Hydraulic Efficiencies for Colorado Department of Transportation Type C and D Median Inlets

Amanda L. Cox, Ph.D., P.E.
Parks College of Engineering, Aviation and Technology
Saint Louis University

National Hydraulic Engineering Conference 2014
August 21, 2014

PROJECT BACKGROUND

- Sump conditions arise in highway medians draining storm-water runoff from highway road surfaces into storm sewers
- Type C and D are the most commonly used inlets to collect storm runoff along highway medians
- Type C has a 35-inch by 35-inch opening area with steel bars
- Type D is two Type C grates together

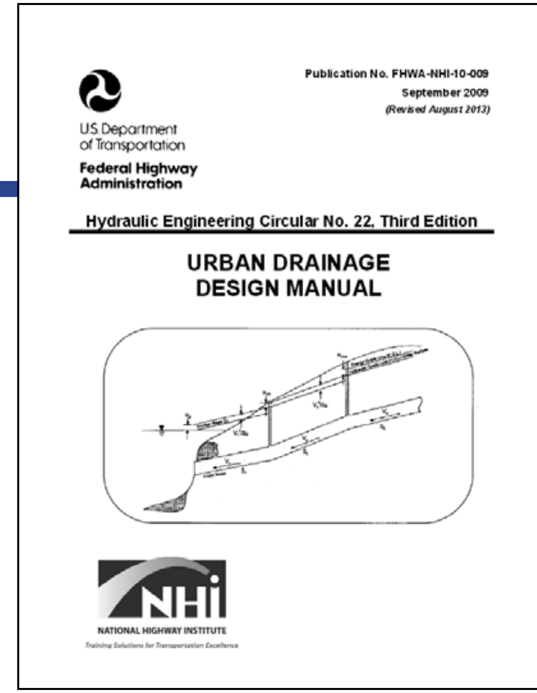
Type C Inlet (Standard)

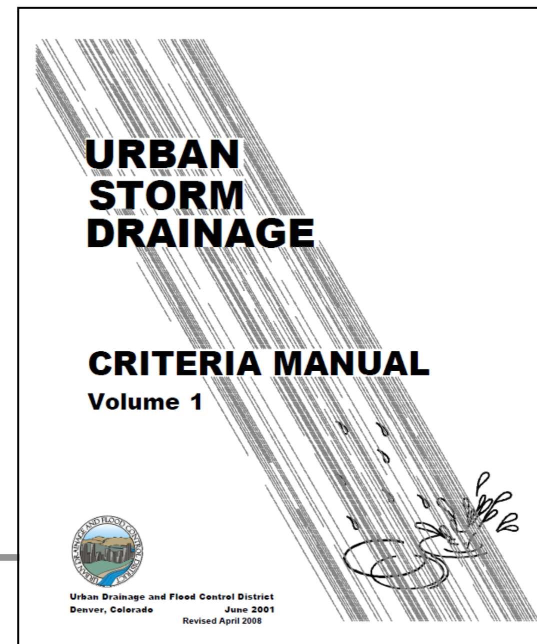
Type D Inlet (Closed Mesh)

SAINT LOUIS UNIVERSITY

PROJECT BACKGROUND

- Current design practices for computing hydraulic capacity of median inlets
  - Hydraulic Engineering Circular No. 22 (**HEC-22**) Urban Drainage Design Manual (Federal Highway Administration (FHWA, 2001))
  - Urban Storm Drainage Criteria Manual (UDFCD, 2008)
- Use classic orifice and weir equations to determine the hydraulic capacity of inlets in sump conditions
- Data specific to Type C and D inlets were not available to evaluate the accuracy of the classic orifice and weir equation method





PROJECT BACKGROUND

- Inclined grates were theorized to minimize effects of debris on inlet capacity
- Physical data not available for verification
- The objectives of this study were to:
  - Use a scaled hydraulic physical model to evaluate the accuracy of current design methods to predict the hydraulic capacity of Type C and D inlets
  - Develop design equations to predict discharge conveyance
  - Assess debris behavior with inclined inlets

30 degree

CURRENT PRACTICE – HEC-22 AND UDFCD MANUAL

- Hydraulic capacity

$$Q = \min(Q_o, Q_w)$$

- Classic orifice equation (cfs)

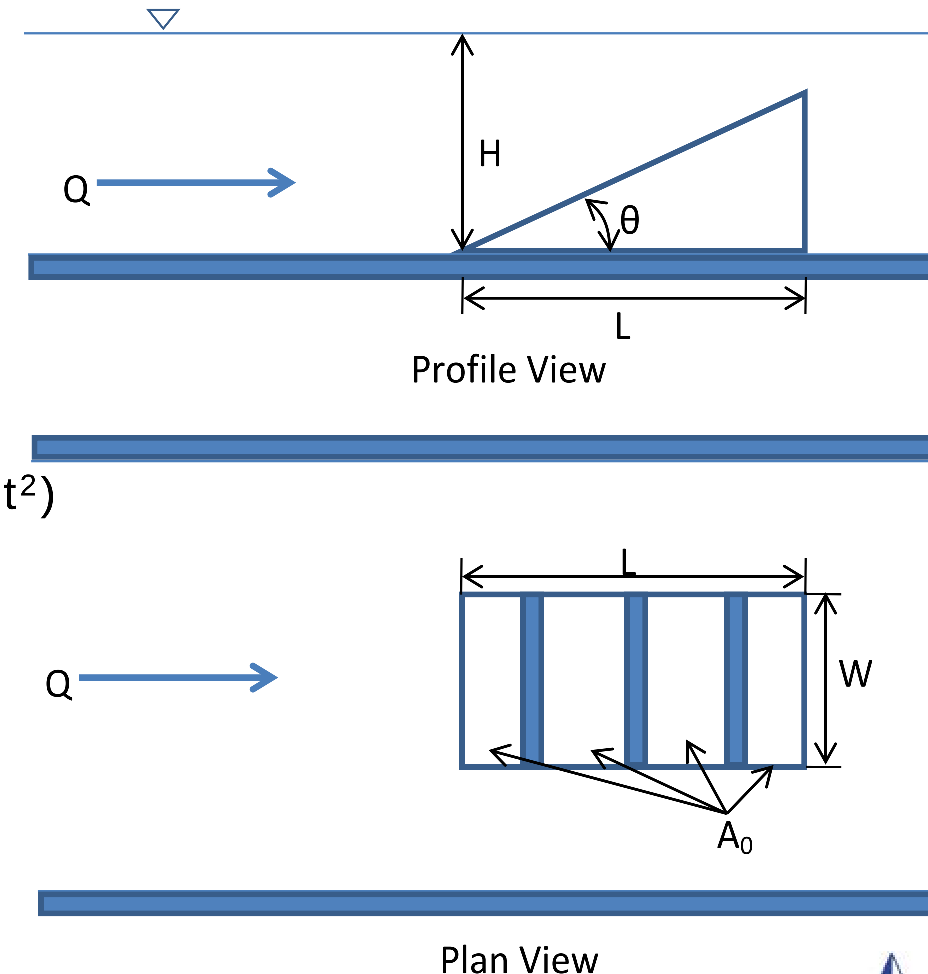
$$Q_o = C_o A_o \sqrt{2gd}$$

  - C_o = 0.67
  - A_o = Inlet clear opening area (ft^2)
  - d = Flow depth (ft)
  - g = gravitational acceleration (ft/s^2)

- Classic weir equation (cfs)

$$Q_w = C_w P d^{1.5}$$

  - C_w is 3.00
  - P = Weir perimeter (ft)



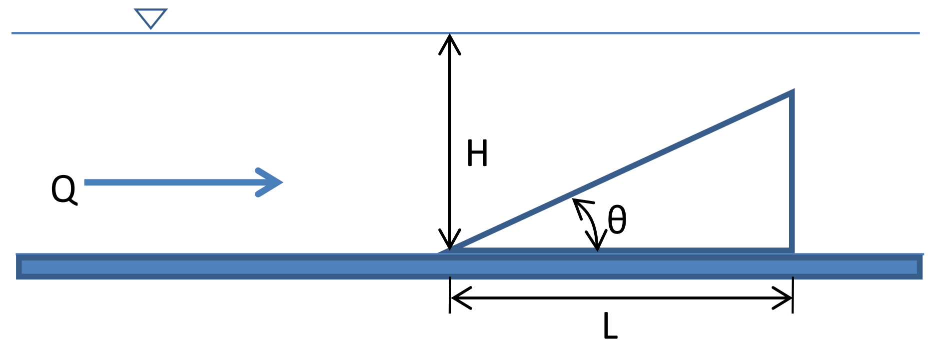
SAINT LOUIS UNIVERSITY

INCLINED GRATES

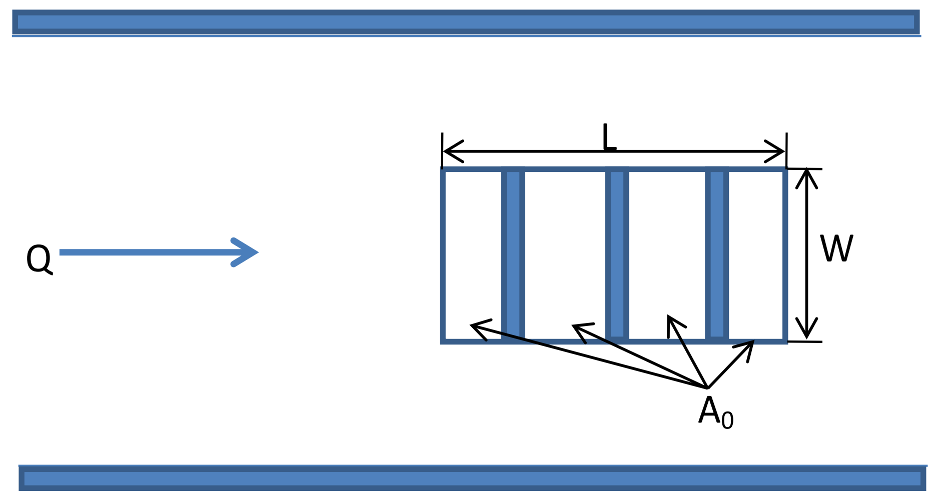
- Zlatkin (2008) – UC Denver Technical Paper
- Similar approach of

$$Q = \min\left(Q_o, Q_w\right)$$

- With orifice and weir equations were modified for grate inclination
- Further divided by a condition of submergence
  - Defined as a flow depth above the topmost elevation of the inclined grate ($d > d_b$)



Profile View

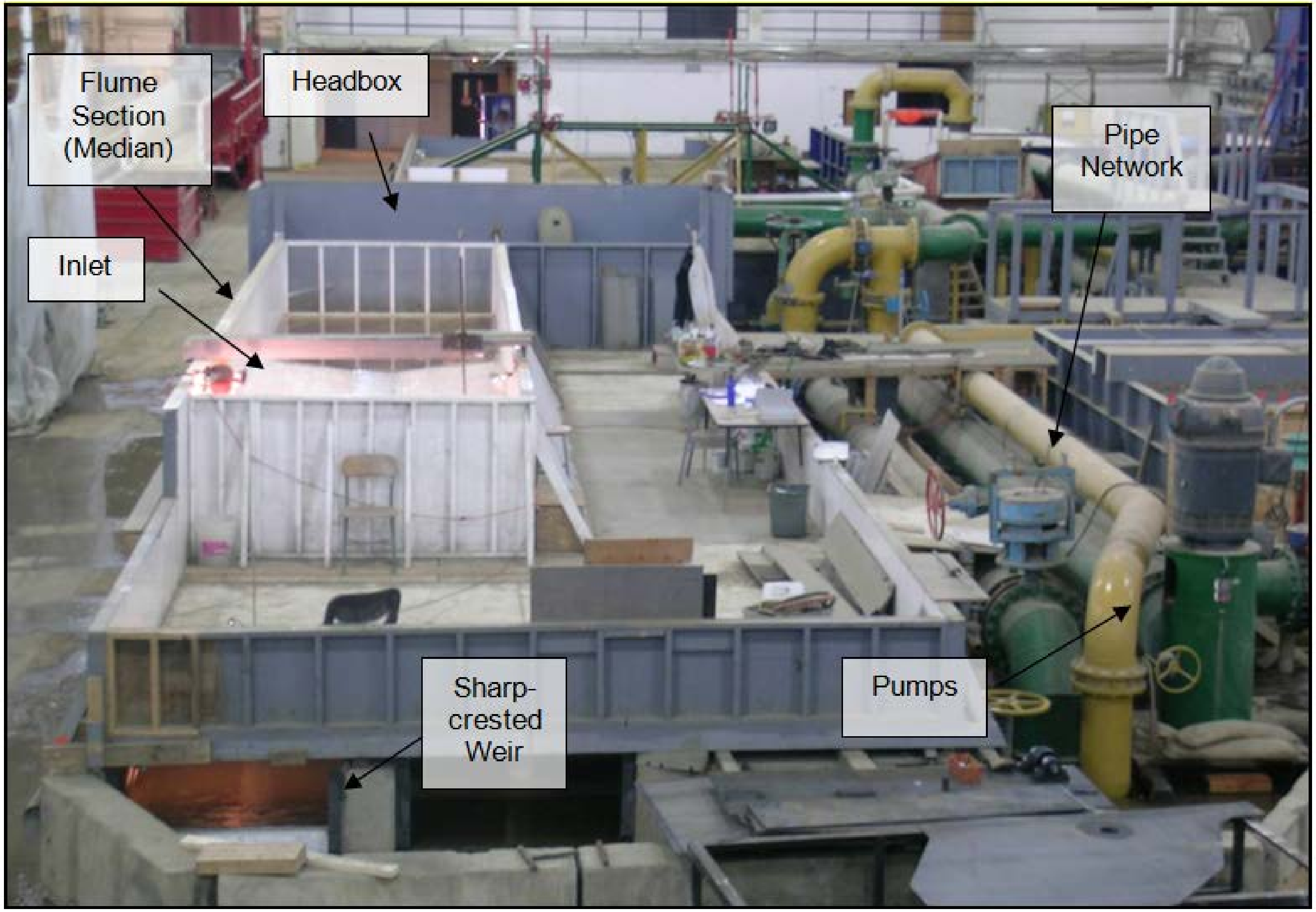


Plan View

ZLATKIN (2008) – UC DENVER TECHNICAL PAPER

- Orifice Flow
  - Unsubmerged $$Q_{o,unsubmerged} = \frac{2}{3} C_d nWd \frac{\cos\theta}{\sin\theta}\sqrt{2gd}$$
  - Submerged $$Q_{o,submerged} = \frac{2}{3} C_d nW \cos\theta \frac{L}{d_b}\sqrt{2g}\left[d^{1.5} - (d - d_b)^{1.5}\right]$$
- Weir Flow
  - Unsubmerged $$Q_{w,unsubmerged} = \frac{2}{3} C_d \sqrt{2g}(W - 0.2d)d^{1.5} + \frac{8}{15} C_d \sqrt{2g}\tan(90 - \theta)d^{2.5}$$
  - Submerged $$Q_{w,submerged} = \frac{2}{3} C_d \sqrt{2g}(W - 0.2d)d^{1.5} + \frac{8}{15} C_d \sqrt{2g}\cot(\theta)\left[d^{2.5} - (d - d_b)^{2.5}\right]$$
- Theoretically based but not verified with physical data

PHYSICAL HYDRAULIC MODELING



- Provide data for evaluation of median-inlet hydraulic conditions
- 3:1 Froude-scale physical model
- Located at the Hydraulics Laboratory at Colorado State University's Engineering Research Center

PHYSICAL HYDRAULIC MODELING

- 10% median side slopes
- 1.35% longitudinal slope towards the sump
- Bottom channel width of 2.7 ft
- Roughness provided by square wooden blocks
  - calibrated to achieve Manning's *n* of 0.031 model (0.037 prototype)
- Model "concrete pad" roughness of 0.013 (0.016)

SAINT LOUIS UNIVERSITY

HYDRAULIC-MODEL CONFIGURATIONS

SIX GRATE CONFIGURATIONS EVALUATED

Type C Inlet On-grade

Type C Inlet Depressed

Type D Inlet On-grade

Type D Inlet Depressed

Type D Inlet Rotated

Type D Rotated and Depressed

SAINT LOUIS UNIVERSITY

HYDRAULIC-MODEL CONFIGURATIONS

FOUR GRATE ANGLES (SHOWN ON TYPE C INLET)

horizontal

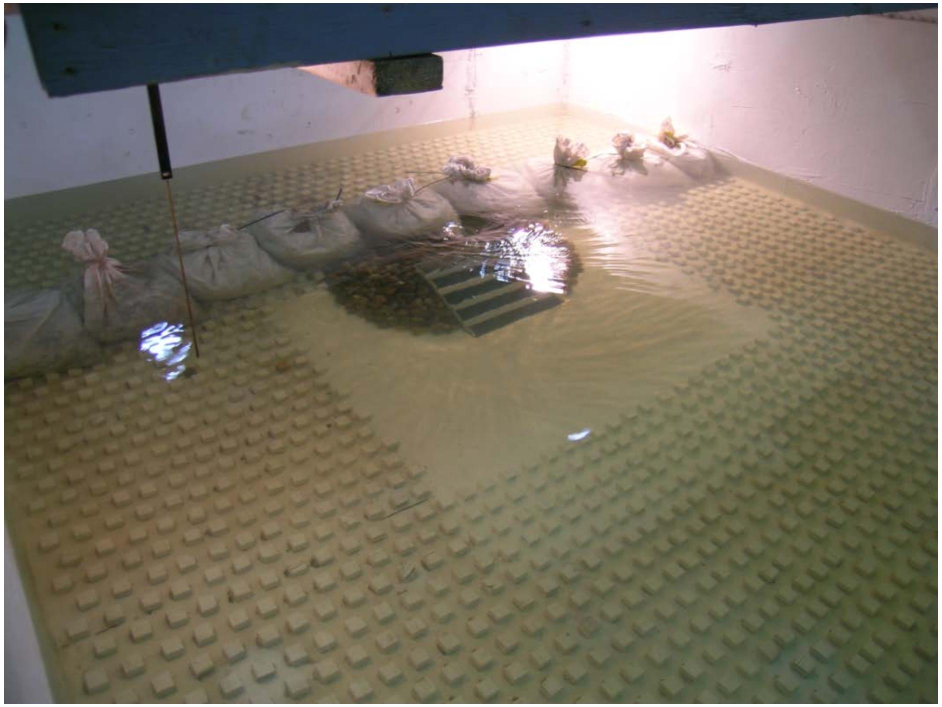
10 degree

20 degree

30 degree

PHYSICAL MODELING

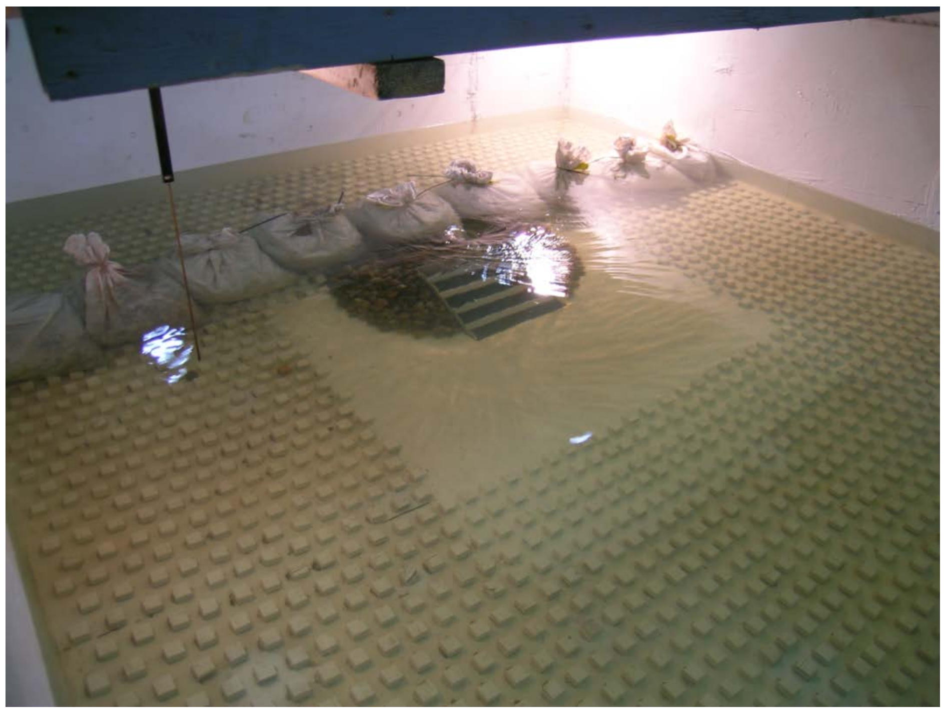
- 96 tests total from variations of inlet configurations, grate angles, and flow depths
- Prototype flow depths ranged from 1.00 to 4.13 ft
- Prototype discharges ranged from 17 to 120 cfs



SAINT LOUIS UNIVERSITY

TEST PROCEDURES

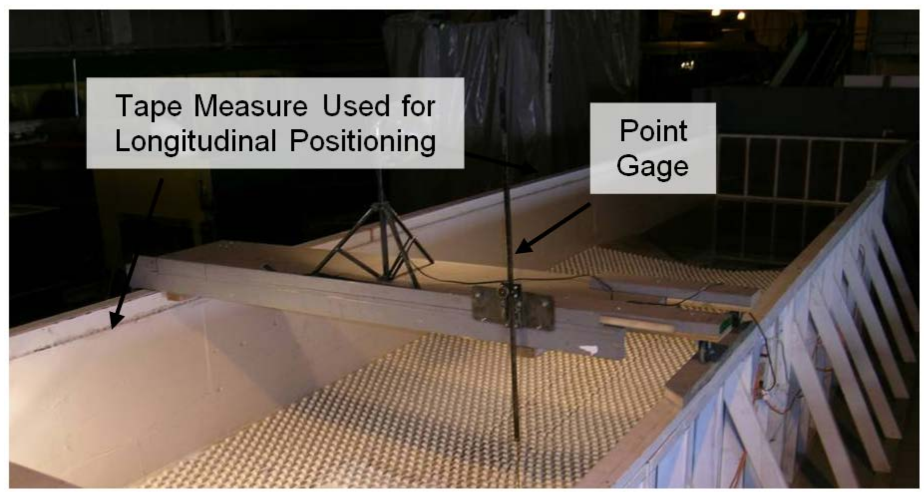
- Main objective
  - to obtain stage-discharge data for steady-state flow conditions



SAINT LOUIS UNIVERSITY

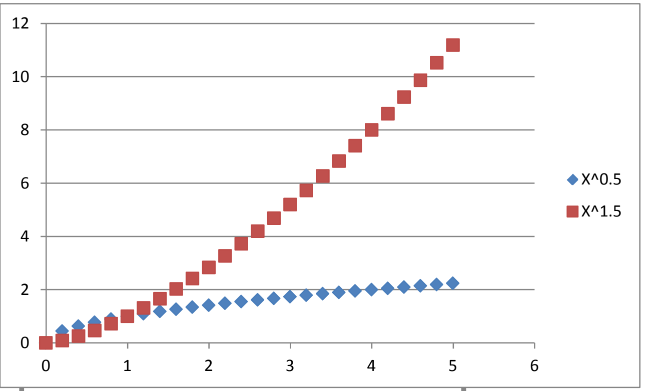
TEST PROCEDURES

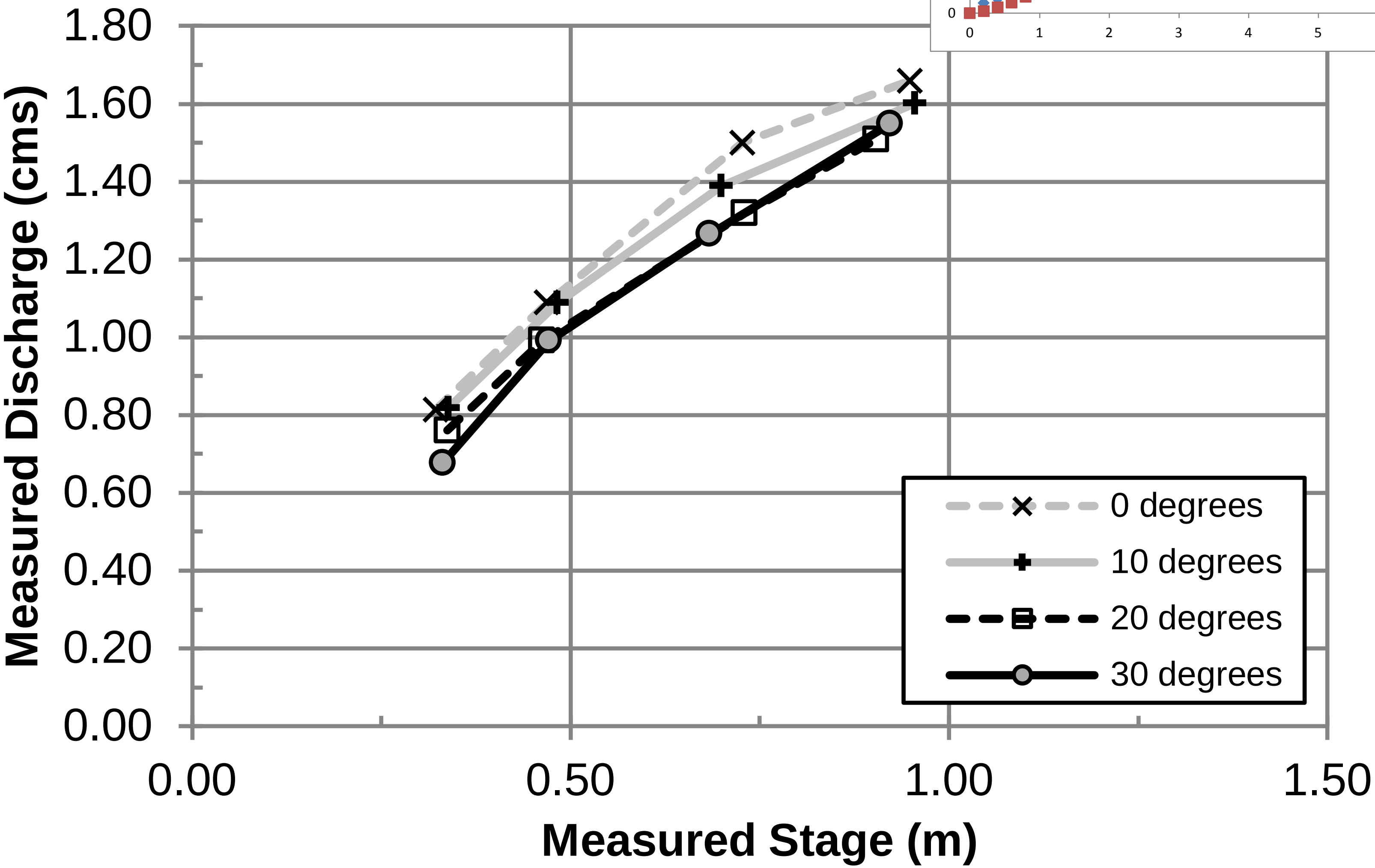
- Inflow measured with a full-bore electro-magnetic flow meter
- Outflow measured with a rectangular sharp-crested weir
- Flow depths measured at two locations
  - Both lateral to the front edge of the grate at the flume walls
  - Measured using a point gage
  - Chosen to be free of surface curvature from flow being drawn into the inlets



RESULTING DATA

TYPE C INLET EXAMPLE





SAINT LOUIS UNIVERSITY

DATA ANALYSIS

HORIZONTAL-GRATE INLET CONFIGURATIONS

- Predicted discharges were computed using HEC-22 and the UDFCD (2008) method
  - Orifice discharge coefficient (C_o) of 0.67
  - Weir discharge coefficient (C_w) of 3.00
  - Recorded stage readings

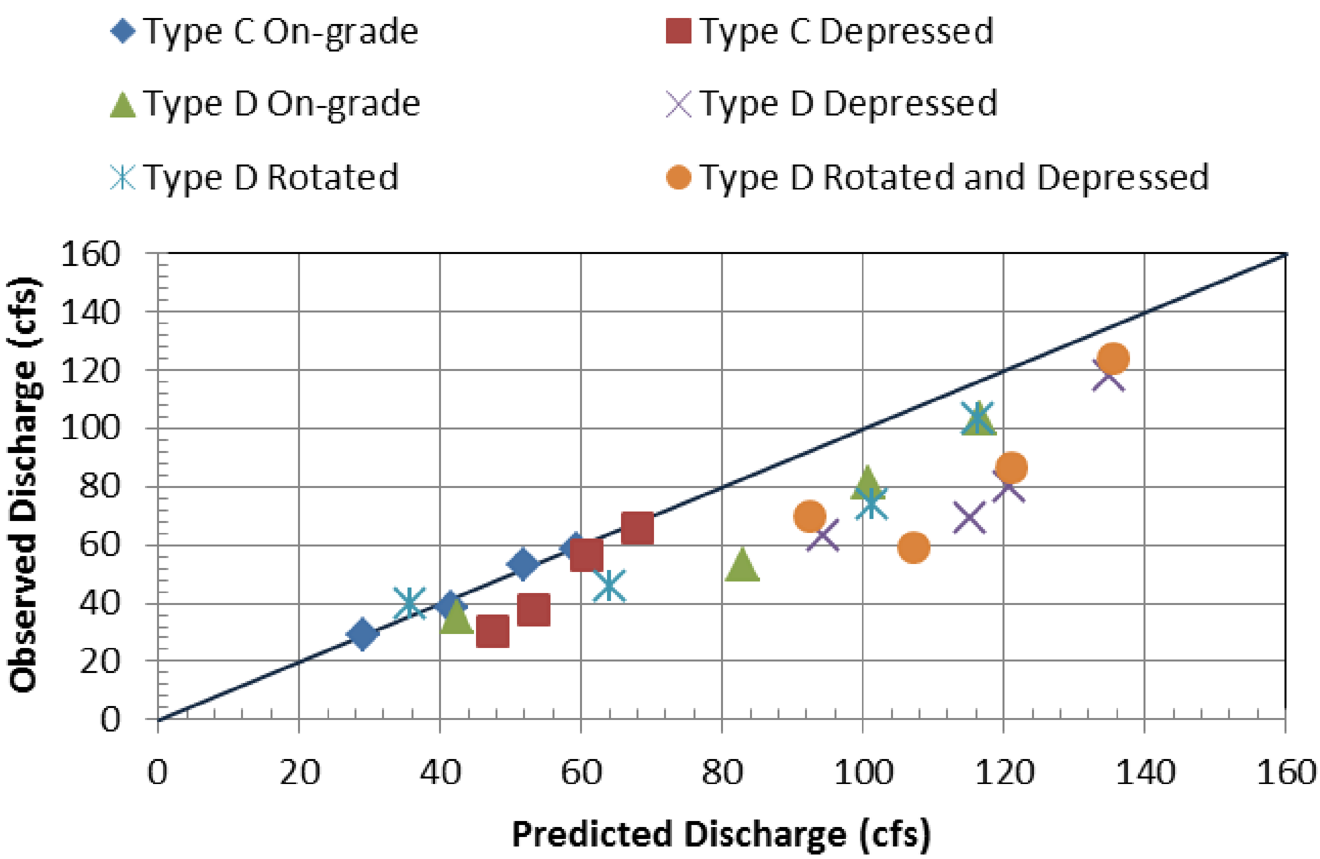
$$Q_o = C_o A_o \sqrt{2gd}$$

$$Q_w = C_w P d^{1.5}$$

SAINT LOUIS UNIVERSITY

DATA ANALYSIS

HORIZONTAL-GRATE INLET CONFIGURATIONS

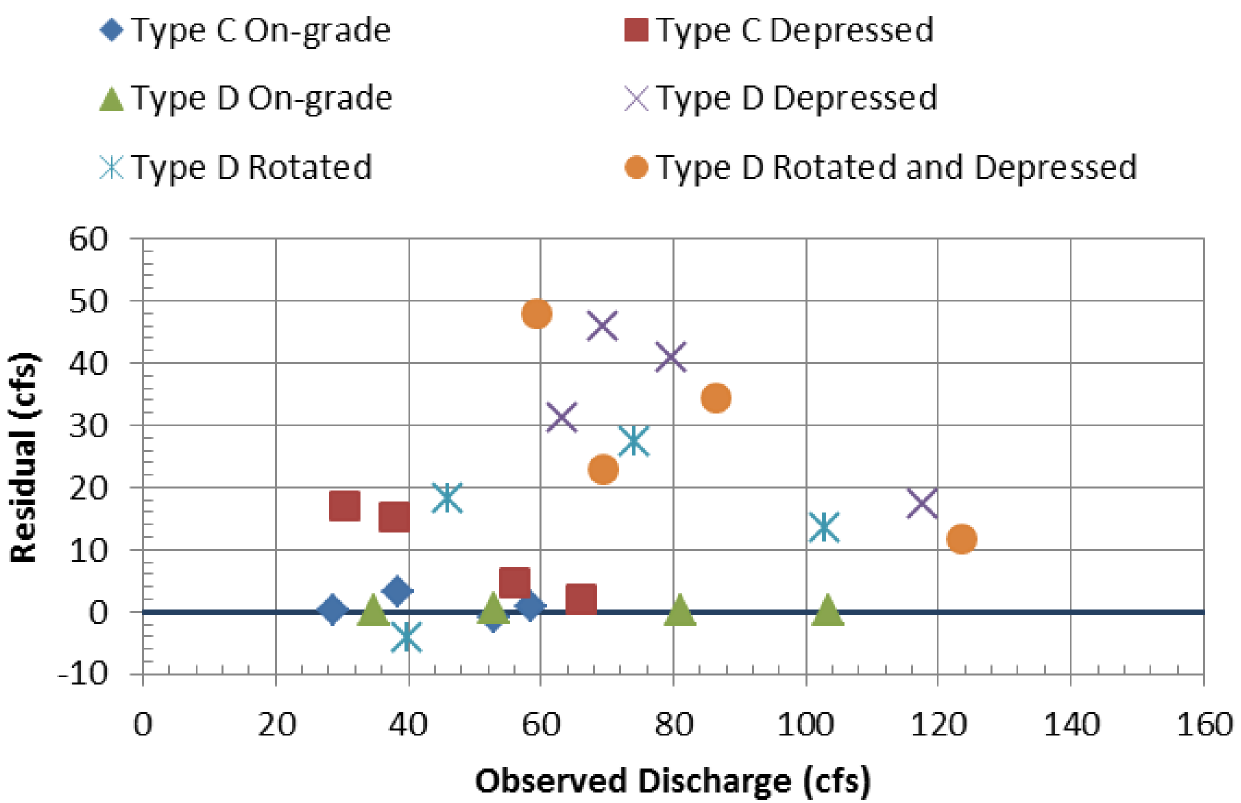


- Type C on-grade predicts well
- Others not as well
- 28% mean absolute percent error
- 81% max percent error

SAINT LOUIS UNIVERSITY

DATA ANALYSIS

HORIZONTAL-GRATE INLET CONFIGURATIONS



- Generally over predicted observed discharges
- Max error ~50 cfs
- Over predicted discharge by an average of 28%

SAINT LOUIS UNIVERSITY

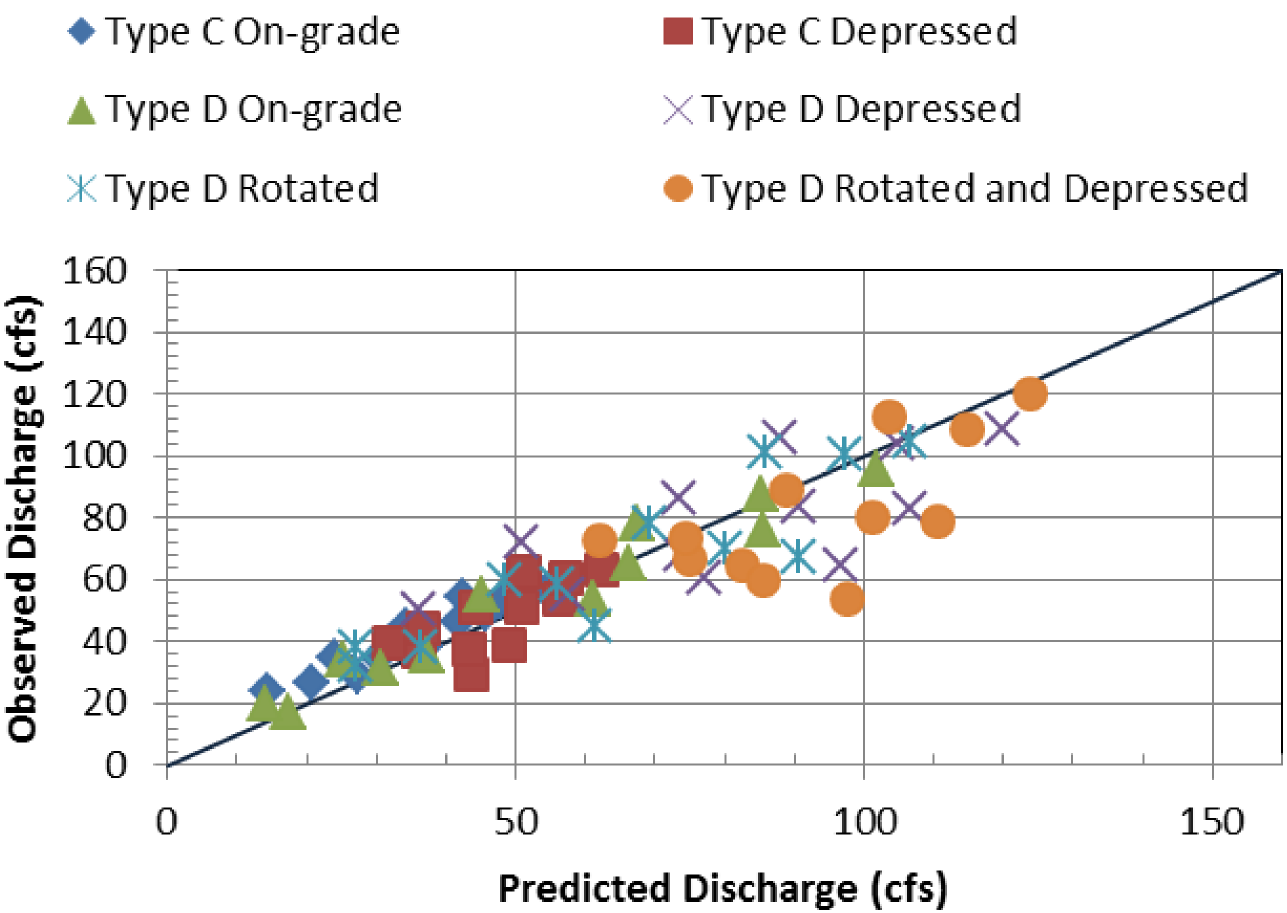
DATA ANALYSIS

INCLINED-GRATE INLET CONFIGURATIONS

- Predicted discharges were computed using Zlatkin (2009) method
  - Discharge coefficient (C_d) of 0.65

DATA ANALYSIS

INCLINED-GRATE INLET CONFIGURATIONS

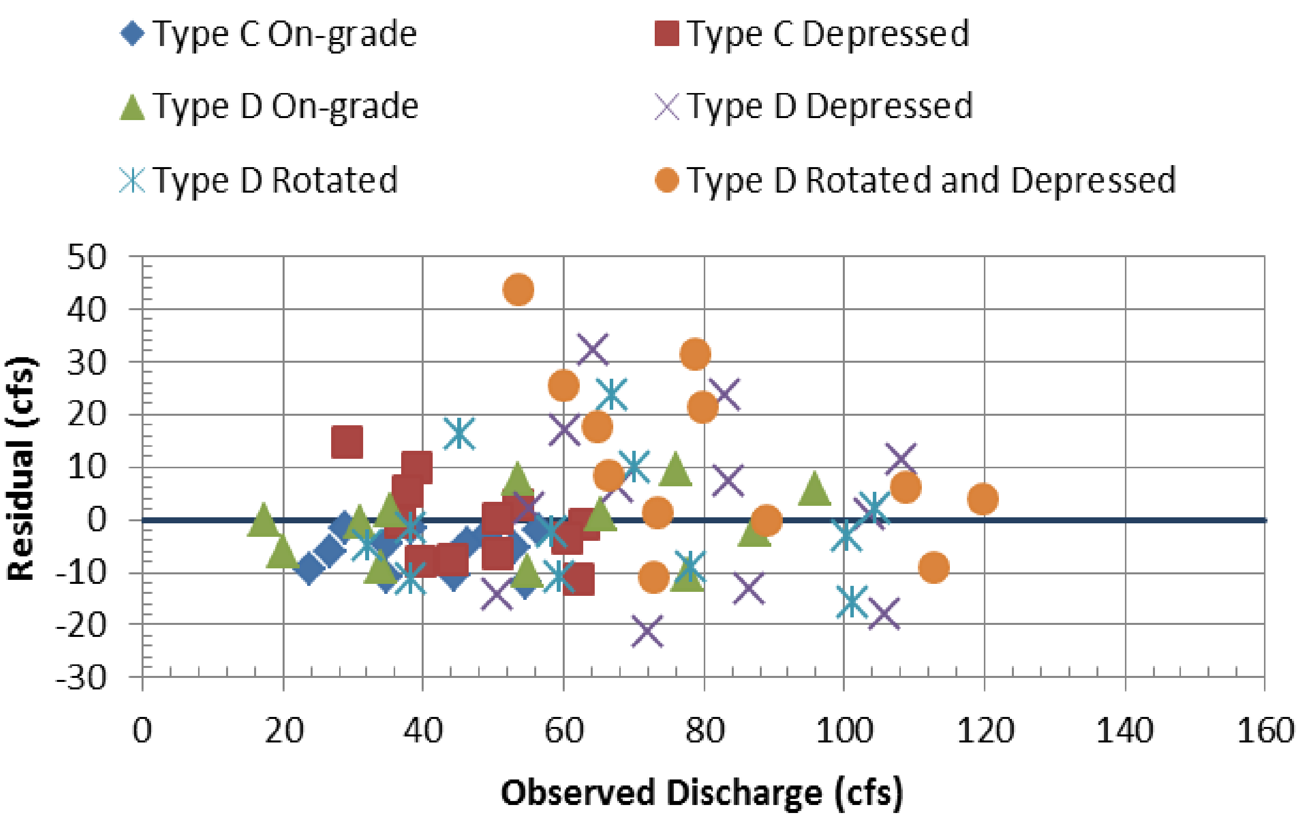


- Predicts well for on-grade inlets
- Others not as well
- 16% mean absolute percent error
- 82% max percent error

SAINT LOUIS UNIVERSITY

DATA ANALYSIS

HORIZONTAL-GRATE INLET CONFIGURATIONS



- Errors nearly equally distributed above and below zero
- Max error ~45 cfs
- Over predicted discharge by an average of 0.5%

SAINT LOUIS UNIVERSITY

DESIGN EQUATION DEVELOPMENT

- First, calibrated discharge coefficients for exiting equations
- Majority of flows were classified as orifice flow
  - 67 orifice, 21 weir, and 8 transitional
- Evaluated several forms of orifice prediction equations
  - Classical dimensional analysis
  - Empirical regressions
- Empirical orifice flow regression equation
  - Coefficients determined using the least squares method

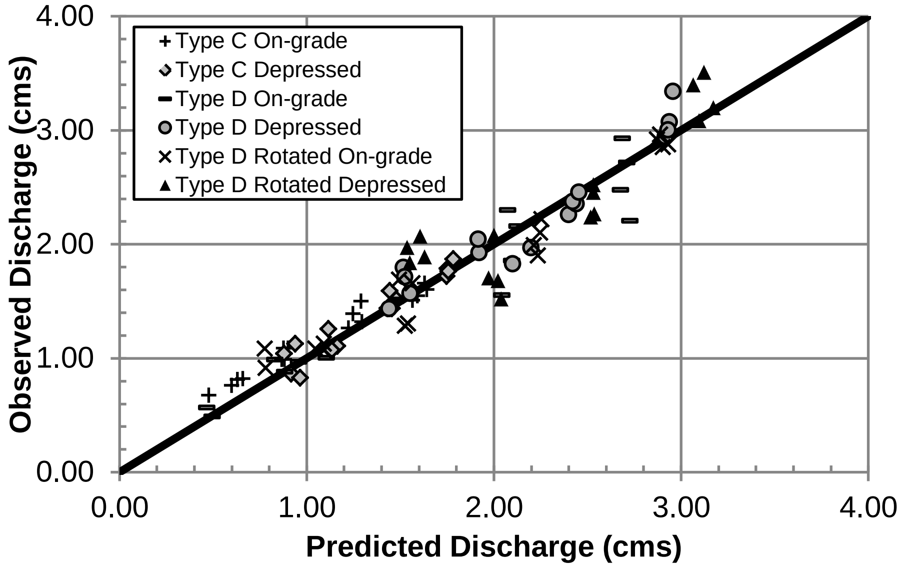
$$\mathrm{Q_{0,depressed} = 0.64nB^{0.86}L^{0.76}H^{0.88}}$$

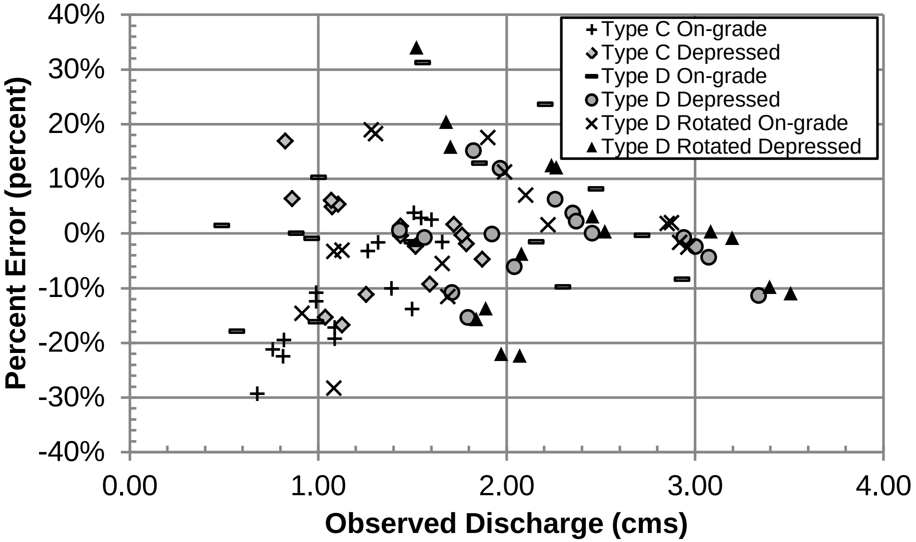
$$Q_{0,on-grade} = 0.54nB^{0.82}L^{0.75}H^{0.93}$$

- Developed to be dimensionally homogeneous (independent of prototype scale)
- Grate-inlet angle not found to be statistically significant

DESIGN EQUATION DEVELOPMENT

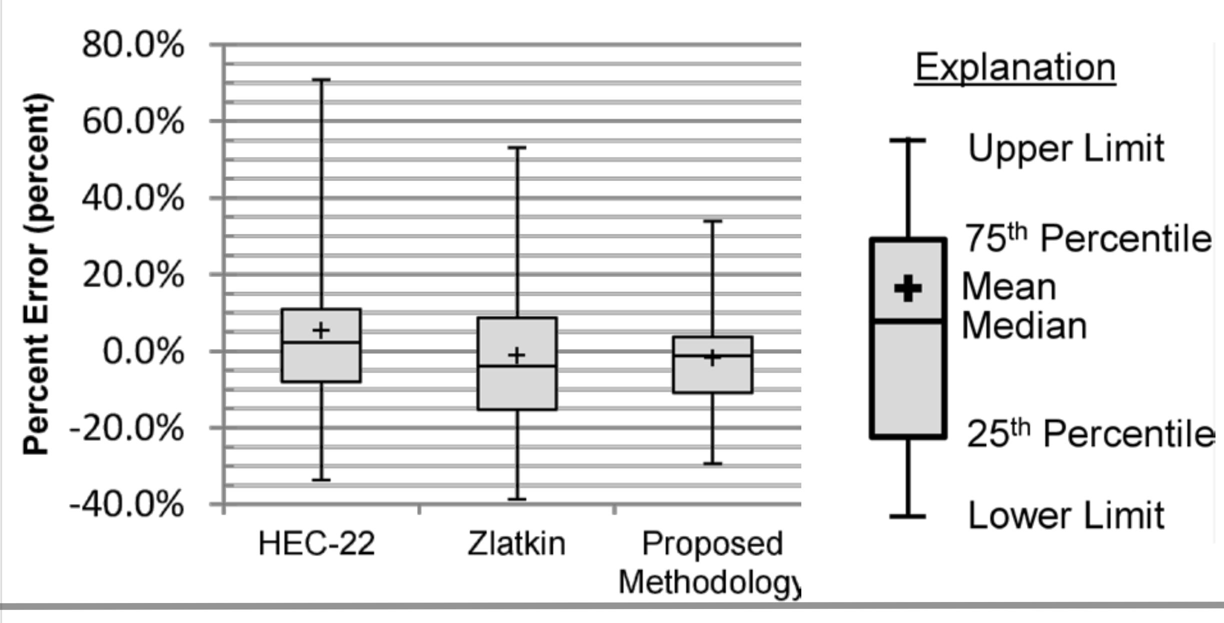
- Coupled empirical orifice-flow equation with Zlatkin's weir flow equation for a new all-encompassing method





SUMMARY OF METHODS

Methodology	Mean Absolute Percent Errors		
	All	All Weir	All Orifice
HEC-22, Literature	42%	94%	37%
HEC-22, Fitted	13%	18%	13%
Zlatkin, Literature	18%	16%	19%
Zlatkin, Fitted	16%	16%	16%
Proposed Methodology	9%	14%	9%



SAINT LOUIS UNIVERSITY

SUMMARY

- Objective was to evaluate the hydraulic efficiencies of the CDOT Type C and D highway median storm drain inlets
- A 3:1 Froude-scale model of a highway median
- Model consisted of a constructed highway median channel with one interchangeable inlet
- 96 total hydraulic tests
- Variations in inlet configuration and grate angle
- Flow-depth and discharge data were collected

SUMMARY

- Measured stage-discharge data were compared to predicted discharges
  - HEC-22/UDFCD (2008) method
  - Zlatkin method for inclined grates
- Empirical regression equation developed to predict orifice-flow conveyance
- New design method proposed that couples empirical orifice-flow equation with Zlatkin weir-flow equation

ACKNOWLEDGEMENTS

- Contributing Authors
  - James Woidt
    - Former Masters Student - Colorado State University
  - Ken MacKenzie
    - Denver Urban Drainage and Flood Control District
  - Dr. Chris Thornton
    - Director of CSU Hydraulics Lab - Colorado State University
- Funding provided by:
  - Denver Urban Drainage and Flood Control District
  - Colorado Department of Transportation
- Other Acknowledgments
  - Dr. James Guo
    - University of Colorado, Denver
  - Brendan Comport
    - Former CSU Masters Student

Questions??

SAINT LOUIS UNIVERSITY

3:1 FROUDE SCALING

Geometry	**Scale Ratios**
Length, width, and depth (L_r)	3.00
All slopes	1.00
Kinematics	**Scale Ratios**
Velocity (V_r)	1.73
Discharge (Q_r)	15.6
Dynamics	**Scale Ratios**
Fluid density (ρ_r)	1.00
Manning's roughness (n_r)	1.20

3:1 FROUDE SCALING

Feature	Prototype Design
Scale (prototype:model)	3:1
Channel length (ft)	64
Channel width (ft)	24
Channel side slopes (%)	10
Channel longitudinal slope (%)	1.35
Approach section length (ft)	42
Downstream back slope (%)	10
Side slopes at inlet (%)	10
Average Manning's roughness	0.037
Surface material	1/8-in. steel plate
Inflow control	butterfly valve / diffuser screen
Inflow measurement	electro-magnetic flow meter
Outflow measurement	weir / point gage
Grate opening area – single grate (ft^2)	5.9
Depth of flow (ft)	3