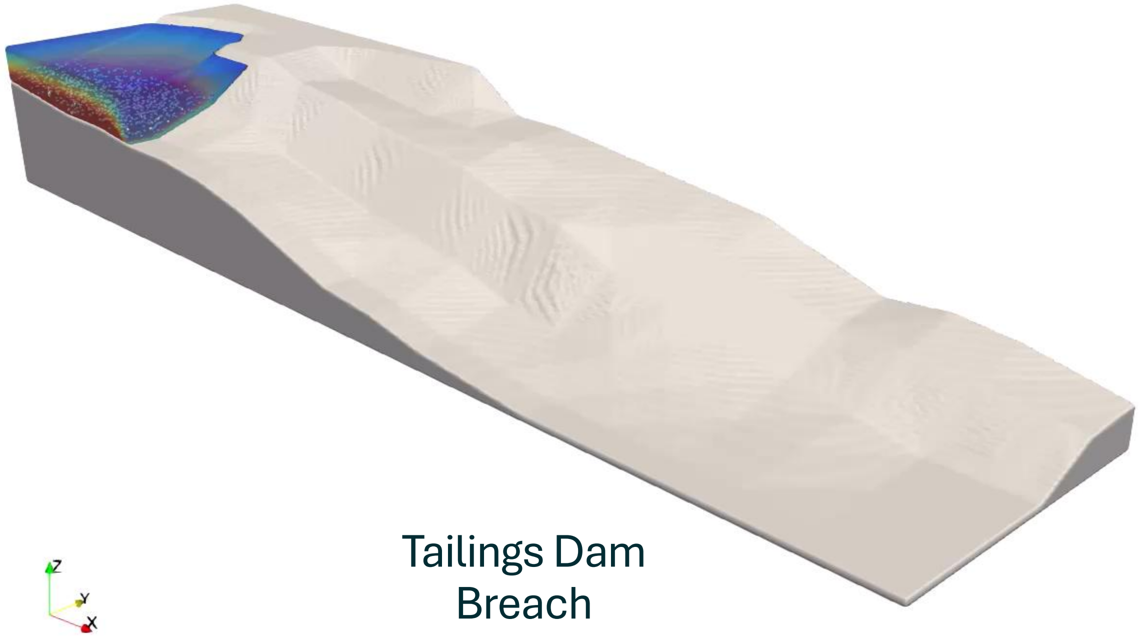
Siphon Spillways



Coastal Protection

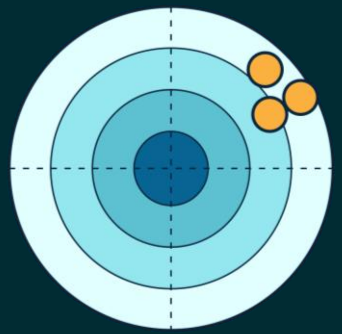


Landslide



Tailings Dam
Breach

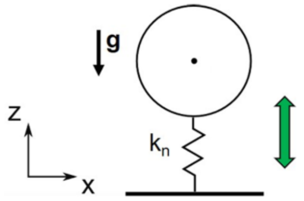
Is the DEM accurate?

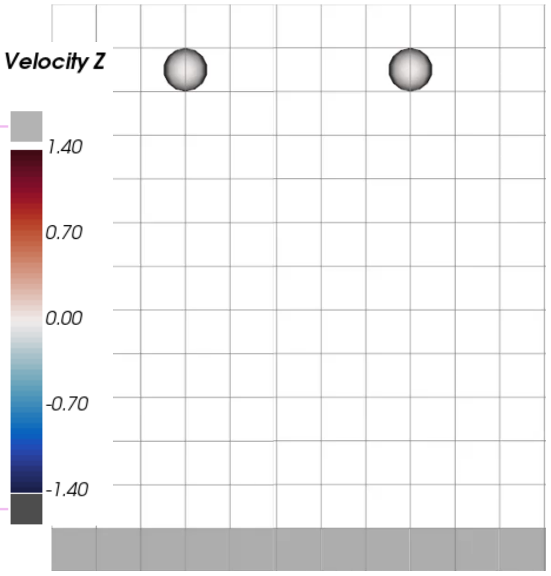


V&V cases

Particle-Particle Interaction

Bouncing ball
(Verification)

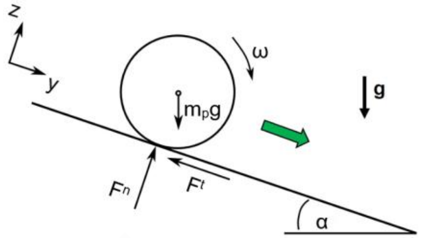


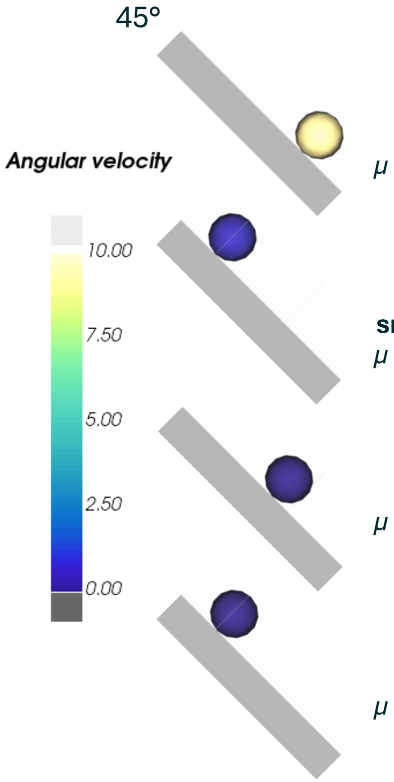


No damping (e = 1.0)

With damping (e = 0.8)

Particle on slope
(Verification)





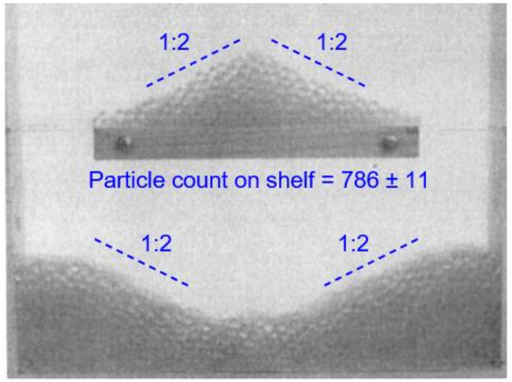
Rolling only – no resistance
$\mu = \tan 60° = 1.73$
$\mu_R = 0$

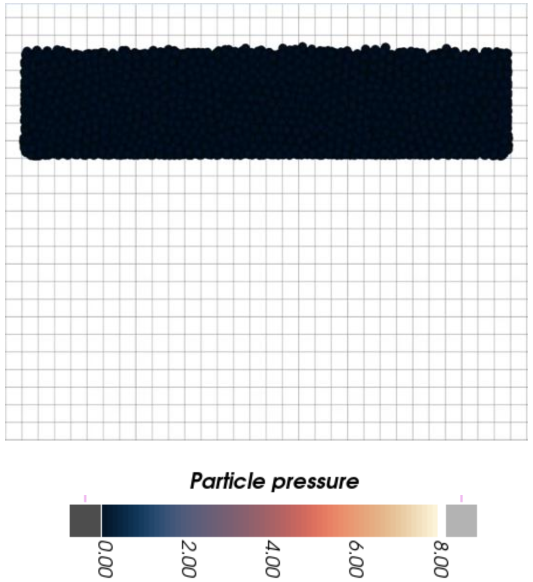
Rolling only – small resistance
$\mu = \tan 60° = 1.73$
$\mu_R = 0.2$

Sliding only
$\mu = \tan 30° = 0.58$
$\mu_R = 0.8$

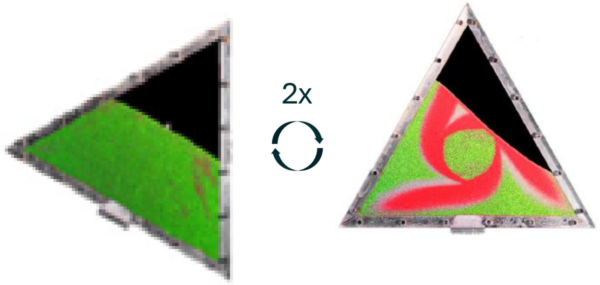
Static
$\mu = \tan 60° = 1.73$
$\mu_R = 1.5$

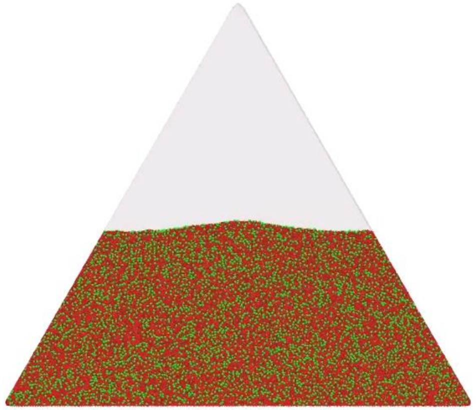
Pile formation
(Validation)





Triangular drum
(Validation)

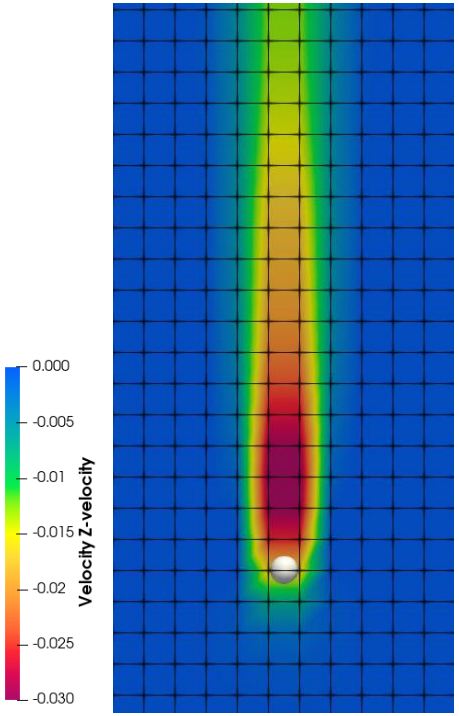




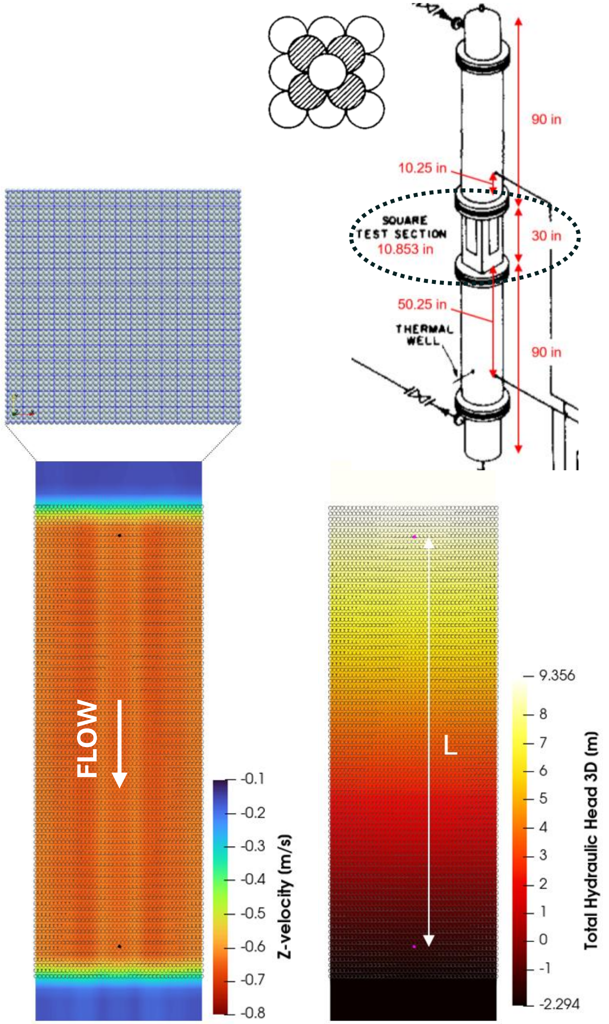
V&V cases

Fluid-Particle Interaction

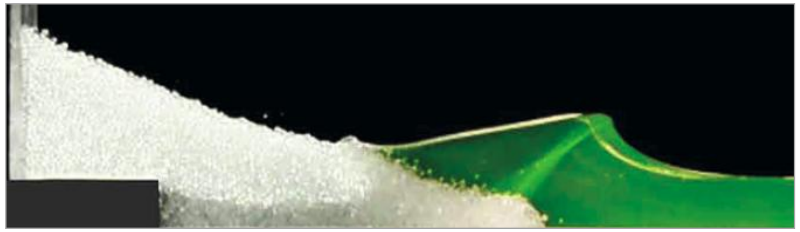
Particle Settling
(Verification & Validation)

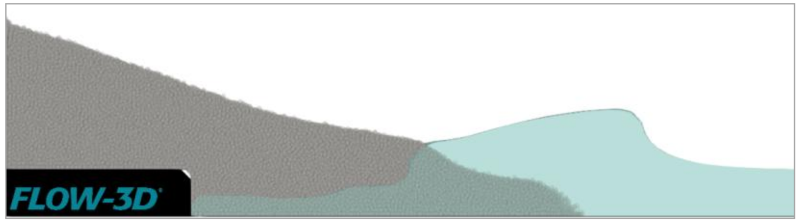


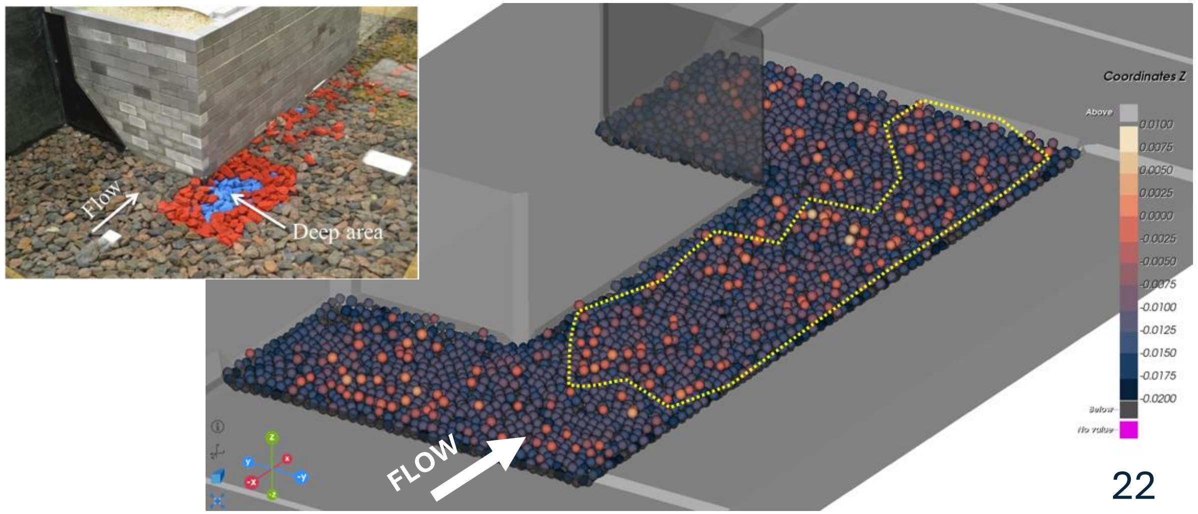
Packed Bed (Δ*P*)
(Verification & Validation)



Any case specific to the application
(Validation)



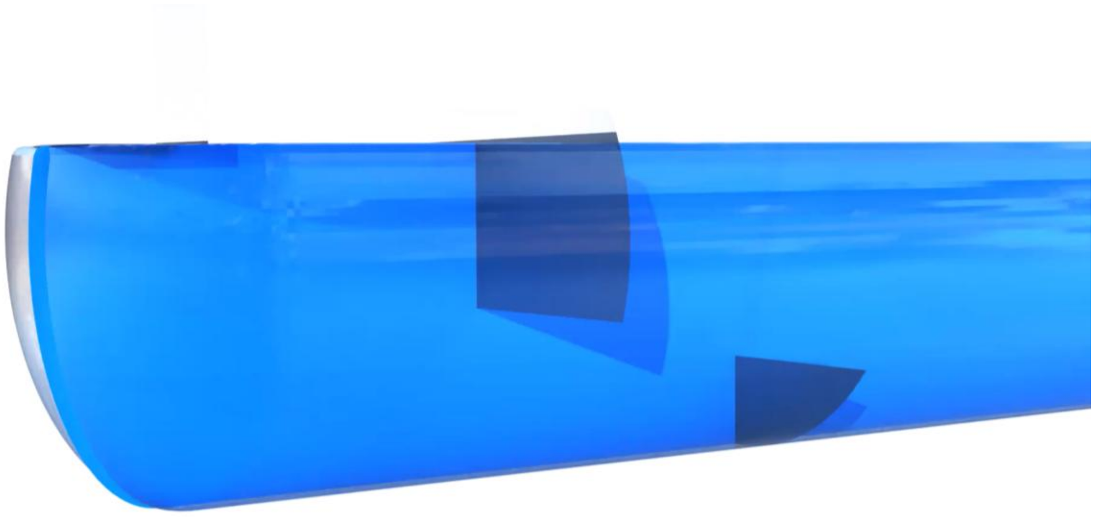


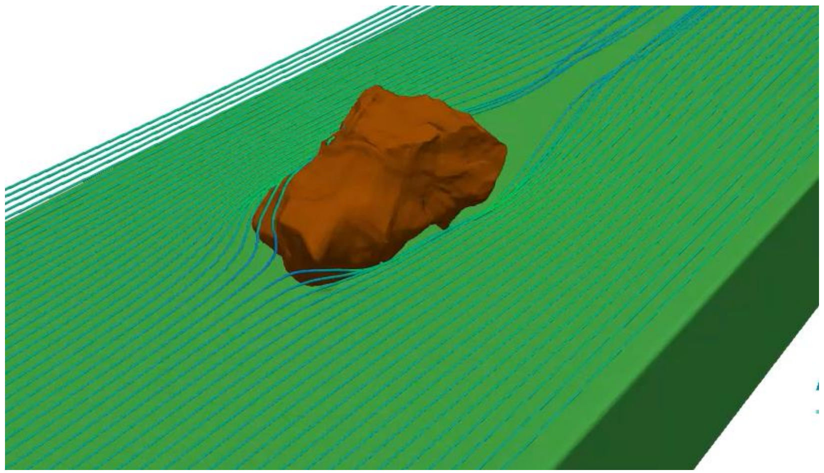


Is the DEM reliable?

Aspects of Reliability

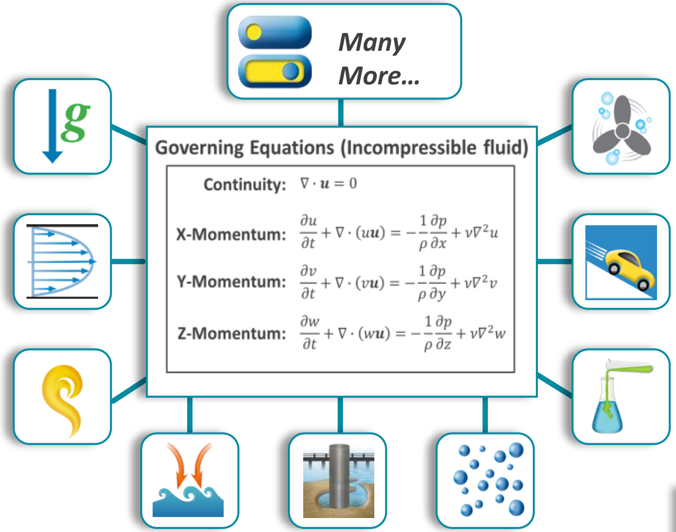
- Flexibility
  - The particles can be represented in different ways
  - The CFD framework is couple with multiple physics solvers

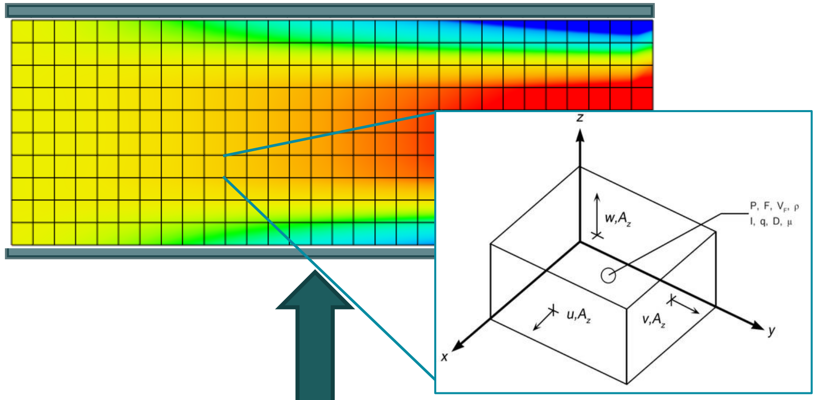




Aspects of Reliability

- Flexibility
    - The particles can be represented in different ways
    - The CFD framework is couple with multiple physics solvers
- Stability
    - These complex coupling will rarely lead to instabilities – it must converge!





Discretized Equations

$$u_{i,j,k}^{n+1} = u_{i,j,k}^{n} + \delta t^{n+1}\left[-\frac{p_{i+1,j,k}^{n+1} - p_{i,j,k}^{n+1}}{(\rho\delta x)_{i+\frac{1}{2},j,k}^{n}} + G_x - \mathrm{FUX} - \mathrm{FUY} - \mathrm{FUZ} + \mathrm{VISX} - \mathrm{BX} - \mathrm{WSHX}\right]$$

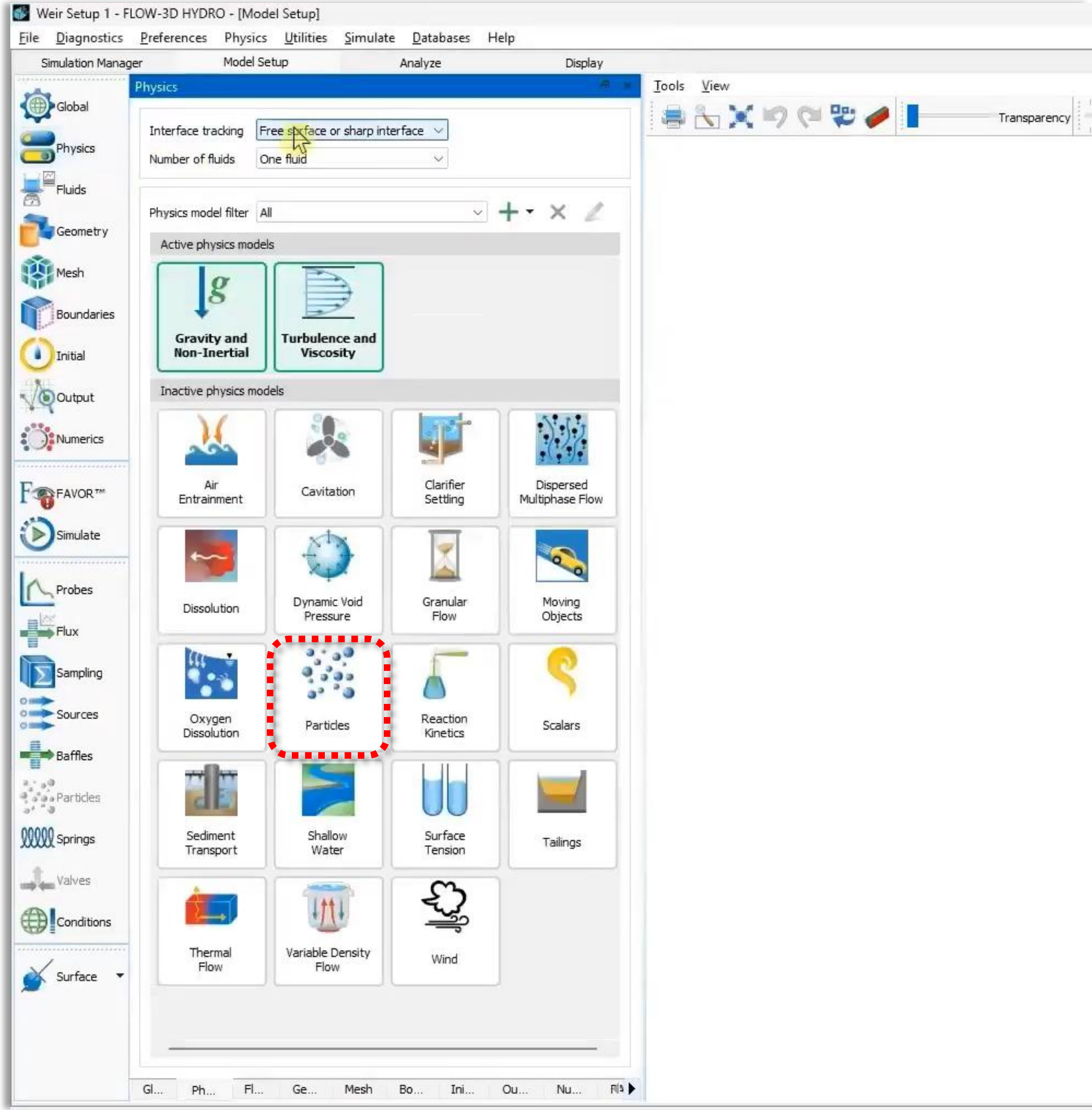
$$v_{i,j,k}^{n+1} = v_{i,j,k}^{n} + \delta t^{n+1}\left[-\frac{p_{i,j+1,k}^{n+1} - p_{i,j,k}^{n+1}}{(\rho\delta y)_{i,j+\frac{1}{2},k}^{n}} \cdot R_{i+\frac{1}{2}} + G_y - \mathrm{FVX} - \mathrm{FVY} - \mathrm{FVZ} + \mathrm{VISY} - \mathrm{BY} - \mathrm{WSHY}\right]$$

$$w_{i,j,k}^{n+1} = w_{i,j,k}^{n} + \delta t^{n+1}\left[-\frac{p_{i,j,k+1}^{n+1} - p_{i,j,k}^{n+1}}{(\rho\delta z)_{i,j,k+\frac{1}{2}}^{n}} + G_z - \mathrm{FWX} - \mathrm{FWY} - \mathrm{FWZ} + \mathrm{VISZ} - \mathrm{BZ} - \mathrm{WSHZ}\right]$$

How practical can DEM be?

Aspects of Practicality

- Graphical User Interface
  - Power for the people
    – not only for the hardcore ones!
  - Your time & energy focused on the assessment (not on debugging)



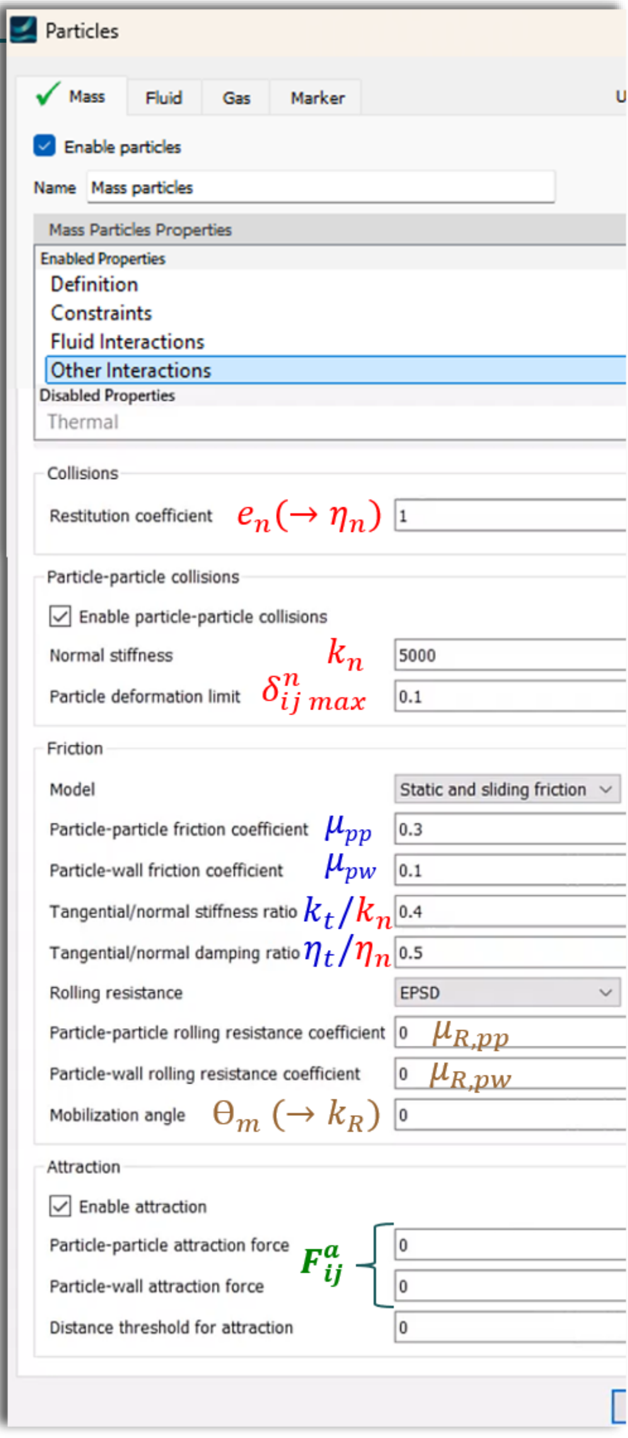
Aspects of Practicality

- Graphical User Interface
  - Power for the people – not only for the hardcore ones!
  - Your time & energy focused on the assessment (not on debugging)
- Guidance from DEM Community
  - Too many parameters to select – guidance is required to reduce uncertainties and need for extensive sensitivity tests
  - Best practices needed

Material Pair	e_n (Restitution)
Steel - Steel	0.75 - 0.85
Glass - Glass	0.90 - 0.95
Rubber - Concrete	0.60 - 0.75
Rock - Rock	0.50 - 0.70
Sand - Sand	0.10 - 0.30
Wood - Wood	0.40 - 0.60

Material Pair	μ (Friction Coeff.)
Steel - Steel	0.40 - 0.60
Rock - Rock	0.50 - 0.70
Sand - Sand	0.50 - 0.65
Gravel - Gravel	0.55 - 0.75
Rubber - Concrete	0.60 - 0.85
Wood - Wood	0.25 - 0.50
Ice - Ice	0.01 - 0.10

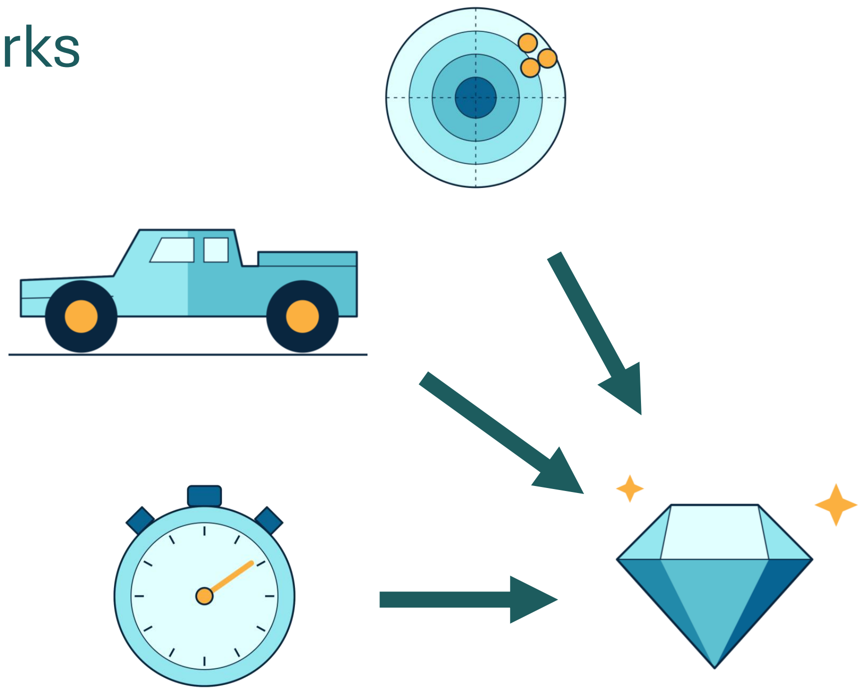
Material Pair	μ_R (Rolling Res.)
Sphere on sphere	0.01 – 0.05
Sphere on flat surface	0.01 – 0.03
Sand / gravel	0.1 – 0.5
Rock / ore	0.2 – 0.6
Coal particles	0.1 – 0.4
Grain / seeds	0.05 – 0.2
Pharmaceutical pellets	0.05 – 0.3



DEM challenges in a commercial environment

Challenges to be overcome

- Knowing what particle-to-particles parameters to select for each material
- Lack of stablished benchmarking test sequence for different cases
- Knowing when angular particles are required
- Particle-to-cell ratio limitation (<<1) in some frameworks
- Sampling of the particle packing not so practical
- Particle count limitation / computational cost
- Immense lack of DEM users in the market



Thank you!

Questions?