THREE-DIMENSIONAL COMPUTATIONAL FLUID DYNAMICS (CFD) FLOW MODELING FOR CULVERT IN SOUTH FLORIDA

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“The Greater Everglades: A Living Laboratory of Change”

Integrate the “Science of change” into Planning for the future; and, that we use Science and Planning to help us move forward with effective Policy for a sustainable future.
Introduction

• Modern day agriculture activities have brought about a “Nutrients-Contaminants Change” to the greater everglades ecosystem, triggering the need for “Restoration Change” and the construction of canals, treatment wetlands and hundreds of water control structures designed to improve the water quality of runoff and remove pollutants.

• Implementation of Computational Fluid Dynamics improves our understanding of scour and the accuracy of flow measurements that are used to measure the effectiveness of District structures, and involves the integration of “the ‘Science of change’ into Planning for the future.”
Contaminated water from Lake O. and catchment areas around inflow canal

High concentration of phosphorus

Inflow $Q$?

Loading $= Q \times \text{Conc.}$

Acceptable levels of phosphorus

Outflow $Q$?

WCA - Everglades
Flow Structures

- 300 culvert structures are active at the District
- > 135 spillways and weirs in South Florida control/release about 70% of total water volume
- Culverts and spillways are the predominant hydraulic structures for flow ratings in South Florida

![Pie chart showing percentages of different flow structures: Pumps 14%, Weirs 7%, Culverts 48%, Spillway 31%]
Accurate flow data are required for mandatory permit compliance, hydrological modeling, evaluation of restoration performance measures, and water supply planning.
Flow Rating Algorithms for Circular Culverts

**Type 2**
- \( h = D(1 - \cos \theta) / 2 \)
- \( R = D(1 - \cos \theta) / 2 \)
- \( K_1 = 1.486 \times 10^{-3} \times A_1 \)
- \( K_2 = 1.486 \times 10^{-3} \times A_1 \)

**Type 3**
- \( h = Y_s = D \)
- \( R = D \)
- \( K_1 = 1.486 \times 10^{-3} \times A_1 \)
- \( K_2 = 1.486 \times 10^{-3} \times A_1 \)

**Type 4**
- \( A_1 = D \)
- \( \theta = \cos^{-1}(1 - 2 \sigma_s / D) \)
- \( R = D / 4 \)
- \( Q = C_s A_1 \left( \frac{2 \sigma_s (H - h)}{K_1} \right) + 2 C_s^3 \left( 1 - \frac{A_1}{K_1} \right) \frac{Q}{K_2} \)

**Type 5**
- \( \gamma_s = G_s \times \left[ \frac{(H - h)^{1/2}}{G_s} \right] \)
- \( \beta = \cos^{-1} \left( 1 - 2 \frac{Y_s}{D} \right) \)
- \( Q = 0.709 \left[ \beta - \frac{\sin(2 \beta)}{2} \right] \left( \frac{sin \beta}{2 \beta} \right)^2 D^{1.1} \)
Flow Measurement

Flow measurement at one culvert costs between $1,500 – $3,000
Past Flow Rating Approach

1. Insufficient flow measurements due to cost and weather limitations
2. Available flow measurements do not cover all the operational regimes of the structure
Issues That Occur at Culvert G328

\[ Q = \sqrt{gD^5 \left( \beta - \sin \beta \cos \beta \right)^3 / 64 \sin \beta} \]
\[ \beta = \cos^{-1} \left[ 1 - 2 \left( \frac{Y_c}{D} \right) \right] \]
\[ Y_c = G_0 \times a \left[ \frac{(h_1 - h)}{G_0} \right]^b \]

\( a = 1.364 \) and \( b = 0.36 \) are the constant coefficients
Application of CFD to Study Flow Simulations

Collect structure & water stage data

Setup CFD model
Calibrate the CFD model
Generate new flow data from CFD analysis

Compare with streamgauging Data

Advantages of CFD
- Study the fundamental aspects of flow fields and energy losses
- Able to generate synthetic flow data for flow rating
- Provide an alternative way to cross test the streamgauging data
- Set up a platform to study more complex flow relative phenomena, such as sediment transport and local scour...
CFD Flow Simulation

**Governing equations, NS:**

\[
\frac{\partial u_j}{\partial x_j} = q
\]

\[
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) = \frac{\partial}{\partial x_j}\left[\mu_e \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right)\right] - \rho g \frac{\partial \zeta}{\partial x_i} + F_i
\]

**Turbulence model:**

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j k) = \frac{\partial}{\partial x_j}\left(\frac{\mu_e}{\sigma_k} \frac{\partial k}{\partial x_j}\right) + G_k - \rho \varepsilon
\]

**\(K-\varepsilon\) model**

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j \varepsilon) = \frac{\partial}{\partial x_j}\left(\frac{\mu_e}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j}\right) + \frac{\varepsilon}{k} (C_1 G_k - C_2 \rho \varepsilon)
\]

**Volume of Fluid (VOF) model for free surface:**

\[
\frac{\partial \alpha_q}{\partial t} + u_i \frac{\partial \alpha_q}{\partial x_i} = S_{\alpha_q}
\]

Phase change

\[
\rho = \alpha_2 \rho_2 + (1 - \alpha_2) \rho_1
\]
FLUENT has been used to investigate the 3D nature of complex flow, evaluate the design improvements, define best-operational practices, and identify operational conditions that may pose risk to structures’ stability which are often found at District water control structures.
New Approach to Flow Rating and Analysis

CFD

Field Measurements

SFWMD Flow Equations

CFD
Flow Analysis for S369 culvert

Levee, culvert and mesh

Inlet

Outlet

Mesh the Flow Domain
## Flow Analysis for S369 culvert

### Comparison of measurement and simulation flow data

<table>
<thead>
<tr>
<th>STATION</th>
<th>HW_AVG</th>
<th>TW_AVG</th>
<th>Gate</th>
<th>Flow Type</th>
<th>MEASURED Q(cfs)</th>
<th>CFD Q(cfs)</th>
<th>CFD vs. Measured Error</th>
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<th>CFD Rating Error</th>
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</tbody>
</table>

### CFD Synthetic Flow vs. Measured FLOW

#### Flow Equations

**Type 4**
- Full RBF Flow
- Outlet is Submerged

\[
Q = \frac{C_1 \cdot D_0}{2 \cdot g \cdot (H - h)} 
\]

\[
A_c = A_s - B \cdot \frac{d}{2} 
\]

\[
A_r = A_s - B \cdot \frac{d}{2} \cdot \frac{g \cdot L}{\sqrt{2g}} 
\]

**Type 5**
- Open Flow
- Rapid Flow at Eddy

\[
Q = \sqrt{y \cdot g \cdot H \cdot d^2} 
\]

\[
J_r = C_1 \cdot \frac{(H - h)^{\alpha}}{C_2} 
\]

where

- \(C_1\) and \(C_2\) are empirical constants.
Culvert G328 1 Solution - Type 6

\[
Q = CA_0 \left( 2g \left( h_1 - h_4 \right) \right) \left[ \sqrt{\left( \frac{A_0}{A_G} \right)^2 + 2C^2 \left( 1 - \frac{A_0}{A_G} + \frac{gn^2L}{(1.49)^2R_0^{4/3}} \right)} \right]
\]

\[
C \approx 0.71
\]

<table>
<thead>
<tr>
<th>Head Water (ft)</th>
<th>Tailwater (ft)</th>
<th>Flow Type</th>
<th>Computed Yc (ft)</th>
<th>Gate Opening(ft)</th>
<th>CFD Q (cfs)</th>
<th>Full Pipe Flow (cfs)</th>
<th>Rela Err (%)</th>
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</table>
Summary

• ANSYS FLUENT has been successfully applied to the flow analysis for culvert and complex hydraulic structures in South Florida.

• CFD synthetic data has been found to have overall relative difference within ±10% with respect to field flow measurements with hydroacoustic flow meters.

• The results presented here demonstrate that synthetic CFD flow data is a plausible alternative to compile data for flow rating improvement.

• It can also be used to generate synthetic data sets to establish preliminary ratings for sites where standard streamgauging techniques are difficult to apply.
Thank You