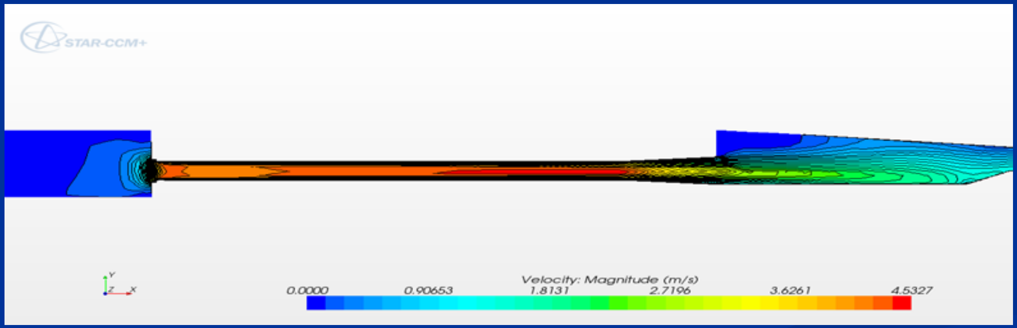
Utilizing Yarnell's Flow Data to Validate & Analyze CFD Models



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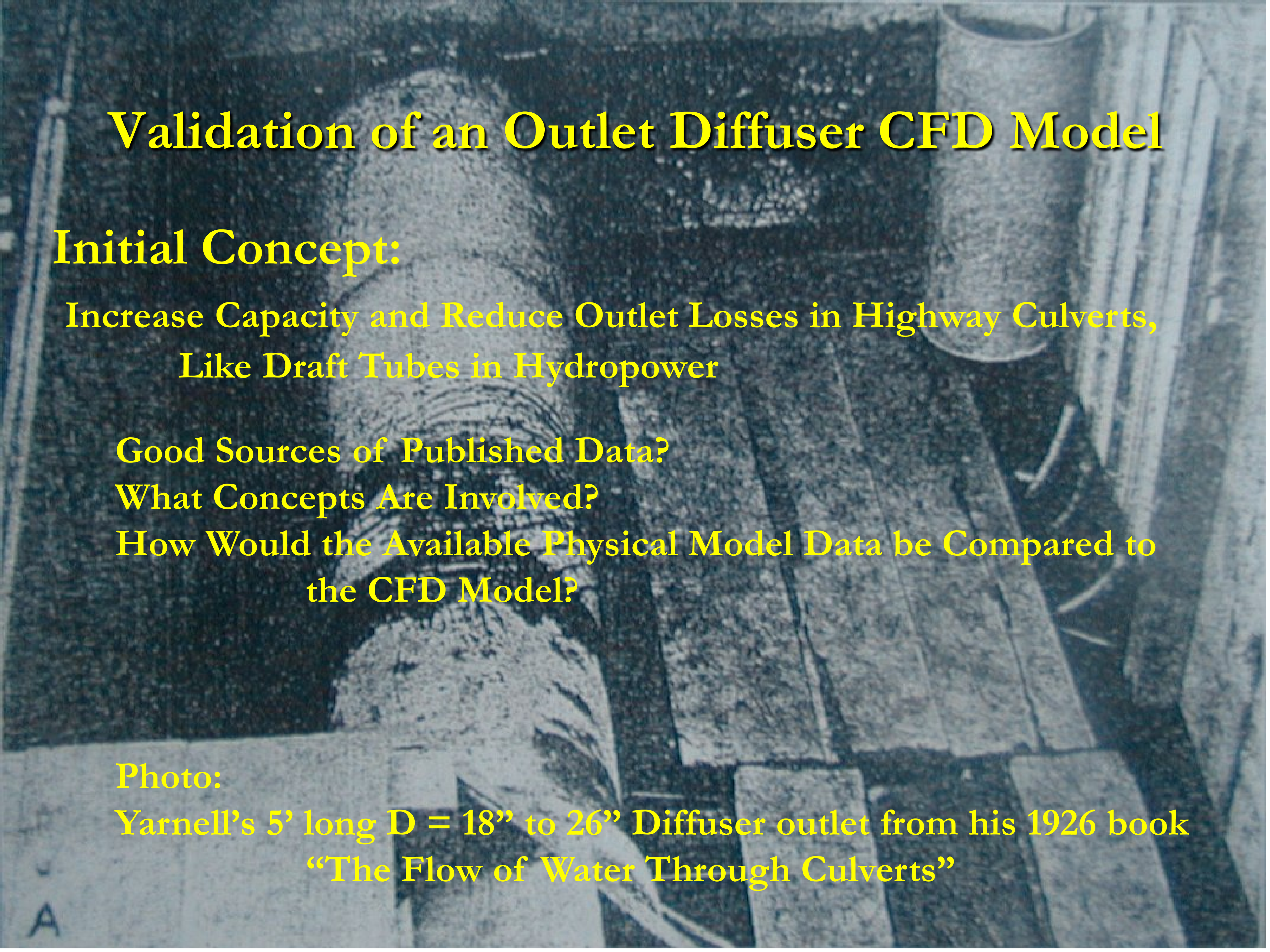


Validation of an Outlet Diffuser CFD Model

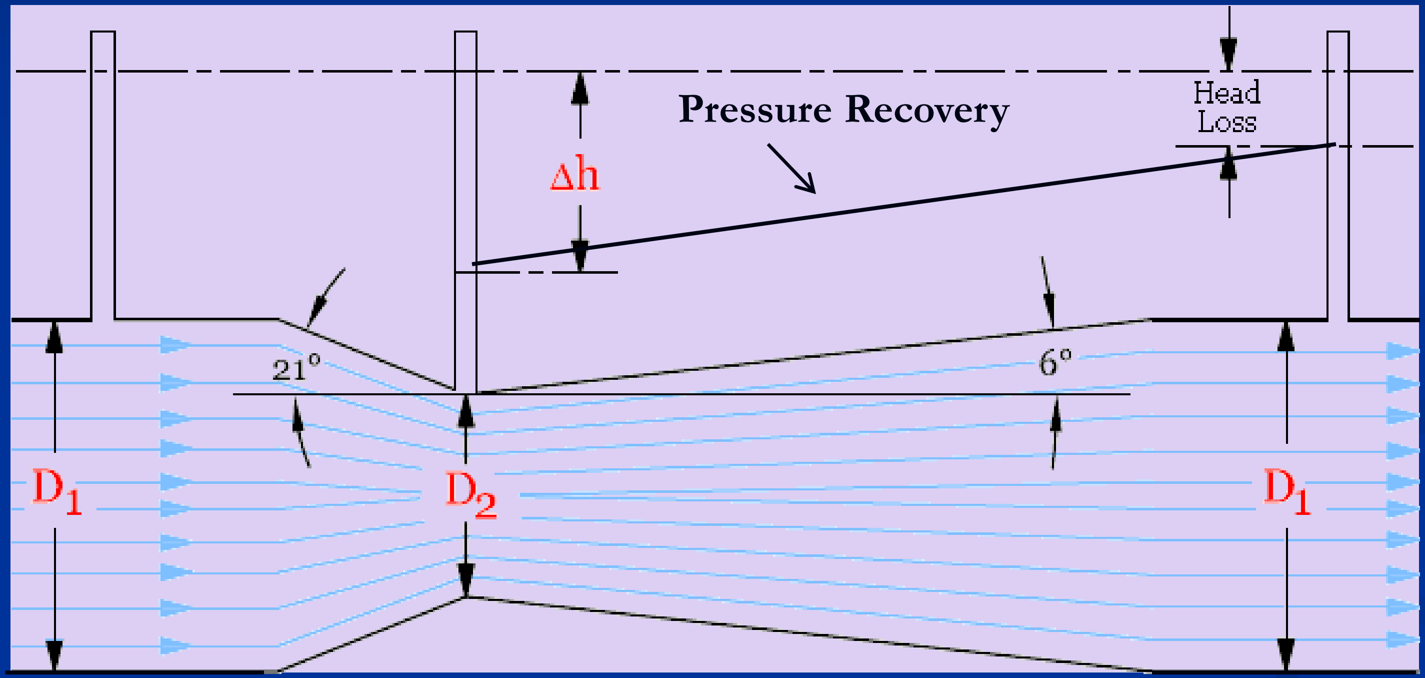
Initial Concept:

Increase Capacity and Reduce Outlet Losses in Highway Culverts,
Like Draft Tubes in Hydropower

Good Sources of Published Data?
What Concepts Are Involved?
How Would the Available Physical Model Data be Compared to the CFD Model?

Photo:
Yarnell's 5' long D = 18" to 26" Diffuser outlet from his 1926 book "The Flow of Water Through Culverts"

What is a Diffuser and How Does it Function?



Source: Wermac.org

This Venturi Meter displays the basic concept.

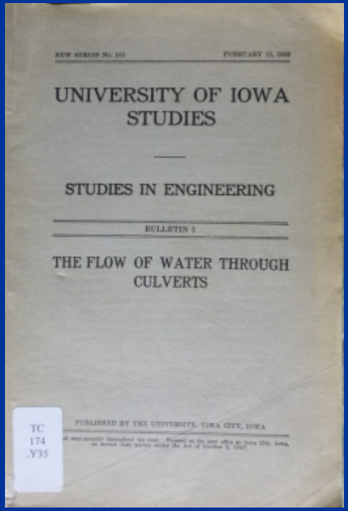
Yarnell's Model – In this case a 3' by 3' box transitioning into a 6'W by 3'H Outlet Diffuser

- **Physical Models**
  - **Real Data**
  - **Point Data**
  - **Traditional Sensors _ Piezometers and Pitot Tubes**
  - Large **Physical** Presence
  - Temporary
  - Difficult to Share

Photo curtesy of Connie Mutel, at the University of Iowa Hydraulics Lab

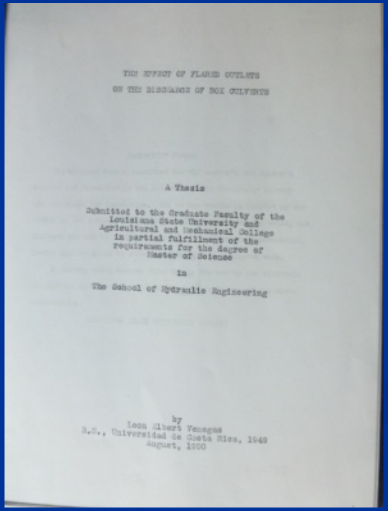
Sources for Physical Diffuser Model Data

- The Flow of Water Through Culverts, Yarnell 1926
  - Pipes, Box Culverts, and Diffusers ("Increasers")
- Effect of Flared Outlets on Discharge of Box Culverts, Venega 1950
  - Effect of flare angle on discharge of box culverts.
- Effect of Length on Performance Characteristics of Diffusers, Smith 1951
  - Effect of diffuser length on discharge of box culverts.


UNIVERSITY OF IOWA
STUDIES

STUDIES IN ENGINEERING

THE FLOW OF WATER THROUGH
CULVERTS


THE EFFECT OF FLARED OUTLETS
ON THE DISCHARGE OF BOX CULVERTS

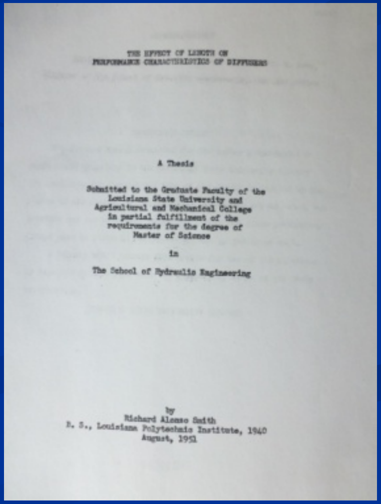
A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

The School of Hydraulic Engineering

by
Leon Albert Venegas
B.S., Universidad de Costa Rica, 1949
August, 1950


THE EFFECT OF LENGTH ON
PERFORMANCE CHARACTERISTICS OF DIFFUSERS

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Submitted to the Graduate Faculty of the
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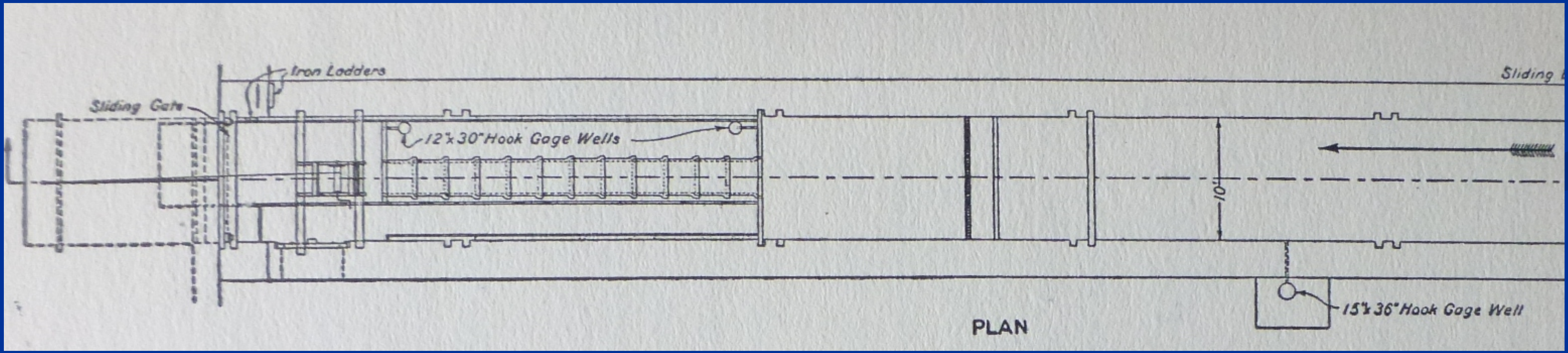
August, 1951

Important Concepts

- Pressure Recovery: Pressure - Velocity Relationship
  - $P_d - P_p = (\rho/2)(V_p^2 - V_d^2)$
- Outlet Losses: Borda-Carnot Derivation (Tullis 2012)
  - $H_o = k_o(V_p - V_c)^2/2g$ where $k_o = (1 - A_p/A_c)^2$
- Effect of Outlet Shape on Pipe Capacity
  - Streamlined Flow:
    - Flume and Syphon Transitions (Hinds 1927)
    - Minimum Energy Culverts (McKay 1971)
- Pipe Roughness and Shear Stress
  - “the action of viscosity … depends in part on the strength of the force field between the molecules” (Anderson 1998)

Data Management - What is Essential?

- Photos/Images/Detailed Descriptions
  - Essential for model geometry re-creation
- Data Tables
  - Precise but hard to digest
- Plots and Charts
  - Excellent for comparison and summary
  - Not very precise



Yarnell's Data for a Pipe with a Diffuser Outlet

GROUP XI—TABLE 79 SHOWING THE EFFECT OF A CONE PLACED AT THE OUTLET END OF A PIPE CULVERT

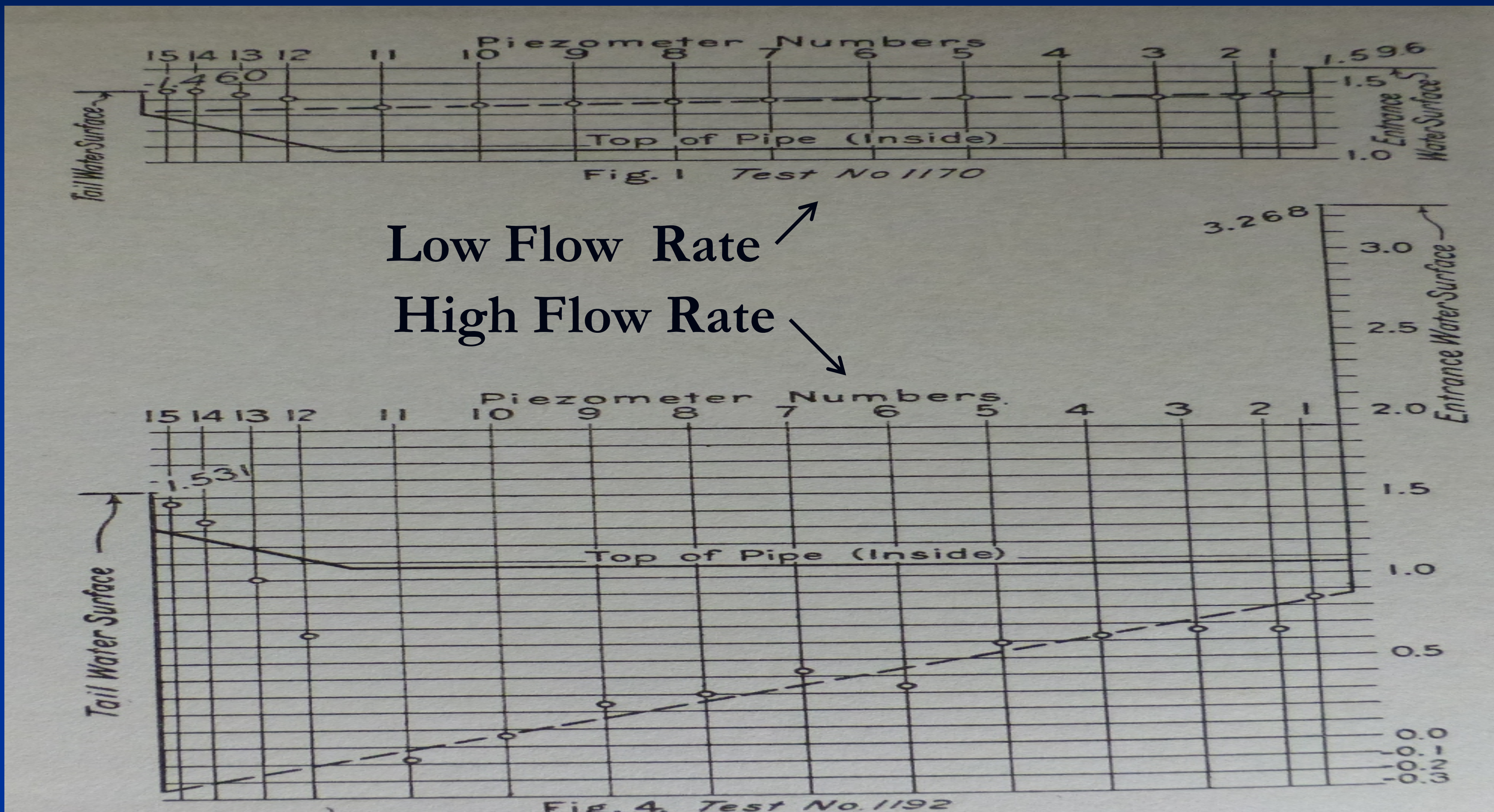
Table 79—18-inch vitrified-clay pipe, with straight endwall entrance and without floor in front of pipe; cone, 60 inches long increasing from 18-inches in diameter to 26 inches in diameter, total length of pipe including cone, 30 feet. Area of cross-section, 1.791 square feet; mean hydraulic radius, 0.3775 (See Plate XI-A)

Test numbers	Q Discharge Cu. ft. per sec.	V Velocity Feet per sec.	$\frac{V^2}{2g}$ Velocity head	Total head on pipe Feet	Friction loss Feet	Entrance loss Feet	Entrance loss coefficient	s Slope	C Chezy coefficient	n Kutter coefficient	n' Manning coefficient	Difference in elevation of water surface between entrance and outlet Feet	Gain in head with increaser at outlet Feet	Gain in head divided by velocity head
1167-1169	4.321	2.143	0.071	0.143	0.061	0.011	0.151	0.00199	78.5	0.0153	0.0162	0.07	0.074	1.047
1170-1172	6.02	3.361	0.176	0.264	0.090	−0.002	−0.011	.00292	101.3	.0124	.0125	0.14	0.128	0.729
1173-1175	8.02	4.478	0.312	0.455	0.133	0.010	0.031	.00435	110.9	.0116	.0114	0.24	0.214	0.686
1176-1178	10.05	5.609	0.489	0.747	0.244	0.013	0.027	.00775	103.8	.0122	.0122	0.38	0.363	0.742
1179-1181	12.14	6.778	0.714	1.069	0.339	0.016	0.023	.01104	105.2	.0121	.0120	0.55	0.519	0.726
1182-1184	14.16	7.908	0.972	1.481	0.470	0.039	0.040	.01534	104.2	.0122	.0122	0.74	0.740	0.761
1185-1187	16.50	9.213	1.319	2.011	0.652	0.039	0.030	.02128	103.3	.0123	.0123	1.00	1.015	0.769
1188-1190	18.96	10.59	1.743	2.667	0.876	0.049	0.028	.02856	102.4	.0124	.0124	1.32	1.353	0.777
1191-1192	21.84	12.20	2.312	3.538	1.118	0.108	0.016	.03647	104.0	.0122	.0122	1.76	1.786	0.772

- This data can be converted into a Performance curve.

Yarnell's Diffuser Piezometer Data

Outlet

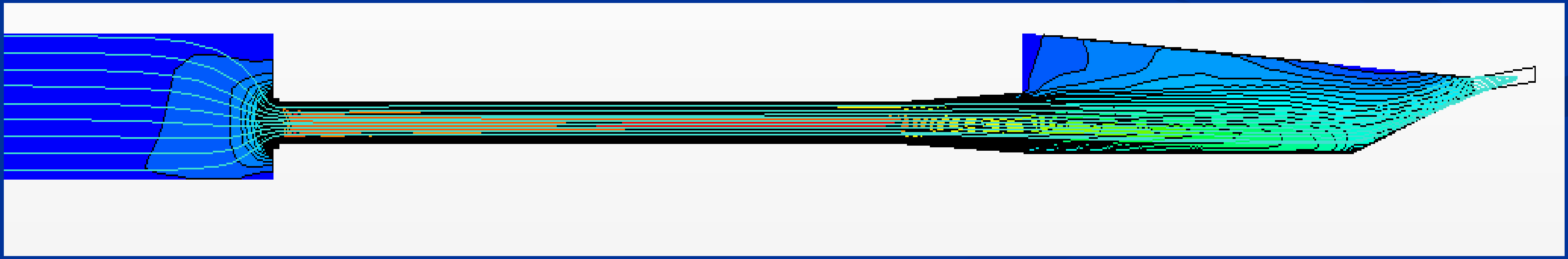


Inlet

The addition of this data can be used to create HGL and EGL plots.

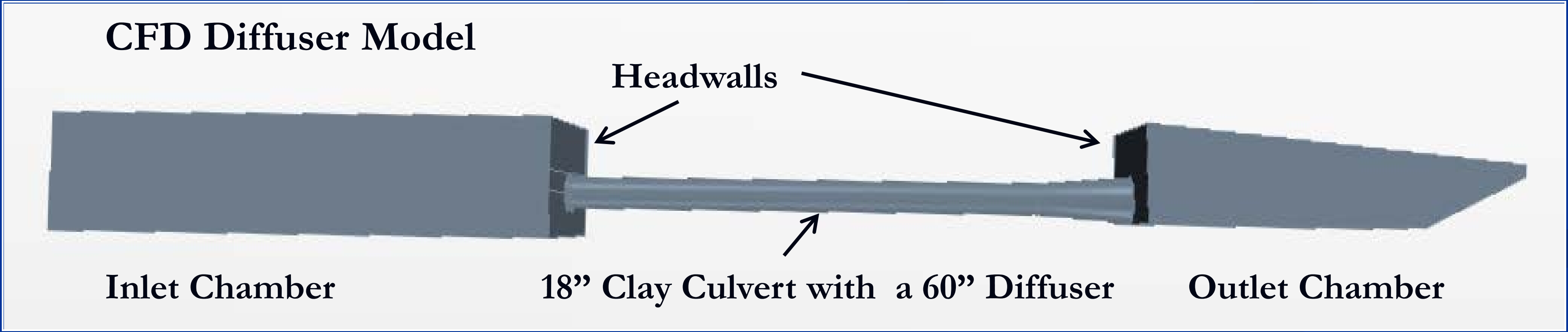
CFD Model Advantages

- CFD Models:
  - Easy to store and share
  - Not limited by physical and cost constraints
- Data and results can be viewed in a number of formats
  - Streamlines and vectors – indicate flow path
  - “Fields” – contoured data indicates gradients
- Data can be combined to display secondary features like shear stress



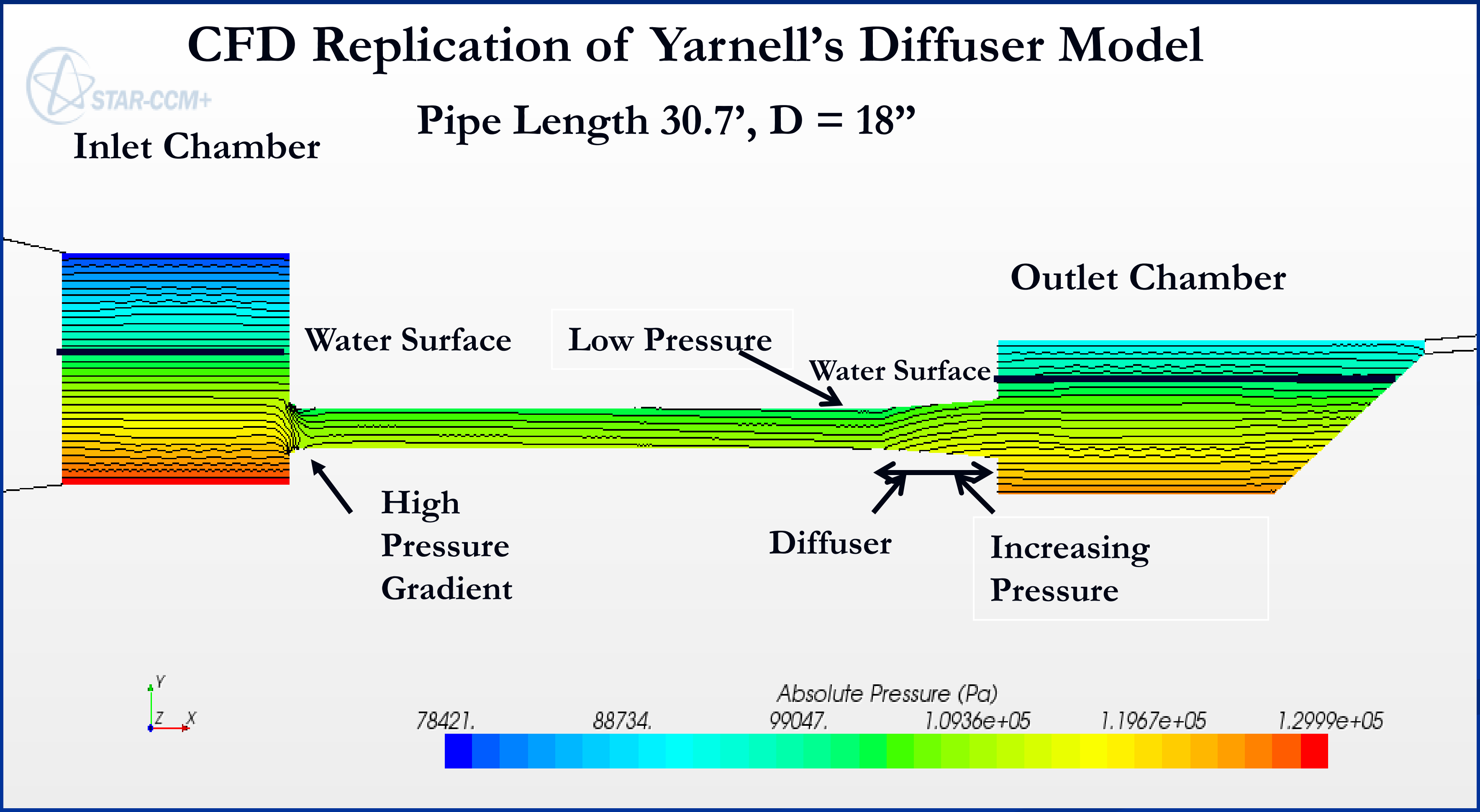
CFD Models *(cont)*

- Comparison of CFD models with physical models is necessary
  - The CFD program Star-ccm+ handles the basic model well
  - Model differences indicate the need for future research

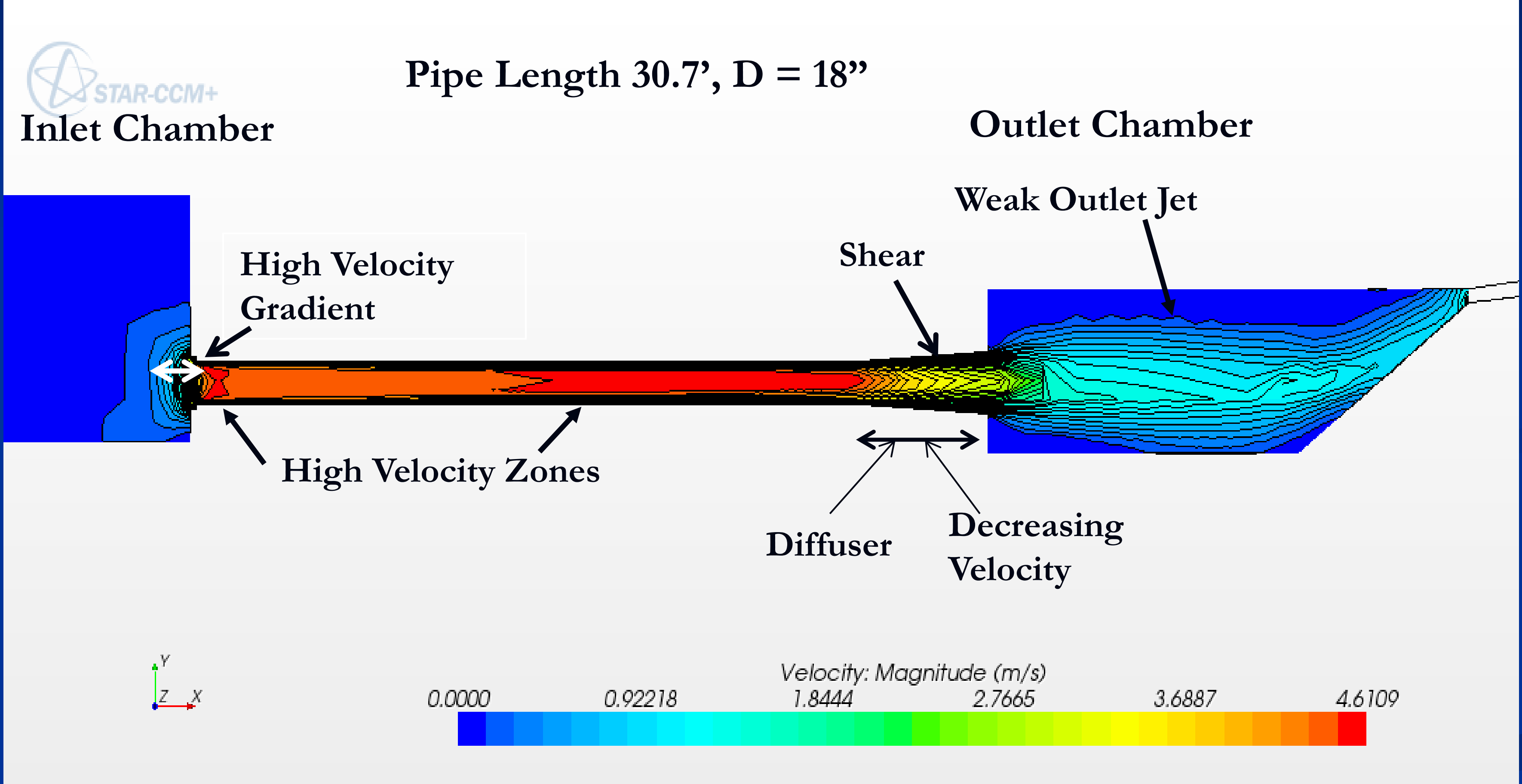


Insights from CFD Simulation Results

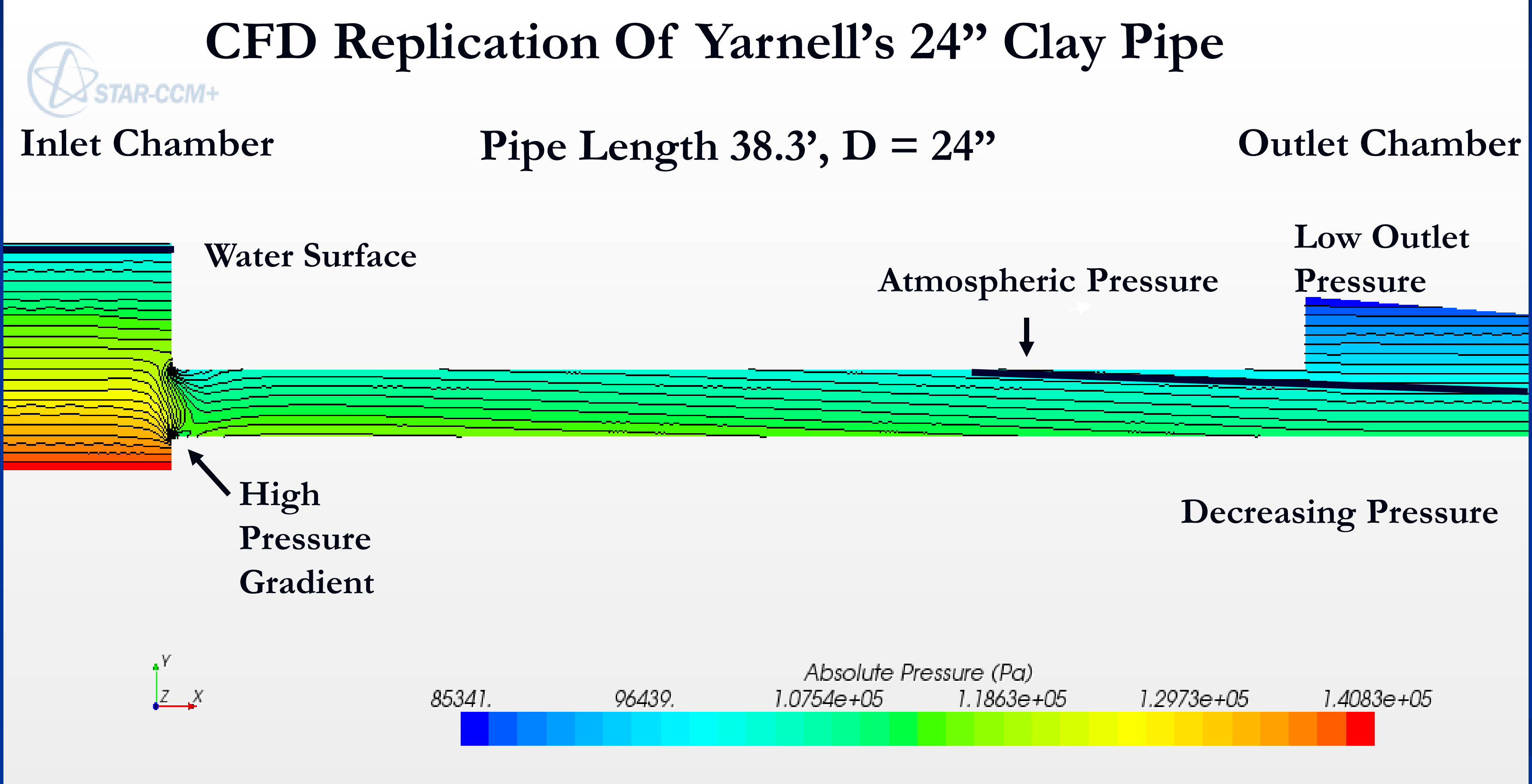
Pressure Profile Q =22 CFS (625 L/s)



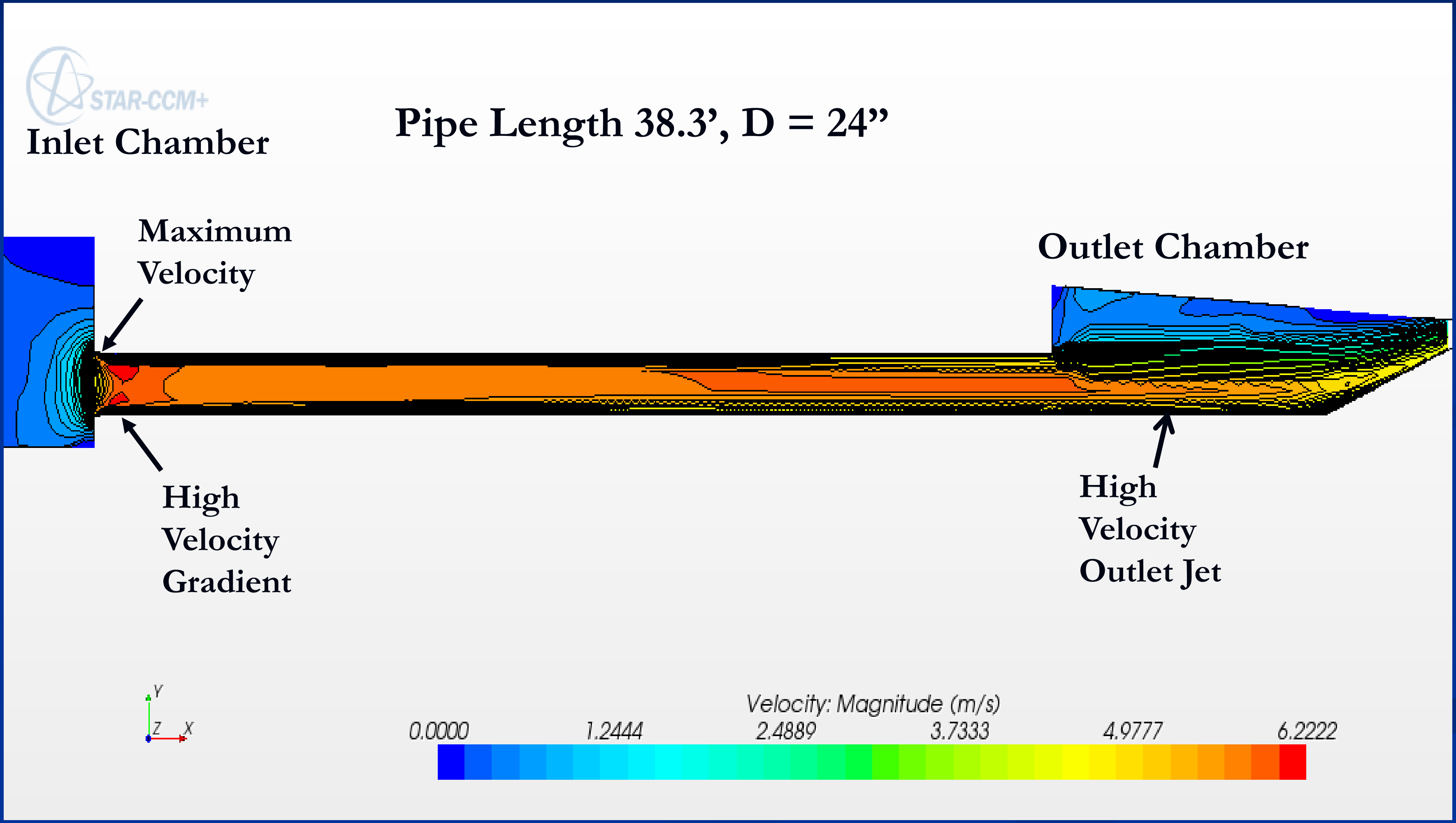
Velocity Profile Q = 22 CFS (625 L/s)



Pressure Profile for a Straight Clay Pipe
Q = 53 CFS (1500 L/s)

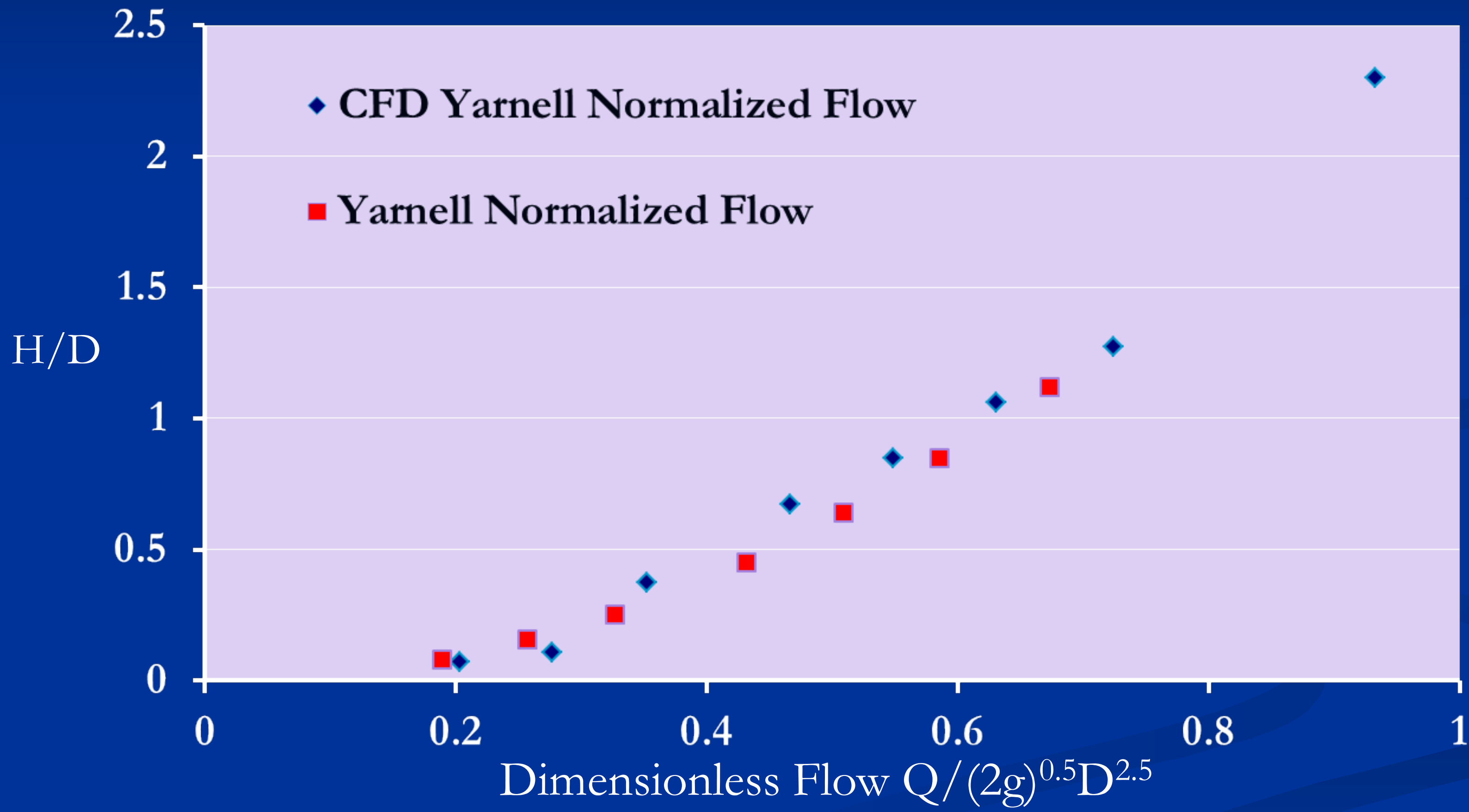


Velocity Profile Straight Clay Pipe
Q = 53 CFS (1500 L/s)



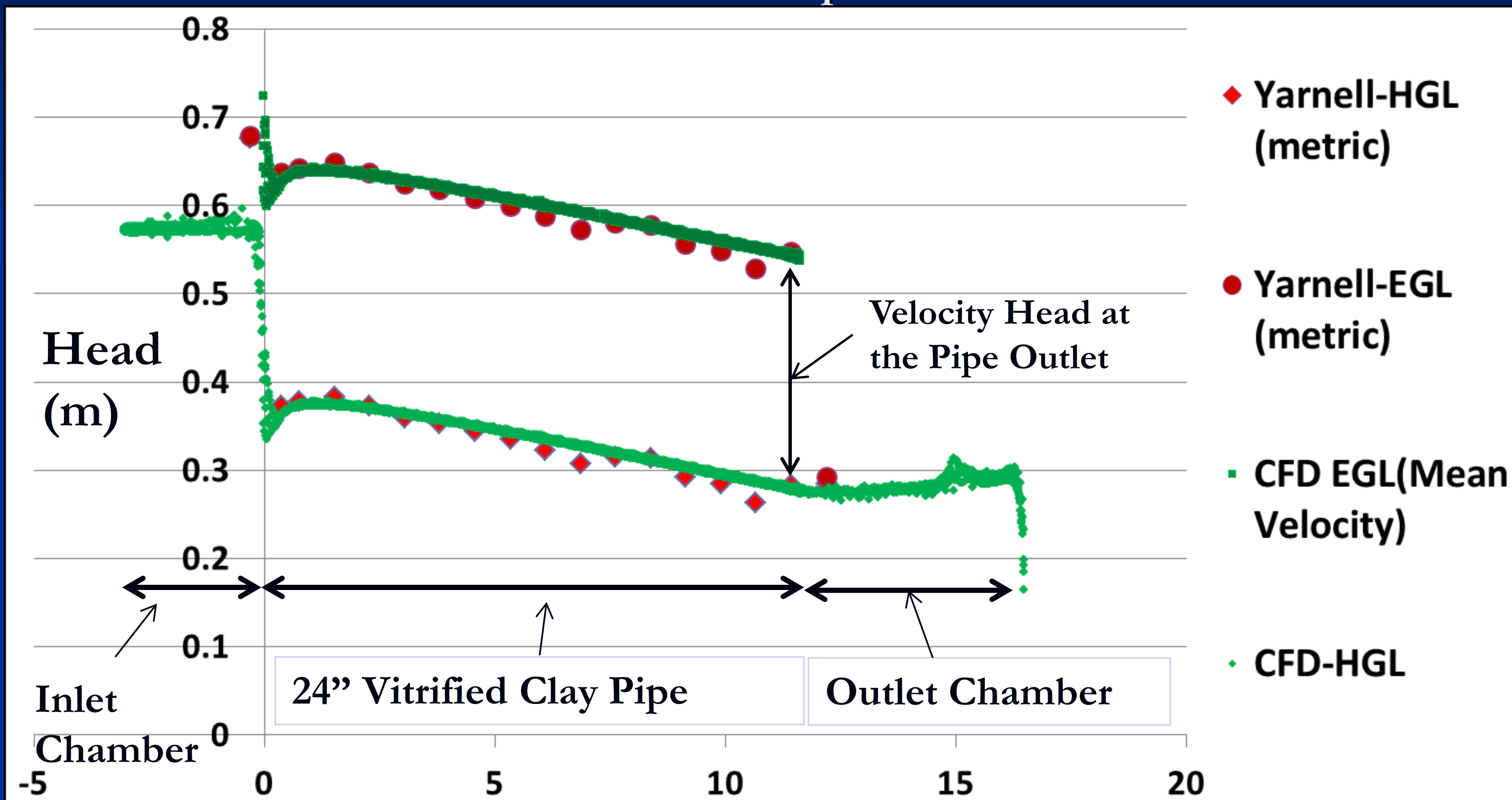
Yarnell & CFD - Performance Curve

D = 24” Clay Pipe Q = 25 CFS – No Diffuser



Yarnell & CFD - HGL & EGL

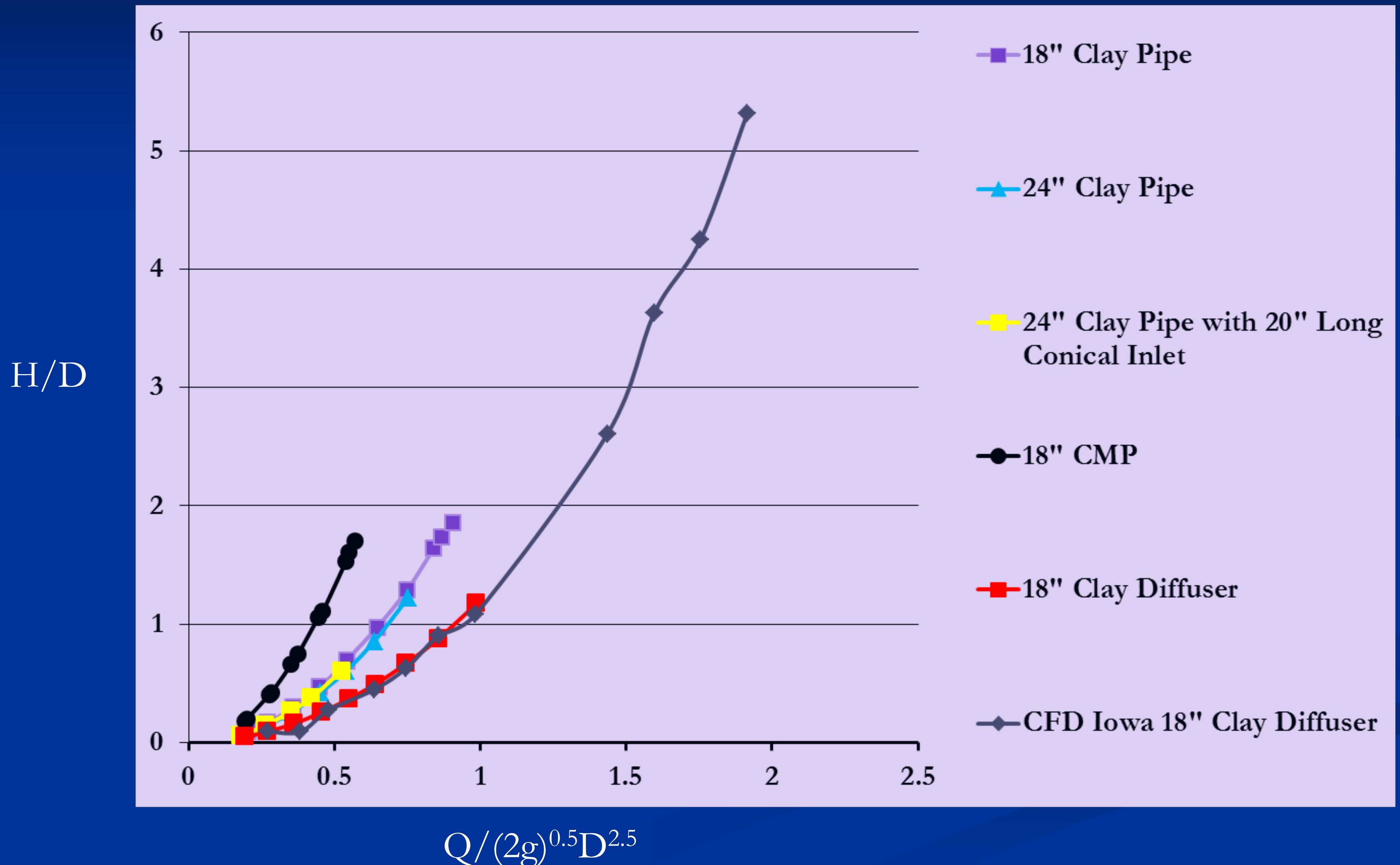
For an 24" Smooth Pipe for 25 CFS



Length from Inlet (m)

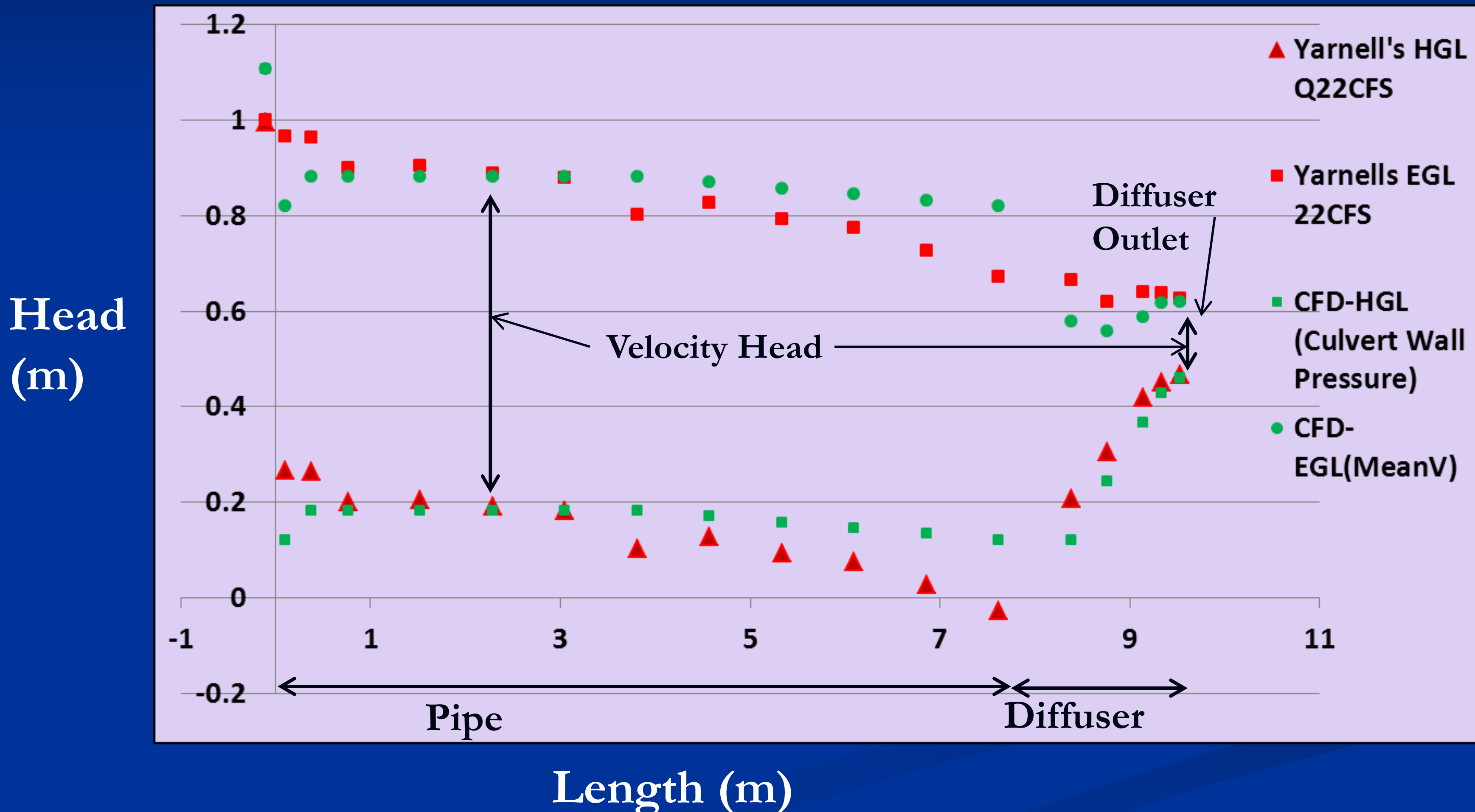
Yarnell & CFD - Performance Curve

D = 18" Clay Pipe with 60"-long diffuser outlet

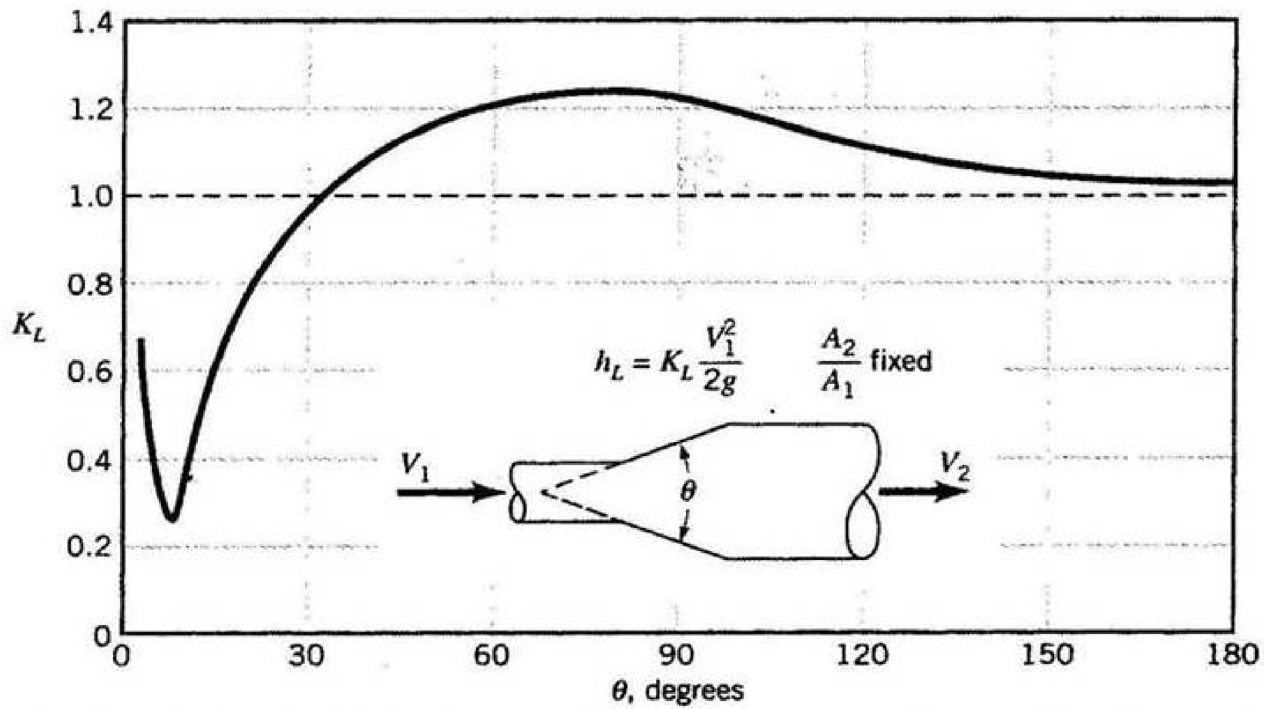


Yarnell & CFD - HGL & EGL

D = 18” Clay Pipe with 60”-long diffuser outlet, Q= 22 CFS



Outlet Loss Coefficient



■ FIGURE 8.29 Loss coefficient for a typical conical diffuser (Ref. 5).

- Source: Source: Fundamentals of Fluid Mechanics, Munson, Young, p. 502 Okiishi, 1998

- Outlet loss coefficient – Minimized at a flare angle of 12°
- At small flare angles shear with the diffuser wall is the source of the loss
- At large angles separation and recirculation are associated with increased losses

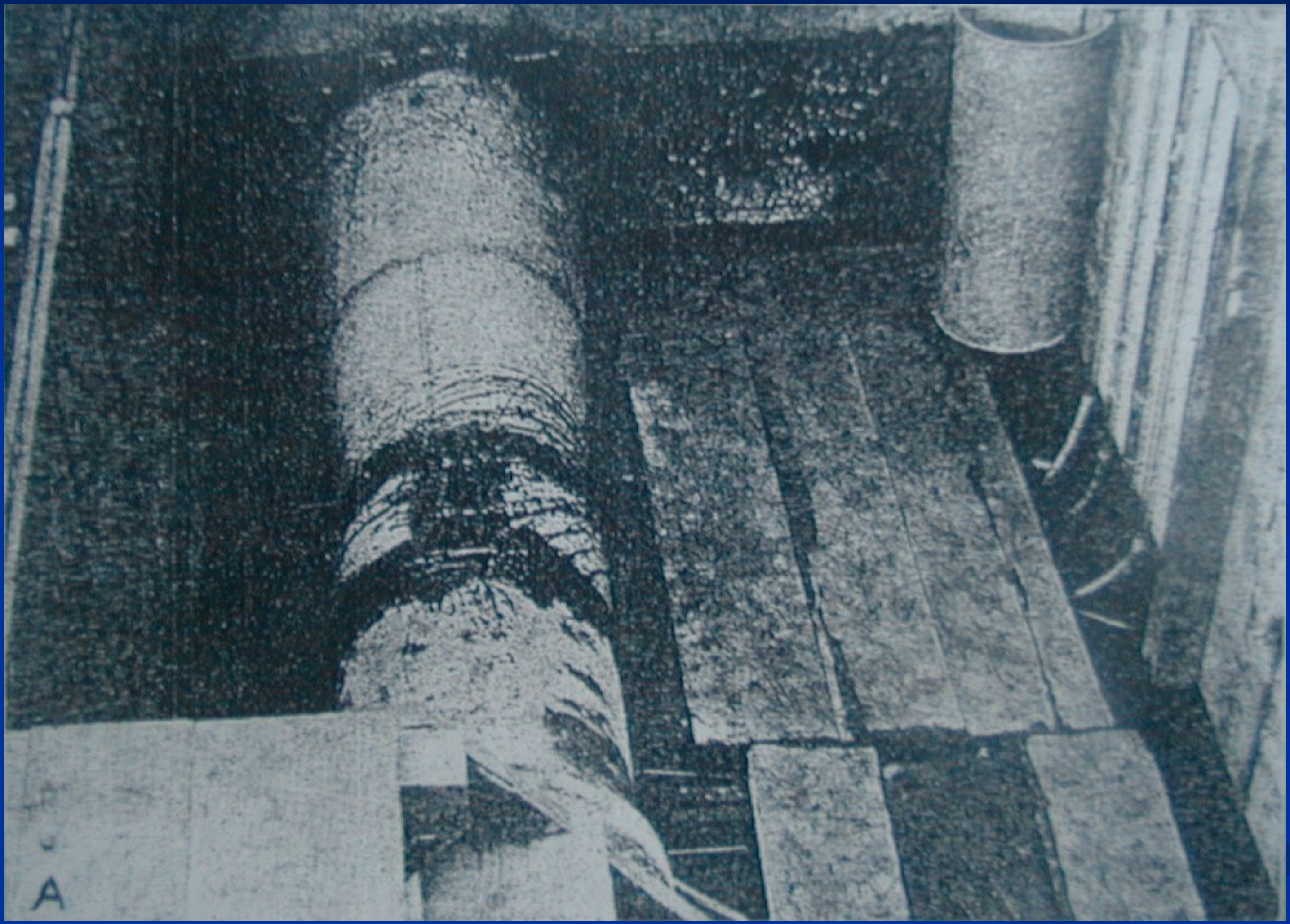
Why the Difference in the Minimum Pressure at the Diffuser Inlet?

- Interaction of water with culvert wall.
  - Pipe Roughness
    - Clay Pipe n=0.0122 (roughness height 0.5mm to 1mm)
- Pipe Wall Shear Stress – Rouse's Research
    - "Wetting agents" (hydrophilic)
      - Allow Culvert to fill when H/D > 0.9
      - Allow Culvert to stay full to the outlet of the pipe creating a vacuum near the outlet of the pipe.
    - Grease or Wax (hydrophobic)
      - Allow water surface to drop away from the top of the pipe near the outlet loosing the vacuum.

Summary

- By utilizing existing physical model data to calibrate/verify the CFD model many questions can be answered.
- CFD models of simple pipes are relatively easy to construct and the results are very close to physical models.
- Properly designed diffusers function very predictably in both Physical and CFD models.
- The unusual physics of diffusers lead to noticeable differences in the model outputs.

Questions



Yarnell's Diffuser outlet

References

Hydraulic Design of Highway Culverts – Third Edition, Schall, James D., Thompson, Philip L., Zerges, Steve M., Kilgore, Roger T., and Morris Johnny L.; April 2012 U.S. Dept. of Transportation, Federal Highway Administration; Hydraulic Design Series No. 5; Publication No. FHWA-HIF-12-026

The Flow of Water Through Culverts; Yarnell, David L., Nagler, Floyd A., Woodward, Sherman M.; 1926; University of Iowa Studies in Engineering

- The Effects of Flared Outlets on the Discharge of Box Culverts; Venegas, Leon E.; 1950; Louisiana State University, MS Thesis, The School of Hydraulic Engineering
- The Effect of Length on Performance Characteristics of Diffusers; Smith, Richard A.; 1951; Louisiana State University, MS Thesis, The School of Hydraulic Engineering
- Conversion of Kinetic to Potential Energy in Flow Expansions; Kalinske, A. A.; 1946; pp.355 – Selected 390; Transactions, American Society of Civil Engineers, Paper No. 2273
- Free Outlets and Self-Priming Action of Culverts; Li, Wen-Hsiung and Patterson, Calvin C.; 1956; pp. 1009-1 – 1009-22; Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers
- Design of Minimum Energy Culverts; McKay, G. R.; 1971; University of Queensland, Australia, Department of Civil Engineering
- Hydraulics of Minimum Energy Culverts Bridge Waterways; Apelt, C. J.; 1981; Conference on Hydraulics in Civil Engineering, Sidney, Australia
- Culvert Hydraulics, A Library Study; Division of Engineering Laboratories; 1962; Hydraulics Branch Report No. Hyd-489; United States Department of the Interior Bureau of Reclamation
- The Hydraulic Design of Flume and Siphon Transitions; Hinds, Julian; 1927; pp.1423 – 1459; Transactions, American Society of Civil Engineers, Paper No. 1690
- Improved Culvert Performance through Design and Research Studies; Bauer, William J.; 1959; Civil Engineering, pp. 53–55.
- Hydraulic Loss Coefficients for Culverts, Tullis, Blake P.; 2012, NCHRP, Transportation Research Board