Three Dimensional Computational Fluid Dynamics Analysis to Determine Flow Capacity of an ADA Compliant Street Drain Grate

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Problem Background

- Urban road preservation projects often require improvements to the pedestrian ramps in order to be ADA compliant.
- Existing storm drain catch basins are frequently located near the existing cross-walks and may be impacted by the improvements. In some cases, the existing catch basin is in the pedestrian access route and the grate must be replaced with an ADA compliant grate.
- ADA compliant grates have a lower hydraulic capacity than the current standard MnDOT grates, but the exact capacity is unknown for on-grade locations.

- Problem: Determine ADA compliant grate hydraulic capacity

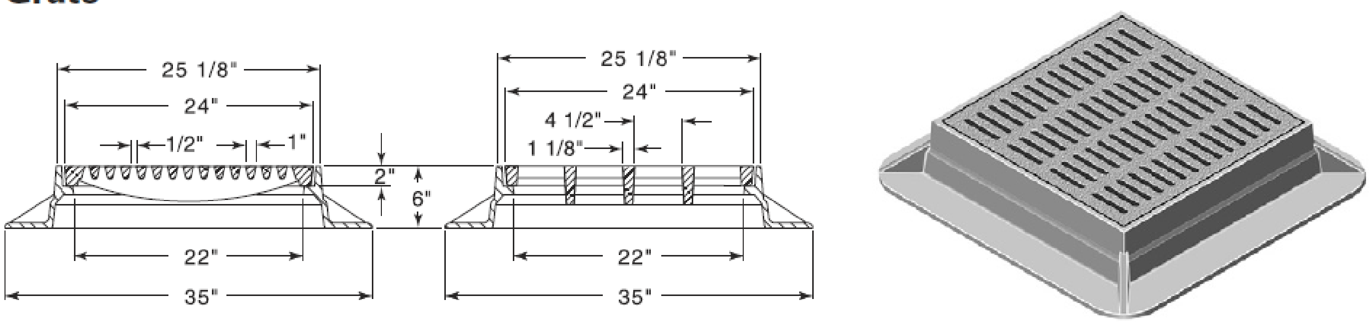
- Traditional flume testing of grate capacity uses conditions and geometry that do not correspond completely to full scale street conditions
- 3D CFD analysis of flow through grates can be done at full scale with a variety of specified geometry arrangements
- Many CFD tests can be run for varying geometry and conditions at relatively low cost.

ADA Compliant Grate and Vane Grate Used as a Basis for Comparison

ADA Compliant Grate

R-3210-Q
Catch Basin Frame, Grate

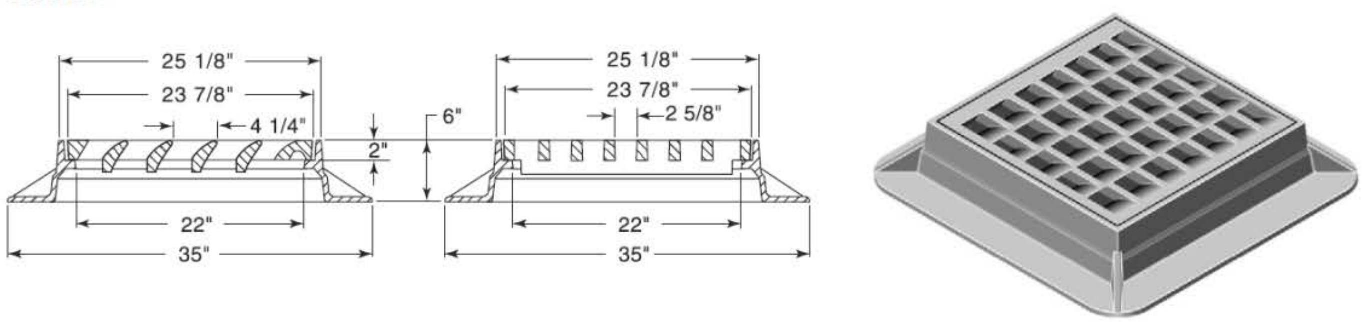
Heavy Duty



Vane Grate

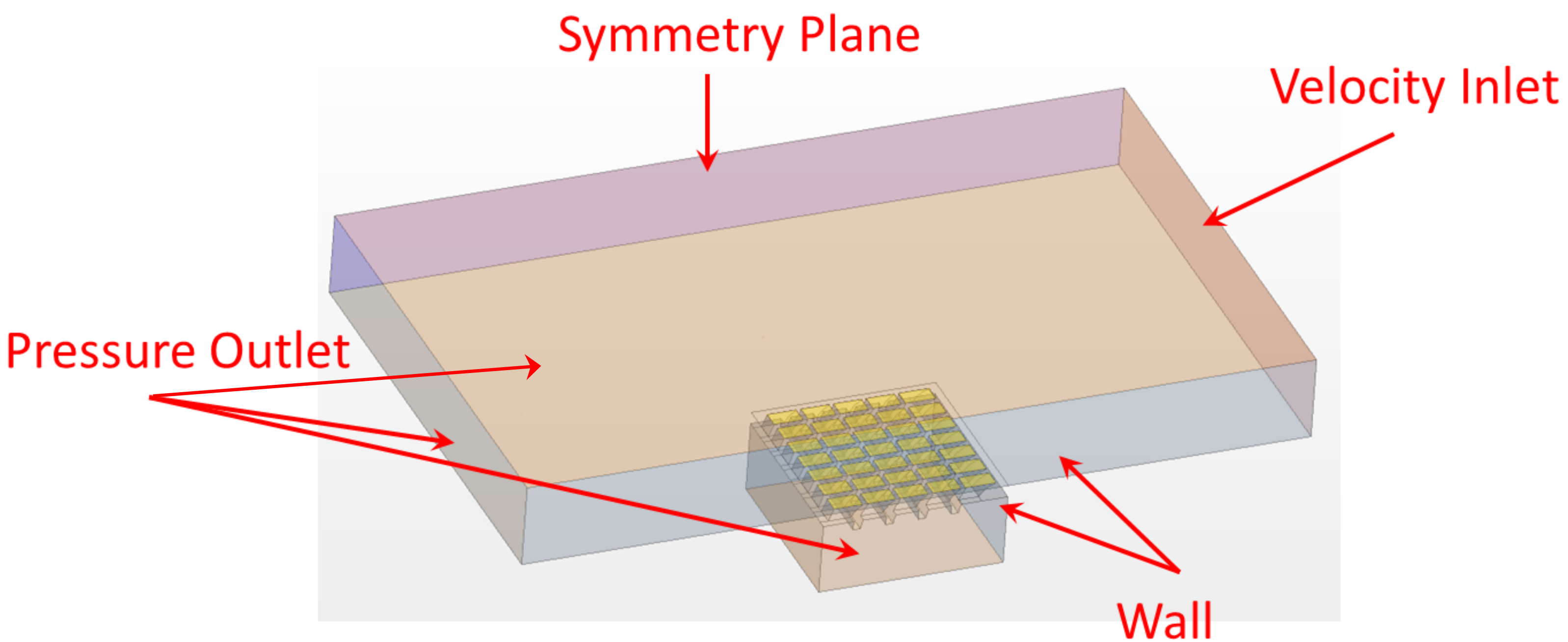
R-3210-L
Catch Basin Frame, Grate

Heavy Duty

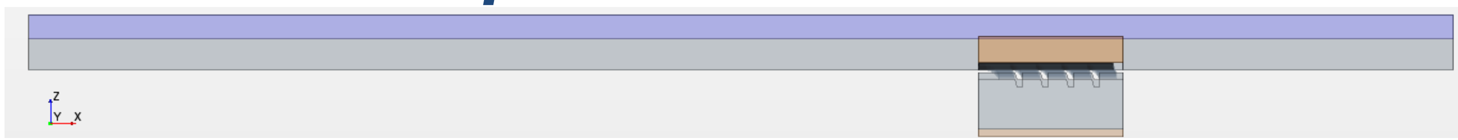


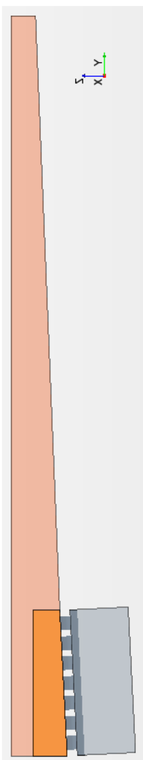
CFD Approach to Determining Grate Performance

- Uses volume of fluid (VOF) physics model
  - Multiphase model (air and water)
  - Keeps track of free surface (including surface tension, etc.)
- Build geometry for grates, catch basin, and street in CAD software
- Generate an adequately refined computational mesh
- Solve partial differential equations (PDEs) governing flow as a boundary value problem that gives fraction of flow entering the catch basin as part of the solution

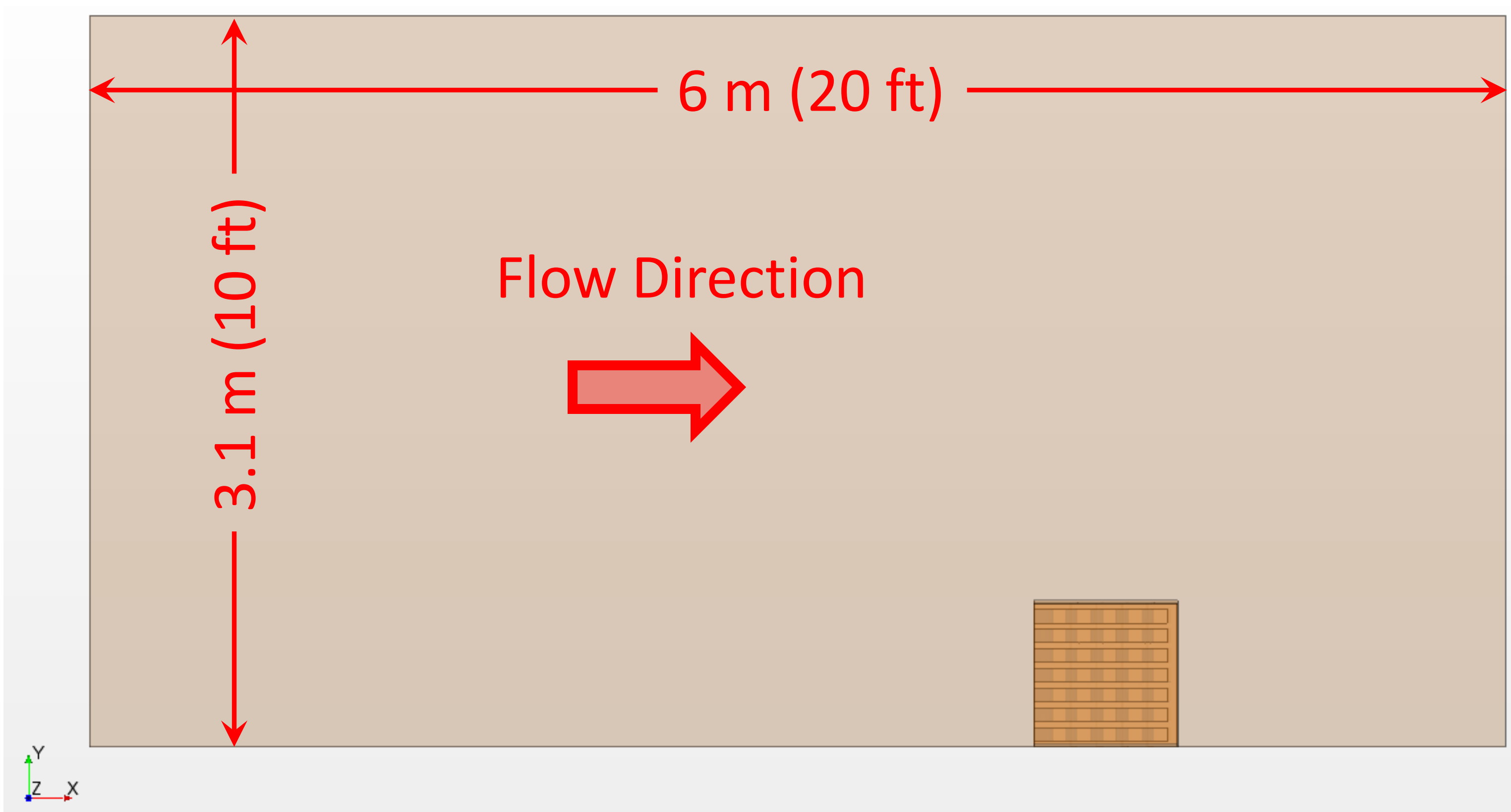


A Typical Extent of the Computational Domain in the CFD models - with space for air above



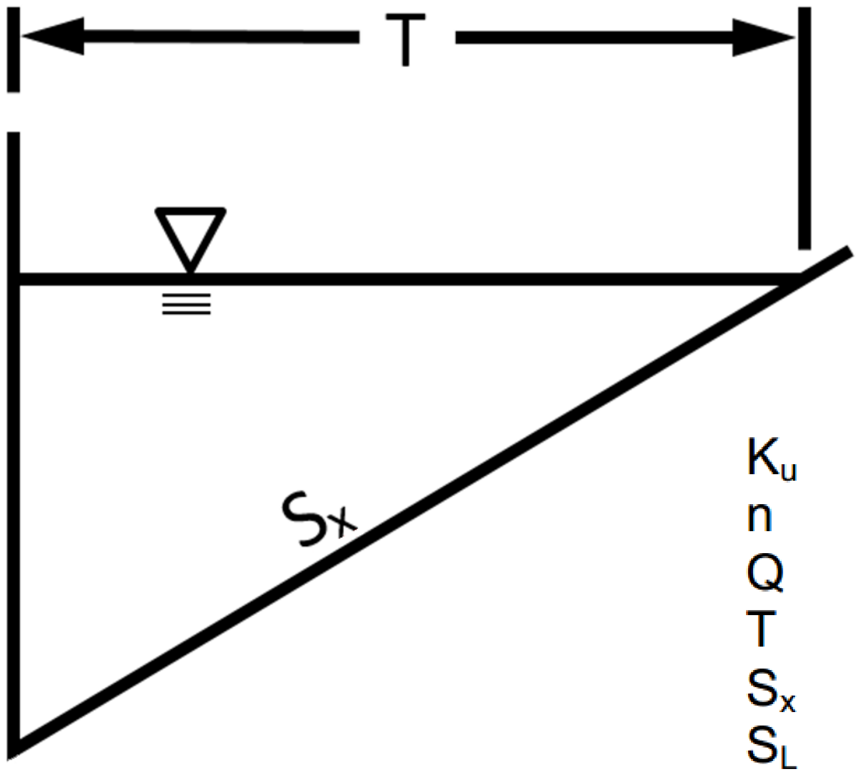


0.23 m (9 in)



CFD Needs the Boundary Conditions (Upstream inlet velocity and street surface roughness height)

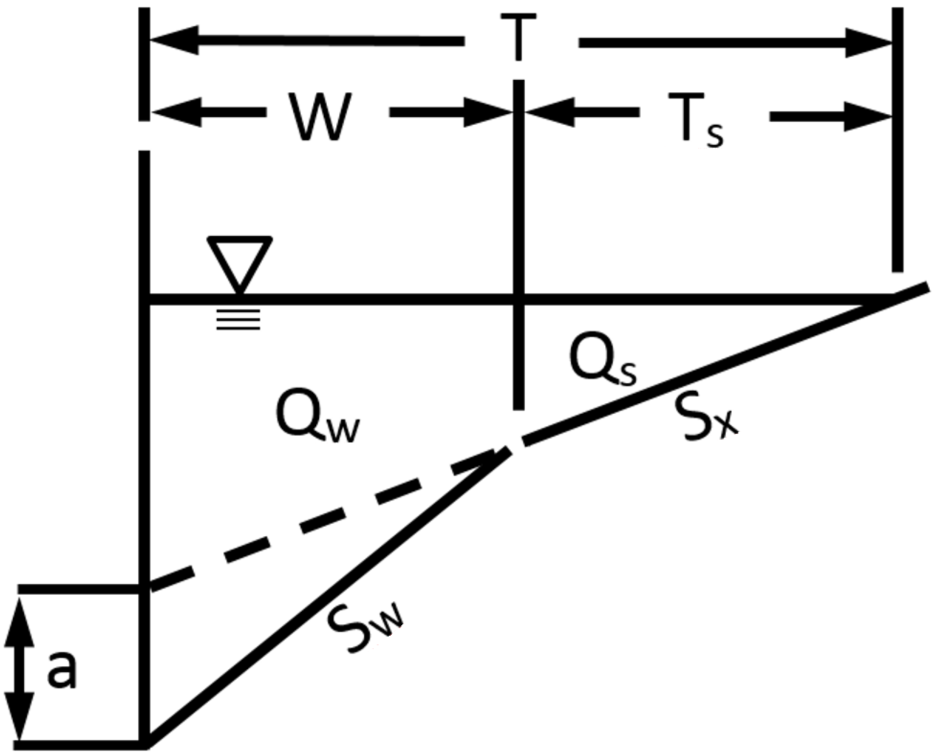
- Use HEC-22 (Urban Drainage Design Manual) equations (4-2 through 4-6 to get volume flow rate Q for street geometry and water spread)
- Then use inlet cross section area to get inlet velocity V from Q



$$Q = \left(\frac{K_u}{n}\right) S_x^{1.67} S_L^{0.5} T^{2.67}$$

K_u	=	0.376 (0.56 in English units)
n	=	Manning's coefficient (Table 4-3)
Q	=	Flow rate, m^3/s (ft^3/s)
T	=	Width of flow (spread), m (ft)
S_x	=	Cross slope, m/m (ft/ft)
S_L	=	Longitudinal slope, m/m (ft/ft)

Volume Flow for Compound Street and Gutter from HEC-22



$$Q = Q_s/(1 - E_0)$$

$$E_0 = \left(1 + \frac{\frac{S_w}{S_x}}{\left(\frac{1 + \frac{S_w}{S_x}}{\frac{T}{W} - 1}\right)^{2.67} - 1}\right)^{-1}$$

Q_w = Flow rate in the depressed section of the gutter, m^3/s (ft^3/s)
Q = Gutter flow rate, m^3/s (ft^3/s)
Q_s = Flow capacity of the gutter section above the depressed section, m^3/s (ft^3/s)
E_o = Ratio of flow in a chosen width (usually the width of a grate) to total gutter flow (Q_w/Q)
S_w = $S_x + a/W$ (figure 4-1 a.2)

Cases

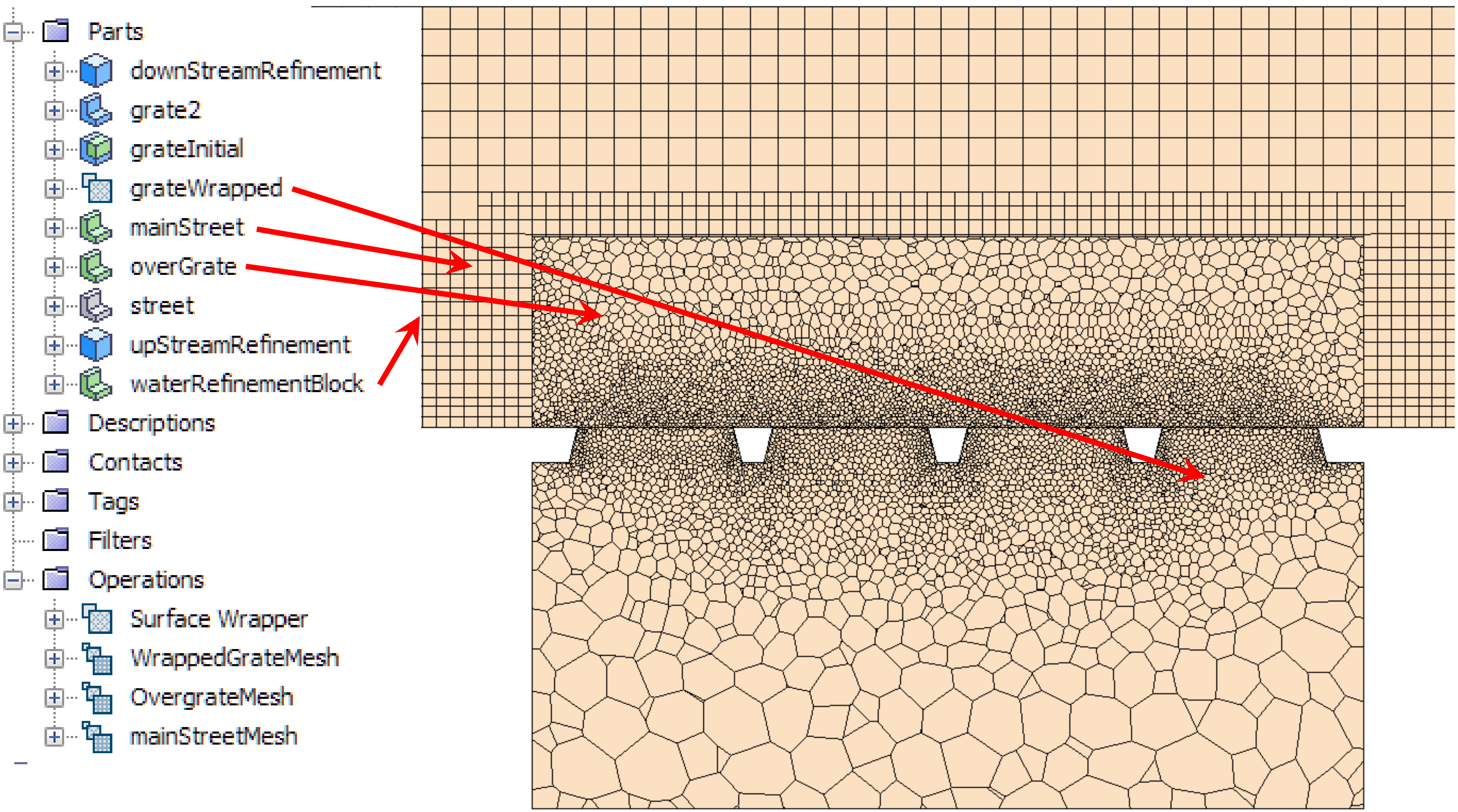
Gutter Width (ft)	Gutter Cross-Slope	Pavement Width for Spread (ft)	Pavement Cross-Slope
2	0.04	8	0.04
2	0.04	6	0.04
2	0.04	6	0.02

Longitudinal Street Slope	0.003	0.005	0.01	0.03	0.05

Additional Gutter Cross-slopes of 0.02 and 0.05 for both grates at longitudinal slope = 0.01

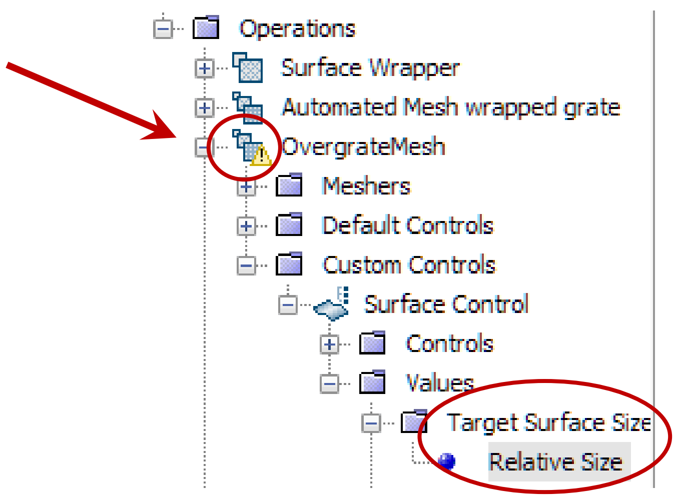
Plus a few additional cases run to confirm trends

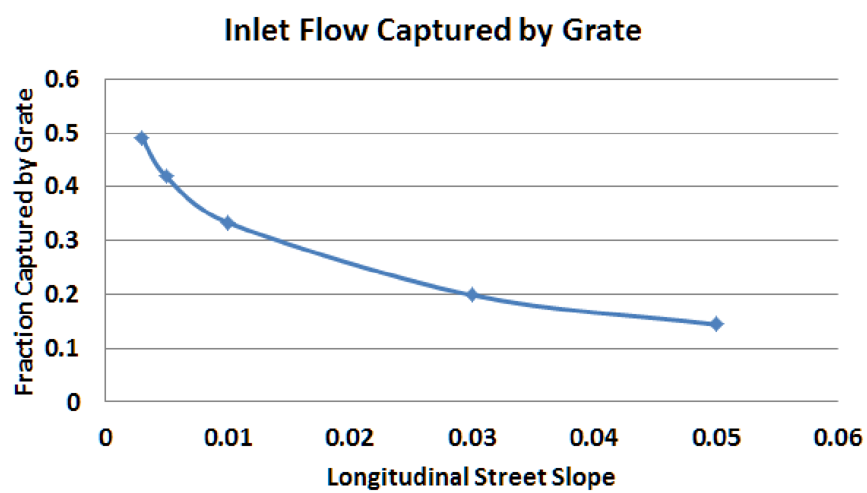
Parts based meshing used for street grate model provides a fine mesh at grate to improve accuracy



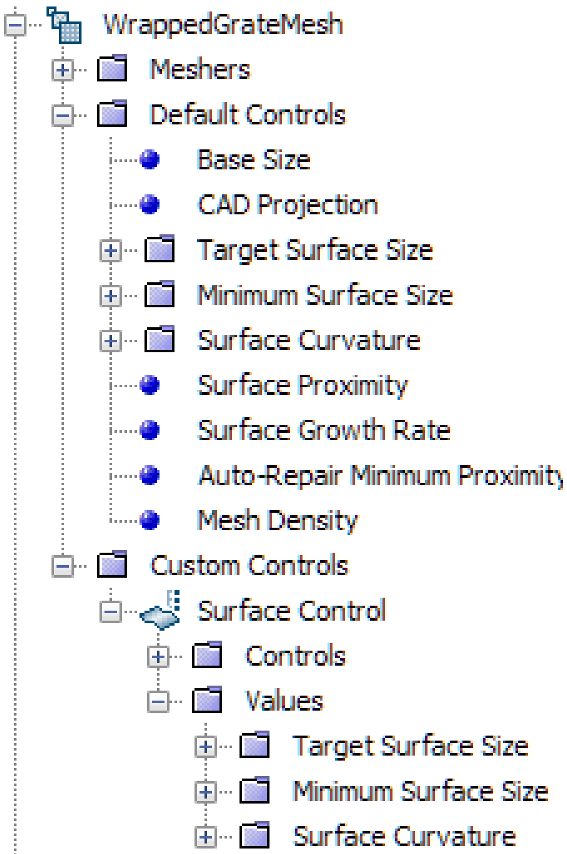
Putting the parts together to get the domain

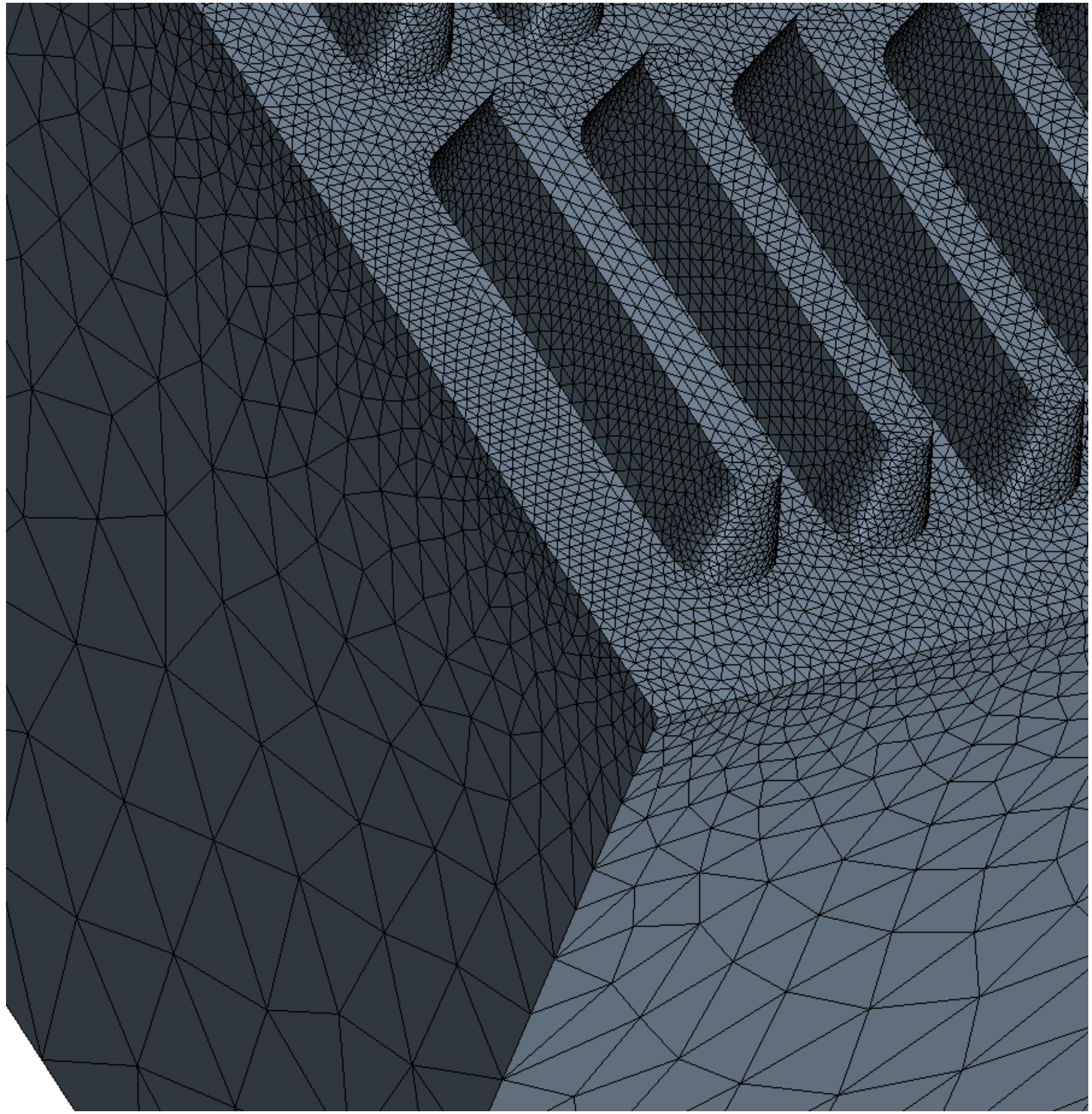
- The grateWrapped, overGrate, and mainStreet parts are assigned to separate regions
- The regions are joined with in place interfaces
- The grateWrapped part has a zero thickness surface covering all of the holes
  - When joined to the overGrate surface with an in place interface, all of the holes are in one interface
  - no need to create an interface for each hole
- Creating interfaces in the overGrate region allows mass flow through the interfaces to be computed via field functions – including the upstream side, street side, downstream side, and flow through the grate holes
- When changing a part operation parameter, only that part needs to be remeshed





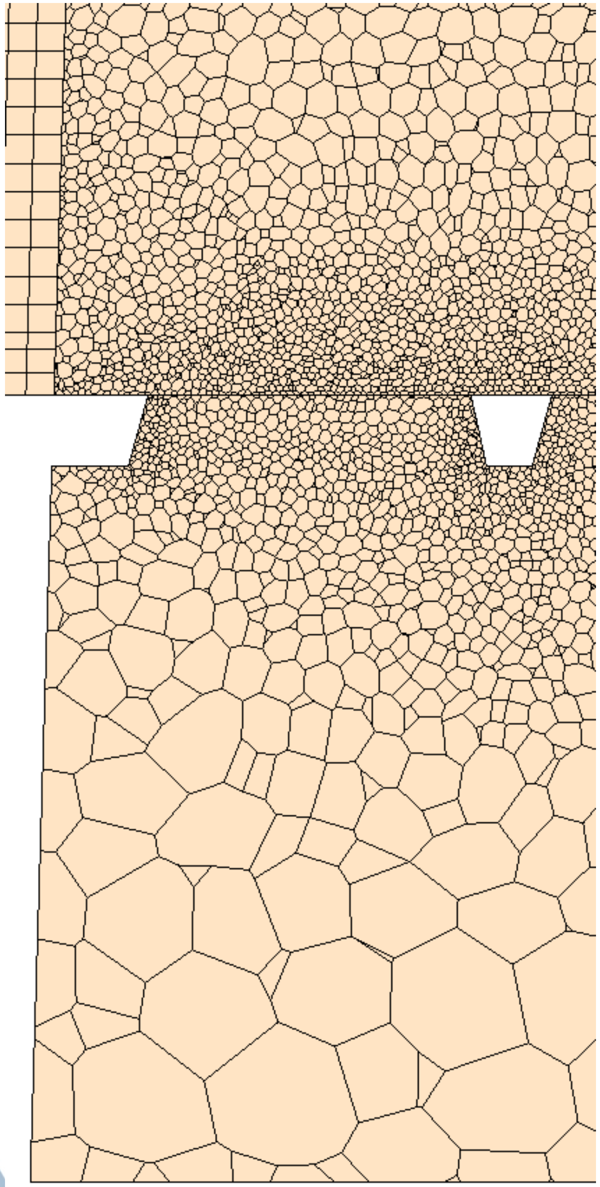
Refined grate surface = fine volume mesh at grate entry

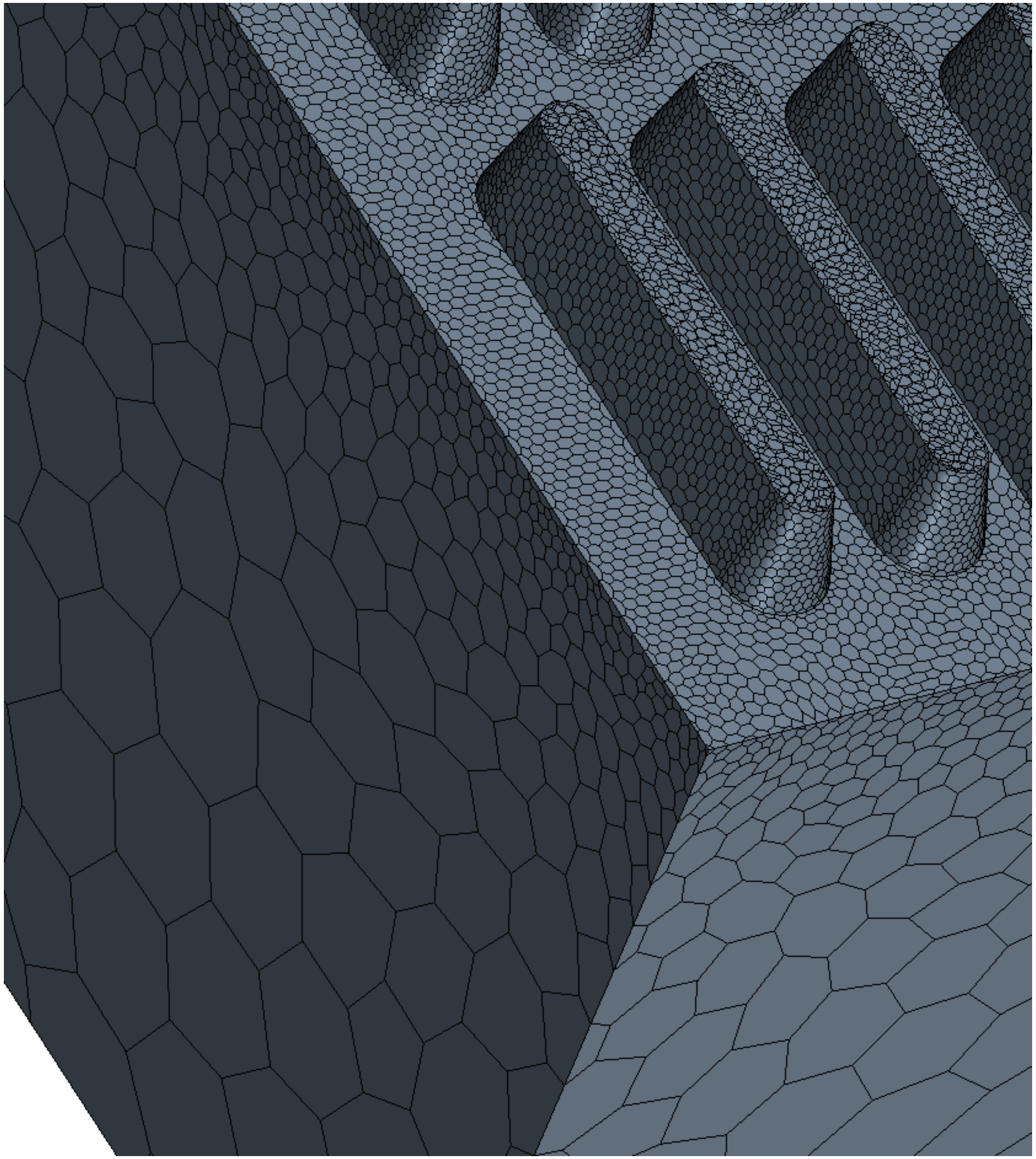




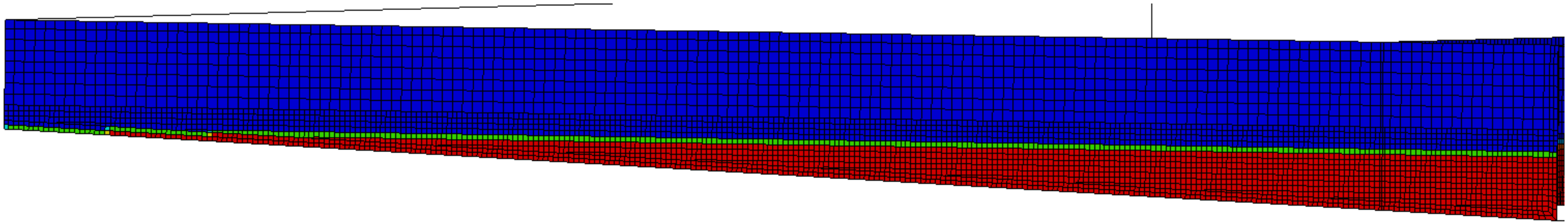
Base size = 4 cm
Target size grate = 10%
Minimum size grate = 5%
Points/circle = 72

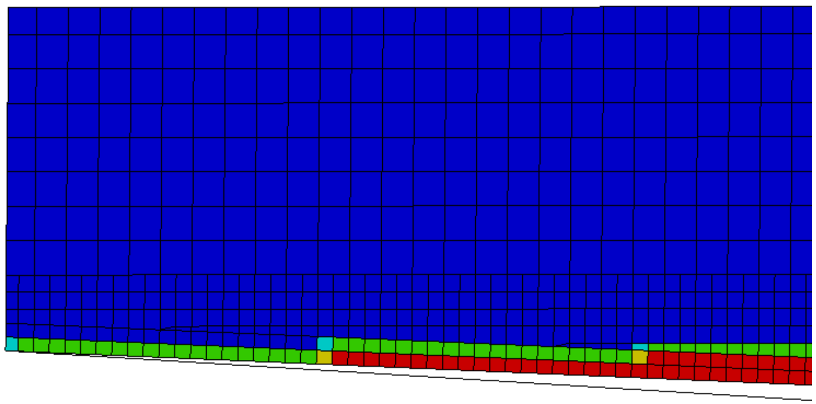
Volume mesh

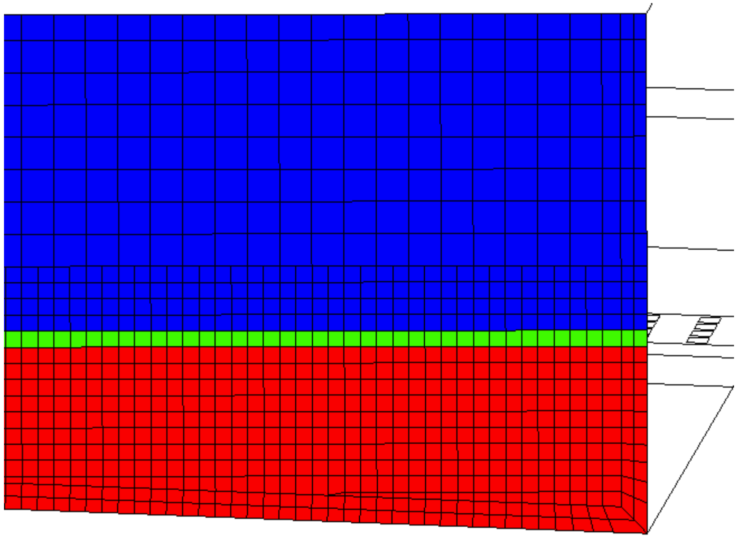




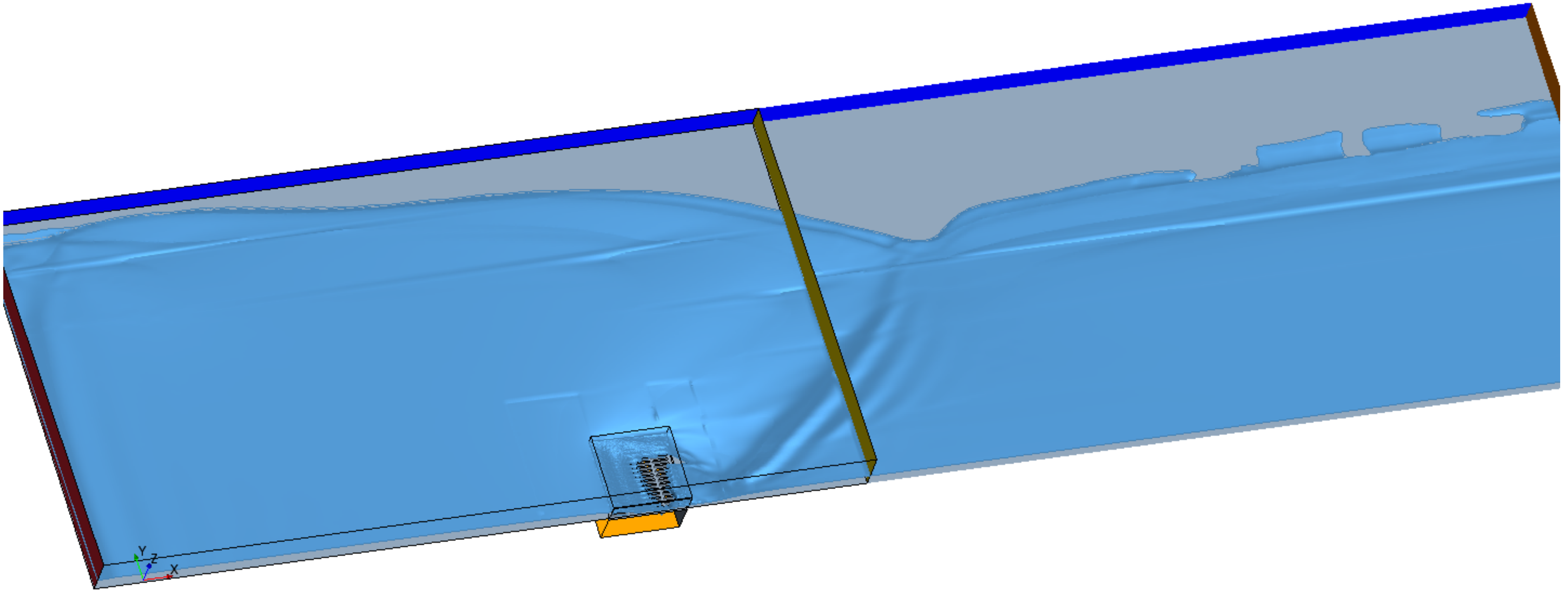
Water refinement block control for finer mesh in water coarser in air zone, base size is 2 cm, refinement block is 50% of base

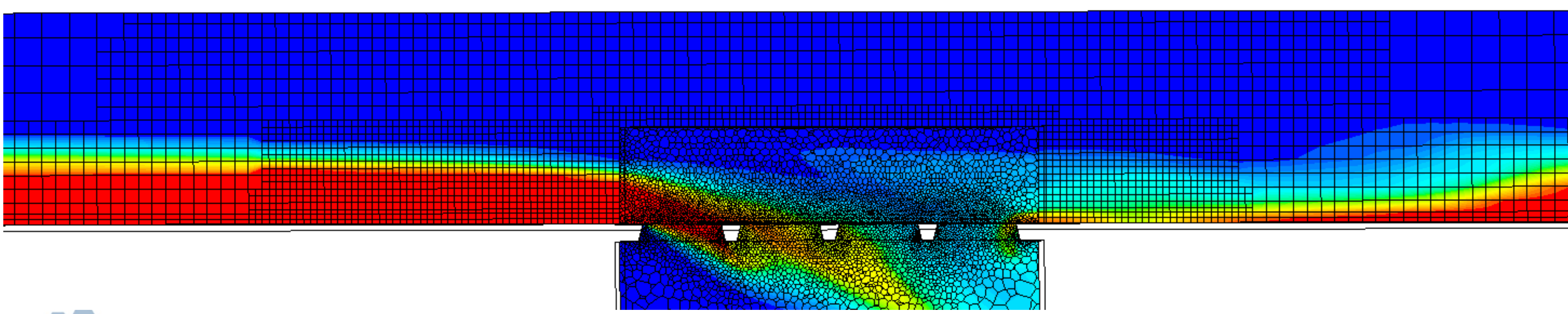




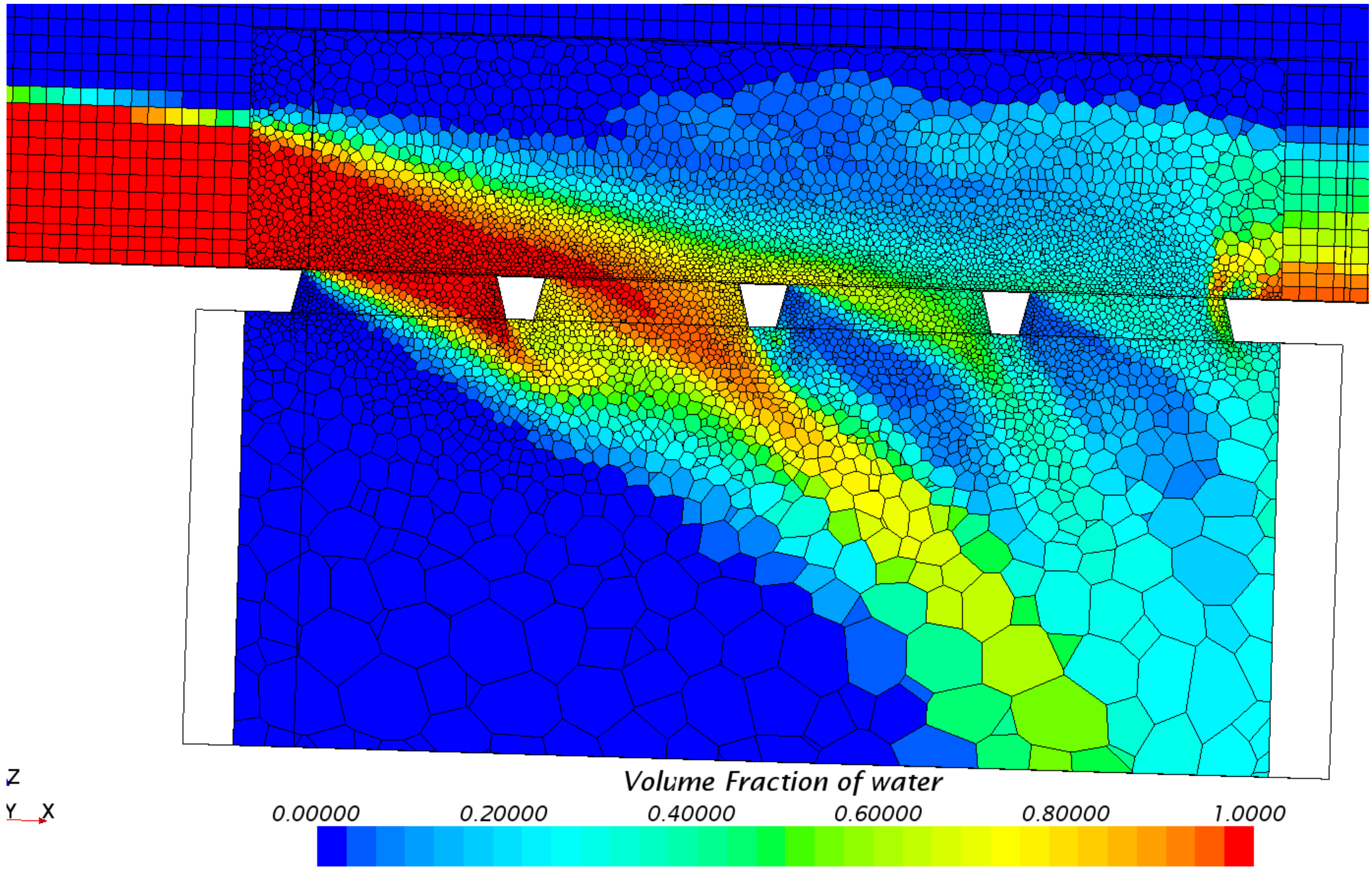


Extended domain test with coarser grid shows smaller domain is O.K. → less expensive to run

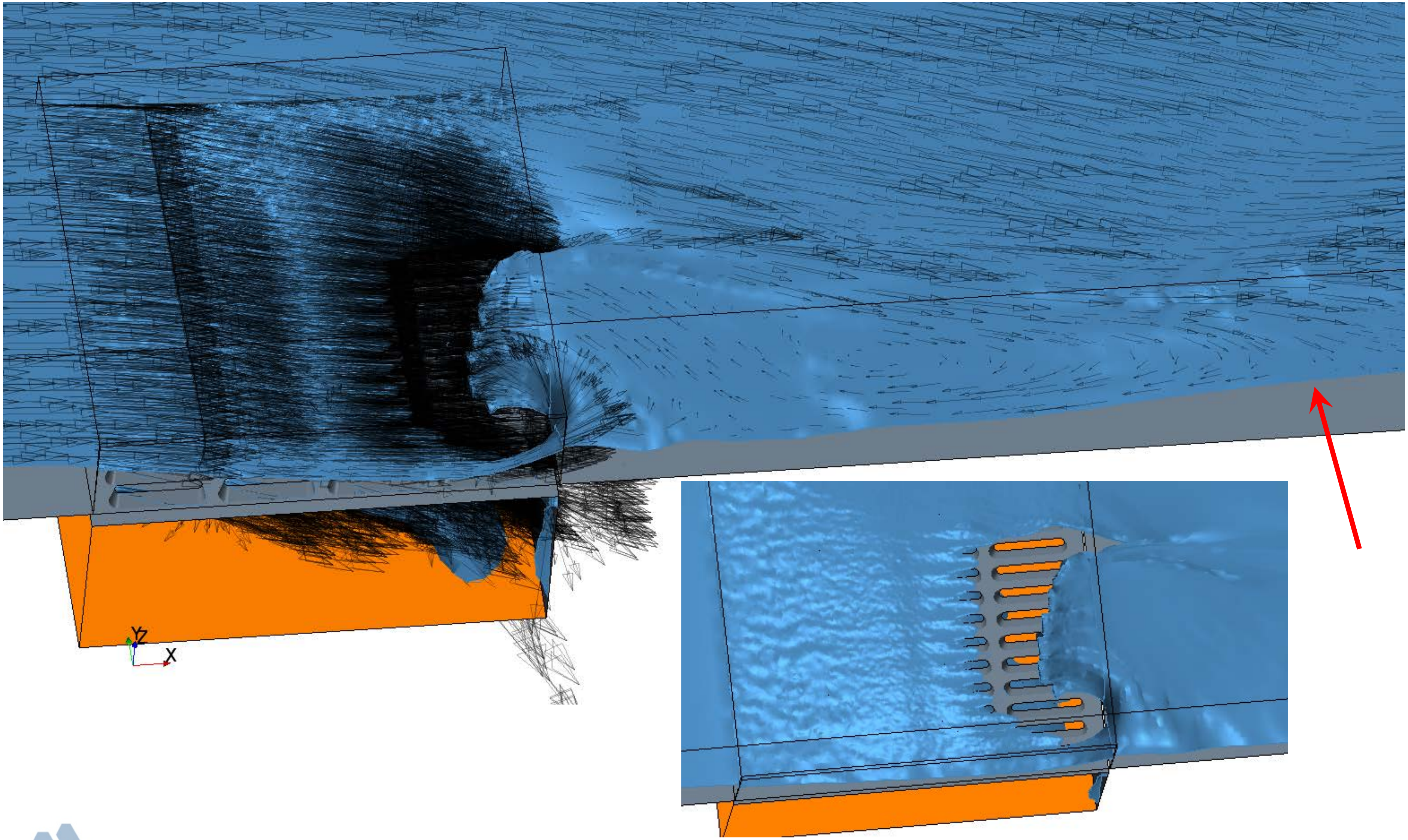




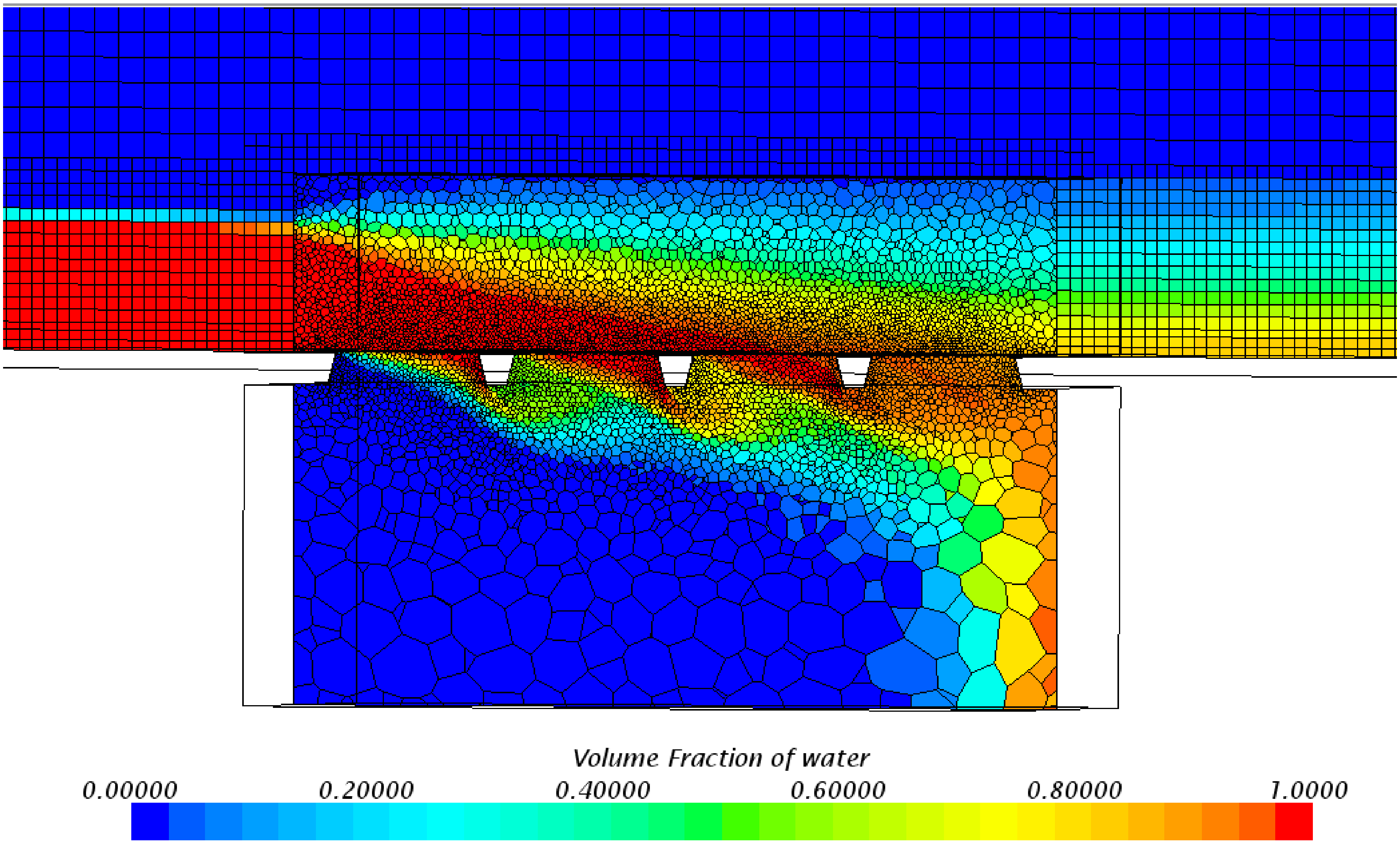
Polys in grate region minimize numerical diffusion



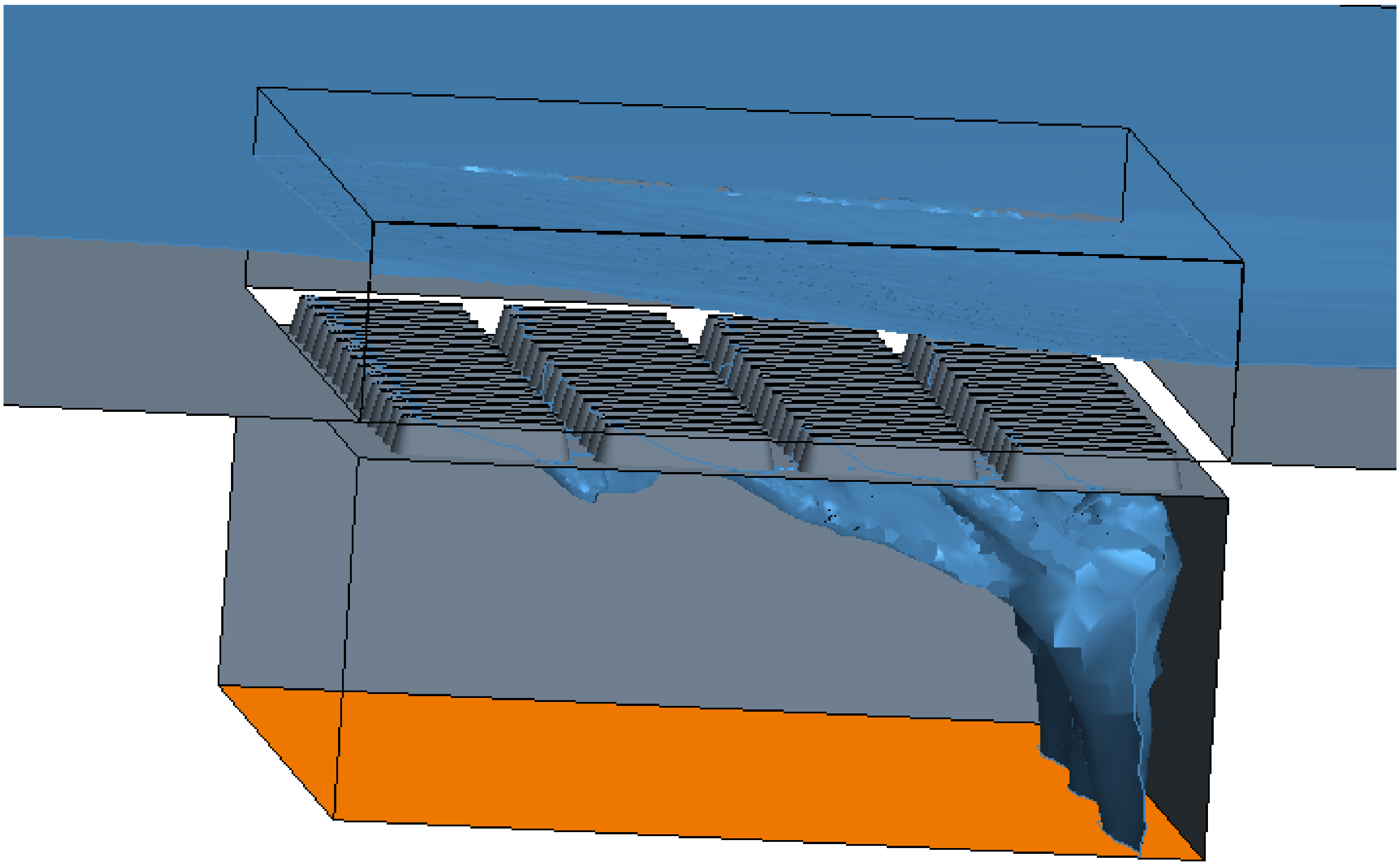
By pass flow at curb gets pushed back into grate for low velocity case (Vin = 0.87 m/s)



Highest longitudinal street slope & velocity Vin = 2.7 m/s, supercritical, case 10

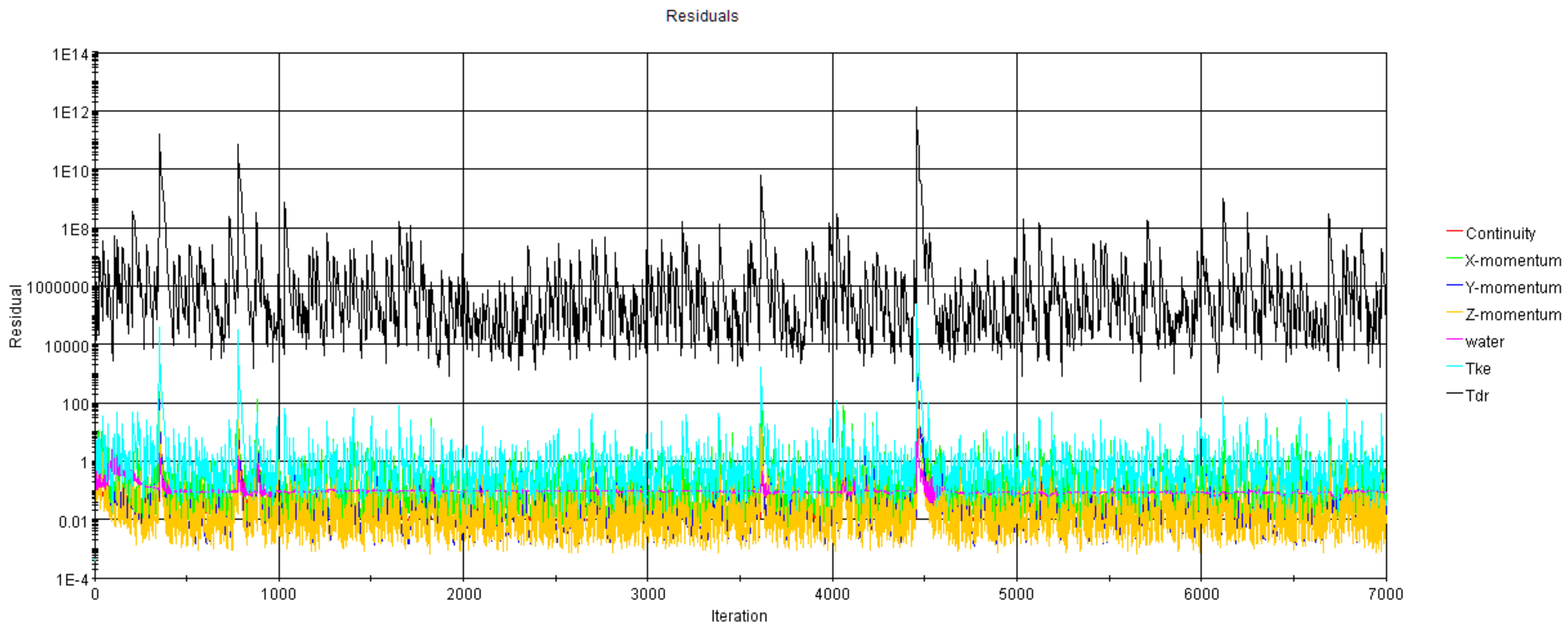


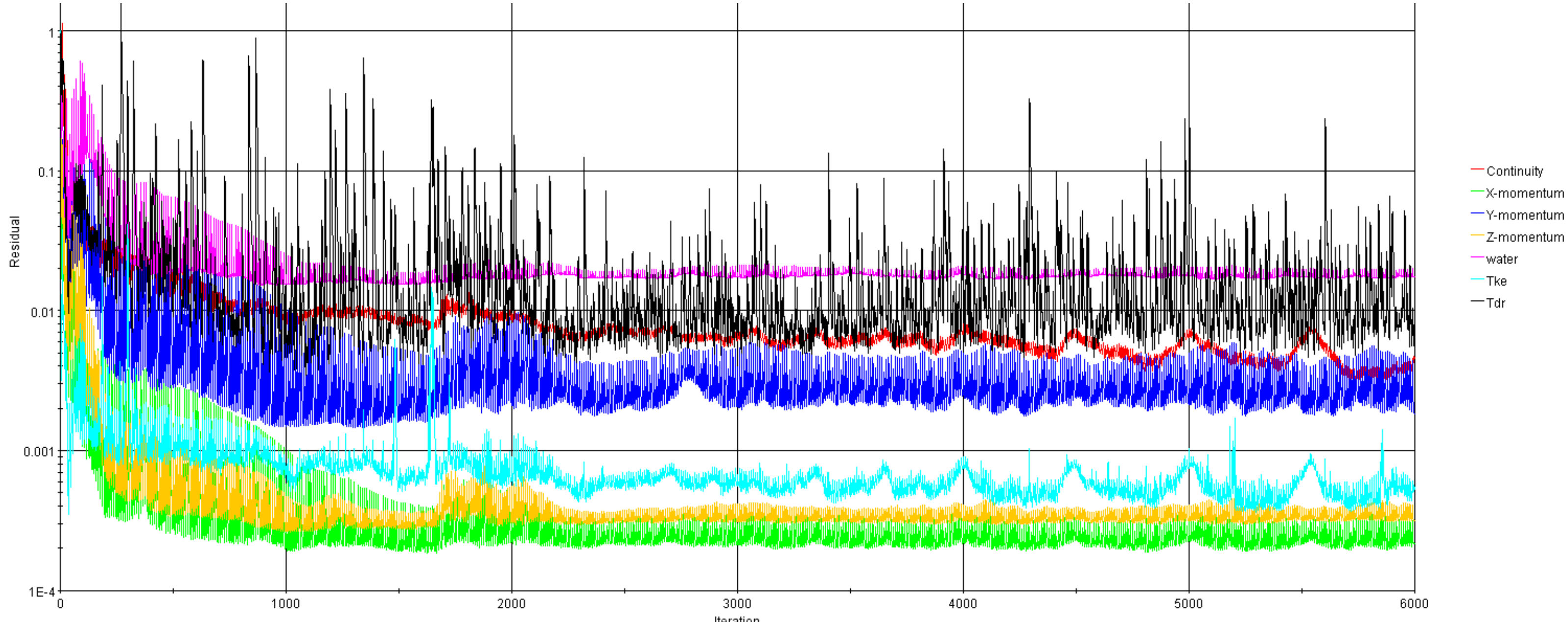
Highest longitudinal street slope & velocity Vin = 2.7 m/s, supercritical, case 10



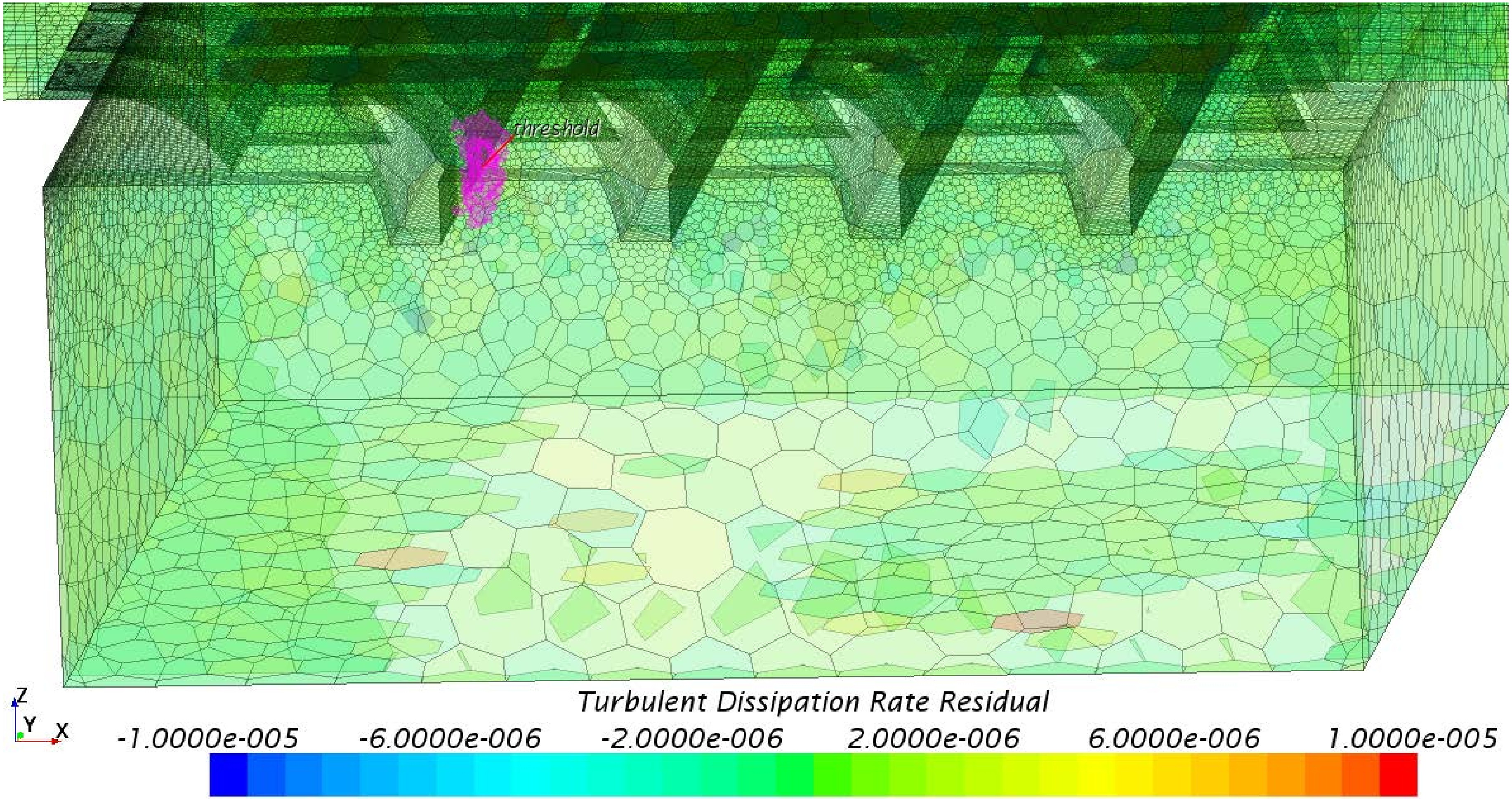
Changing to the vane grate caused convergence problems

- Any significant geometry change in a model can result in convergence problems
- Going far outside the parameter range of a working model can do the same
- Often the problem lies in the mesh
- Solution is to identify where the problem is in the geometry and fix it
  - Change meshing parameters, and remesh
  - Or eliminate bad cells
  - Or modify the geometry – fine details causing problems may not be relevant to flow field behavior of interest
- Many other things can be done

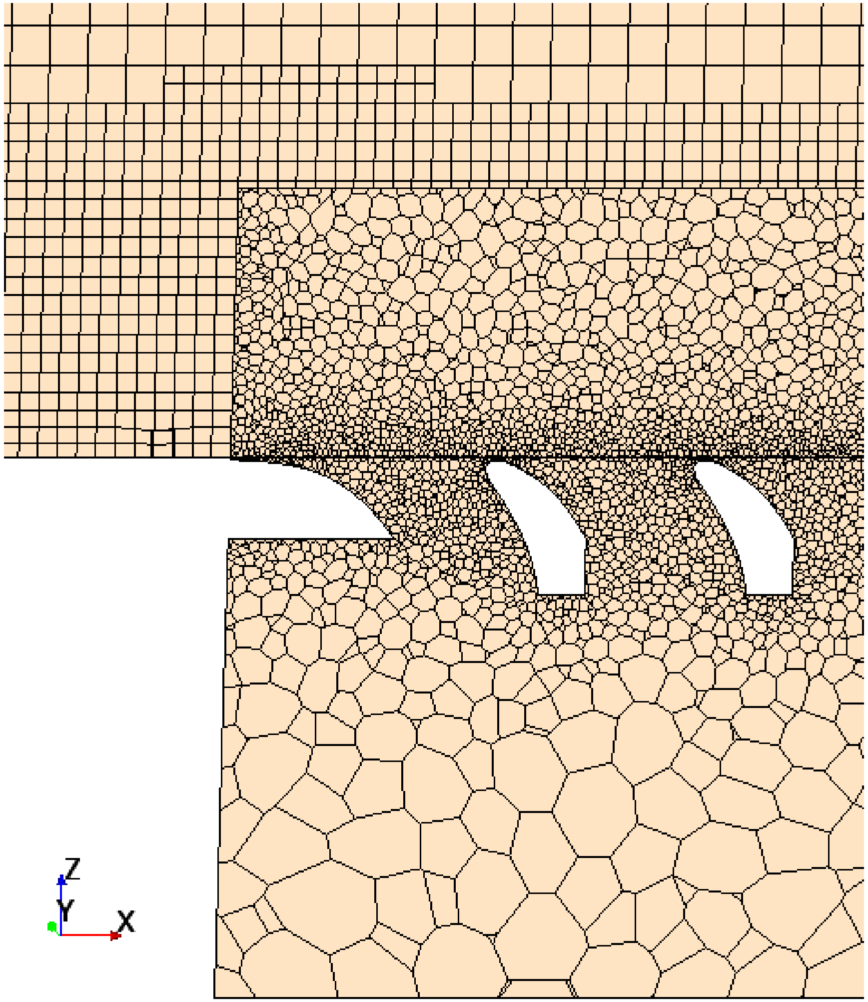

Residuals
Residual
1E14
1E12
1E10
1E8
1000000
10000
100
1
0.01
1E-4
0
1000
2000
3000
4000
5000
6000
7000
Iteration
Continuity
X-momentum
Y-momentum
Z-momentum
water
Tke
Tdr

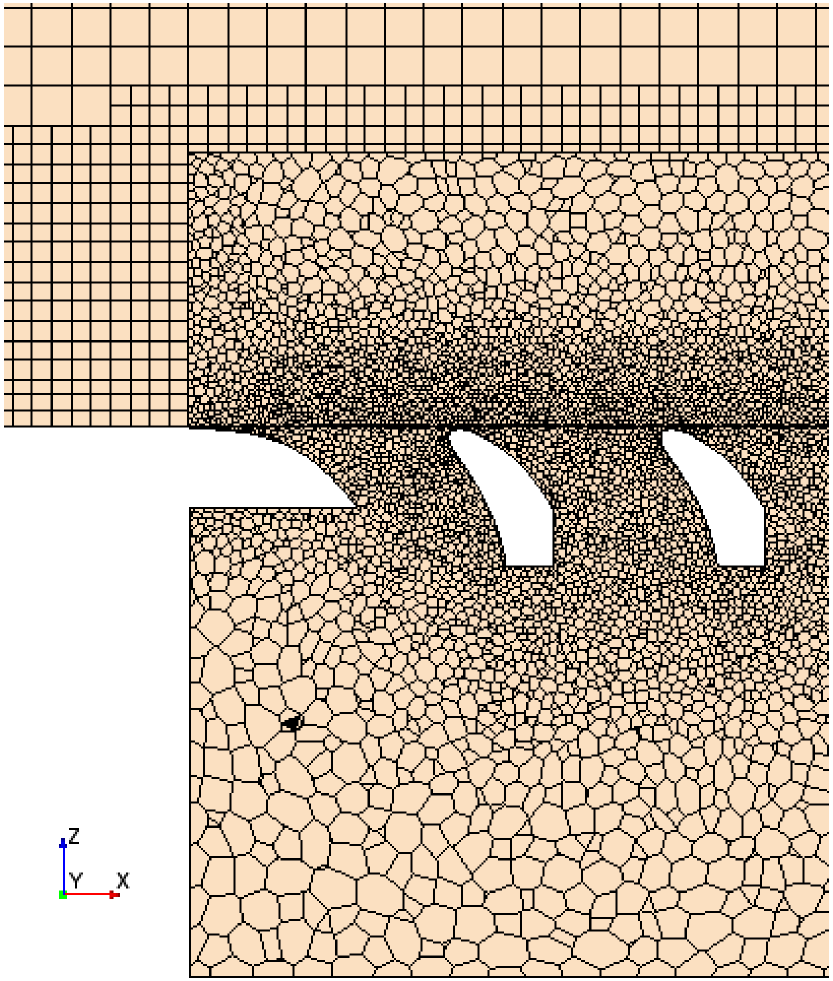

Residual
1
0.1
0.01
0.001
1E-4
0
1000
2000
3000
4000
5000
6000
Iteration
Continuity
X-momentum
Y-momentum
Z-momentum
water
Tke
Tdr

Identification of cells in catch basin with poor convergence

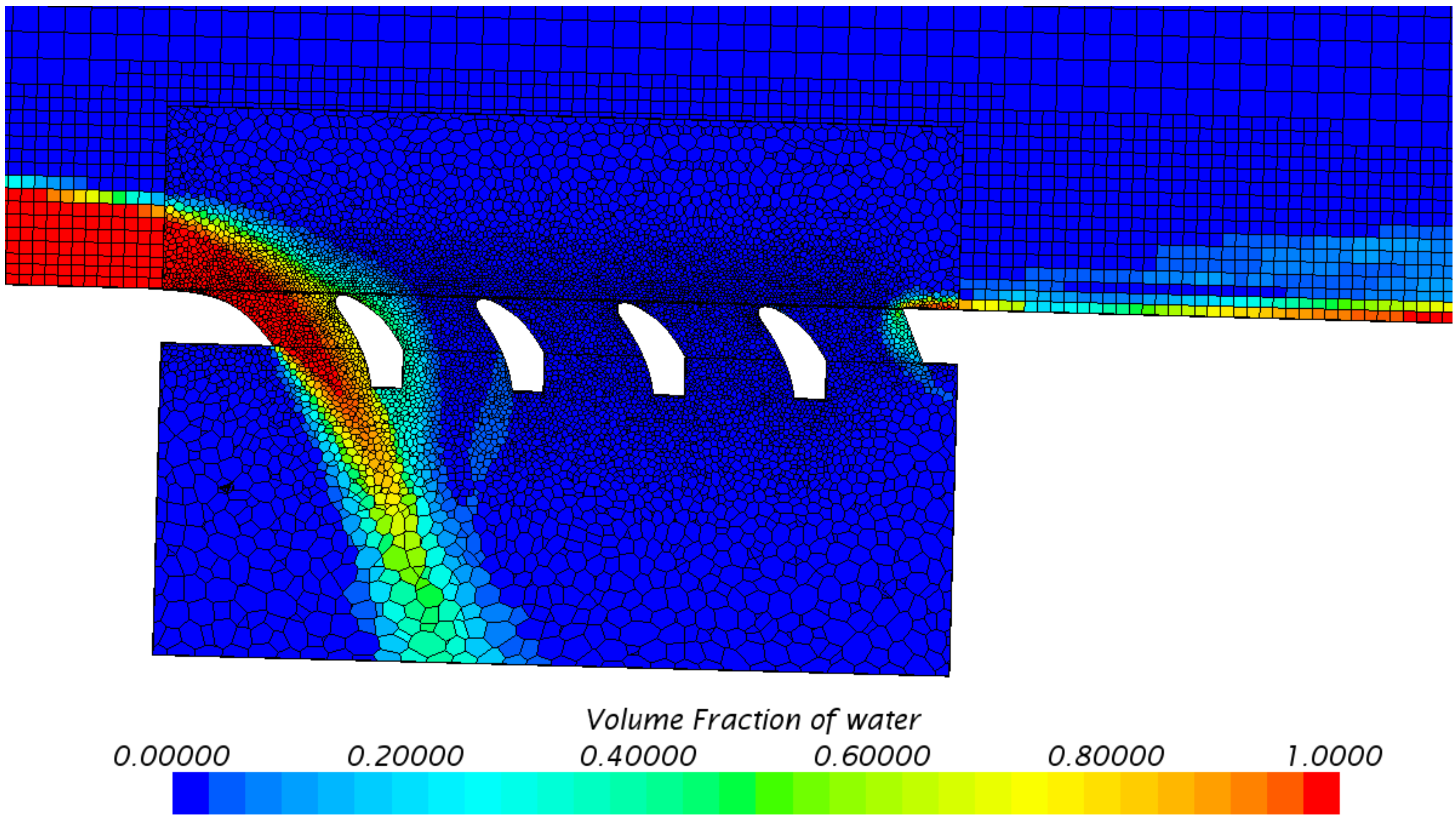


Finer mesh in catch basin on right solved convergence problem

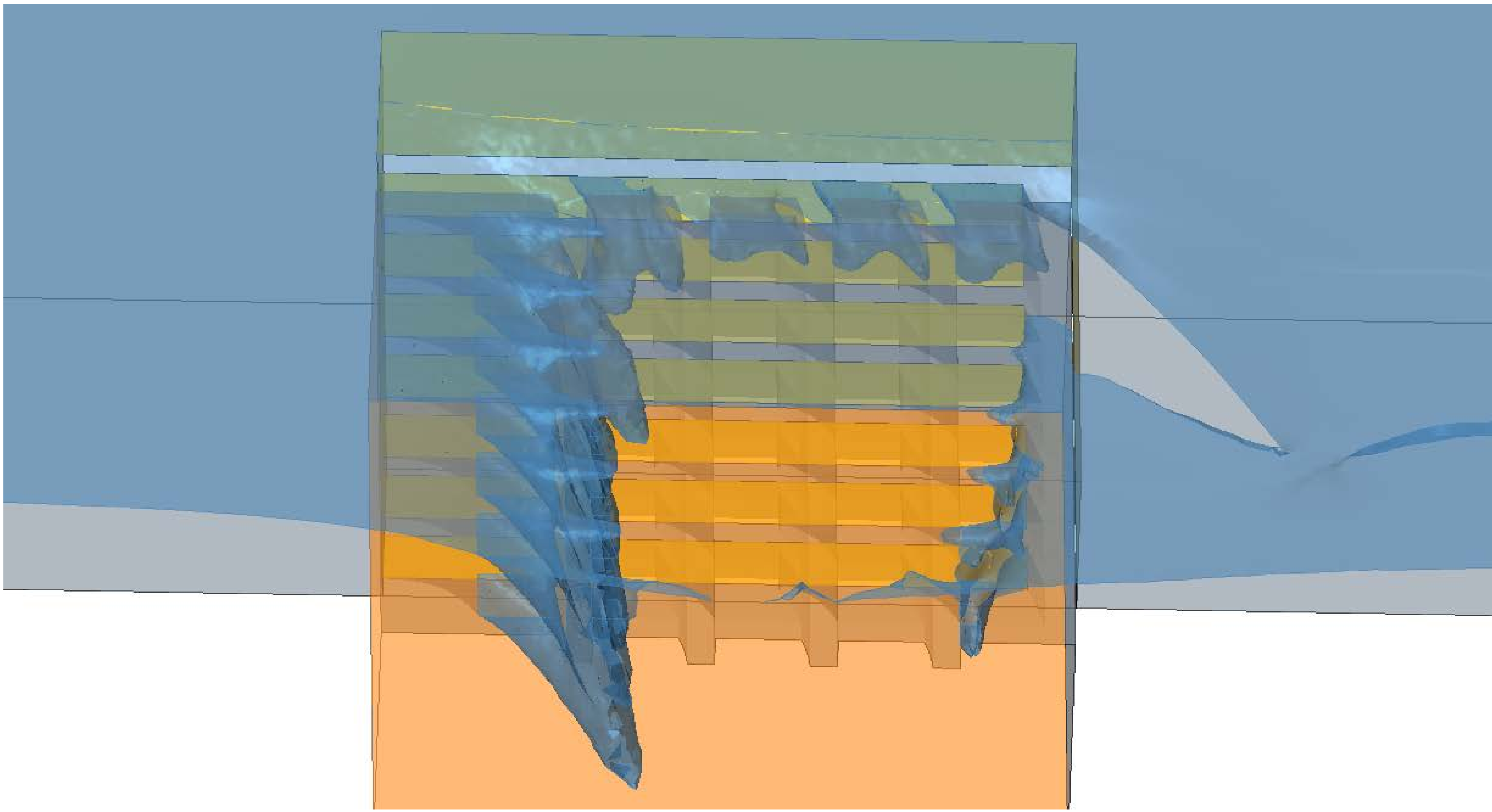




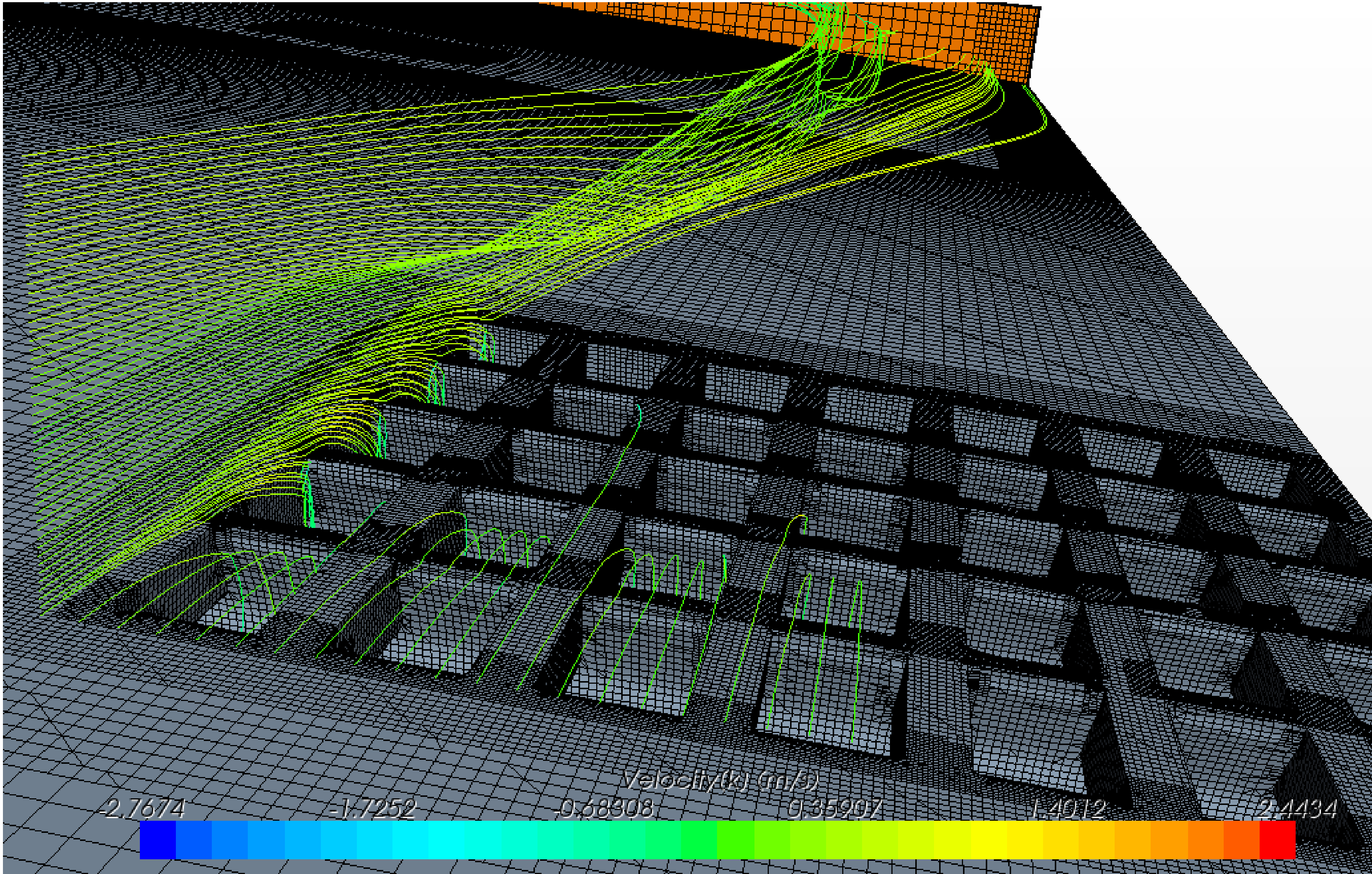
Vane Grate Case - 3 inlet velocity 1.05 m/s
Fr at curb 1.08, street longitudinal slope = 0.03



Vane Grate Case 3 -inlet velocity 1.05 m/s Fr at curb 1.08, street longitudinal slope = 0.03

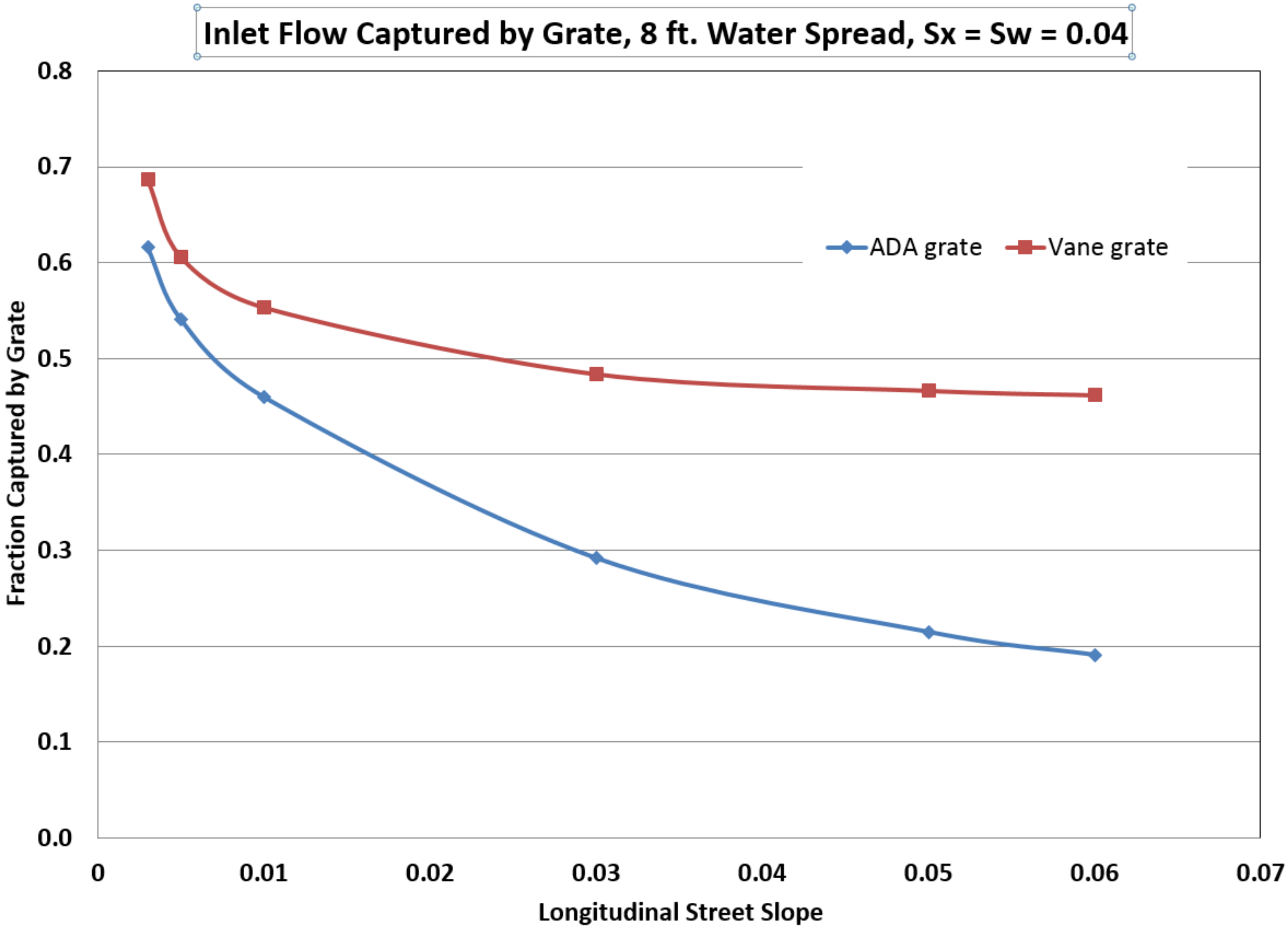


Streamlines

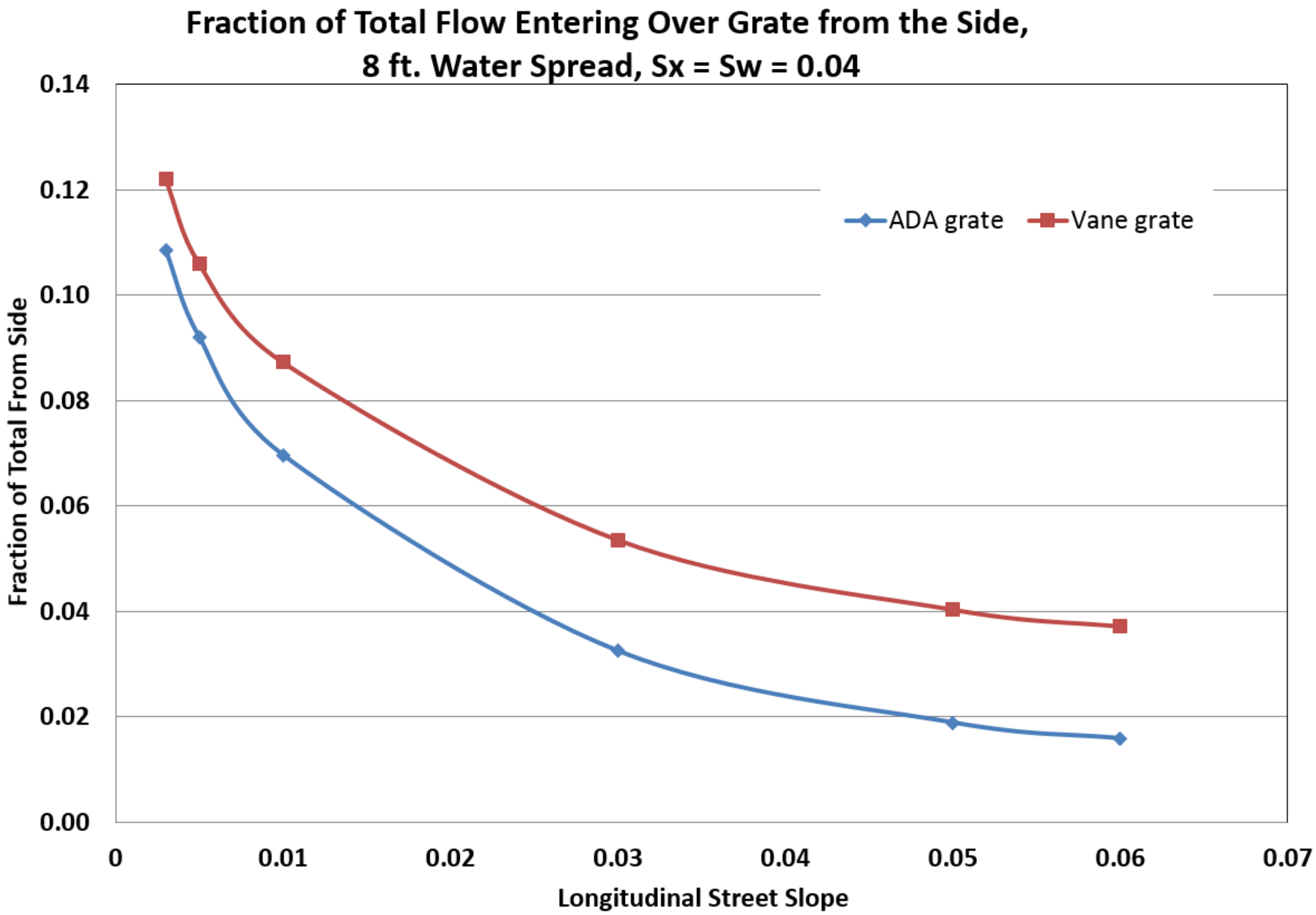


Plotted Results for Cases with Varying Longitudinal Street Slopes

Comparison of inlet flow captured by ADA and vane grates for uniform cross slope 8 ft spread cases



Comparison of total flow entering over grate from side for ADA and vane grates uniform cross slope 8 ft spread cases



Correlations of results all cases with inlet Reynolds or Froude Number

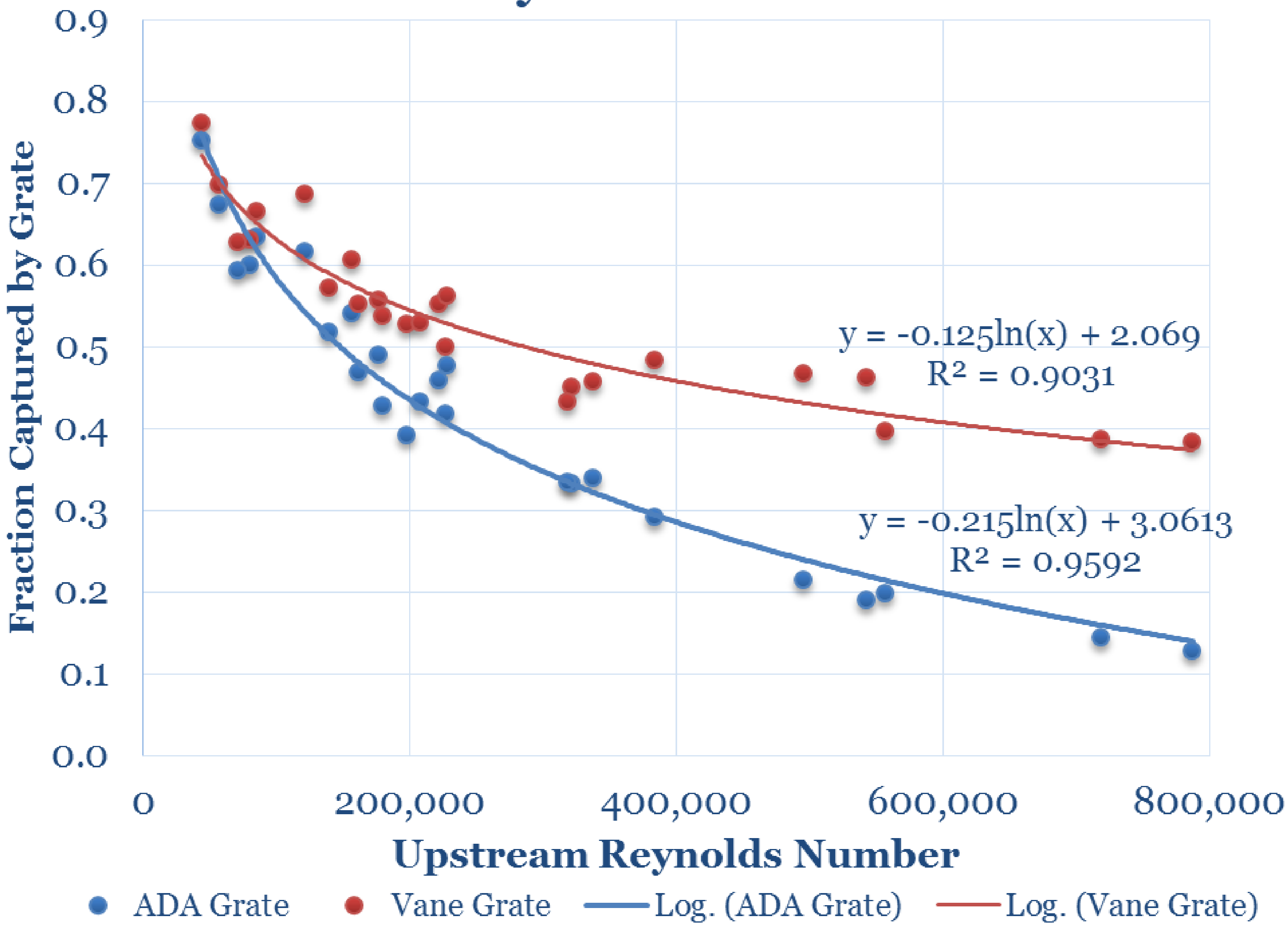
Flow captured vs. Upstream (Inlet) Reynolds Number

- Grate performance appears to correlate well with upstream Reynolds number
  - Represents ratio of (water inertia)/(street and curb surface resistance to flow)
- ADA and vane grate performance are close at low Re near 100,000
- ADA grate performance drops increasingly farther below vane grate performance as Re increases to 790,000.
- At Re = 44,000 both grates capture approximately 75% of the flow
- At Re = 790,000 the vane grate capture drops to 38% of the flow
- At Re = 790,000 the ADA grate capture drops to 13% of the flow

$$R_e = \frac{\rho V d_h}{\mu} = \frac{4\rho Q}{(P_w + P_s + h)\mu} \qquad d_h = \frac{4A}{(P_w + P_s + h)}$$

where ρ is the water density, V is the mean velocity at the inlet cross section, d_h is the hydraulic diameter at the inlet, μ is the water viscosity, Q is the volume flow rate at the inlet, P_w is the gutter width, P_s is the wetted street width, and h is the water depth at the curb. A is the inlet cross section area and $Q = V A$.

Fraction Inlet Flow Captured by Grate vs. Reynolds Number

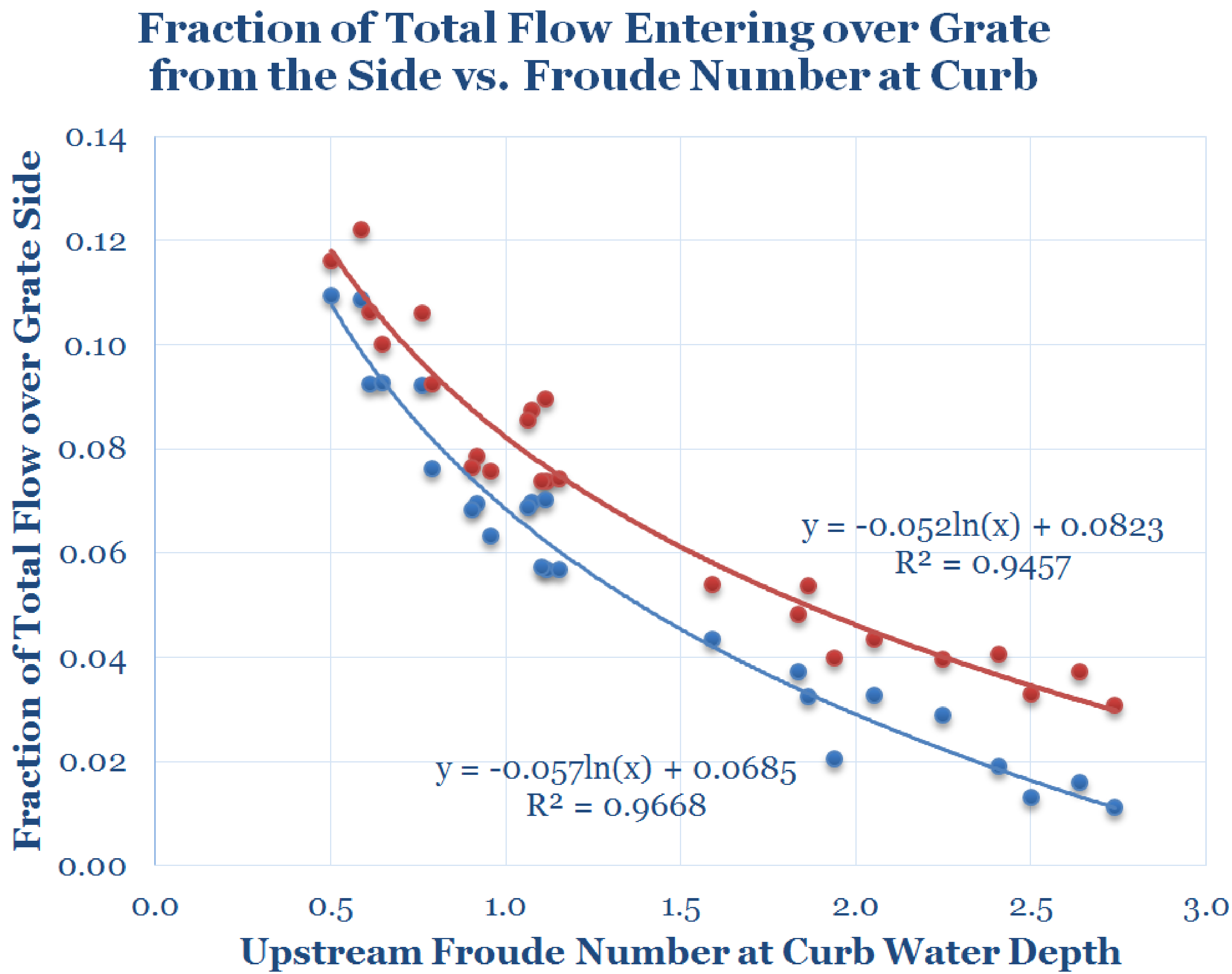


Fraction of Total Flow Entering Over Grate from Side vs. Upstream Froude Number at Curb

- Flow over Grate from side appears to correlate well with upstream Froude number
  - Represents ratio of (water velocity)/(wave speed)
  - Also represents ratio of (water inertia)/(gravitational force)
- Amount entering from side is relatively low for both grates
  - Lower for ADA grate with difference increasing as curb Froude number increases
- At Fr = 0.5, 12% of flow enters over side of vane grate, 11% for ADA grate
- At Fr = 2.7, 3% of flow enters over side of vane grate, only 1% for ADA grate

$$F_r = \frac{V}{\sqrt{gh}}$$

where V is the mean velocity at the inlet cross section, *h* is the water depth at the curb, and g is the acceleration of gravity.

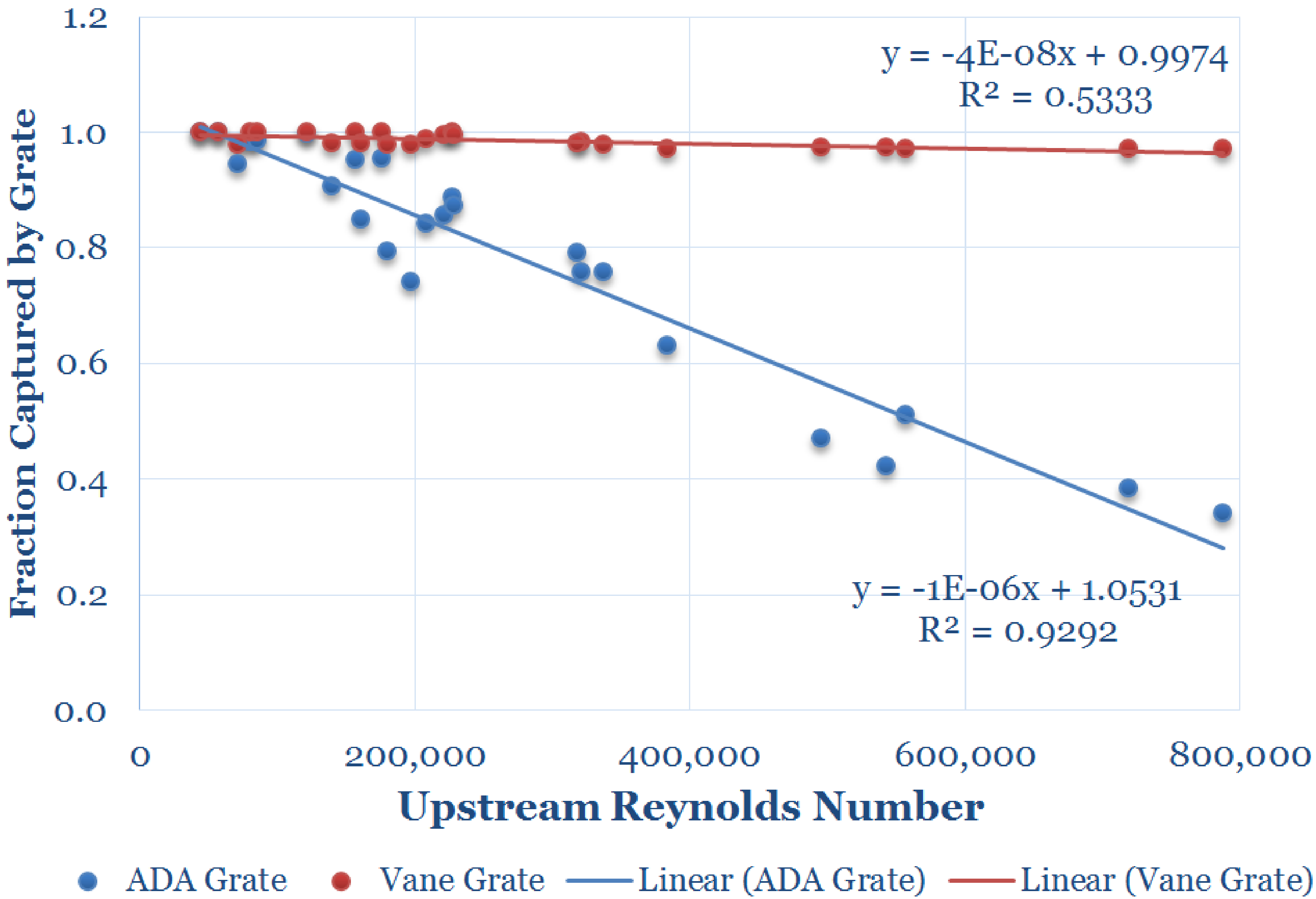


Fraction of Total Flow Entering over Grate from the Side vs. Froude Number at Curb
Fraction of Total Flow over Grate Side
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Upstream Froude Number at Curb Water Depth
y = -0.052ln(x) + 0.0823
R² = 0.9457
y = -0.057ln(x) + 0.0685
R² = 0.9668

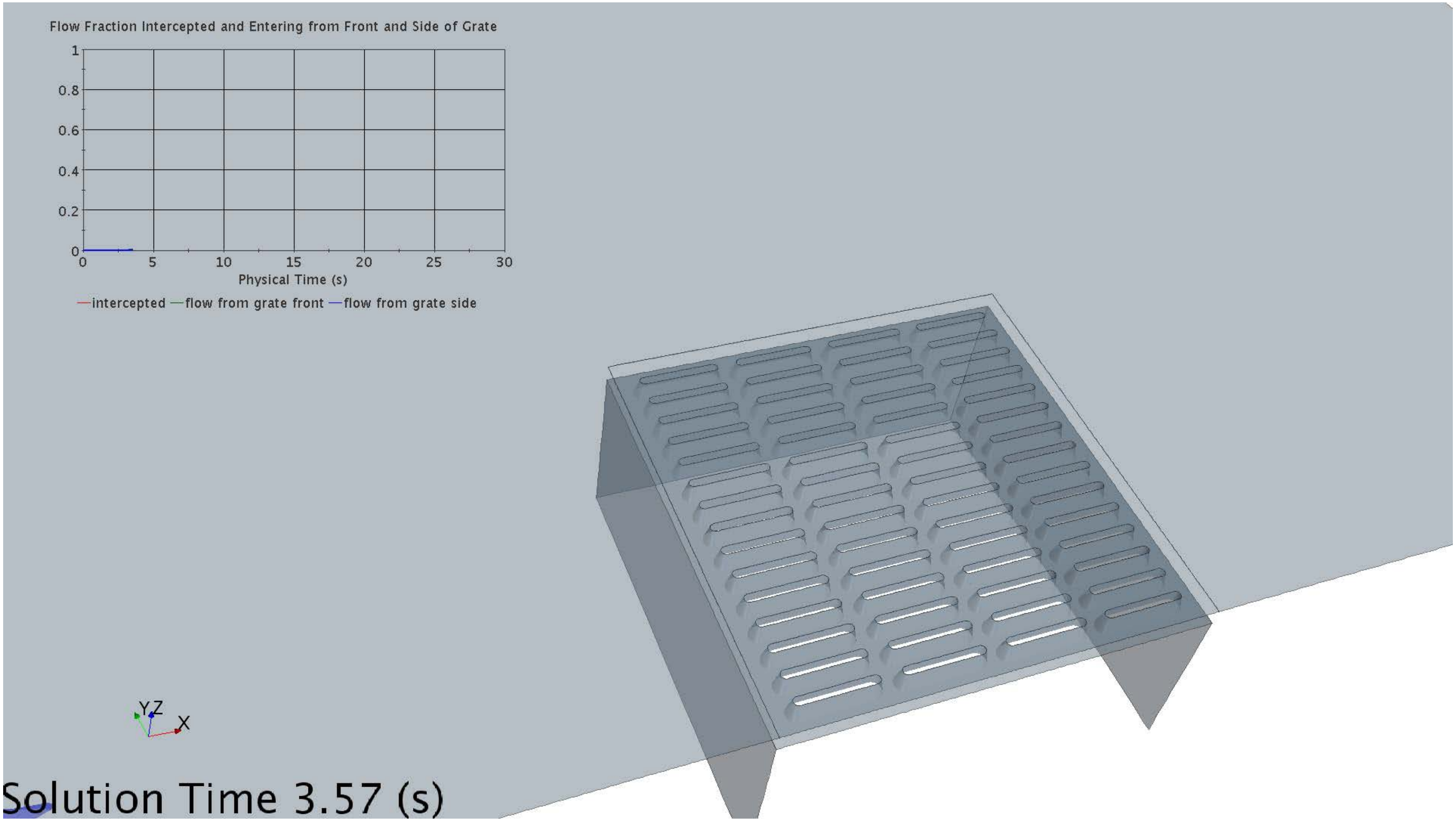
Fraction of Flow Directly over Grate that is Captured vs. Upstream Reynolds Number

- Good illustration of performance difference between the grates
- Once water flows directly over vane grate, nearly all of it ends up in the catch basin
  - Only small dependence on Reynolds number
  - At low Reynolds number all flow entering over vane grate is captured
  - At high Reynolds number (790,000) less than 3% directly over the grate is not captured
- ADA grate performance in capturing flow directly over it is much different
  - At the lowest Reynolds number nearly all flow directly over ADA grate is captured
  - As Re increases less and less flow directly over the ADA grate is captured
  - At Re = 790,000 only 34% of flow directly over the ADA grate is captured

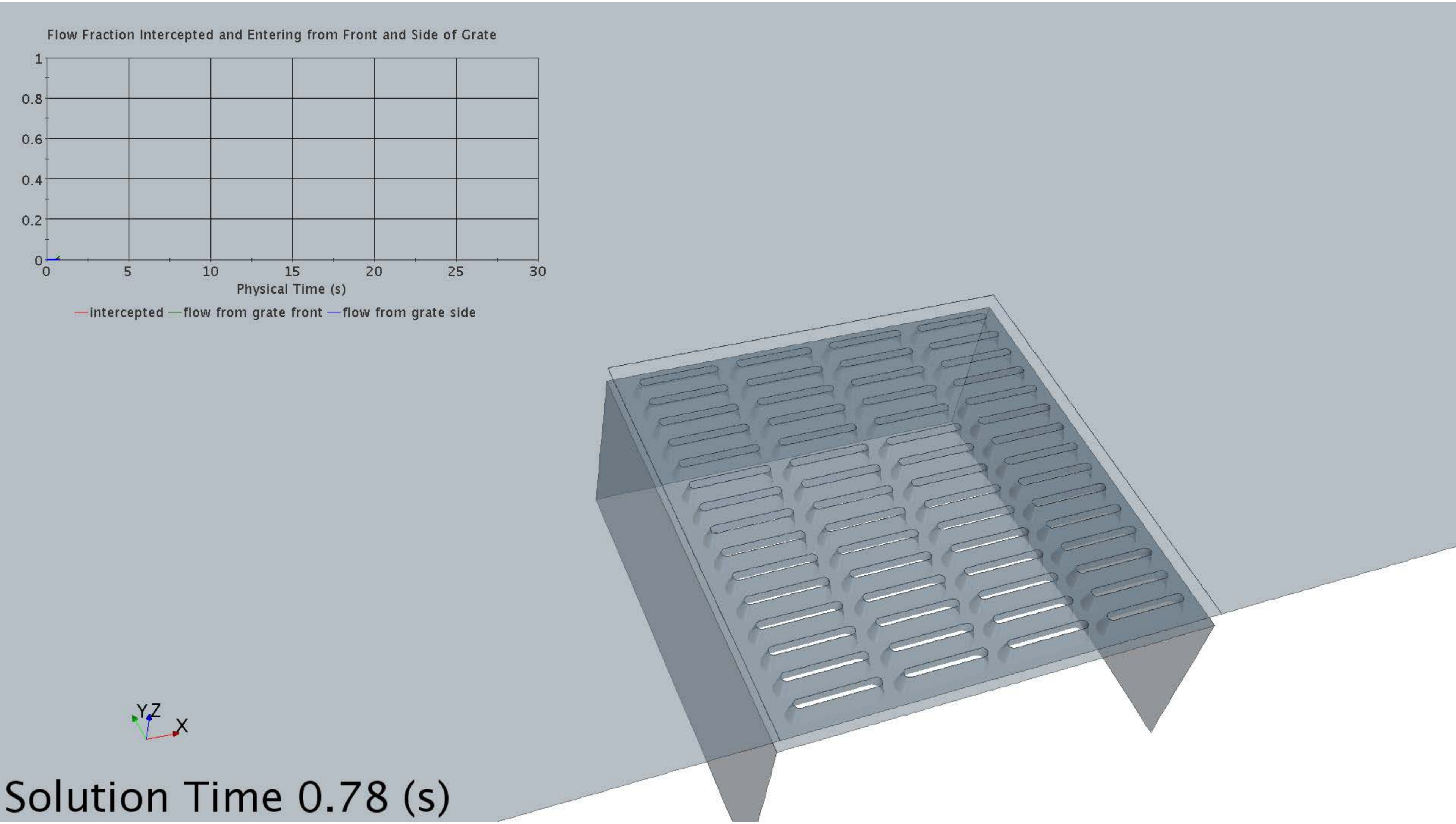
Fraction of Flow Going over Grate that is Captured vs. Reynolds Number



Low flow case



High flow case



Thank you for your attention