

ANALYSIS OF SUCTION INLET GEOMETRIES IN PHOSPHATE DREDGE AND PIT PUMP SYSTEMS USING COMPUTATIONAL FLUID DYNAMICS

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Introduction- Pit and Dredge Systems

- ◆ Dredges and pits used in phosphate industry to mine phosphate matrix
- ◆ Phosphate matrix is a combination of rock, sand, and clay
- ◆ Suction losses and suction performance of pump of great importance



Mosaic's Wingate Liberator Cutter dredge

Background

- ◆ Maximum obtainable concentration of solids on Liberator Dredge at Mosaic's Wingate mine was lower than initially expected.
- ◆ Analysis of the pump and inlet hydraulics was initiated in the summer of 2015.
- ◆ Study included analysis of field data collected from the dredge, as well as computational fluid dynamics (CFD) investigation of dredge and pit pump inlets, in order to determine best designs.



Pit pumps

Objectives

- ◆ Use computational fluid mechanics and field data to analyse dredge and pit pump suction inlet designs in order to :
 - Computationally model 3 dredge inlet designs and 2 pit inlet designs
 - Evaluate and analyse suction piping losses (k values)
 - Focus on impact with respect to NPHSA and bedding tendencies
 - Gain insights into the efficacy of solids uptake and transport for the different designs
 - Determine best dredge and pit inlet designs
 - Make recommendations on how to improve Liberator Dredge performance

Background: NPSHA

- ◆ Net Positive Suction Head available (NPSHA)
- ◆ Absolute pressure at pump impeller eye must exceed vapour pressure by a certain margin in order to prevent cavitation
- ◆ Required energy at pump entrance is expressed in terms of head of the mixture being pumped
- ◆ NPSHR determined by the pump manufacturer, based on water tests
- ◆ NPSHR typically increases for increased flow rate and rotary speed.
- ◆ NPSHA can be expressed as:

$$NPSHA = \frac{p_s - p_{vp}}{\rho_m g} + \frac{V^2}{2g}$$

p_s = absolute pressure at suction inlet

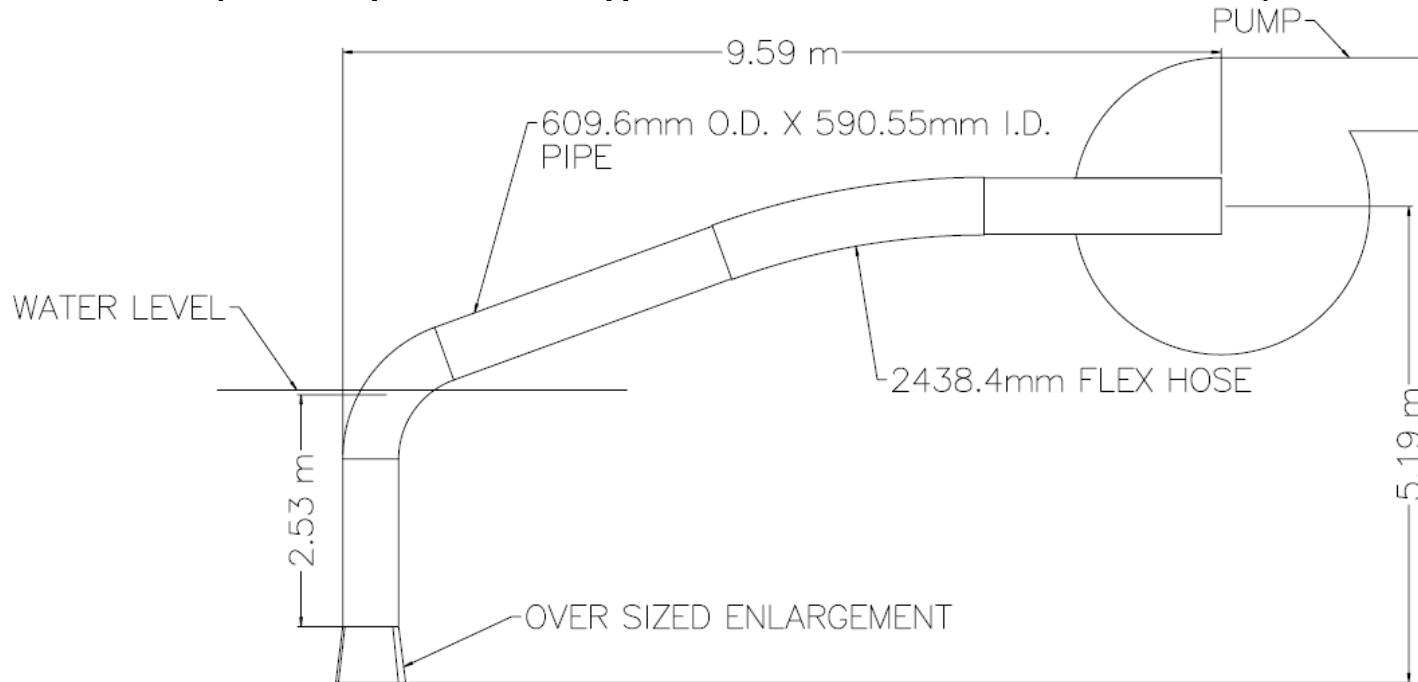
p_{vp} = vapor pressure of water

ρ_m = absolute pressure at suction inlet

V = mean suction pipe velocity

Setup- Pit System

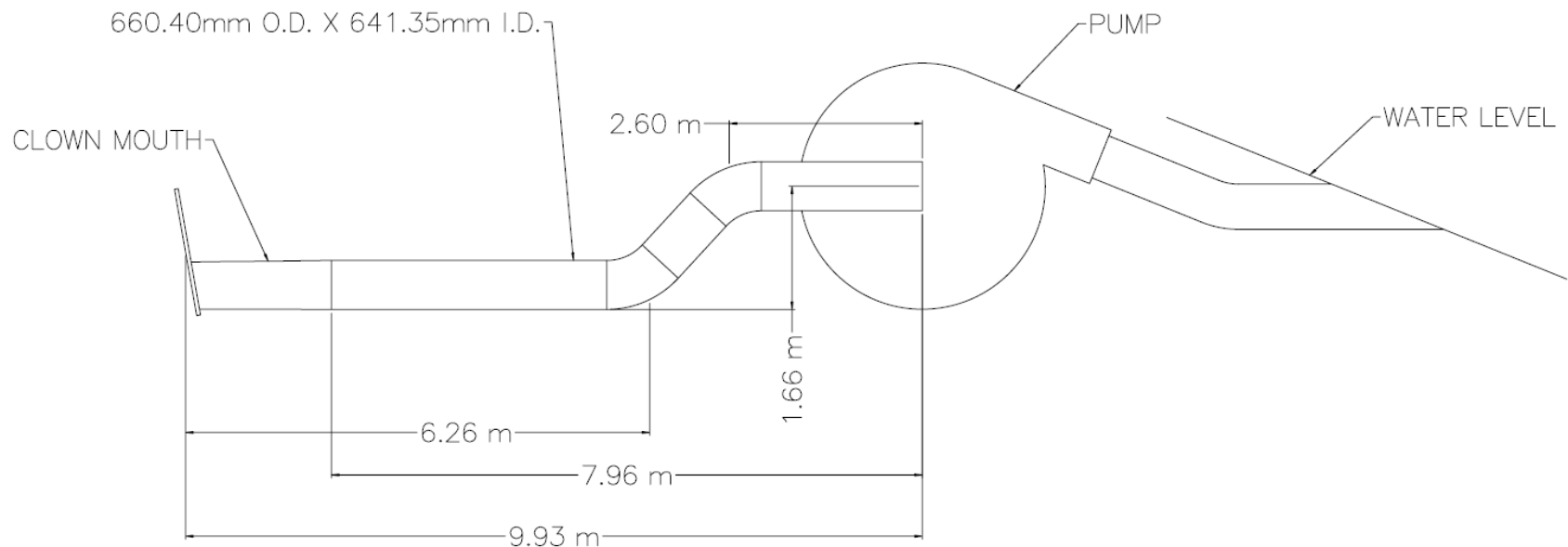
- ◆ Pump mounted on sled, located above free water surface of pit
- ◆ Low NPSHA relative to other applications
- ◆ Pit is made up of vertical earthen walls, with grizzly bars on one side
- ◆ Grizzly bars prevent ingress of oversized material (> 125 mm)



Pit pump suction piping geometry

Setup- Dredge System

- ◆ Ladder pump is fully submerged to increase NPHSA
- ◆ Dredge being analysed is used to remove overburden at Mosaic's Wingate mine, Parrish FL



Cutter dredge ladder pump suction piping geometry

Dredge Field Data Evaluation- NPSHA

- ◆ Mixture flow rate and slurry density measured using acoustic flow meter and nuclear densometer
- ◆ Depth of suction inlet measured using a pressure gauge
- ◆ “Vacuum” reading is taken, which gives the pressure difference between the inside and the outside of the suction pipe at pump inlet
- ◆ Absolute pressure at the suction inlet can be calculated from the vacuum reading, if the depth of the vacuum sensor below water surface is known
- ◆ NPSHA on dredge can then be calculated from these measurements as :

$$NPSHA = \frac{(\rho_w g h + p_a) - \Delta p_{vac} - p_{vp}}{\rho_m g} + \frac{V^2}{2g} - a$$

ρ_w = density of water

h = depth of the sensor below free water surface,

p_a = atmospheric pressure

a = depth of the vacuum sensor below the pump suction centerline.

Δp_{vac} = the vacuum measurement

- ◆ Using this equation, it was determined that NPSHA was usually 3-7.5 m lower than NPSHR
- ◆ To remedy, on-shore booster pump was removed, thereby reducing flow rate and NPSHR, resulting in cavitation free operation.
- ◆ Vibration levels were subsequently observed to be significantly reduced
- ◆ Thrust collar and shaft thrust groove had previously been damaged from cavitation-no problems since

Dredge: Field Data/Operating Conditions

- ◆ Dredge ladder pump is a GIW 3 vane with 0.610 m suction and discharge, and 1.57 m impeller
- ◆ Dredge inlet inner pipe diameter, $D = 0.641$ m (25.25")
- ◆ Solids volumetric concentration = 10 %
- ◆ Mass median particle diameter, $D_{50} = 350$ μm
- ◆ Inclination angle $\sim 20^\circ$
- ◆ Flow rate, $Q = 6360$ m^3/hr (28,000 gpm)
- ◆ Mean pipe velocity, $V = 5.5$ m/s
- ◆ Maximum velocity at the limit of stationary deposition is approximately 6 m/s \rightarrow bed may be present
- ◆ Recommended to replace piping with a smaller inner pipe diameter to rectify this issue and mitigate risks related to bedding and system instabilities

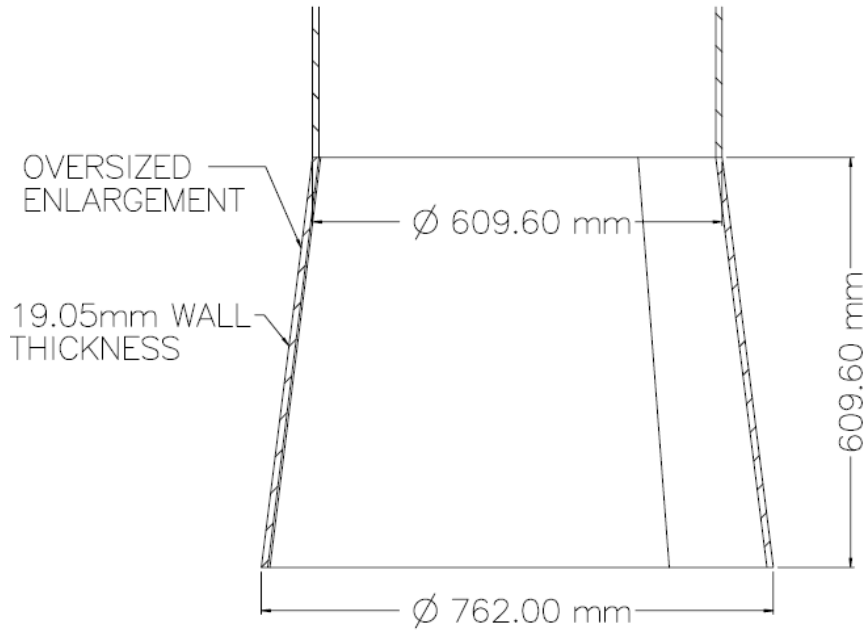
Pit:

- ◆ Pit pump is a GIW 3 vane with 0.508 m discharge, 0.635 m suction, and 1.57 m impeller (20x25x62 inch), and is specifically designed for pit applications to have low NPSH requirements
- ◆ Pit inlet inner pipe diameter, $D = 0.590$ m (23")
- ◆ Mass median particle diameter, $D_{50} = 350$ μm
- ◆ Flow rate, $Q = 3520$ m^3/hr (15,500 gpm)
- ◆ Mean pipe velocity = 3.6 m/s

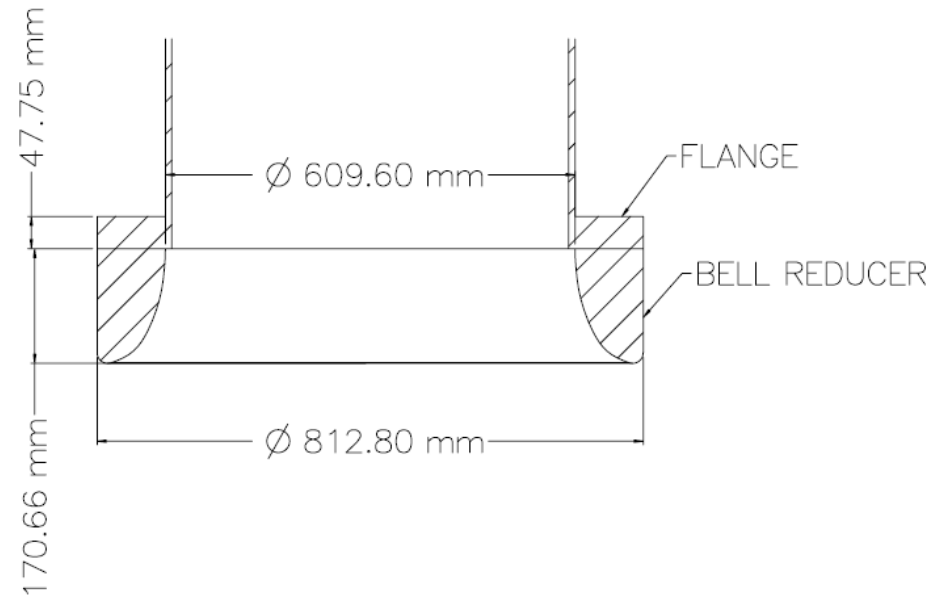
Computational Models

- ◆ Computational simulations performed using Star CCM + V 10.06
- ◆ K- epsilon V2F turbulence model used together with low y^+ treatment
- ◆ Turbulence model is particularly well suited for modelling separated flows, which were observed in initial runs performed using the $k-\omega$ turbulence model
- ◆ Captures near wall turbulence effects more accurately, which is crucial for accurately estimating the losses (k values) in these separated flows.
- ◆ Steady state flow modelled using segregated flow solver with gravity off.
- ◆ Density and viscosity of liquid set to water values at 20 °C
- ◆ Maximum y^+ value in each of the simulations was no greater than 1.0

Pit Inlet Geometries

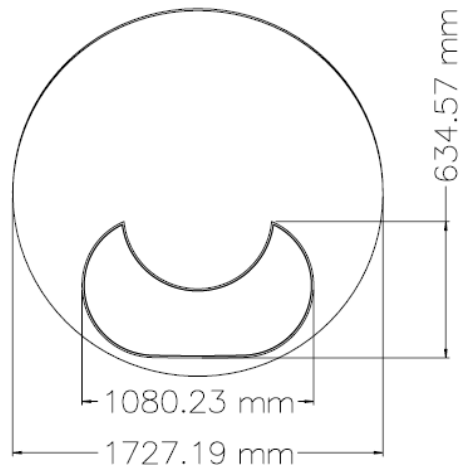
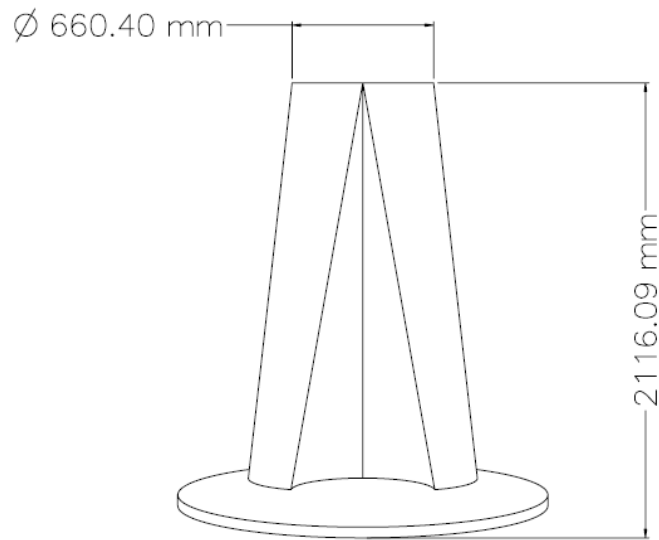


Oversized Enlargement (O.E.)

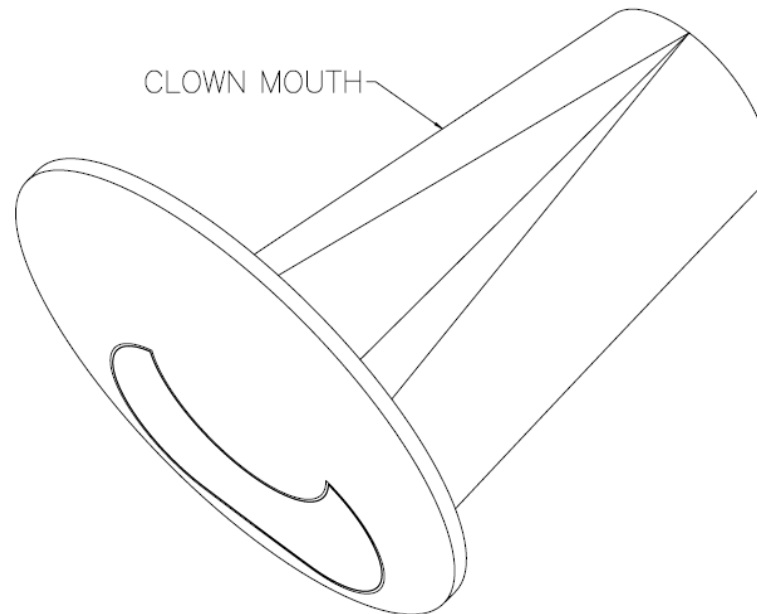


Elliptical Bell Reducer

Dredge Inlet Geometries: Clown Mouth (C.M.)

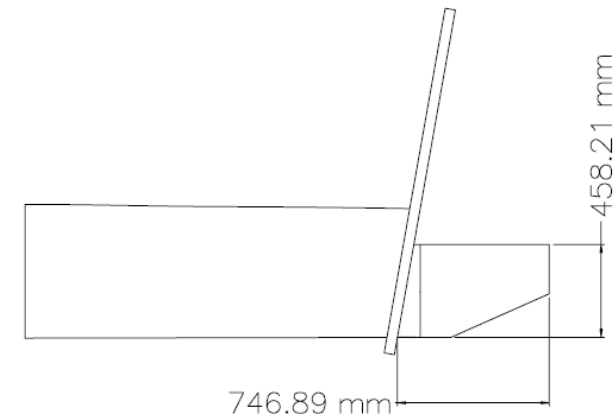
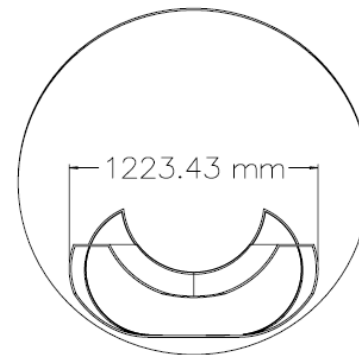
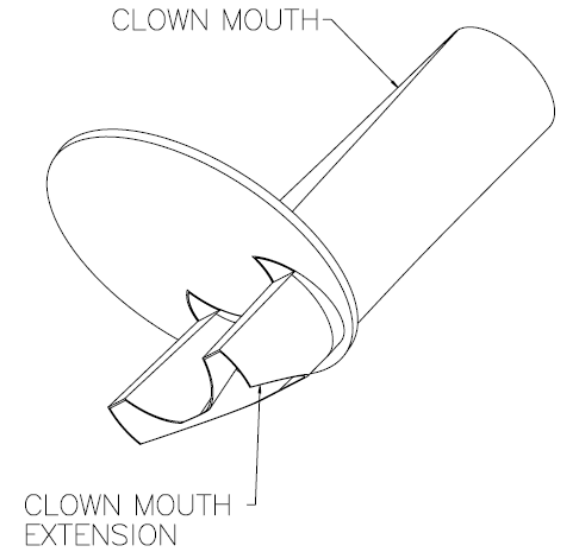
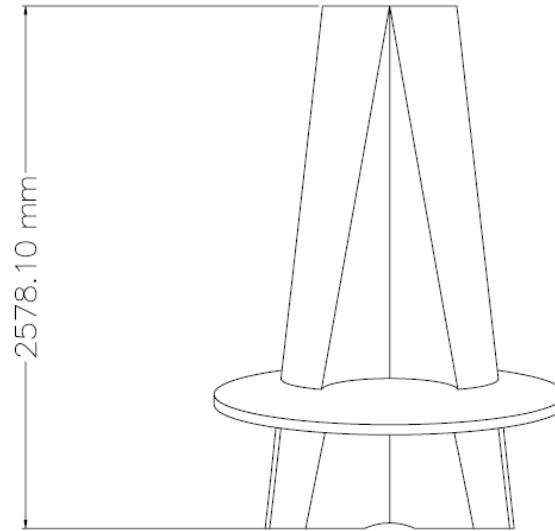


- ◆ Existing Design
- ◆ “Clown mouth” allows cutter shaft to pass over top of hydraulic inlet



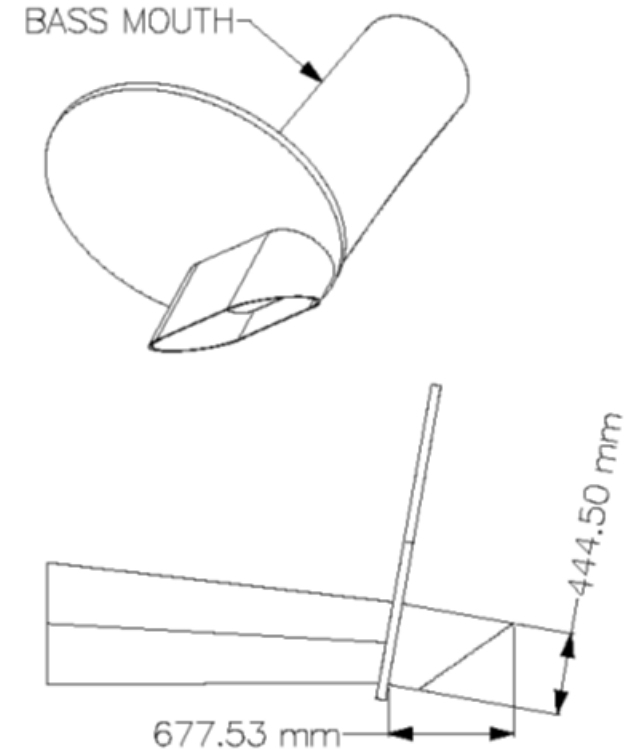
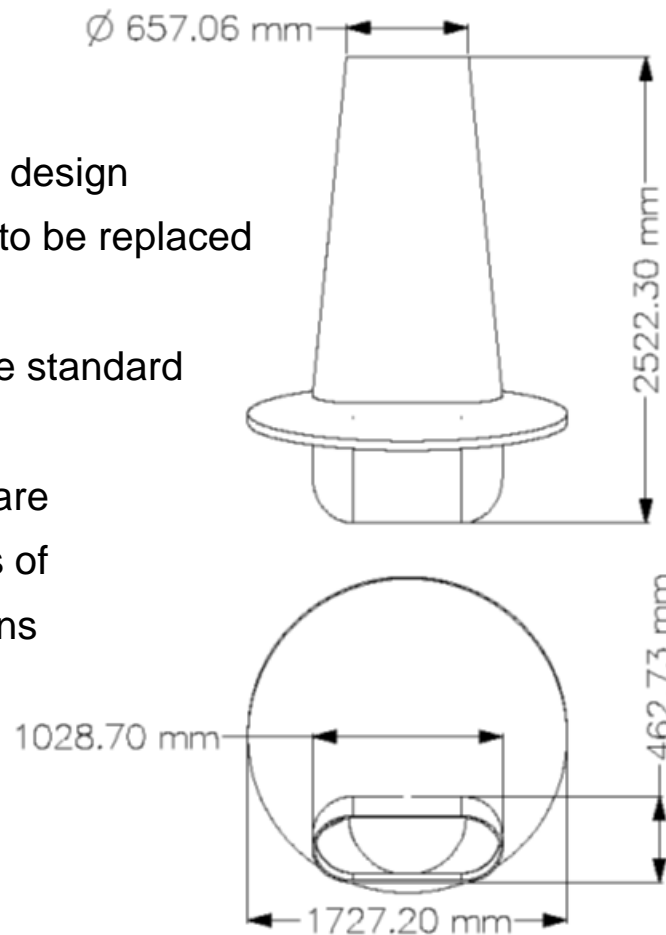
Dredge Inlet Geometries: Clown Mouth with Extension (C.M.E.)

- ◆ Possible Candidate to replace clown mouth design
- ◆ Extension would be added onto existing clown mouth inlet



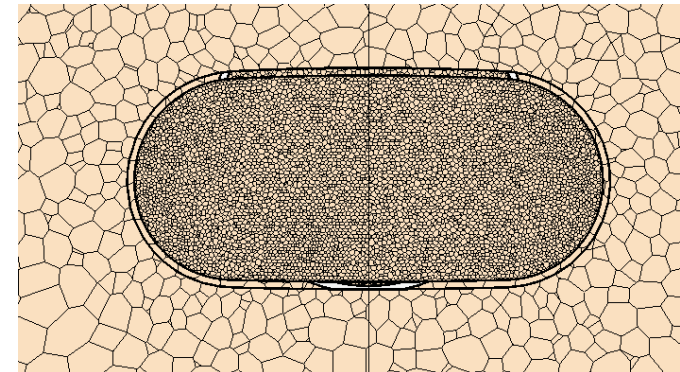
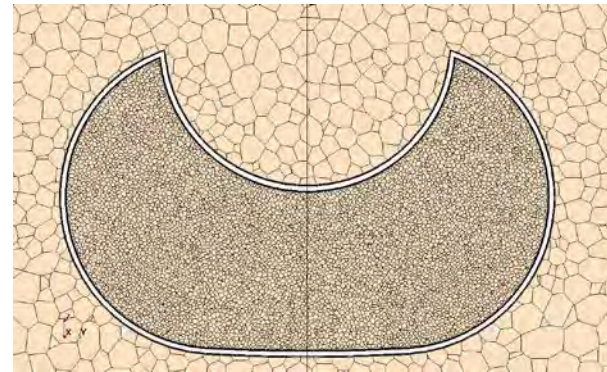
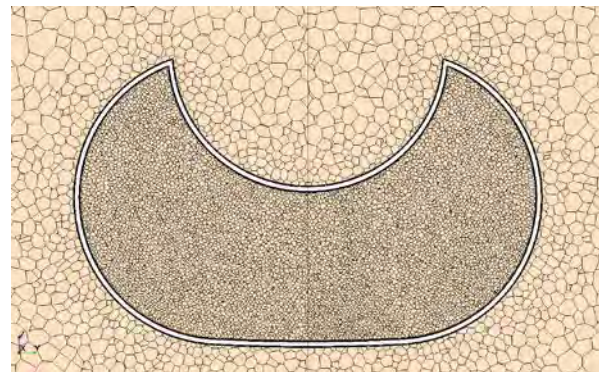
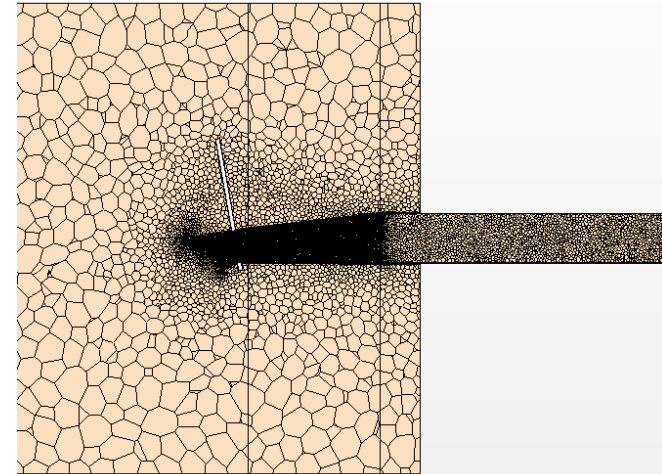
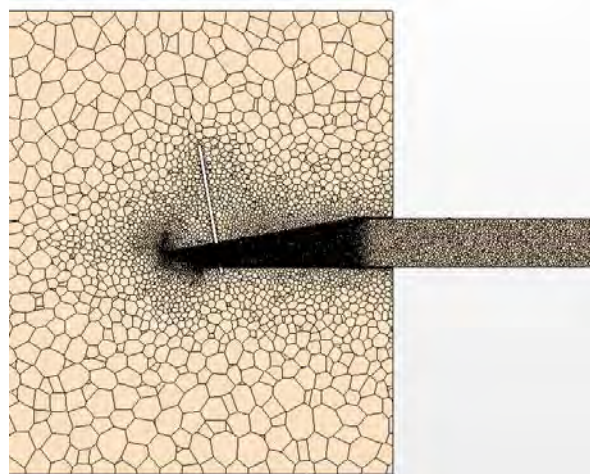
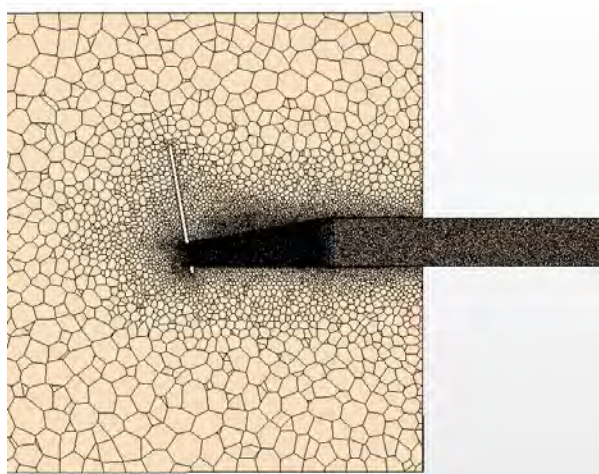
Dredge Inlet Geometries: Bass Mouth (B.M.)

- ◆ Possible Candidate to replace clown mouth design
- ◆ Entire inlet would need to be replaced to install this design
- ◆ Closer in design to more standard “bayonet” inlets
- ◆ Eliminates “tips” which are present in the openings of other two dredge designs



Computational Setup- Dredge Inlet Meshes

- ◆ Polyhedral meshes used for all simulations, dredge and pit
- ◆ Prism layers used at wall boundaries, base size = 0.06 m
- ◆ Mesh size refined in specific areas in order to add accuracy where necessary
- ◆ Coarse grid used in pond volume further away from inlets to reduce cell count and required Comp. time



Clown Mouth

- 3.9 Million Cells
- 15.5 Million Vertices

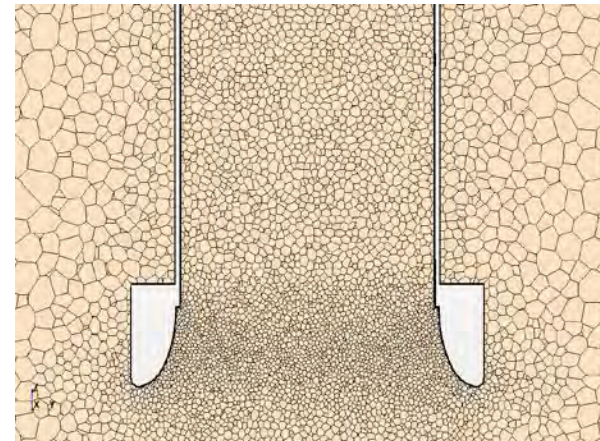
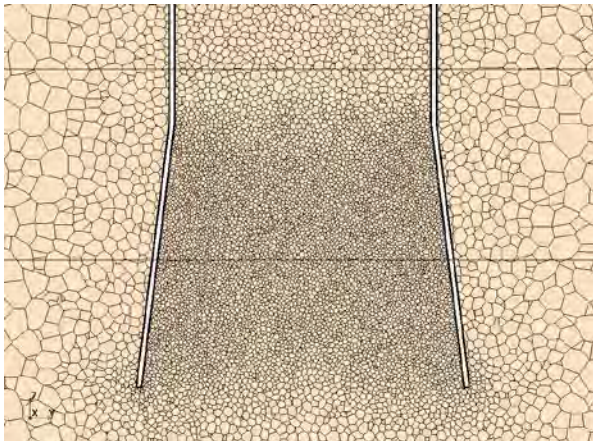
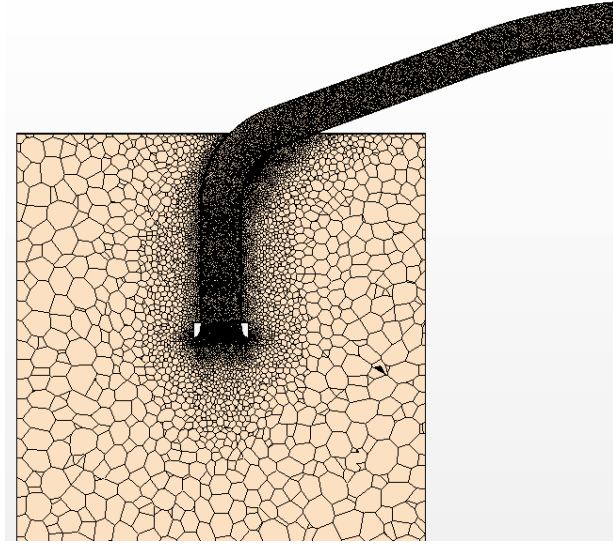
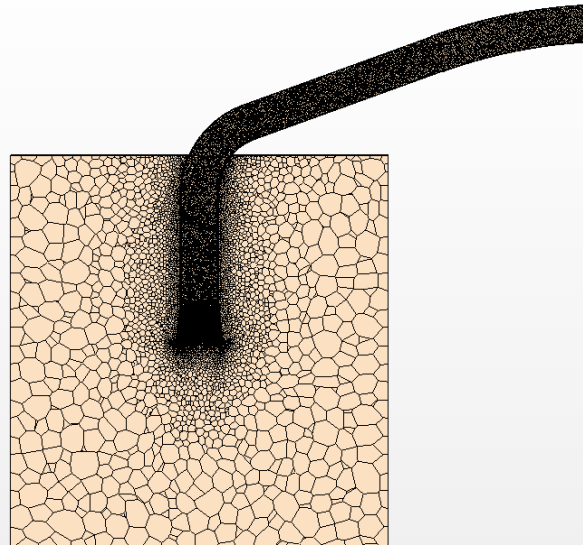
Clown Mouth w/ Ext.

- 5.0 Million Cells
- 20.2 Million Vertices

Bass Mouth

- 4.0 Million Cells
- 16.1 Million Vertices

Computational Setup- Pit Inlet Meshes



Oversized Enlargement

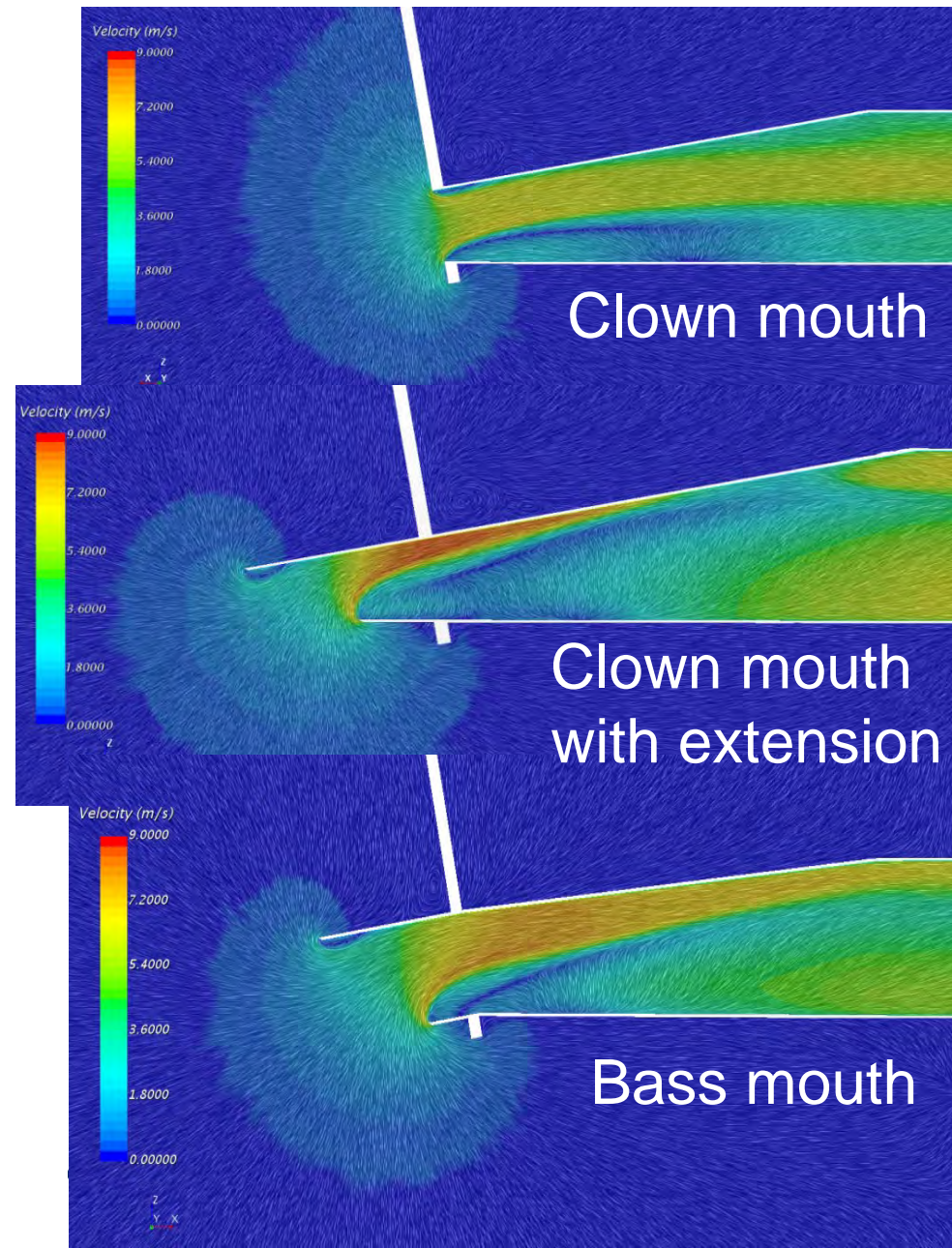
- 3.0 Million Cells
- 10.9 Million Vertices

Elliptical Bell Reducer

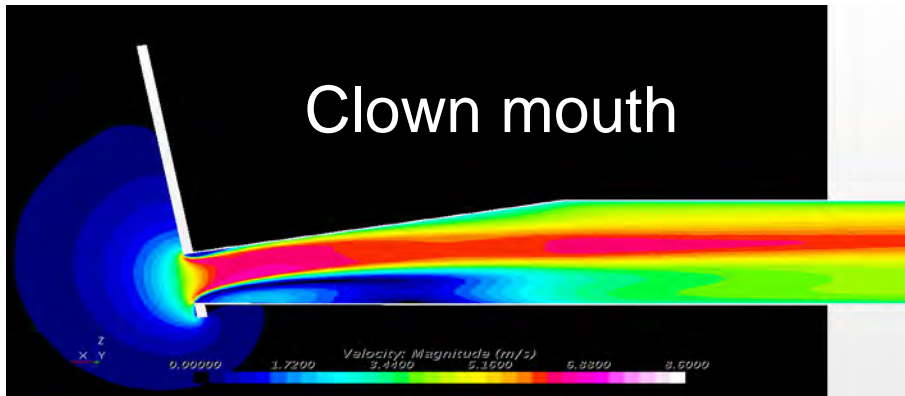
- 2.4 Million Cells
- 8.2 Million Vertices

Results- 2D Velocity Vector Maps- Center-plane

- ◆ Legend limits: 0 - 9 m/s for all 3 plots
- ◆ Dead zone present in all 3 designs
- ◆ Increased velocity in region over dead zone for all 3 designs
- ◆ C.M pull mostly from front, while other two designs pull from bottom and front
- ◆ C.M.E. has relatively high velocities on upper wall near connection → high wear.

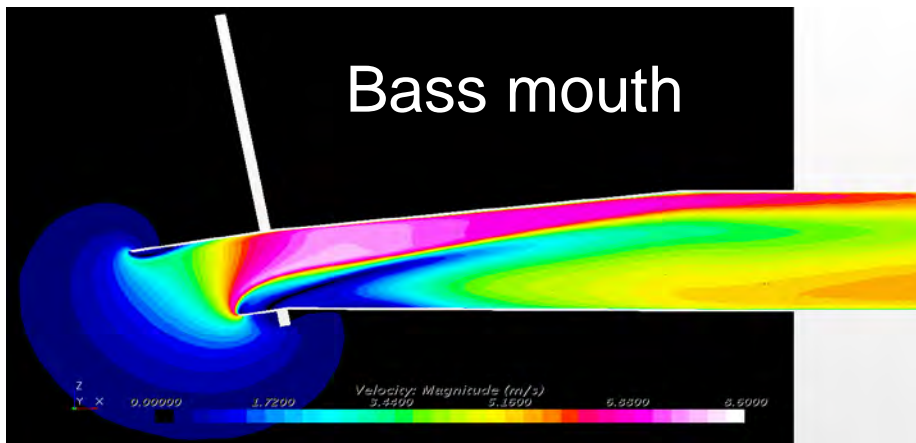
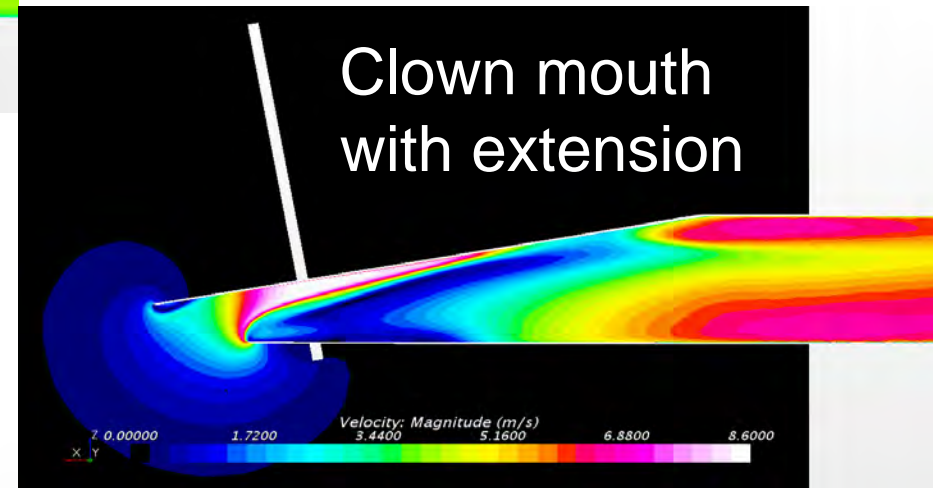


Results- Velocity Contour Maps- Center-plane



- ◆ Legend limits: 0 – 8.6 m/s for all 3 plots
- ◆ Difference in pond inlet zones apparent
- ◆ High velocity central flow maintained in C.M and B.M.

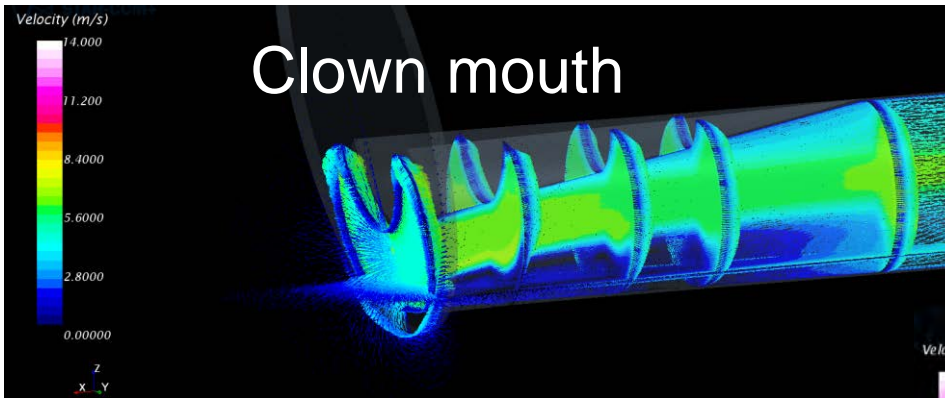
- ◆ High velocity flow diverted around dead zone to the top and outside of C.M.E.



- ◆ C.M.E. and B.M. show slightly higher velocities than C.M at center-plane.

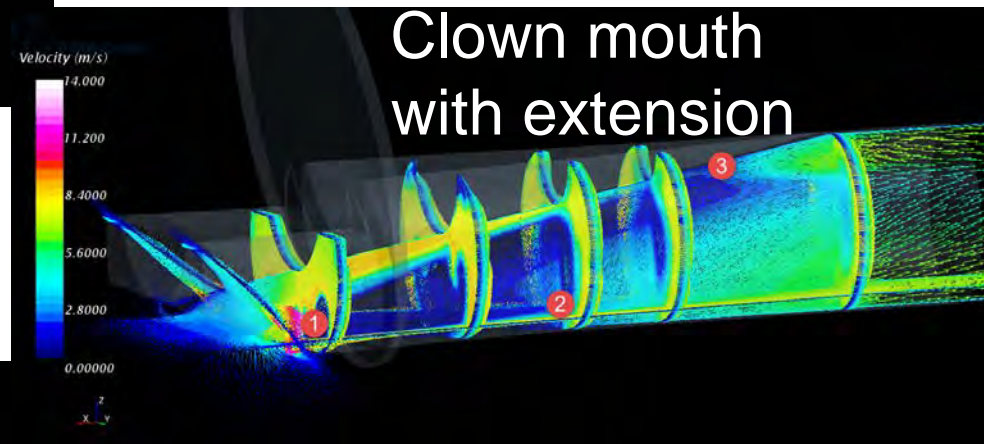
Results- 3D Velocity Vector Maps – Isometric View

Clown mouth



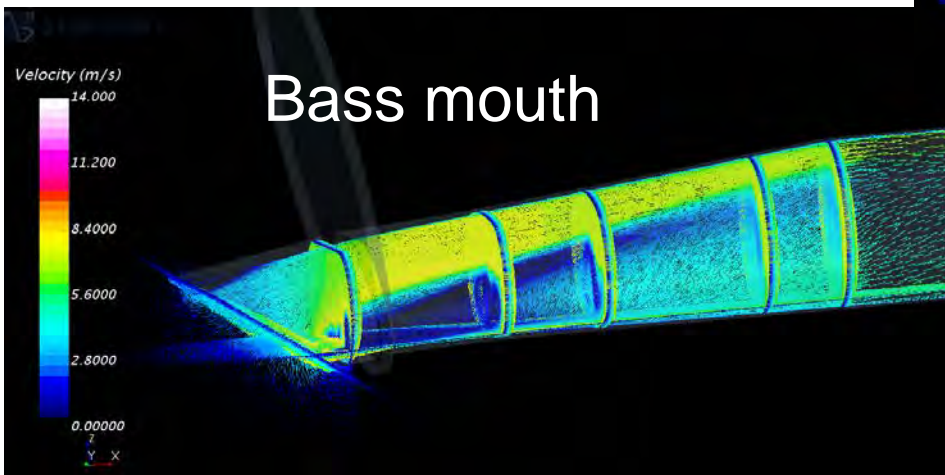
- ◆ Legend limits: 0 - 14 m/s for all 3 plots
- ◆ C.M.E. exhibits highest velocities near inlet (on bottom near sides)

Clown mouth with extension



- ◆ Highest velocities of C.M. and B.M. ~ 8 m/s.
- ◆ Differences in shapes of dead zones apparent

Bass mouth



- ◆ Dead zone X- sec. shape for C.M.E.: “ω” → “o”
- ◆ Dead zone less 3D for other two designs

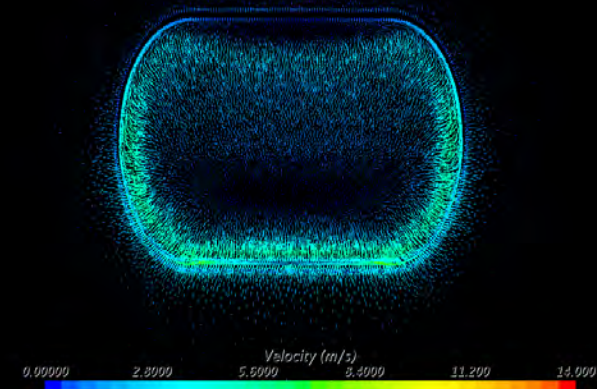
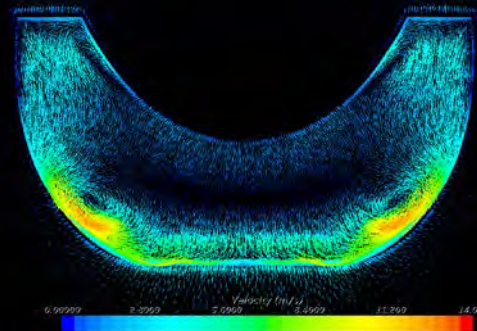
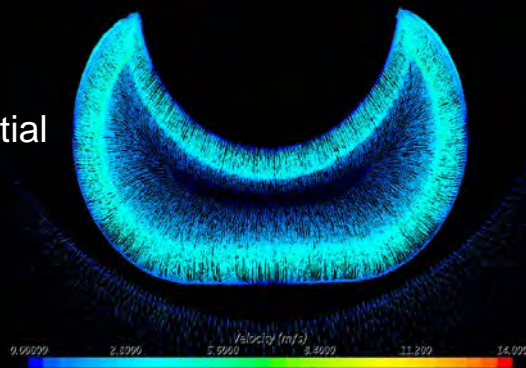
Results- Velocity Vector Maps at Inlets

Clown Mouth

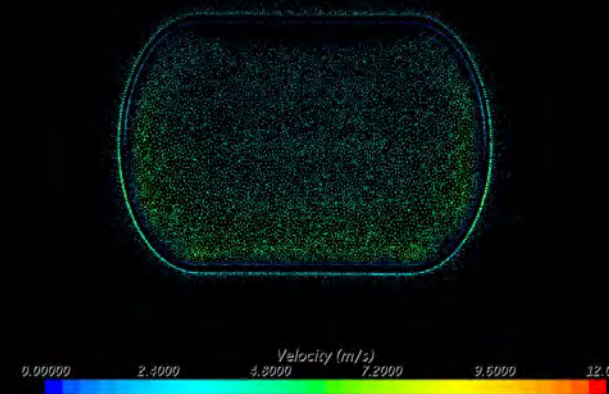
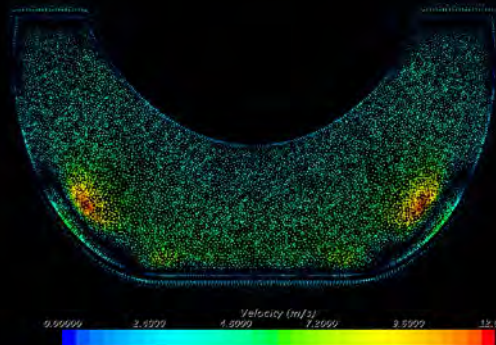
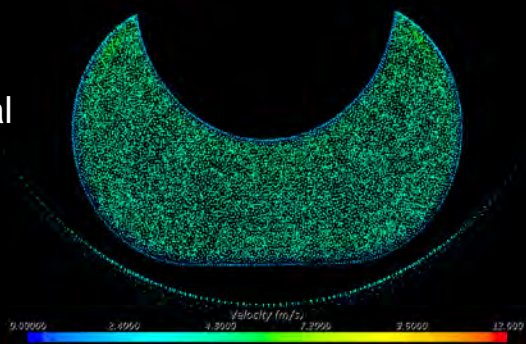
Clown Mouth w/ Ext.

Bass Mouth

Tangential

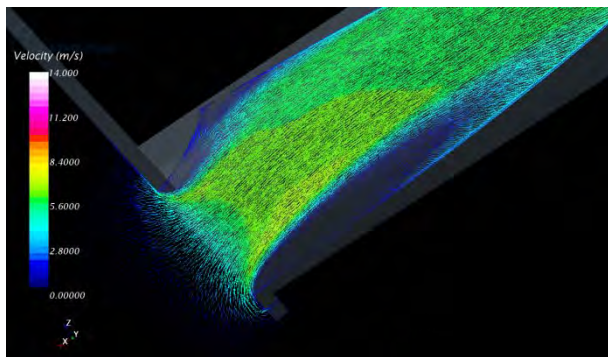
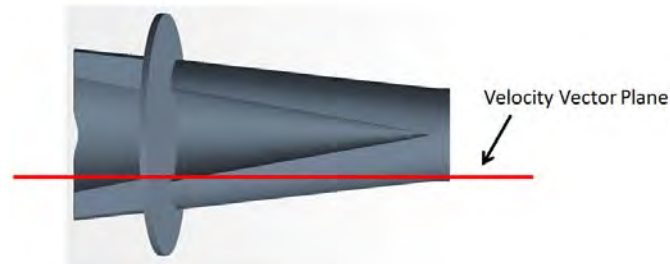


Normal

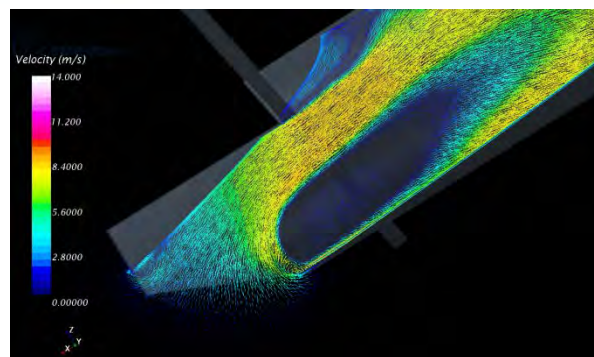


- ◆ Legend limits: 0 - 14 m/s for all 3 plots
- ◆ C.M. and B.M. inlet velocities more uniform than C.M.E.
- ◆ Two counter-rotating vortices present on either side of C.M.E. w/ high velocities (13 m/s) near walls → wear concerns.

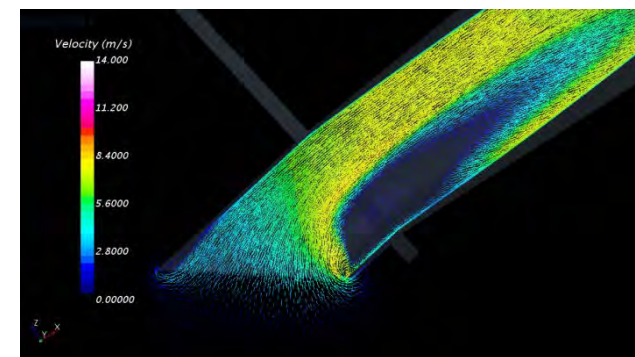
Results- Velocity Vector Maps off-center



Clown Mouth



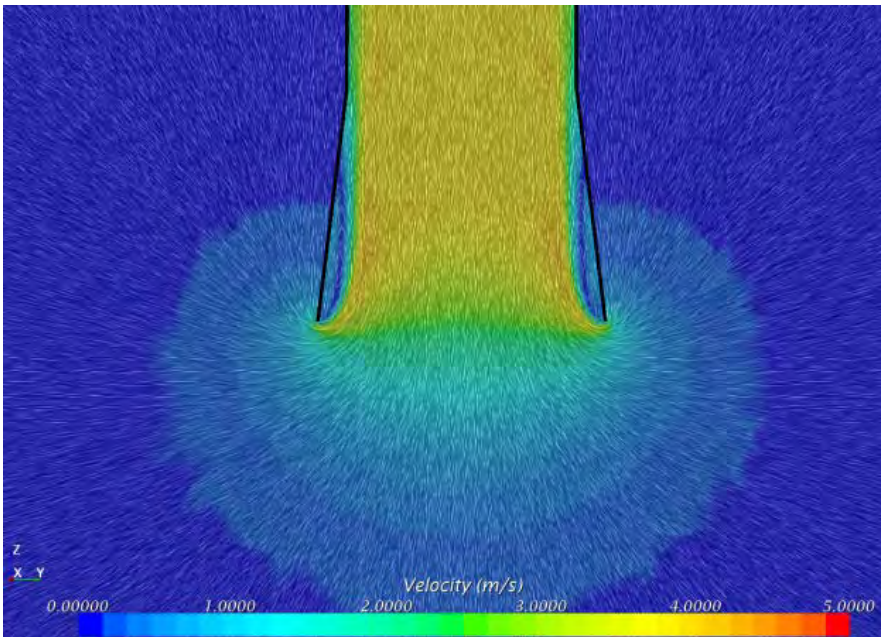
Clown Mouth w/ Ext.



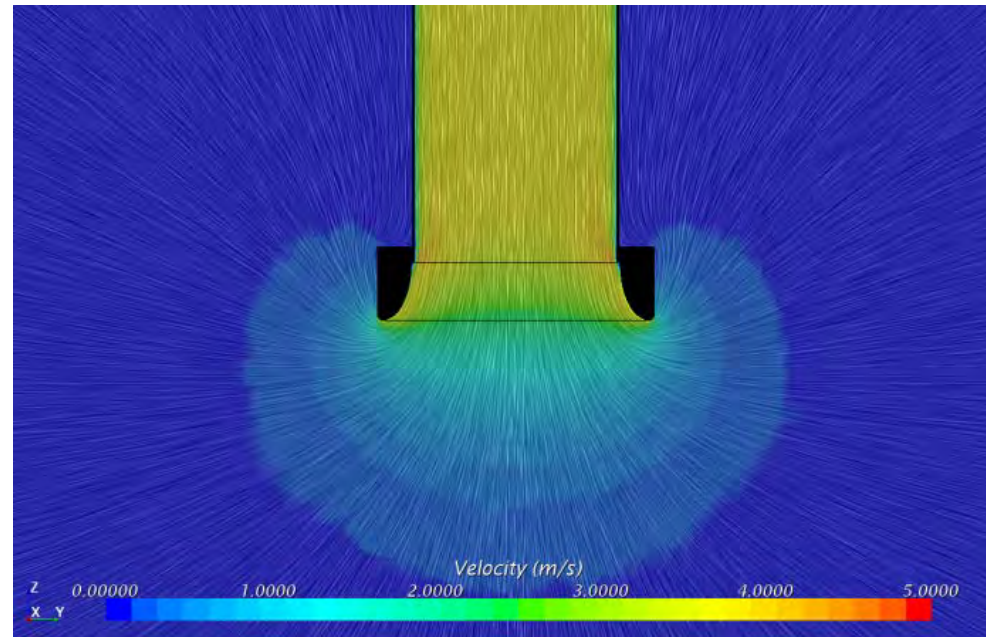
Bass Mouth

- ◆ Legend limits: 0 - 14 m/s for all 3 plots
- ◆ All 3 designs have re-circulations zones
- ◆ C.M.E. and B.M. will pull more solids off the bottom than C.M.
- ◆ Re-circulation zones could potentially cause problems related to bedding and stability.
- ◆ No indication here that prospect designs would be any worse than existing.

Results- Pit Inlet Velocity Vector Maps at center-plane



Oversized Enlargement (O.E.)

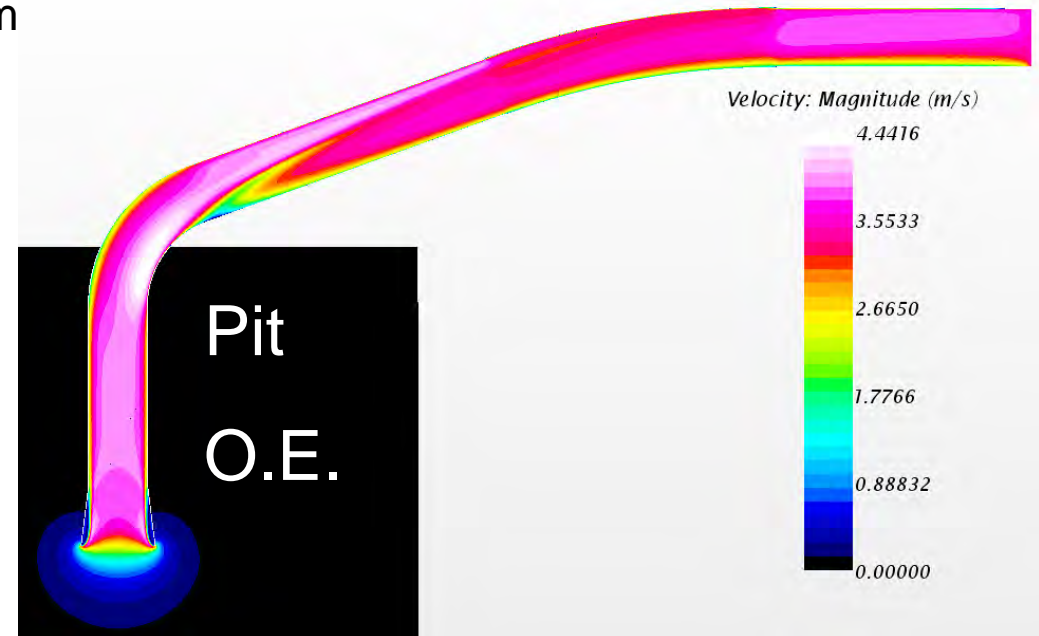
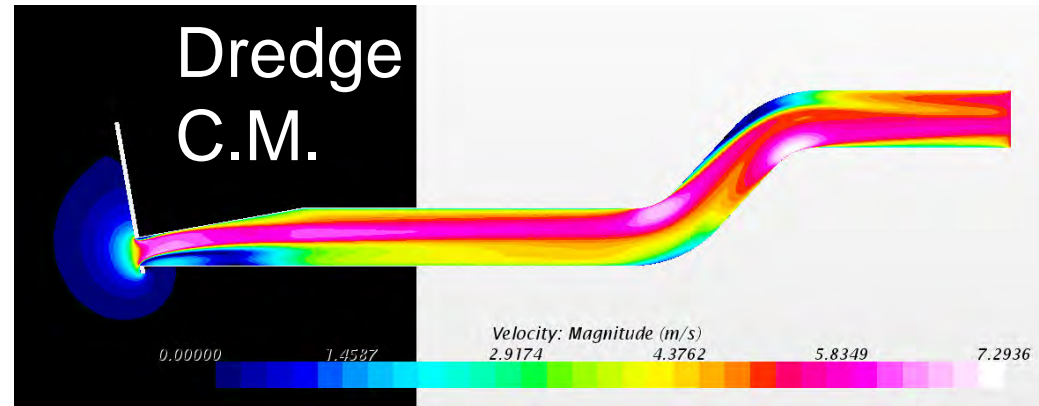


Elliptical Bell Reducer (E.B.R.)

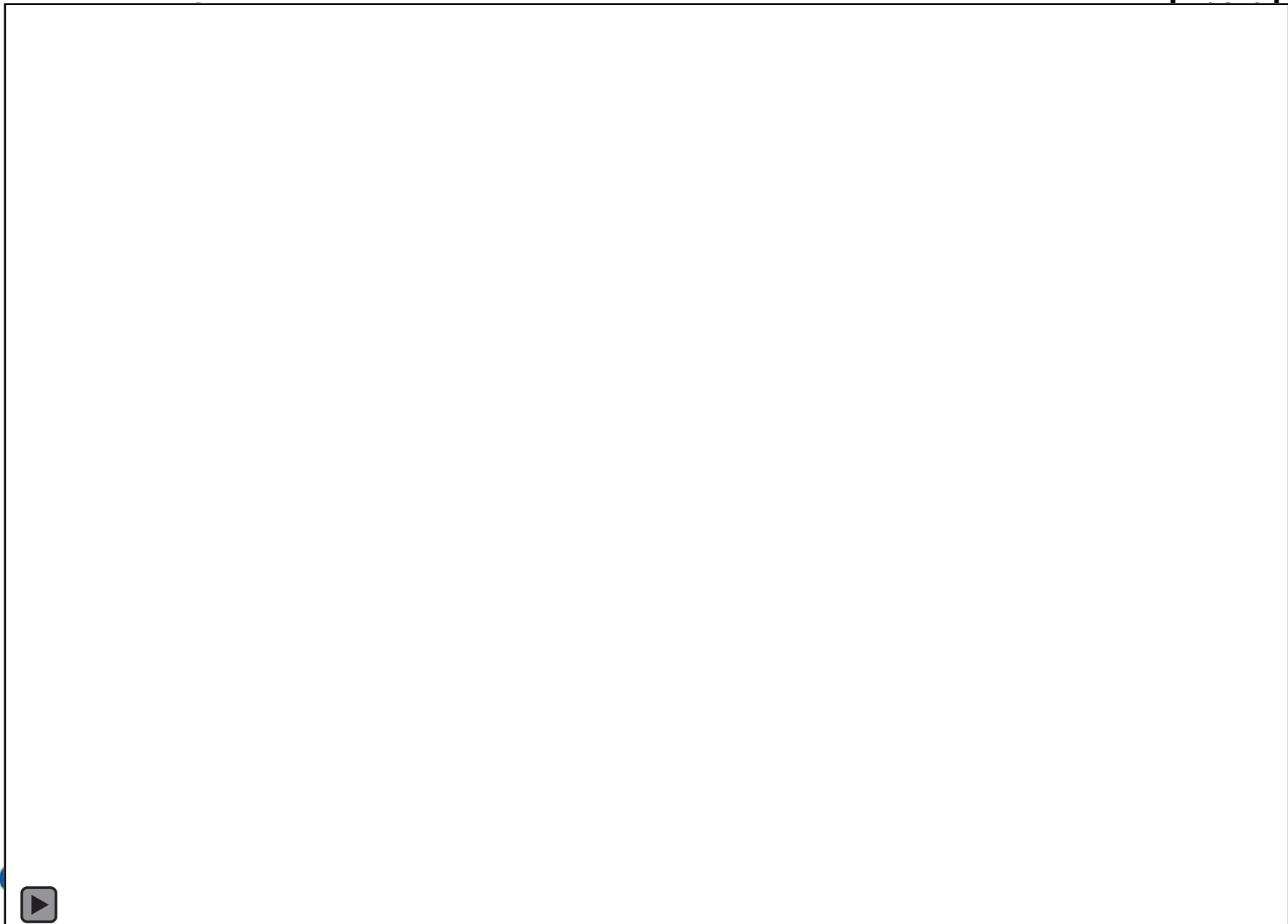
- ◆ Legend limits: 0 - 5 m/s for both plots
- ◆ Oversized enlargement has small recirculation zone.
- ◆ Recirculation zone in O.E. is occupied by wall material in E.B.R.
- ◆ Maximum inlet velocity for both designs ~ 4.3 m/s (line Vel. = 3.6 m/s).
- ◆ Zone of increased velocities ~ 2D
- ◆ Better looking velocity profiles than dredge designs

Results- Piping Velocities at center-plane

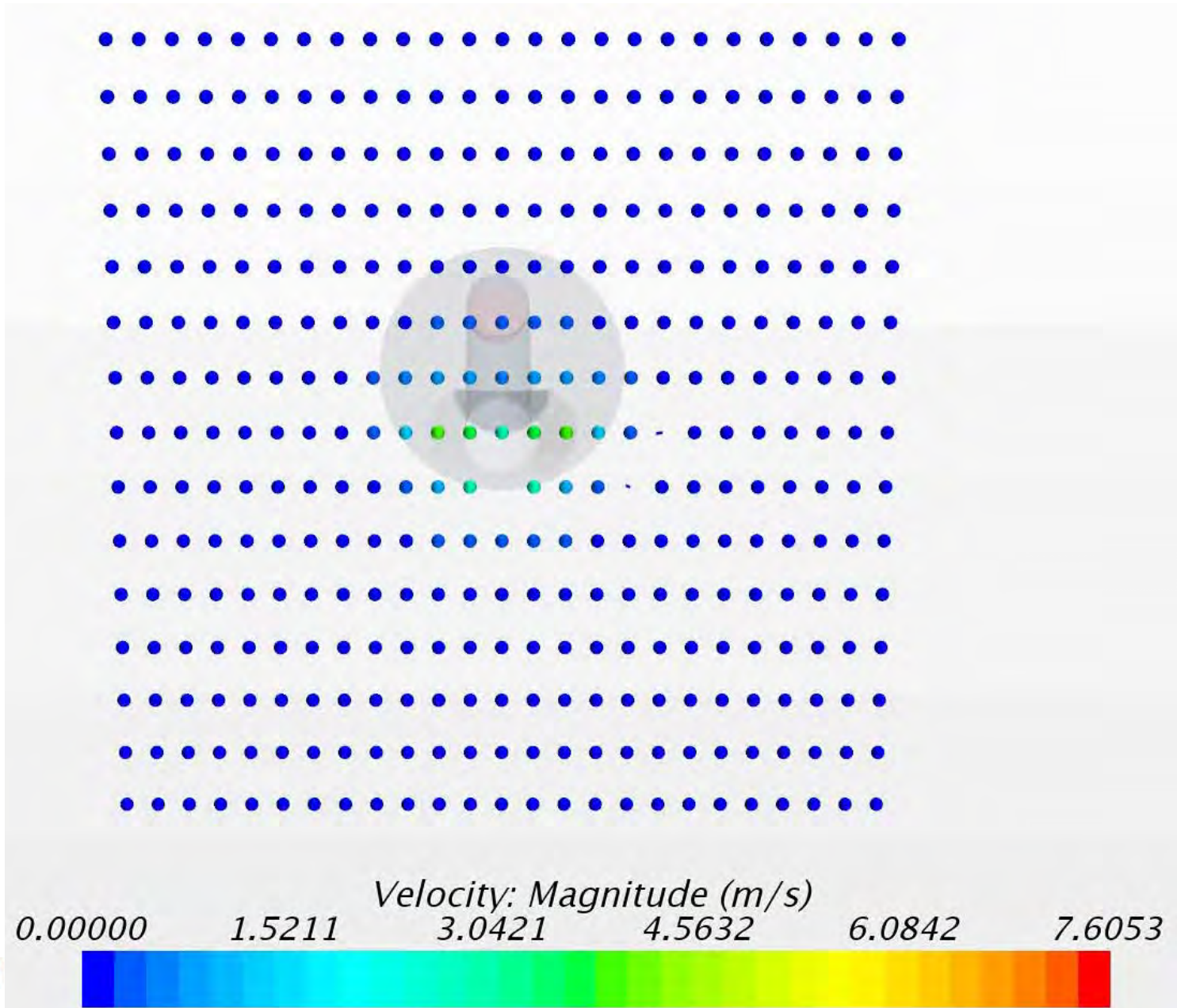
- ◆ Legend limits: 0 – 7.3 m/s for dredge
- ◆ Legend limits; 0 - 4.4 m/s for Pit
- ◆ Non-uniformity in dredge piping vel. propagates a long way downstream
- ◆ Pit piping velocities much more uniform



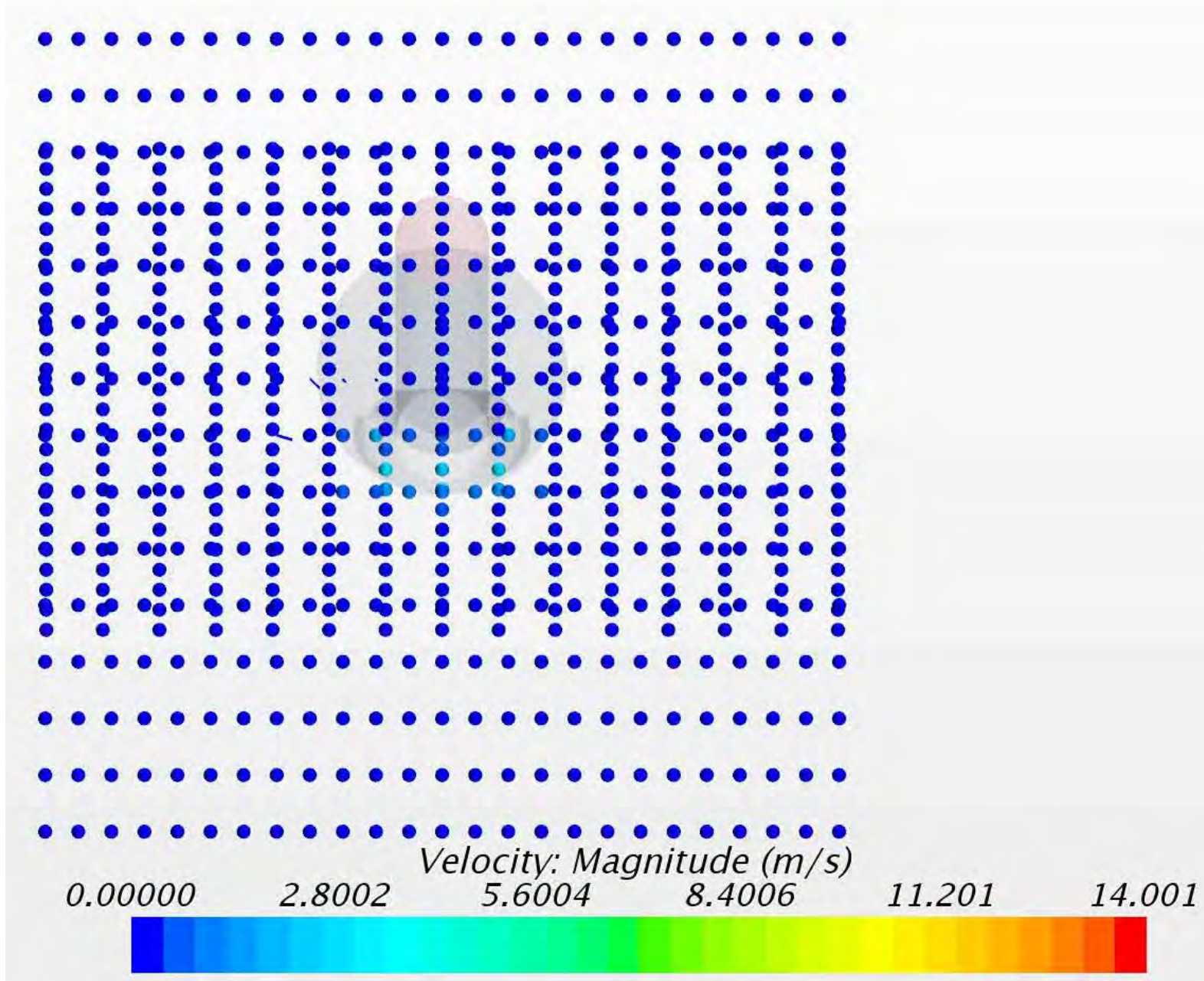
Video Results: Clown Mouth Streamlines



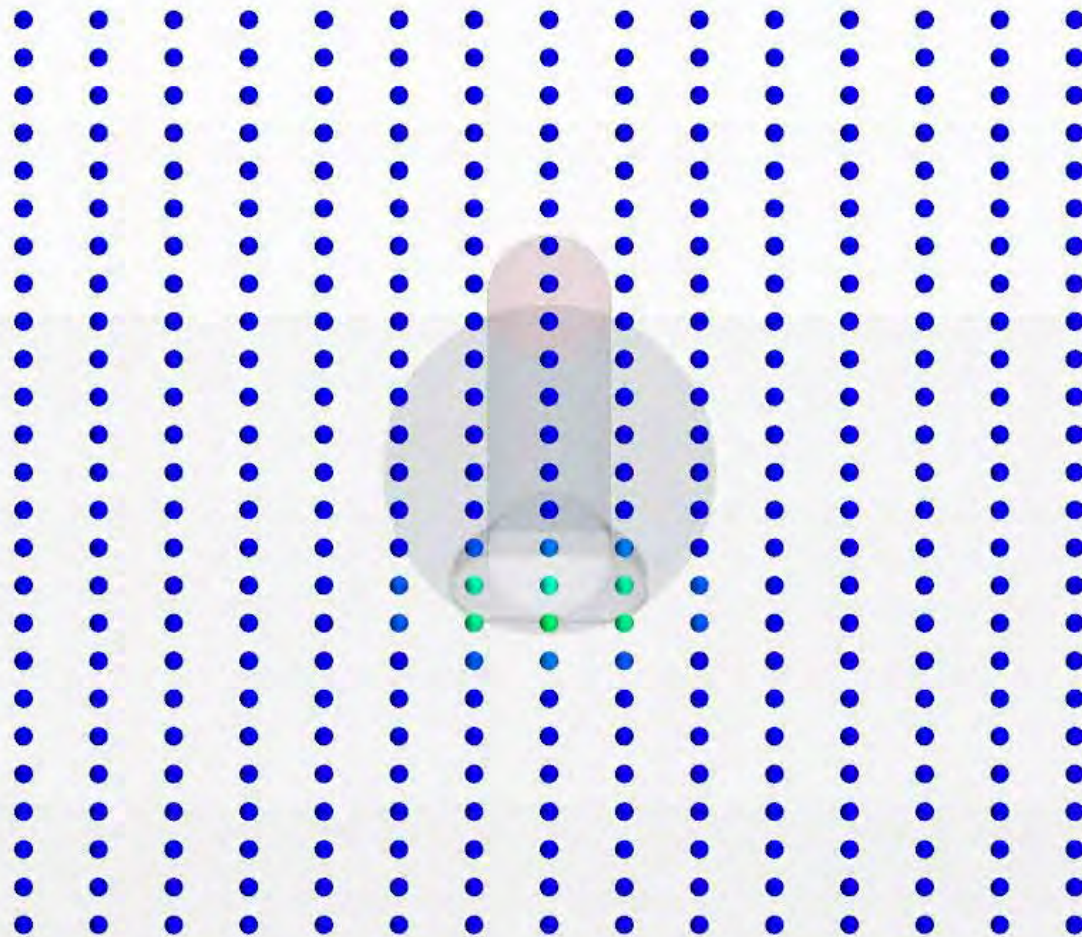
Video Results: Solids uptake- Clown Mouth Front View



Video Results: Solids uptake- Clown Mouth w/ Ext. Front View



Video Results: Solids uptake- Bass Mouth Front View



Analysis

$$K = \frac{2\Delta P_s}{\rho_w V_m^2} - 1$$

$$AR = \frac{\text{Inlet Area}}{\text{Pipe Area}}$$

$$H_l = K \frac{V^2}{2g}$$

Inlet Geometry	Calculated K value	Area ratio	Line Velocity (m/s)	Head loss (m)
Clown Mouth- Dredge	0.336	1.278	5.47	0.51
Clown Mouth w/ Ext.- Dredge	0.98	1.489	5.47	1.49
Bass Mouth - Dredge	0.68	1.674	5.47	1.04
Bell Reducer - Pit	0.124	1.749	3.57	0.08
Oversized Enlargement- Pit	0.25	1.571	3.57	0.16

- ◆ Clown mouth with ext. K value ~ K value of inward projecting pipe
- ◆ Clown mouth K value < Bass Mouth K value < Clown Mouth w/ Ext. K value
- ◆ Increase in K value from C.M. to C.M.E. and B.M. is due to going from flush to projected
- ◆ Oversized enlargement K value ~ K value for chamfered inlet
- ◆ Bell reducer K value ~ K value for rounded inlet (0.111)
- ◆ Lower K value of bell reducer (1/2 that of O.E) due to lack of recirculation zone.

Conclusions and Future Recommendations

- ◆ Three different dredge inlet designs and 2 different pit pump designs were analysed.
- ◆ K values of all 5 devices were relatively modest- all less than 1.0, maximum head losses 1.5 meters for the clown mouth with extension.
- ◆ Dredge inlets showed non-uniform velocity profiles and large recirculation zones.
- ◆ Pit inlets showed much more uniform velocity profiles and no large recirculation zones.
- ◆ Elliptical bell reducer found to be the better pit inlet design:
 - Lower losses
 - More uniform inlet velocities
 - Absence of any re-circulation zone
- ◆ Field data indicated insufficient NPSHA- remedied by removal of on-shore booster
- ◆ Bass mouth found to be best dredge inlet design
 - Smaller recirculation zone- mitigates bed formation and associated instabilities
 - Relatively low k value
 - More uniform inlet velocities
 - No large vortices
 - Pulls solids off bottom of pond and closer to cutter

Conclusions and Future Recommendations (contd.)

- ◆ Hydraulic design of inlet is not only factor that can limit solids concentration.
- ◆ Solids liberation achieved with cutter head is also equally important.

- ◆ Recommendations:
 - **Install bass mouth dredge inlet.**
 - **Reduce dredge inlet pipe diameter from 641 mm (25.25 “) to 584 mm (23”) to prevent bedding in suction piping.**
 - **May need to increase cutter head rotational speed (currently 18 rpm).**

Questions

???