CFD Modeling of Rockery Walls in the River Environment

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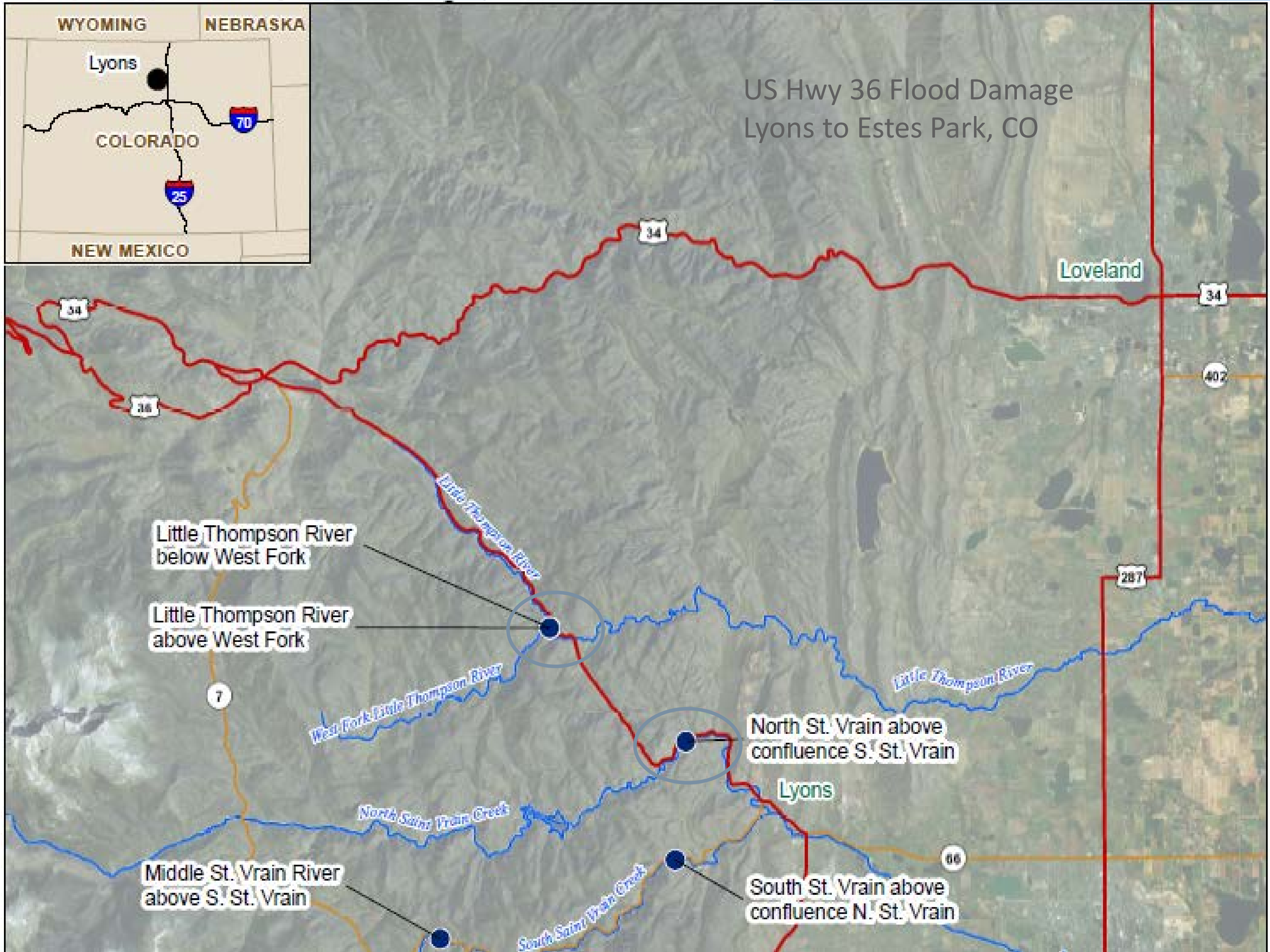
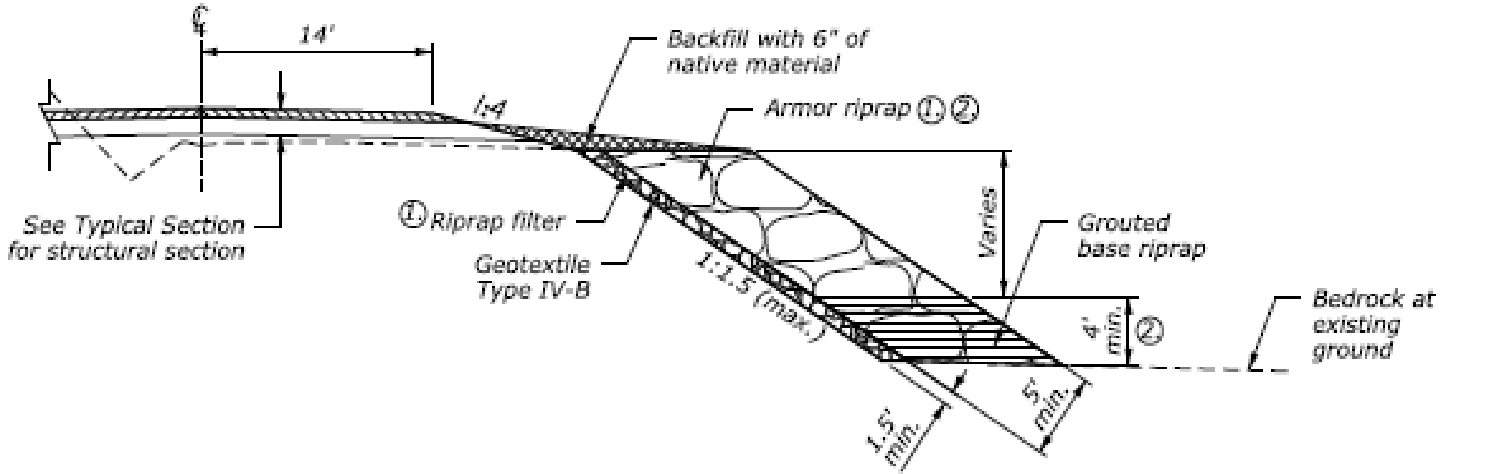
Part I: Introduction

Bart Bergendahl

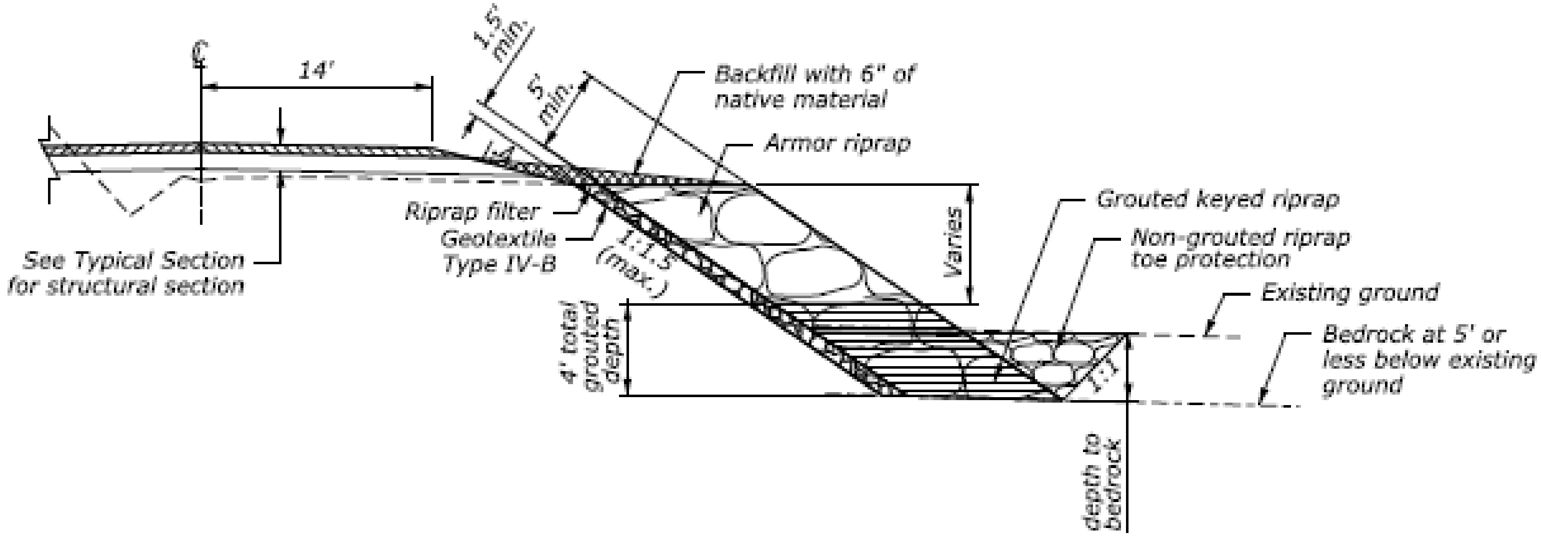

US Hwy 36 Flood Damage
Lyons to Estes Park, CO
WYOMING
NEBRASKA
Lyons
70
COLORADO
25
NEW MEXICO
34
36
Loveland
402
287
7
66
Little Thompson River
Little Thompson River below West Fork
Little Thompson River above West Fork
West Fork Little Thompson River
North St. Vrain above confluence S. St. Vrain
Lyons
North Saint Vrain Creek
Middle St. Vrain River above S. St. Vrain
South St. Vrain above confluence N. St. Vrain
South Saint Vrain Creek

Preliminary Rainfall / Runoff Data

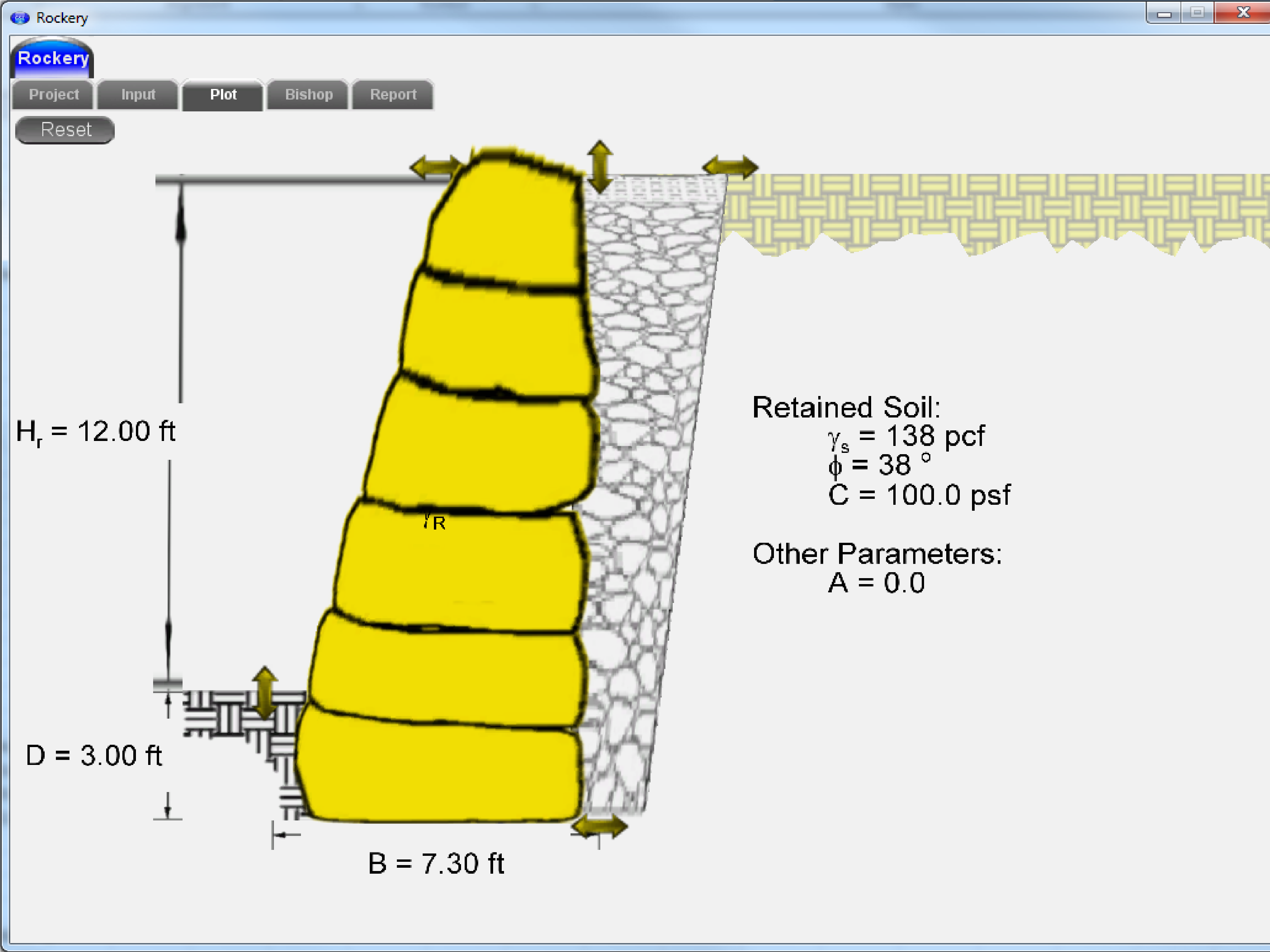
Rainfall (Sept 9-18, 2013)			
Location	**Duration**	**Measured**	**Return Int. (NOAA)**
Button Rock Dam	6 hour	4.37 inches	1000 year
	10 day	16.13 inches	>1000 year
Peak Discharges			
Location	**Q100 (FEMA)**	**Measured**	**Return Int. (FEMA)**
North St. Vrain Crk.	4310 cfs	12,300 cfs	>500 year
Little Thompson R.	2585 cfs	7800 cfs	>500 year



TYPICAL EMBANKMENT ARMORING SECTION BEDROCK AT EXISTING GROUND



TYPICAL EMBANKMENT ARMORING SECTION BEDROCK 5' OR LESS BELOW EXISTING GROUND



Rockery
Rockery
Project
Input
Plot
Bishop
Report
Reset
H_r = 12.00 ft
γ_R
D = 3.00 ft
B = 7.30 ft
Retained Soil:
γ_s = 138 pcf
ϕ = 38 °
C = 100.0 psf
Other Parameters:
A = 0.0

Question…

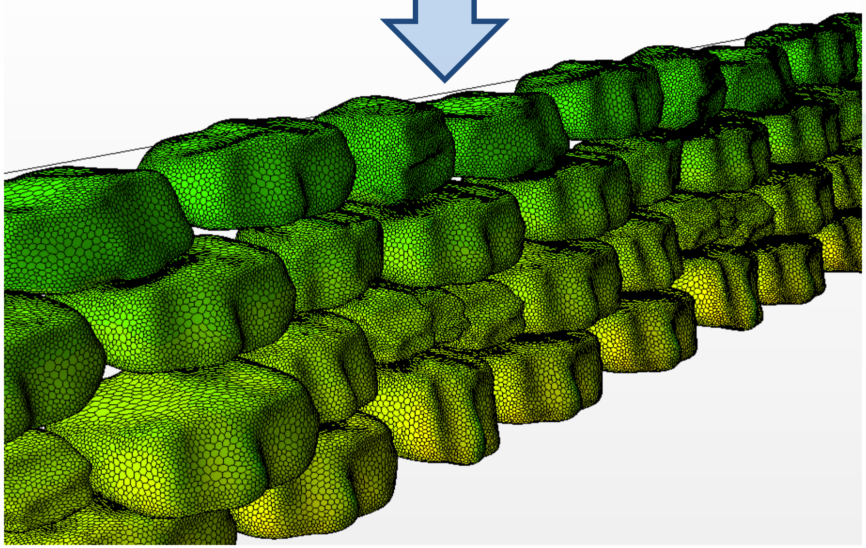
- If large, loose rock riprap (e.g. D50 = 3’; D100 = 5.5’) is theoretically unstable when placed on a 1:1 slope of a river bank, can same rock be stable when stacked in a near-vertical orientation (i.e. a dry-stack rockery wall at the river bank)?

- Knowledge gap for hydraulics and geotech
- Design guidance needed for riverine and coastal applications
- Enter TRACC of Argonne National Laboratory and technical assistance thru CFD Modeling…

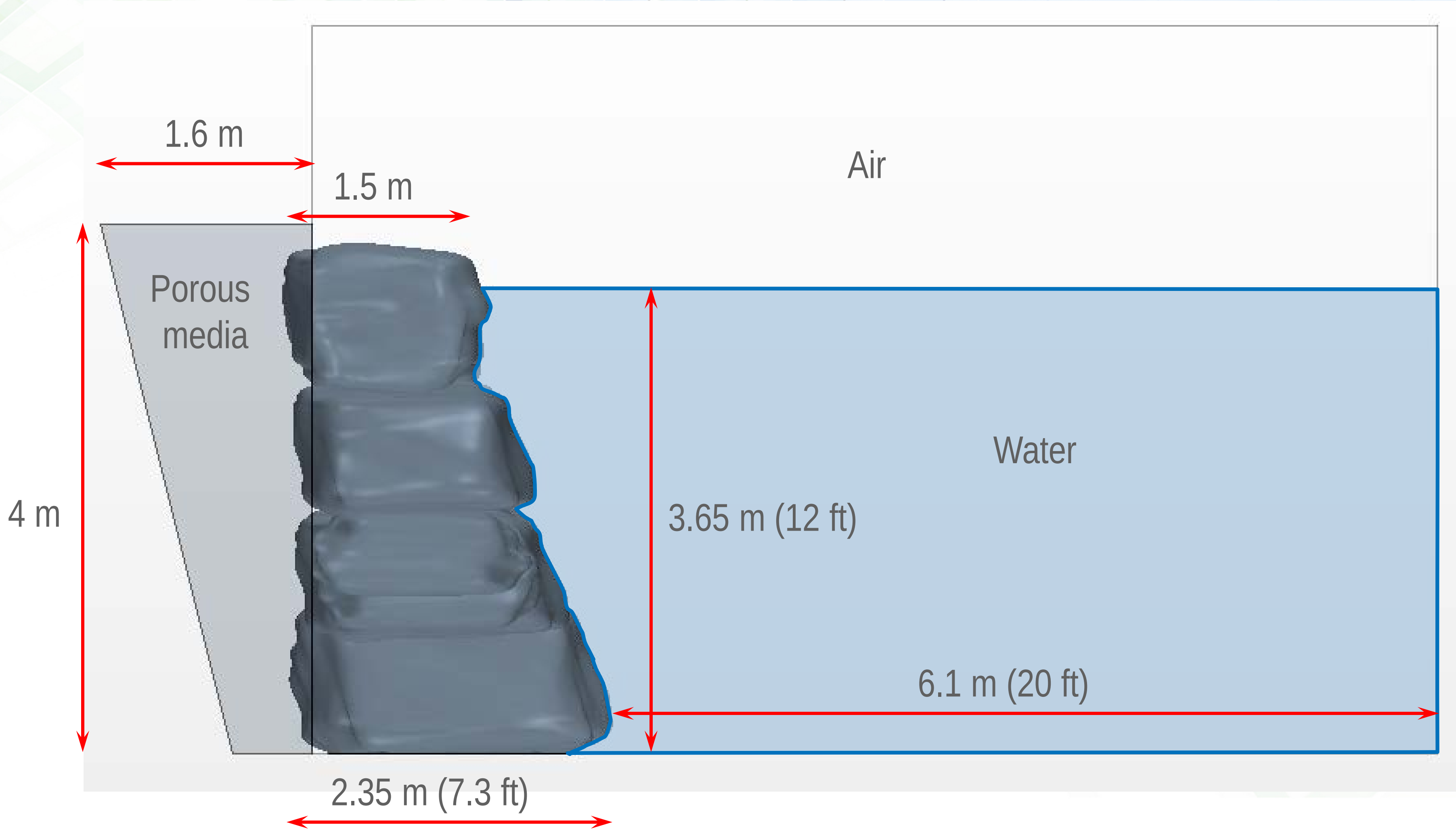
Part II: CFD modeling

Cezary Bojanowski

Steven Lottes

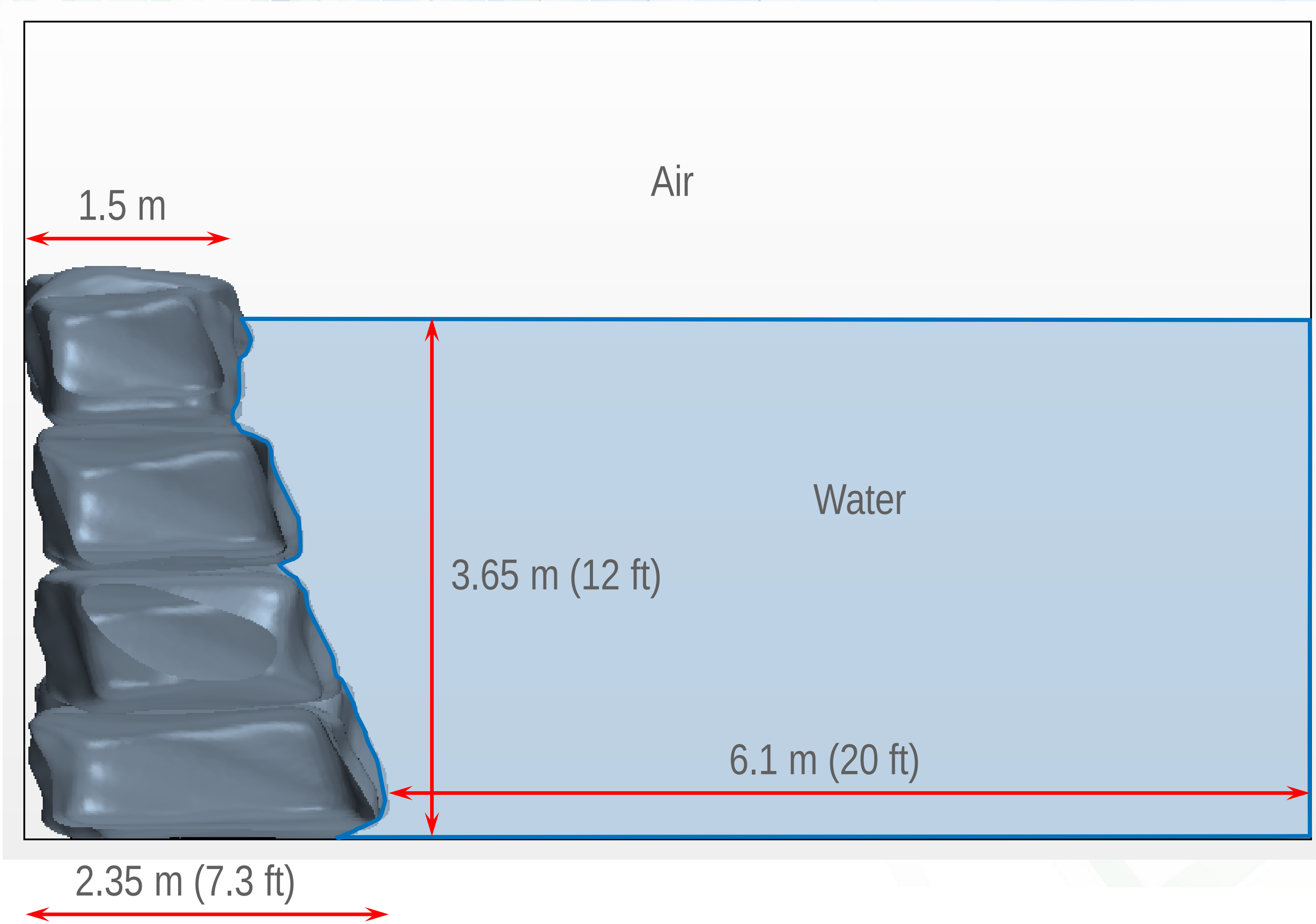


Geometry of the base model - Case 1

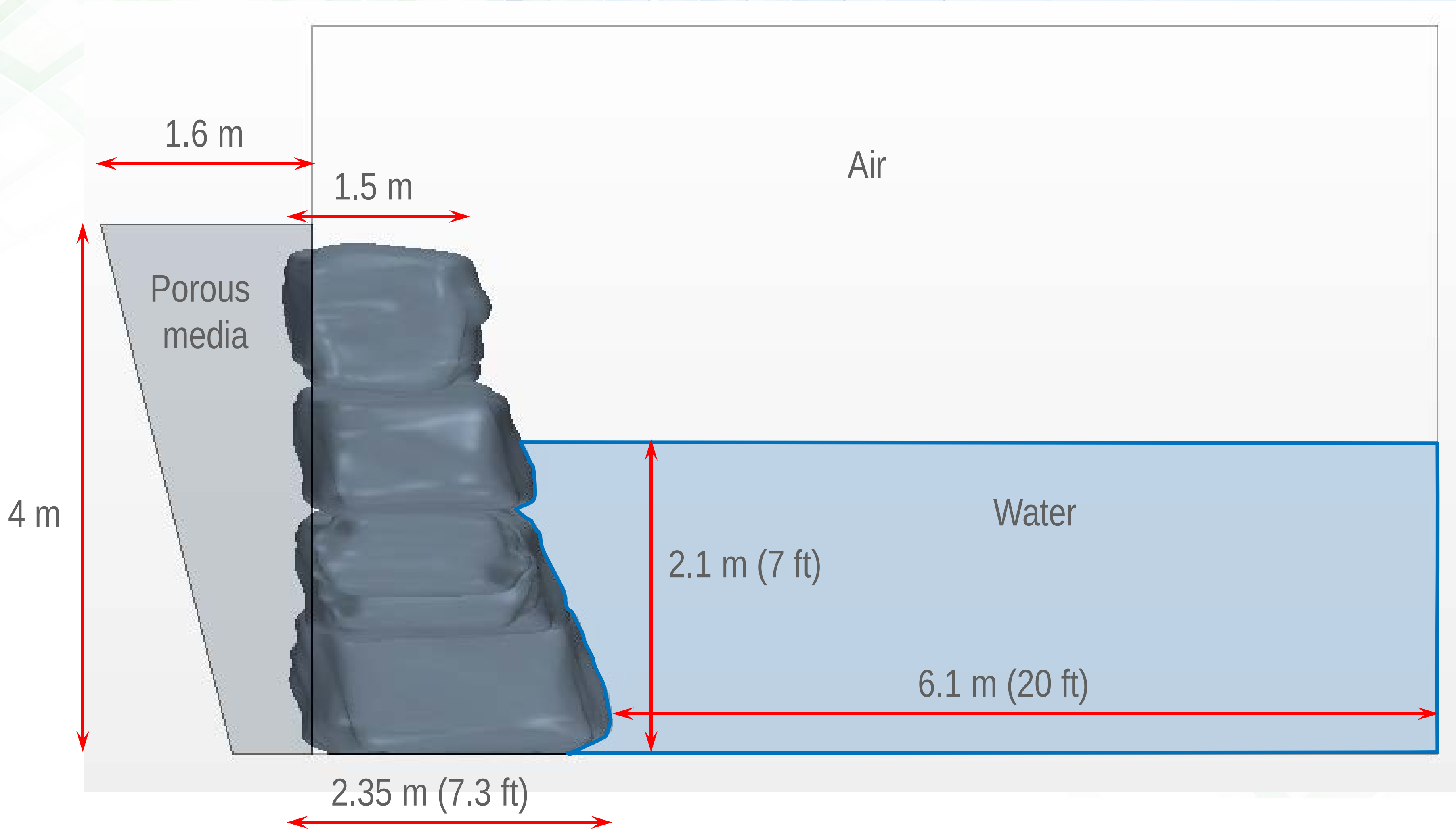


Geometry of the model without filler - Case 2, 3

No porous media
+
More space for the flow



Geometry of the base model - Case 4



Analyzed cases

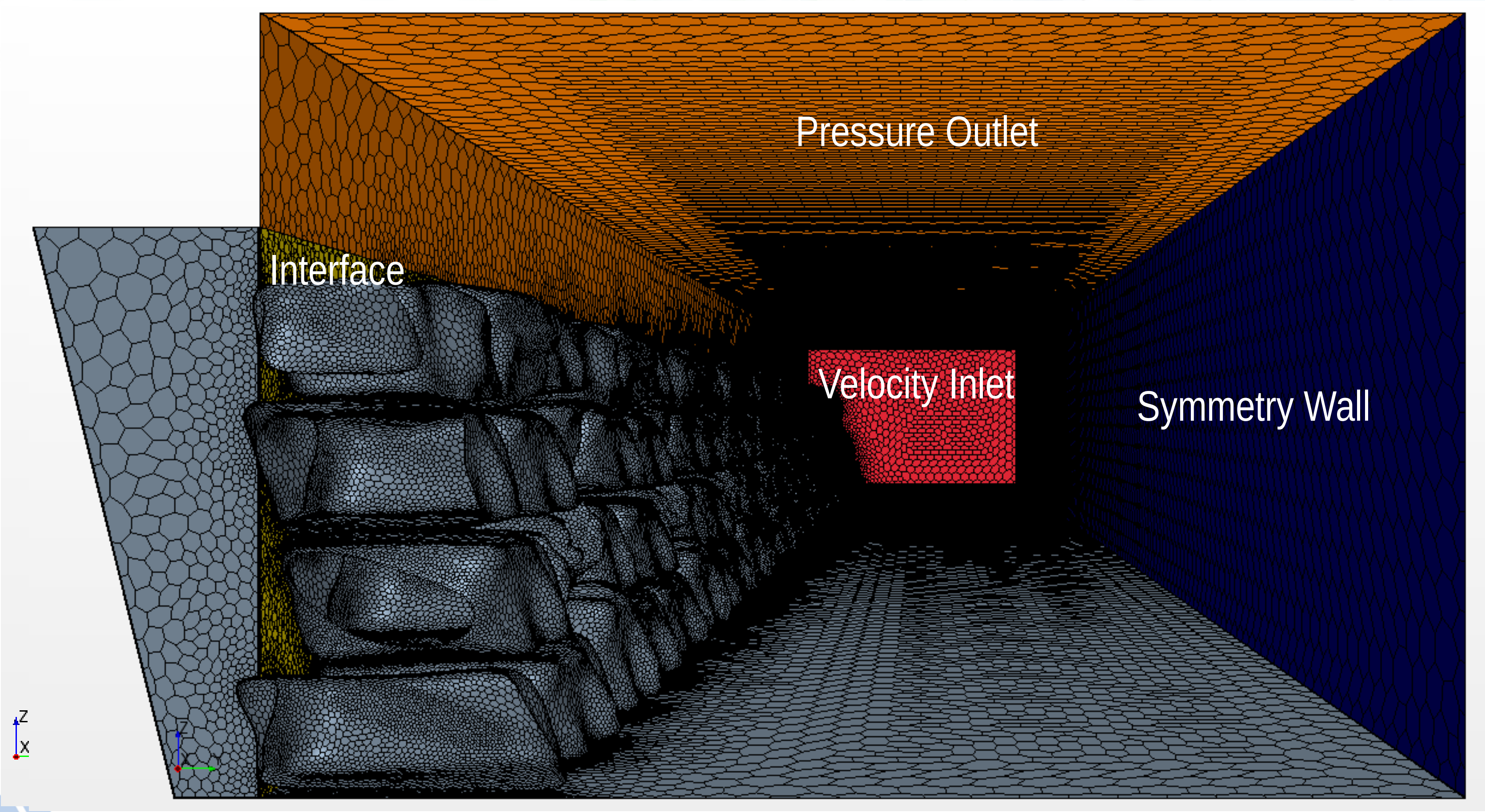
- Analyzed basic cases:

Case No.	Water height	Inlet velocity	Angle at inlet	Filler model
1	12 ft	4.25 m/s 14 ft/s	0 deg	Porous media
2	12 ft	4.25 m/s 14 ft/s	0 deg	Void + Wall
3	12 ft	4.25 m/s 14 ft/s	20 deg	Void + Wall
4	7 ft	3.5 m/s 11.5 ft/s	0 deg	Porous media
5	7 ft	3.5 m/s 11.5 ft/s	0 deg	Void + Wall

- Additionally, following cases were run:
  - Curved wall model
  - Rocks protruding into the flow
  - Scaled rocks

Volume mesh on the base model

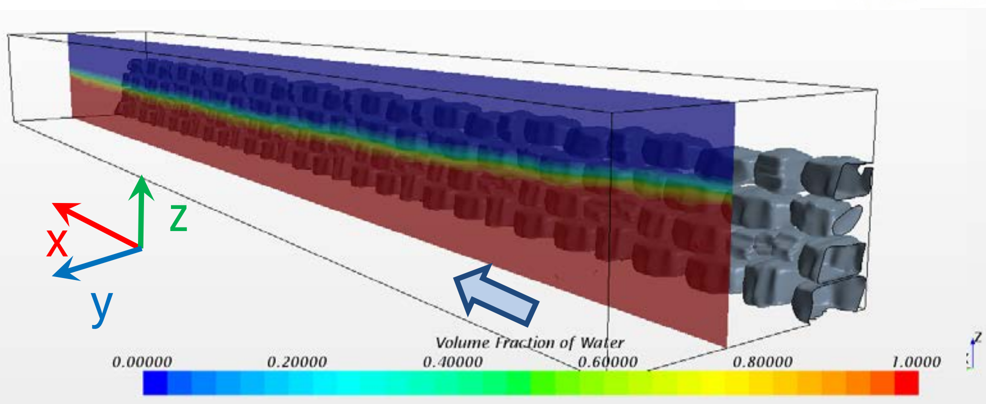
- 1.5 M - 5.2 M polyhedral cells (denser mesh around the rocks)
- Length of the model 50 m
- Unsteady Reynolds Averaged Navier Stokes model with k-epsilon turbulence and Volume of Fluid



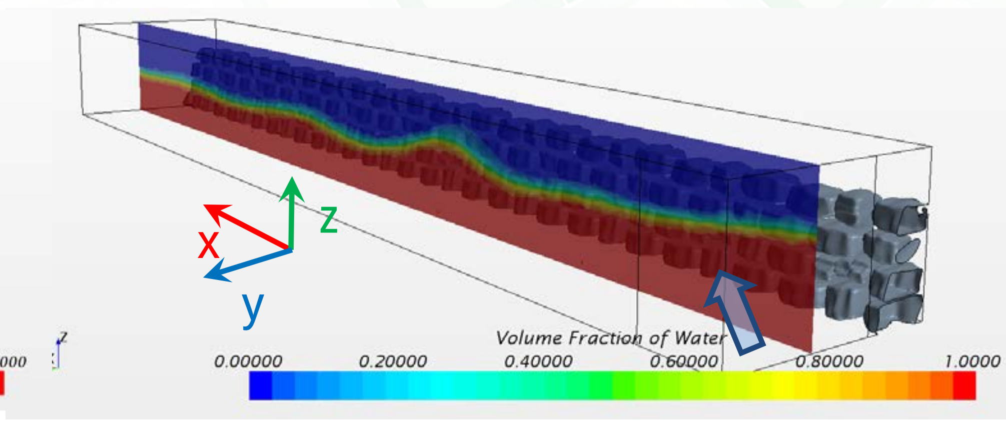
Volume fraction of water in computational cell

- The model for free surface flow tracking in CFD terminology is called volume of fluid (VOF).
- It may be sensitive to the time step of calculations and it requires careful initialization of the simulation.
- The time step of calculations was set to 0.1 s.
- The simulations were run for 100+ seconds (depending on the case) until stable results were obtained.

Case 2

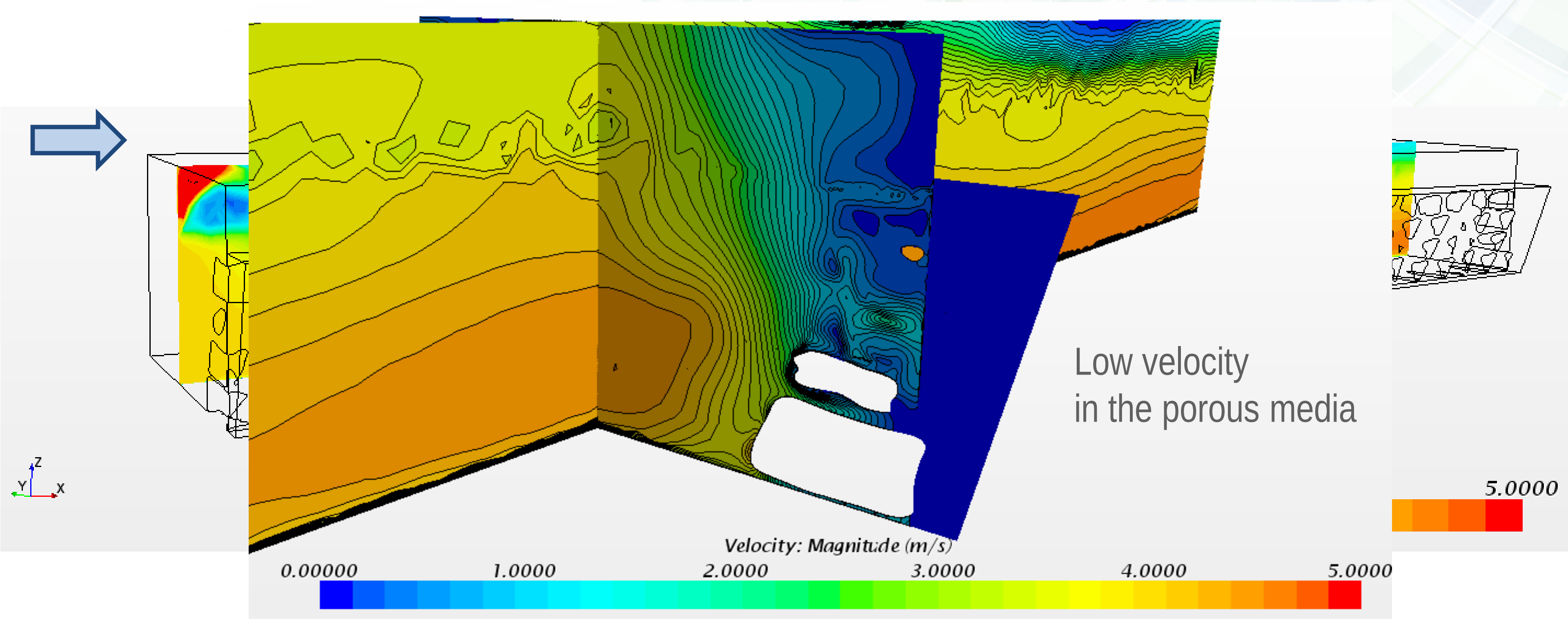


Case 3



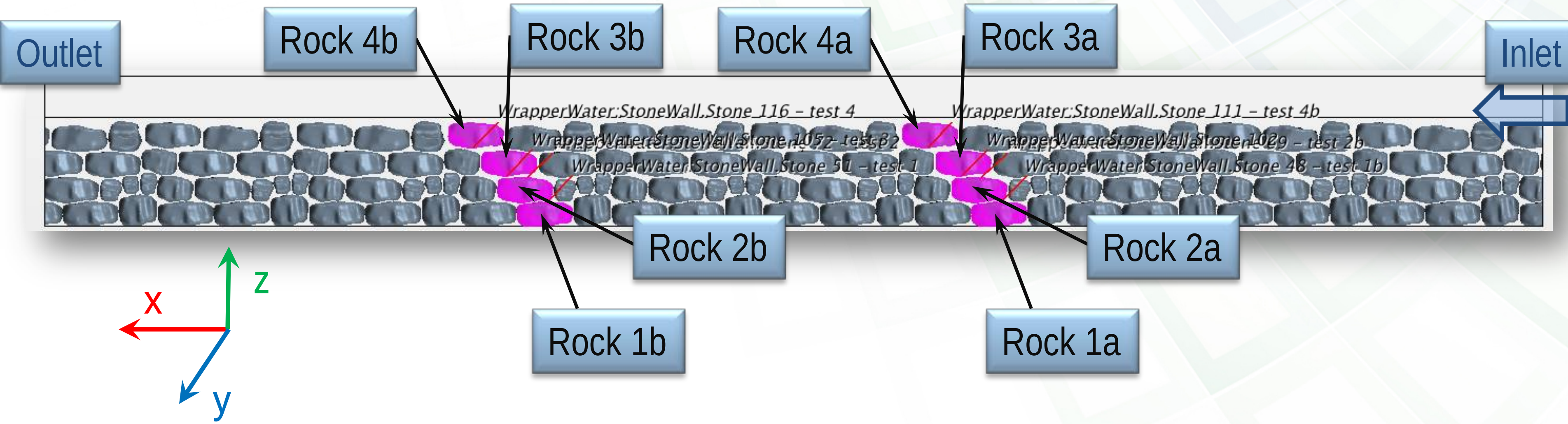
Velocity

- Porous media model averages the properties of the filler.
- Flow velocities in the porous media model are usually very low as compared to the main flow.
- More conservative results can be obtained if there is a narrow void behind the rocks ending at a rough continuous wall that allows for some flow.



Location of rocks of interest

- The rocks of interest have the same frontal area i.e. projection on XZ plane
- Having the same XZ projection allows for comparison of the forces normal to the flow (Y force).
- Their projection in YZ plane is different due to the slope of the wall.
- Forces on the rocks at two locations are compared.



- Positive X force means along the flow
- Positive Y force means a force pulling the rock into the flow
- Positive Z force means an upward force

Dry weight of rocks of interest

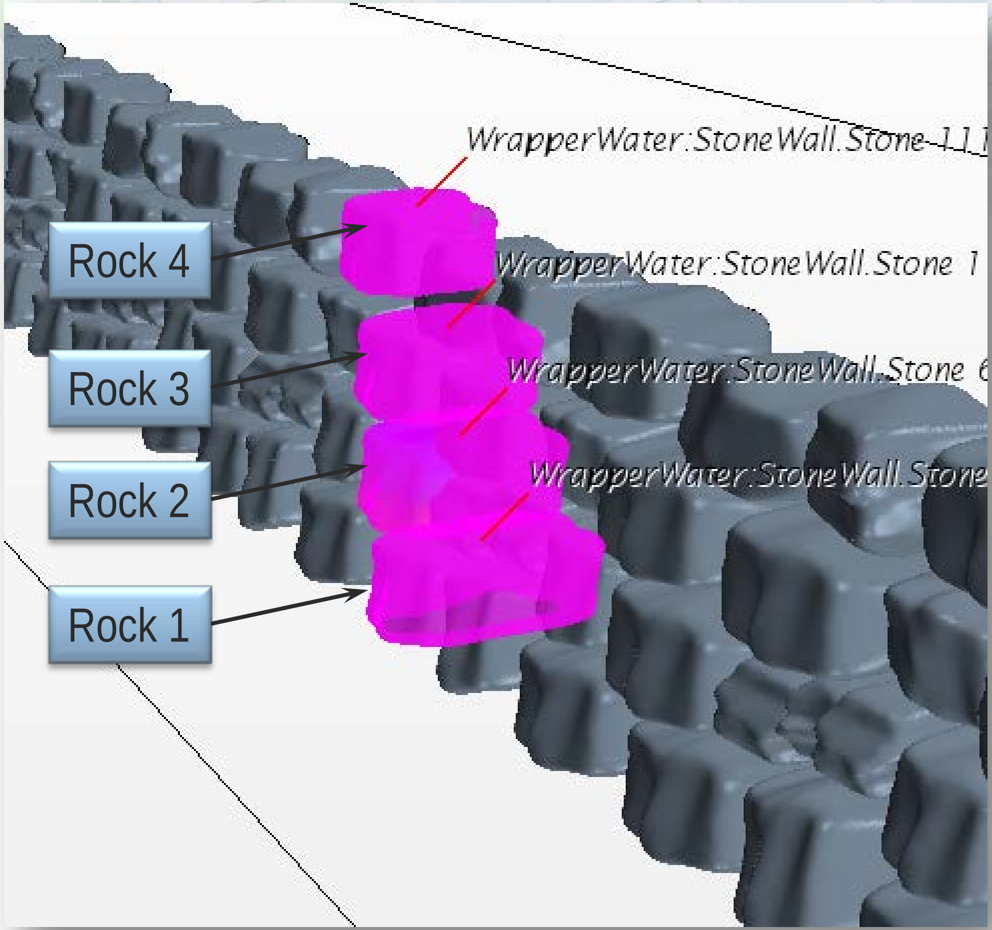
Weight = V * rho * g = Vol * 2,500 kg/m^3 * 9.81 m/s2
Submerged Weight = V * (rho$_s$ - rho$_w$) * g = Vol * 1,500 kg/m^3 * 9.81 m/s^2

- Weight of rock 4 = 45,000 N
- Volume of rock 4 = 1.83 m^3

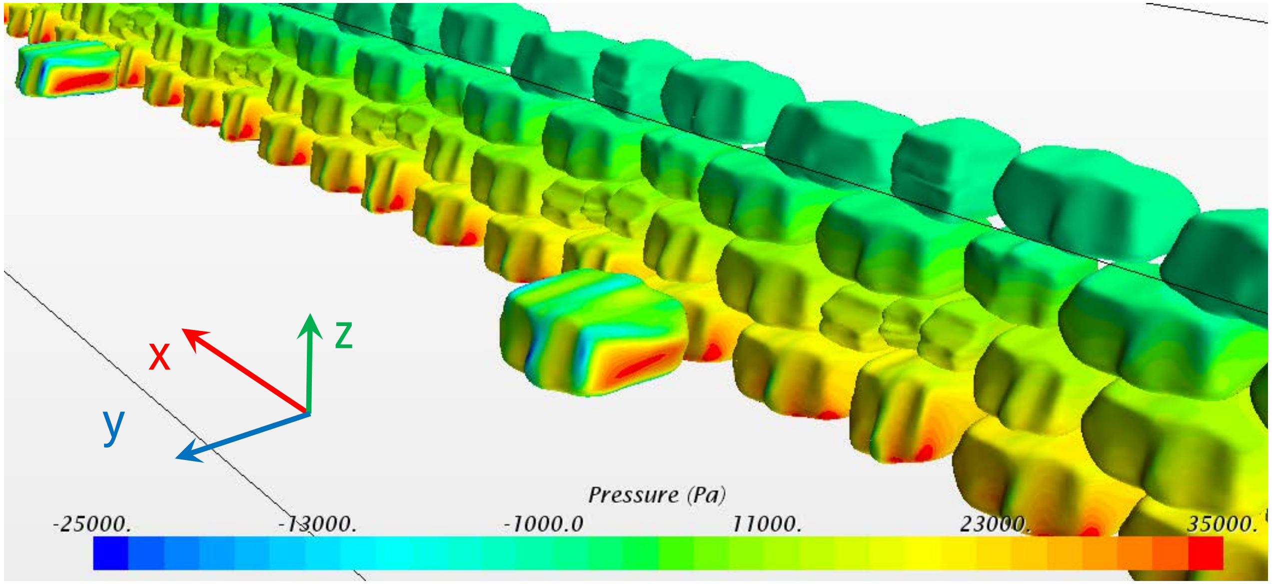
- Weight of rock 3 = 54,900 N
- Volume of rock 3 = 2.24 m^3

- Weight of rock 2 = 62,600 N
- Volume of rock 2 = 2.55 m^3

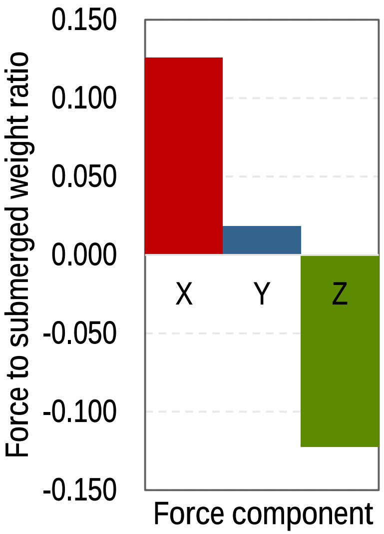
- Weight of rock 1 = 71,800 N
- Volume of rock 1 = 2.92 m^3



Hydrodynamic forces on a single rock in the flow

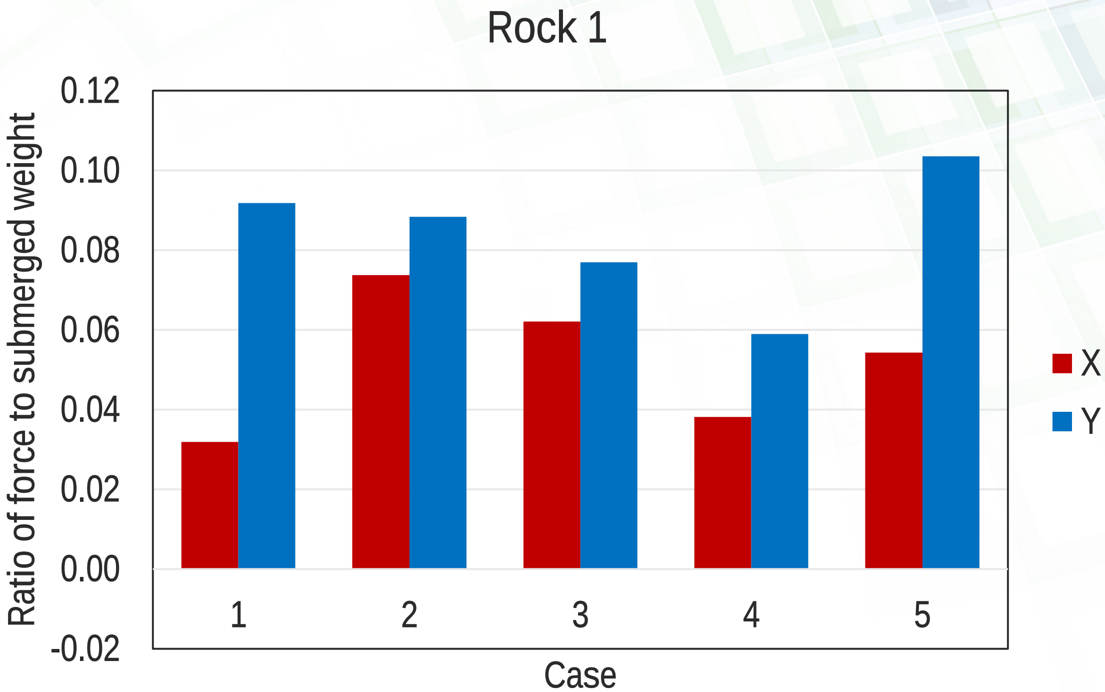


- Overall Z force consists of the following components:
  - Weight
  - Buoyancy
  - Drag
  - Contact forces
- Z force from CFD consists of TWO only:
  - Buoyancy
  - Drag
- Presented graphs show only the drag component (the hydrodynamic components only)

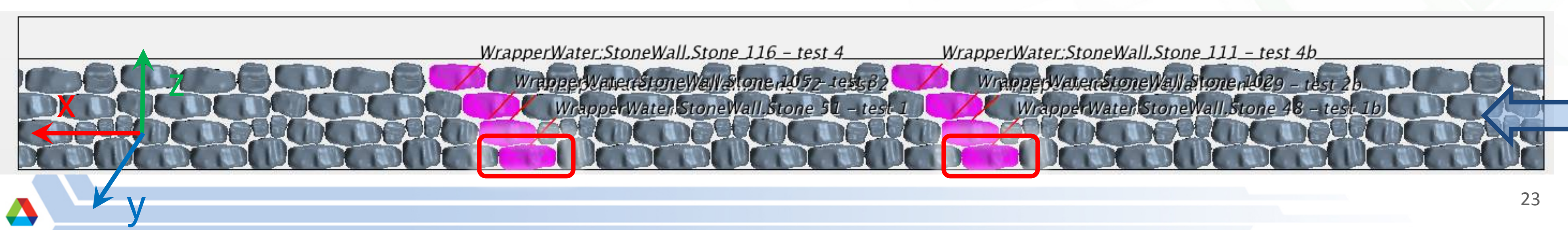


Forces on Rock 1a and 1b

- Rock 1 is partially buried so the Z force is not included because pressure integration over bottom surface can't be done.
- Dry weight of rock 1 = 71,800 N

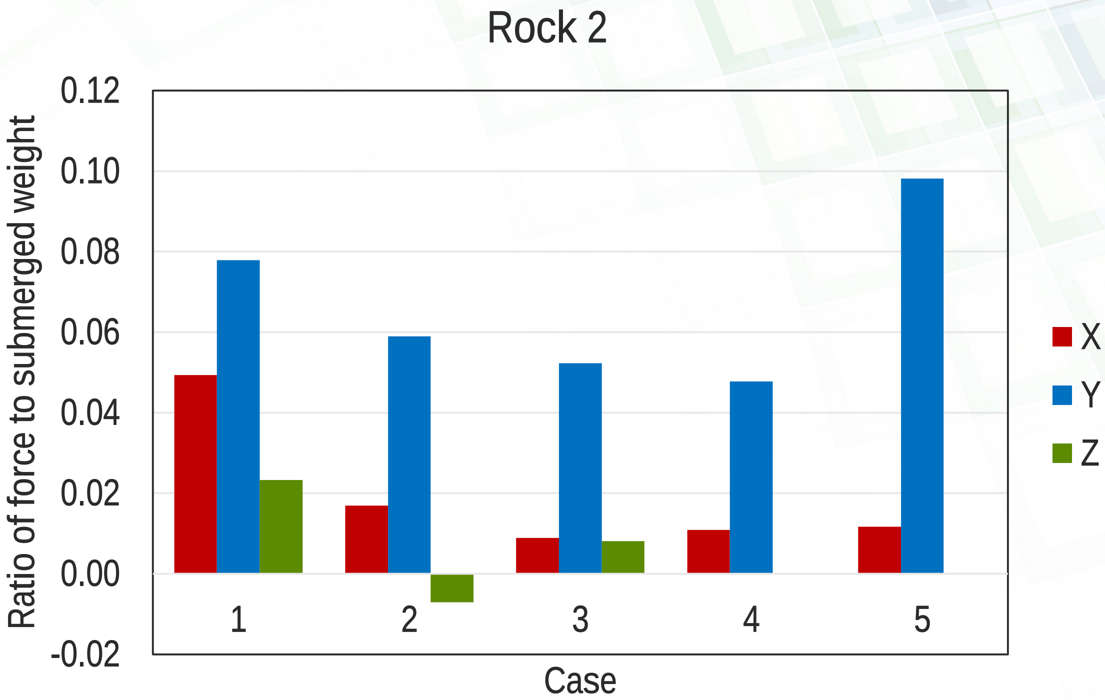


Case No.	Water height	Inlet velocity	Filler model
1	12 ft	14 ft/s	Porous
2	12 ft	14 ft/s	Void
3	12 ft	14 ft/s @20 deg	Void
4	7 ft	11.5 ft/s	Porous
5	7 ft	11.5 ft/s	Void

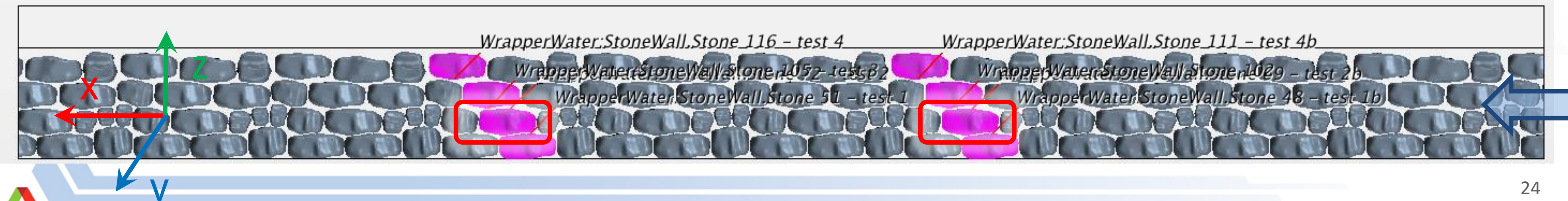


Forces on Rock 2a and 2b

- The simulations are transient causing the forces tend to fluctuate by a small amount as waves pass.
- Dry weight of rock 2 = 62,600 N

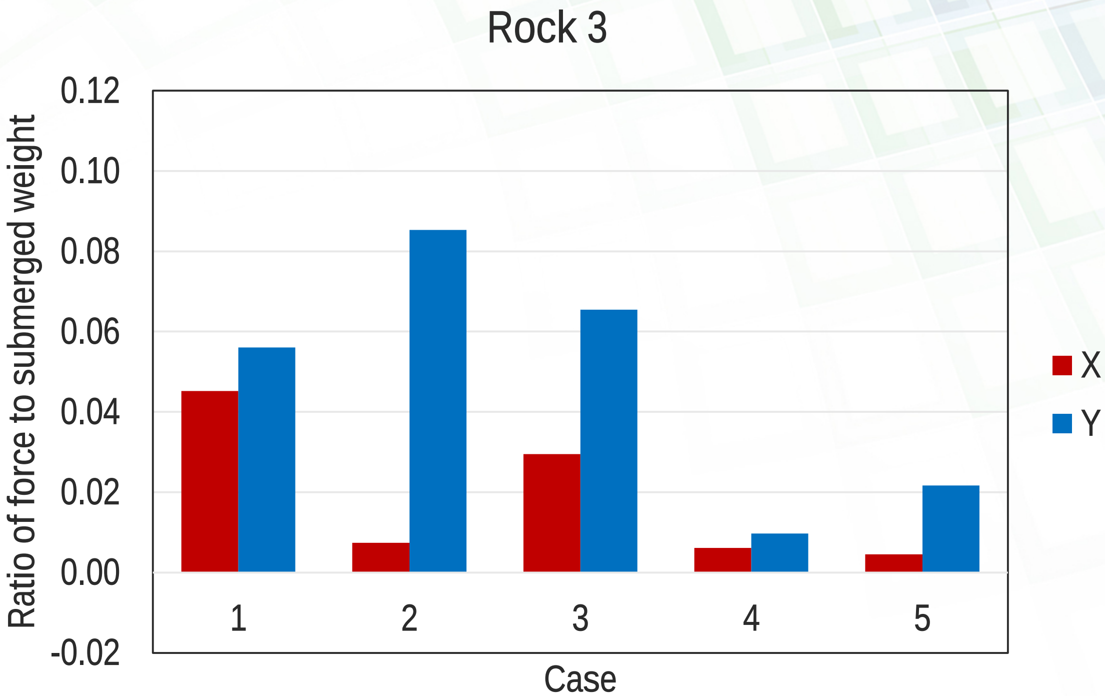


Case No.	Water height	Inlet velocity	Filler model
1	12 ft	14 ft/s	Porous
2	12 ft	14 ft/s	Void
3	12 ft	14 ft/s @20 deg	Void
4	7 ft	11.5 ft/s	Porous
5	7 ft	11.5 ft/s	Void

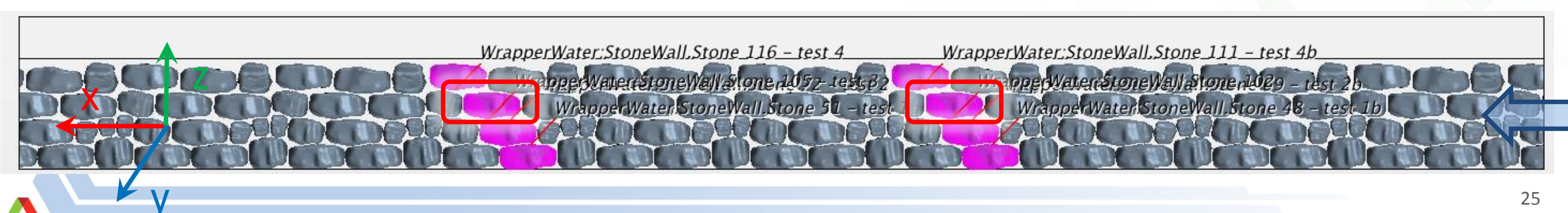


Forces on Rock 3a and 3b

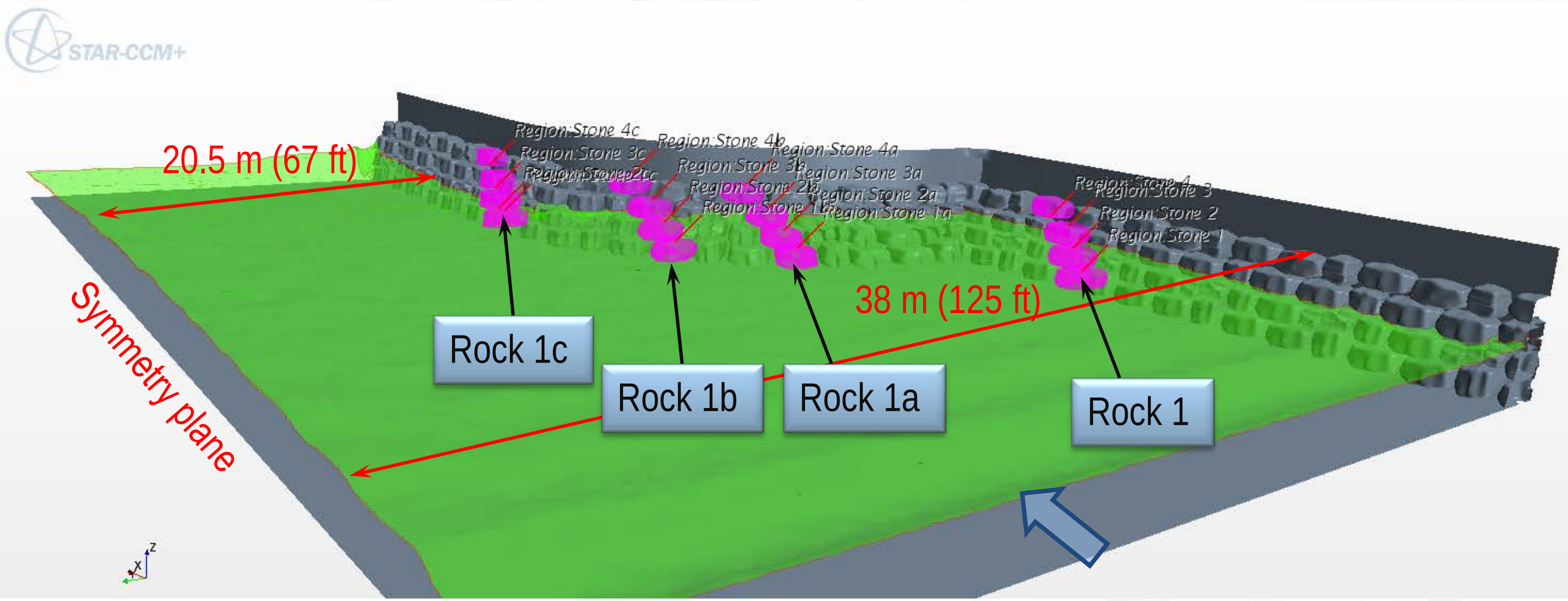
- Rock 3 is only partially covered with water in cases 4 and 5, Rock 4 is dry in these cases
- Dry weight of rock 3 = 54,900 N



Case No.	Water height	Inlet velocity	Filler model
1	12 ft	14 ft/s	Porous
2	12 ft	14 ft/s	Void
3	12 ft	14 ft/s @20 deg	Void
4	7 ft	11.5 ft/s	Porous
5	7 ft	11.5 ft/s	Void

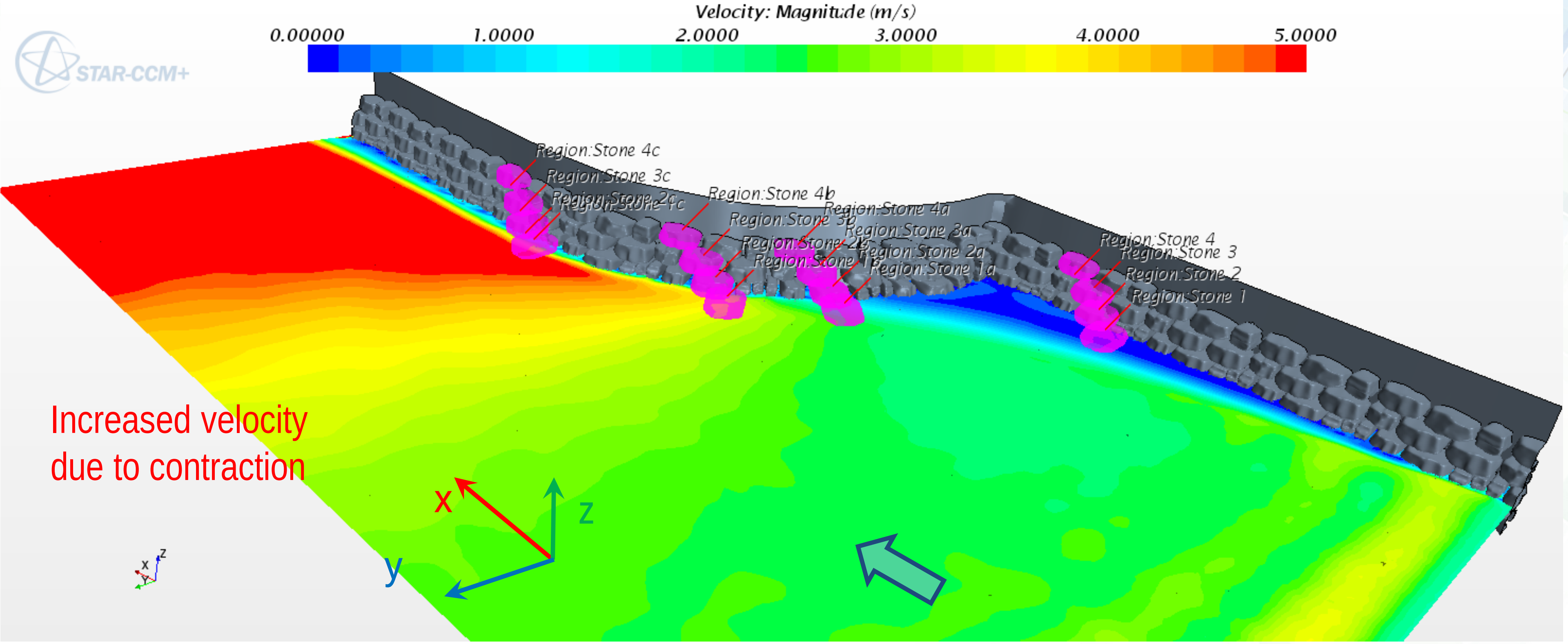


Simulations with curved wall model

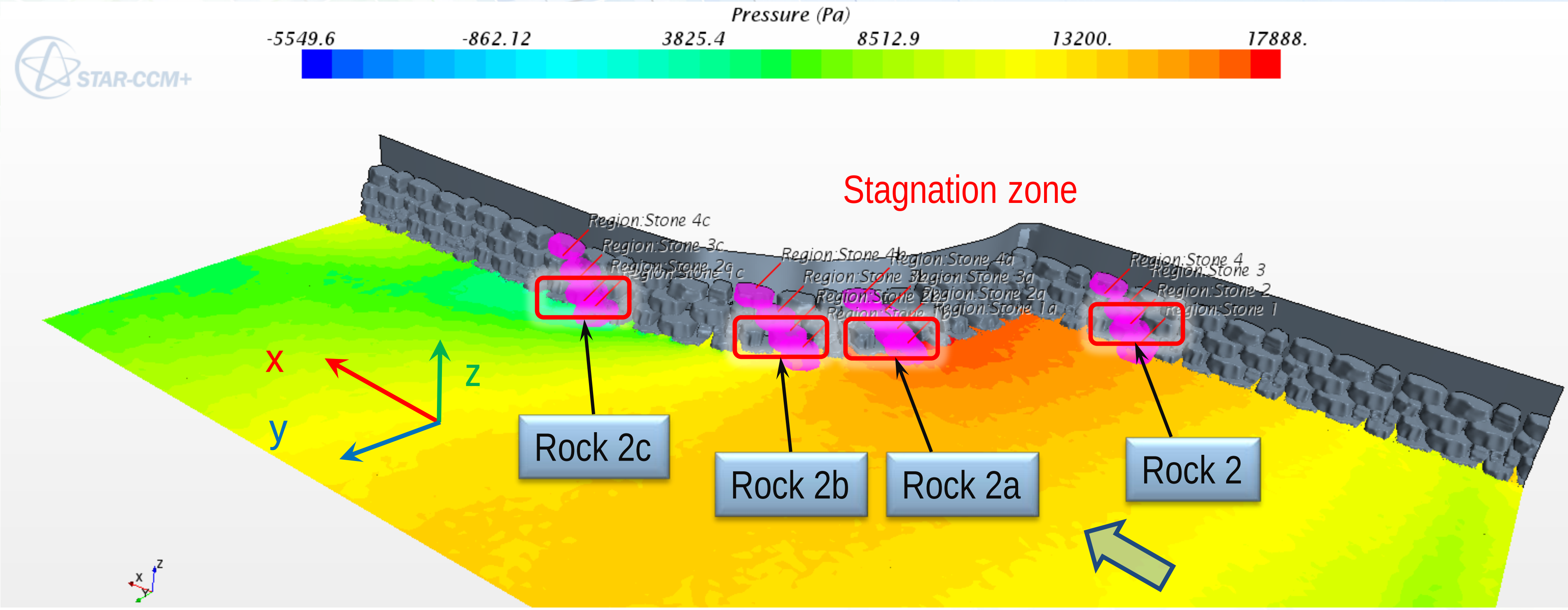


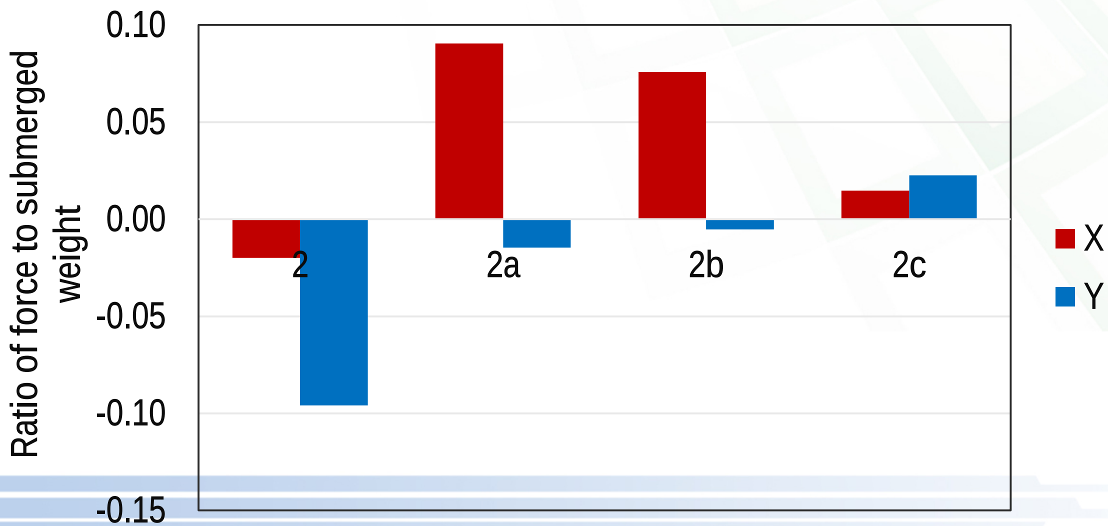
Curved wall model - velocity

- Inlet velocity is set to 2 m/s
- The velocity in the contracted zone increases to 6 m/s

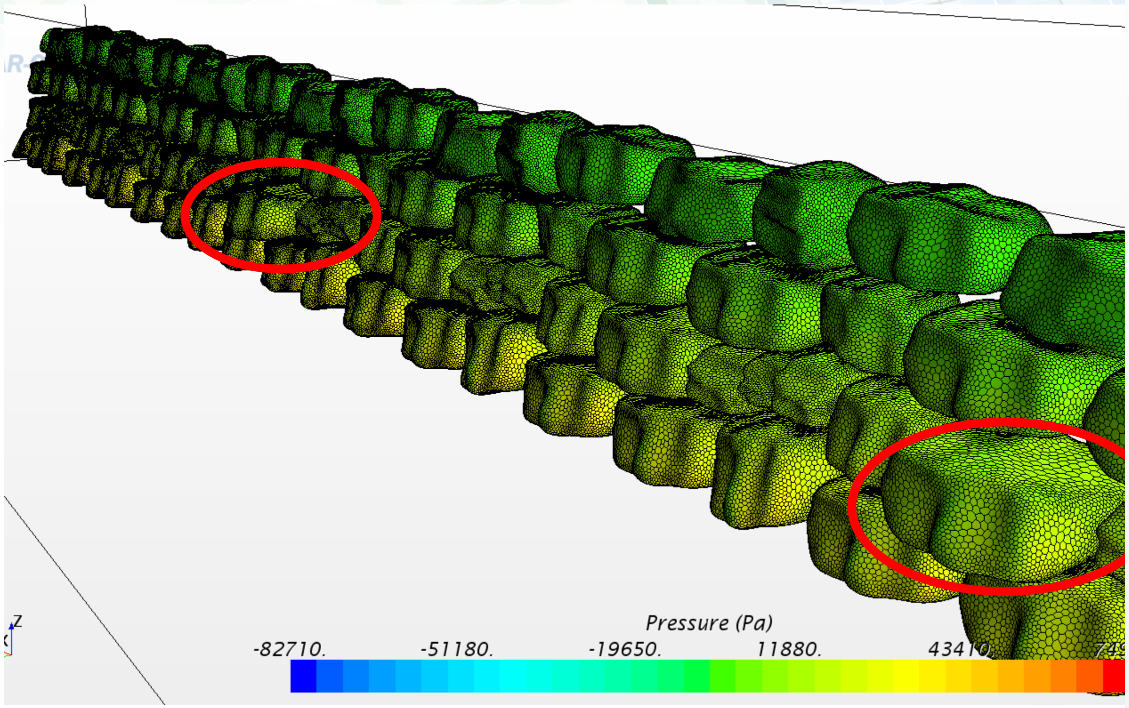


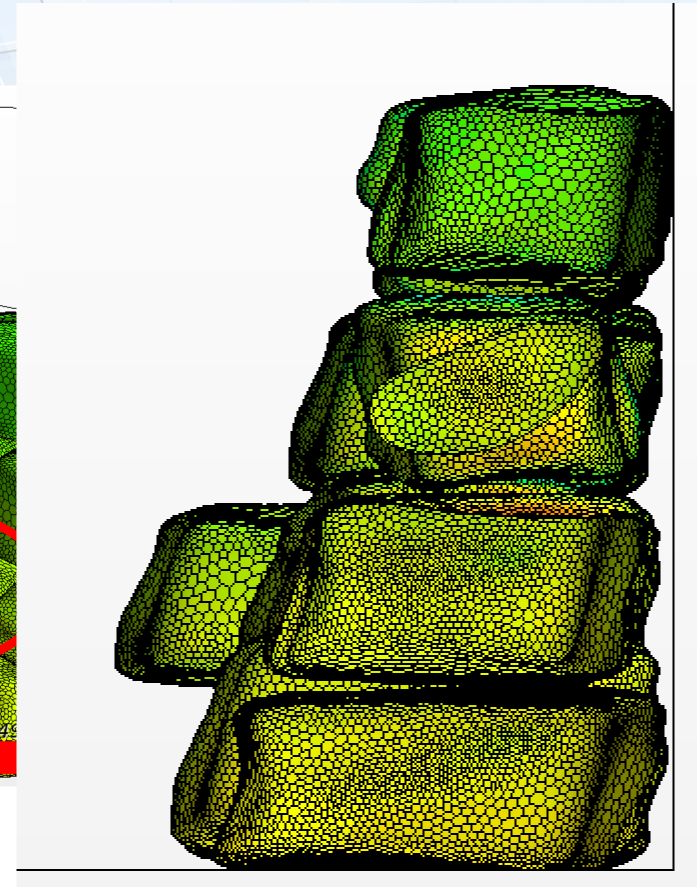
Curved wall model - pressure

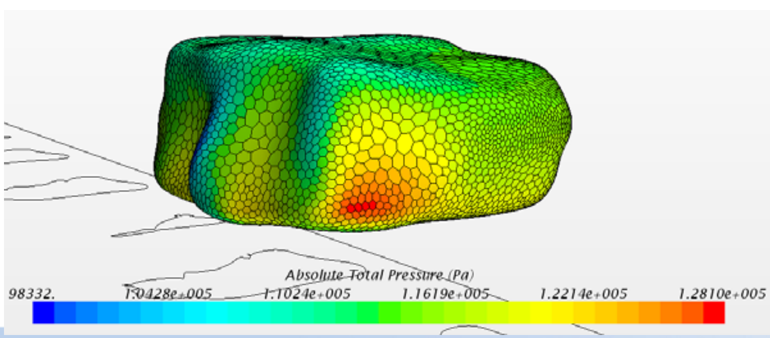




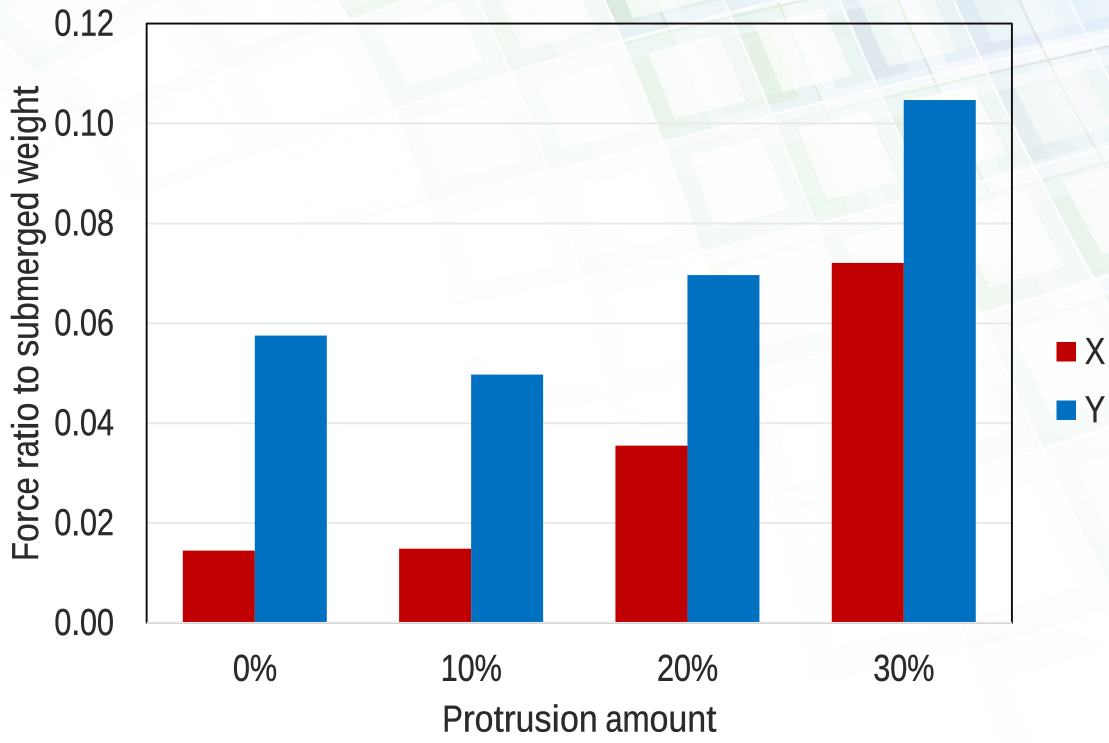
Simulations with rocks protruding into the flow 10, 20, and 30 % of depth (0.6 m =~2 ft)

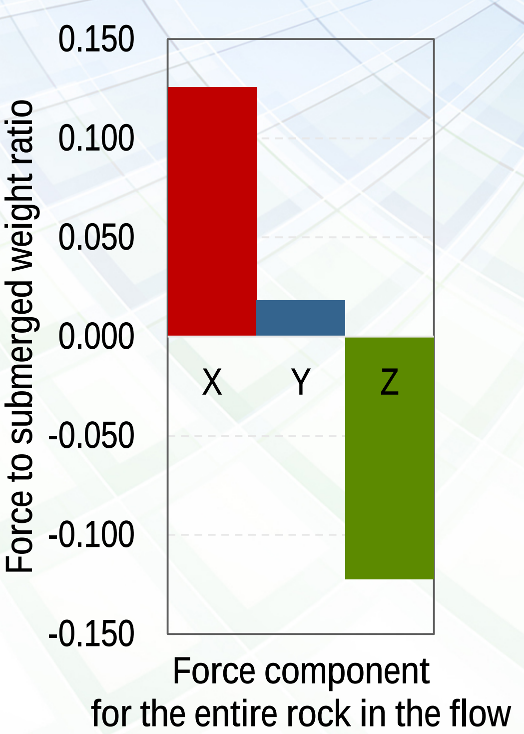






Simulations with rocks protruding into the flow





Simulations with scaled geometry

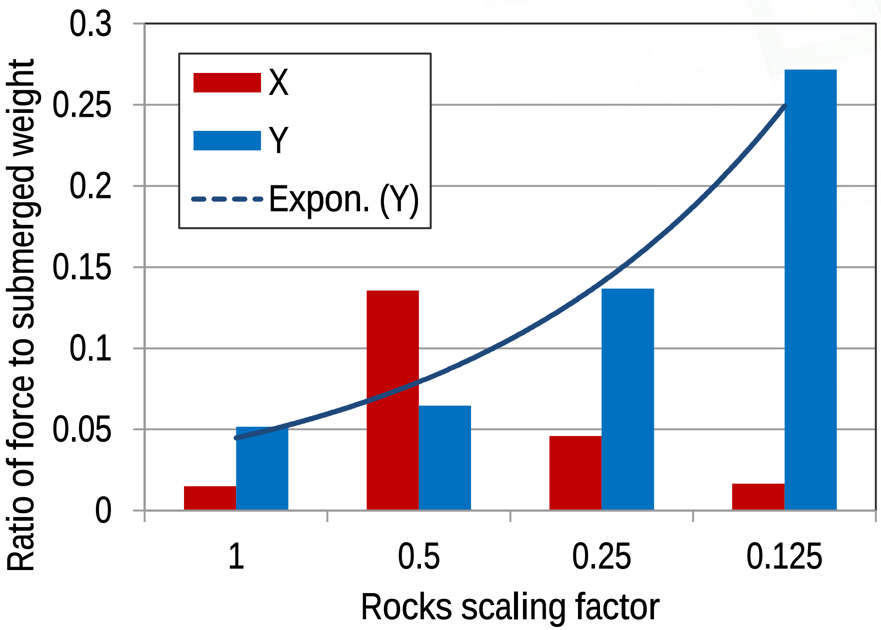
- The rocks have been scaled down in size 2, 4, and 8 times in each direction
- The volume (and mass) decreased 8, 64, and 512 times

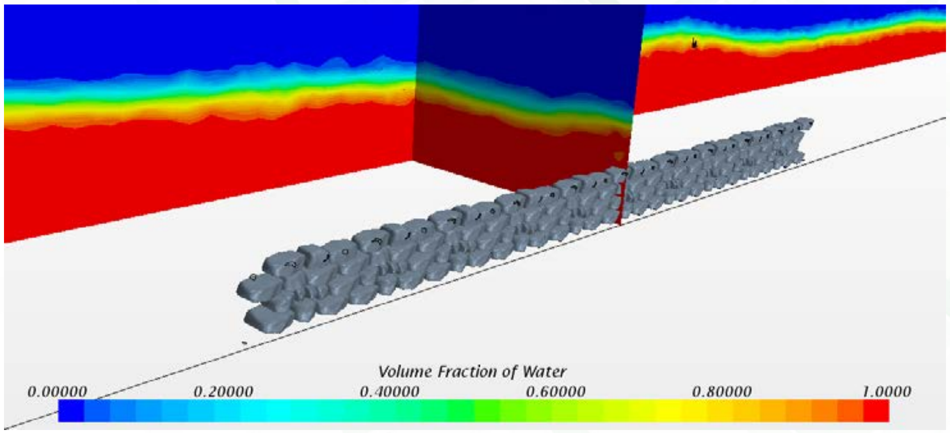
Scale factor	Volume factor	Mass (kg)	Characteristic size (m)
1.0	1.0	6400	2 x 2 x 1
0.5	0.125	800	1 x 1 x 0.5
0.25	0.015625	100	0.5 x 0.5 x 0.25
0.125	0.001953125	12.5	0.25 x 0.25 x 0.125

- The rock size has changed but the domain size and conditions did not.
- Similar mesh settings were preserved to keep the Y+ at similar level.
- Initial runs were with Y+ = 150 , new meshes have been built to lower it down to about 50

Results ratio of X and Y force to the weight

- The ratio was averaged over six rocks of the same size at the same height.
- There is no clear trend for X force.
- For the Y force an increasing ratio was expected.
- The ratio of the Y force to weight varies from **0.05** to **0.27** for the smallest rocks (12.5 kg or 25 lb)





Summary

- For the basic cases the lateral (Y) force ratio to the submerged weight of the rock varies from 0.05 to 0.11.
- The streamwise (X) component ratio has a lot more variation but is usually below 0.1.
- The depth at which the rock is placed influences slightly the lateral (Y) force ratio. If it is buried or partially submerged the ratio will vary.
- Curved wall setup didn't increase these forces.
- Protrusion of a rock into the flow will increase the ratios but even 30% of protrusion didn't cause the ratio to go significantly above 0.1.
- For the scaled rocks the Y force components grow with the decreasing size. For smaller rocks (1 ft x 1 ft x 0.5 ft) the ratio can be even up to 0.27.

Thank you!

Extra slides

Initial Conditions

Case (1) 12ft of water

$W := 20\ ft$ $\quad L := 12\ ft$

$W = 6.096\ m$ $\quad L = 3657.6\ mm$

$S := 0.023$ $\quad k := 1$ $\quad n := 0.05$

$R := \frac{L \cdot W}{W + 2 \cdot L} \cdot \frac{1}{m}$ $\quad R = 1.6625$

$V := \frac{k}{n} \cdot R^{\frac{2}{3}} \cdot S^{\frac{1}{2}} \frac{m}{s}$ $\quad \boxed{V = 4.2567\ \frac{m}{s}}$

Froude Nuber

$v_1 := 4.25\ \frac{m}{s}$ $\quad g := 9.81\ \frac{m}{s^2}$ $\quad d := 12\ ft$

$Fr := \frac{v_1}{\sqrt{g \cdot d}}$ $\quad \boxed{Fr = 0.7095}$

Case (2)7ft of water

$W := 20\ ft$ $\quad L := 7\ ft$

$W = 6.096\ m$ $\quad L = 2133.6\ mm$

$S := 0.023$ $\quad k := 1$ $\quad n := 0.05$

$R := \frac{L \cdot W}{W + 2 \cdot L} \cdot \frac{1}{m}$ $\quad R = 1.2551$

$V := \frac{k}{n} \cdot R^{\frac{2}{3}} \cdot S^{\frac{1}{2}} \frac{m}{s}$ $\quad \boxed{V = 3.5291\ \frac{m}{s}}$

Froude Nuber

$v_1 := 3.5\ \frac{m}{s}$ $\quad g := 9.81\ \frac{m}{s^2}$ $\quad d := 7\ ft$

$Fr := \frac{v_1}{\sqrt{g \cdot d}}$ $\quad \boxed{Fr = 0.765}$