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

Alexander Mann
Hydrologist, Surface Water Resources Division
Maine Department of Transportation
Environmental Office
16 State House Station
Augusta, Maine 04333-0016
Ph. 207-215-6328  Alexander.Mann@maine.gov
Acknowledgements

- David Yarnell (d. 1937), USDA and University of Iowa Hydraulics Lab
- Dr. Kornel Kerenyi, FHWA Turner Fairbanks Hydraulics Lab
- Dr. Steve Lottes, Transportation Research and Analysis Computing Center
- Dr. Charles Hebson, Chief Hydrologist. Maine Dept. of Transportation
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?

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 courtesy 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.
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
This data can be converted into a Performance curve.
Yarnell’s Diffuser Piezometer Data

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**
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 $Q = 22 \text{ CFS} \ (625 \text{ L/s})$

CFD Replication of Yarnell’s Diffuser Model

Pipe Length 30.7’, $D = 18”$
Velocity Profile $Q = 22$ CFS (625 L/s)

Pipe Length 30.7’, $D = 18”$

Inlet Chamber

High Velocity Gradient

High Velocity Zones

Outlet Chamber

Weak Outlet Jet

Diffuser

Decreasing Velocity

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

CFD Replication Of Yarnell’s 24” Clay Pipe

Inlet Chamber | Pipe Length 38.3’, D = 24” | Outlet Chamber

Water Surface | Atmospheric Pressure | Low Outlet Pressure

High Pressure Gradient

Decreasing Pressure

Absolute Pressure (Pa)
85341. 96439. 1.0754e+05 1.1863e+05 1.2973e+05 1.4083e+05
Velocity Profile Straight Clay Pipe
Q = 53 CFS (1500 L/s)

Pipe Length 38.3’, D = 24”
Yarnell & CFD - Performance Curve

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

![Graph showing the comparison between CFD Yarnell Normalized Flow and Yarnell Normalized Flow. The x-axis represents Dimensionless Flow $Q/(2g)^{0.5}D^{2.5}$, and the y-axis represents H/D. The graph includes data points for both methods, illustrating the performance curve.]
Yarnell & CFD - HGL & EGL
For an 24” Smooth Pipe for 25 CFS

Head (m)

Inlet Chamber

24” Vitrified Clay Pipe

Outlet Chamber

Length from Inlet (m)
Yarnell & CFD - Performance Curve

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

\[ \frac{Q}{(2g)^{0.5}D^{2.5}} \]
Yarnell & CFD - HGL & EGL
D = 18” Clay Pipe with 60”-long diffuser outlet, Q= 22 CFS
Outlet Loss Coefficient

- **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


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