Computer Modeling to Support Process Design at the District

*M&R Monthly Seminar, November 18, 2011*

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Plant Design Management
Not just pretty colors and cool visual effects...
Traditional methods of flow analysis and design have limited accuracy and cannot completely address the fluid flow problems.

Three dimensional flows include numerous variables that are difficult to account for such as turbulence, heat and/or mass transfer, settlement, etc.
WHY COMPUTER MODELING

• Used to optimize the new design/geometry
• Can identify operational problems
• Used to solve current operational problems of the existing infrastructure
• Used to simulate fluid behavior in complex applications, for better understanding and visualization
• Simulations are faster and less costly than physical models

\[
\begin{align*}
\frac{\partial}{\partial t} (\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) &= -\nabla p + \nabla \cdot \left[ \mu \left( \nabla \mathbf{v} + \nabla \mathbf{v}^T \right) \right] + \rho \mathbf{g} + \mathbf{F} + \nabla \cdot \left( \sum_{k=1}^{n} \alpha_k \rho \mathbf{v}_{dr,k} \mathbf{v}_{dr,k} \right) \\
\frac{\partial}{\partial t} (\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) &= -\nabla p + \nabla \cdot \left( \mathbf{v}_{dr} \mathbf{v}_{dr} \right) + \rho \mathbf{g} + \mathbf{F} + \nabla \cdot \left( \sum_{k=1}^{N} \alpha_k \rho \mathbf{v}_{dr,k} \mathbf{v}_{dr,k} \right)
\end{align*}
\]
COMPUTATIONAL FLUID DYNAMICS (CFD)

**Equations and Algorithms**
- Discretization of continuous fluid flow behavior
  - Finite volume method
  - Finite element method
  - Boundary element method
  - Integrals and differential equations
- Algorithms – step-by-step procedure for calculations
  - SIMPLE (Semi-Implicit Method for Pressure Linked Equations)

**Fluid Behavior**
- Euler Equations (Ideal fluid)
  - Conservation of Mass
  - Conservation of Momentum
  - Conservation of Energy
- Navier-Stokes Equations
  - Introduced viscous forces to Euler equations
  - Describe the changes in momentum of particles in relation to external pressure and internal viscous forces

**Computerized Aid**
- Developing geometrical model (CAD)
- Programmable software codes
  - OpenFOAM
  - Flow 3D
- Supercomputers for simulations

CFD is a technique for the simulation and analysis of fluid flow using a computer model.
CFD DESIGN PROCESS

- Define the geometry and physical boundary conditions of the system
  - Use CAD or other graphical interface
  - Develop a mesh of discrete elements/cells
- Define the equations of fluid motion to be applied in the simulation
- Define the fluid boundary conditions and properties
- Assemble the components in a programmable code or use commercially available software that suits the application
- Perform the simulations using supercomputers yielding measurable results
- Use a postprocessor for visualizing and analyzing the results

The more accurate the system and fluid are defined, the more accurate are the output results

\[
\frac{\partial}{\partial t} (\alpha_p \rho_p) + \nabla \cdot (\alpha_p \rho_p \vec{v}_m) = -\nabla \cdot (\alpha_p \rho_p \vec{v}_{dr,p})
\]
DISTRICT APPLICATIONS USING COMPUTER MODELING

- Calumet TARP Pumping Station
- TARP Dropshafts
- Calumet Pumping Station
- Egan Pumping Station
- Stickney WS AGT Flow Split
- Calumet Primary Settling Tanks
- North Side Grit Chambers
- North Side Final Settling Tanks
PROJECT OBJECTIVES

- Determine number and size of tanks
- Meet hydraulic and treatment performance criteria
- Optimize variable tank dimension
- Minimize construction costs
Typical Circular Clarifier (US Filter/Envirex Design)

*NOTE: ALTERNATE 6.0 FT FEEDWELL DEPTH ("G" DIMENSION) SHOULD BE INVESTIGATED FOR CFD MODELING*
CFD Modeling Objectives

- Use as Tool to Optimize Key Design Parameters
  - Inlet Pipe
  - Feedwell
  - Side Water Depth

- Evaluate TSS removal efficiencies at various flows
3D Geometry for the Numerical Simulation

Initial Design: Straight rising inlet pipe
Port Design: Inlet with ports
Three Dimensional Model Development

- 1.2 Million Cells
- Simulated on NCSA Supercomputers
  (National Center for Supercomputing Applications)
Flow Field Visualization
Energy Dissipating Inlet (EDI)
Stickney WRP Circular Clarifiers (1935)
New Design: Inlet pipe with open ‘cage’
Visualization of Flow Field
THE TOP ELEVATION OF TAPERED INLET PIPE WAS EVALUATED AT 5, 6, AND 7 FT. BELOW WATER SURFACE

Average Flow

Effect of Free Water Surface

Maximum Flow

FEEDWELL DESIGN EVALUATION:
- 40, 41, 42, 43 AND 44 FT. DIAMETER
- 5, 6, AND 7 FT. FEEDWELL DEPTH
Visualization of Flow Field
DEEPER IS BETTER BUT ……………..
THE TAPERED INLET REMOVES A HIGHER PERCENTAGE OF TSS
FINAL TANK DESIGN

- Diameter: 155’
- Side Water Depth: 15’
- Inlet Pipe Diameter: 4’ tapered to 5’-6”
- Inlet Pipe Elevation: 6’ below water surface
- Feedwel Diameter: 41’
- Feedwel Depth: 5’
- SOR Avg. Day: 1,195 gpd/sf
- SOR Peak Hour: 2,486 gpd/sf
- Detention Time: 1.24h to 2.75h
Primary Settling Tank at CWRP
CFD Modeling Objectives

- Investigate the non-uniform grit distribution in the aerated grit chambers
- Suggest a method which ensures optimal plant operation.
Surveying using state-of-the-art 3-D High-Definition Laser Scanning
Geometry from Laser Scanning Survey
Two different computer systems were used for the 30-min (1800 sec) simulations

- **FLOW-3D**: U of I Hydrosystem Laboratory. 7 node, 56-core Intel Xeon cluster. Each node has 8 cores and 32 GB of RAM. The simulations were conducted using 8 processors. 9-10 days to complete flow simulations.

- **FLUENT**: Argonne National Laboratories. 128 compute nodes with total of 1024 cores. The simulations were conducted using 8 processors. 4-7 days to complete flow simulations.

*Computational Grid*
The flow discharge at gates 1-10 are recorded through the simulation and compared to the field measurements.
Based on flow measurements in Grit Chamber while conduits 11 and 12 were closed with low discharge conditions:

<table>
<thead>
<tr>
<th>Conduit</th>
<th>$Q_{\text{fluent}}$ (cfs)</th>
<th>$Q_{\text{obs}}$ (cfs)</th>
<th>$Q_{\text{fluent}}$ (MGD)</th>
<th>$Q_{\text{obs}}$ (MGD)</th>
<th>%ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>33.8</td>
<td>34.4</td>
<td>21.8</td>
<td>22.3</td>
<td>1.9</td>
</tr>
<tr>
<td>2</td>
<td>29.3</td>
<td>29.8</td>
<td>18.9</td>
<td>19.3</td>
<td>2.0</td>
</tr>
<tr>
<td>3</td>
<td>24.1</td>
<td>24.4</td>
<td>15.6</td>
<td>15.8</td>
<td>1.4</td>
</tr>
<tr>
<td>4</td>
<td>33.2</td>
<td>33.8</td>
<td>21.4</td>
<td>21.9</td>
<td>1.9</td>
</tr>
<tr>
<td>5</td>
<td>20.5</td>
<td>20.7</td>
<td>13.3</td>
<td>13.4</td>
<td>1.0</td>
</tr>
<tr>
<td>6</td>
<td>37.4</td>
<td>38.0</td>
<td>24.1</td>
<td>24.5</td>
<td>1.6</td>
</tr>
<tr>
<td>7</td>
<td>42.2</td>
<td>42.9</td>
<td>27.3</td>
<td>27.8</td>
<td>1.7</td>
</tr>
<tr>
<td>8</td>
<td>22.9</td>
<td>23.3</td>
<td>14.8</td>
<td>15.1</td>
<td>1.6</td>
</tr>
<tr>
<td>9</td>
<td>40.1</td>
<td>40.9</td>
<td>25.9</td>
<td>26.4</td>
<td>1.9</td>
</tr>
<tr>
<td>10</td>
<td>17.6</td>
<td>18.1</td>
<td>11.4</td>
<td>11.7</td>
<td>2.7</td>
</tr>
<tr>
<td>11</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>301.0</strong></td>
<td><strong>306.4</strong></td>
<td><strong>194.5</strong></td>
<td><strong>198.0</strong></td>
<td><strong>1.8</strong></td>
</tr>
</tbody>
</table>

The maximum error between the field measurements and the simulation results is around 2.7%.
Simulation with 225MGD inflow showing formation of secondary currents on cross sections right after the bend.
SEDIMENT TRANSPORT SIMULATION—SUMMARY

Initial simulations:
Mass particles asymmetry increases as Q increases
FLOW WITH GRIT MATERIAL INTRODUCED TO DOMAIN

(Video Simulation)

t = 142.5s

iso-density = 1800 kg/m³

Q = 375 mgd

Q_{grit}/Q = 1.2%
BULLE’S EFFECT (1926)
Uneven sediment distribution due to bifurcation

Sediment discharge is larger through the tributary than over the main channel

\[ Q_{s\text{-in mc}} = Q_{s\text{-out mc}} + Q_{s\text{-out tr}} \]
\[ Q_{s\text{-out mc}} < Q_{s\text{-out tr}} \]

Although,
\[ Q_{s\text{-out mc}} > Q_{s\text{-out tr}} \]
There is a clear Proof of Secondary current generation and recirculation due the 23° 31’ Bend.

The simulations show the existence of a non-uniform flow distribution across the 12 distribution conduits which is more pronounced as Q increases.

Non-Uniform distribution of sediment due to the Bulle’s effect, enhanced by the secondary current at the bend, has been observed for larger flow discharges.

Sediment transport simulations show that sediment distribution is symmetric for lower discharges (e.g. $Q=150$ MGD) but becomes asymmetric for higher flow discharges (e.g. $Q => 300$ MGD). As $Q$ increases sediment particles (simulated in the range of 75 and 1000 microns) tend to increase in conduits on the south side (11 and 12).
PROPOSED SOLUTIONS TO CONSIDER...

Vanes making 20° angle with the side wall of the approach channel.
FLOW PATTERN FOR SUSPENDED SEDIMENT AND BEDLOAD MATERIAL WITH VANES PRESENT IN THE SYSTEM

Q_s/Q_w=0.06

3 vanes @ 20 deg

Q (MGD)=501

Time (s) = 1500.0
PROPOSED SOLUTIONS TO CONSIDER...
SINGLE JET LOCATED ON THE LATERAL WALL DIVERTS THE SOLIDS TO NORTH SIDE CONDUITS, HOWEVER CAUSES SOME ACCUMULATION AT THE “WRIST” AND CONDUITS 1-5.

<table>
<thead>
<tr>
<th>Grit Collected</th>
<th>Original</th>
<th>Pressure Jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Side</td>
<td>747.85</td>
<td>733.03</td>
</tr>
<tr>
<td>South Side</td>
<td>753.63</td>
<td>691.05</td>
</tr>
<tr>
<td>North/South</td>
<td>0.99</td>
<td>1.06</td>
</tr>
<tr>
<td>Total (m3)</td>
<td>1501.48</td>
<td>1424.08</td>
</tr>
<tr>
<td>Total (million gallons)</td>
<td>0.40</td>
<td>0.38</td>
</tr>
</tbody>
</table>
SEVERAL FLOW TRAINING STRATEGIES WERE CONSIDERED:

- **Triangular steps** of height 1.5-1.6ft (50cm) are placed in checkerboard pattern starting from bend until the “wrist” of the approach channel. (OPTION 1)

- Several variations in terms of location and length of these triangular steps were considered. (OPTION 2, 3)

- An **arch-shaped perforated wall** at the wrist of the approach channel was considered. (OPTION 6)

- Triangular steps were placed near the south side lateral wall starting from the bend until the wrist of the approach channel. (OPTION 4)

- Finally, a **guide wall** following the south side lateral wall starting from the bend until the wrist with 3 triangular steps at the wrist was considered. (OPTION 5: variation of Option 4)
SEVERAL FLOW TRAINING STRATEGIES WERE CONSIDERED:

- Triangular steps in checkerboard pattern starting from the bend until the "wrist" of the approach channel.

- Several variations in terms of location and length of these triangular steps were considered.

- An arch-shaped perforated wall at the wrist of the approach channel was considered.

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Option 5, continuous guiding baffle following the south-side lateral wall of approach channel with triangular steps at the wrist.
Original Domain

- Suspended Load
- Bed Load: $d_{50} = 1\text{mm}$

$Q = 300 \text{ MGD}$

- $Q_s/Q_w = 0.06$
- $Q = 300 \text{ MGD}$
- $x = -10 \text{ ft}$
- $z = 30 \text{ ft}$

Time (s) = 539.99
Option 5

Q = 300 MGD

Suspended Load

Bed Load
d50 = 1mm

Qs/Qw = 0.06

Q (MGD) = 300

x = -10 ft

z = 30 ft

Vel (ft/s): 0.1 2.0 8.5

Time (s) = 540.00
OPTION 5: \( Q = 300 \) MGD FLOW

<table>
<thead>
<tr>
<th>%Change in Amount</th>
<th>Pool1</th>
<th>Pool2</th>
<th>Pool3</th>
<th>Pool4</th>
<th>Pool5</th>
<th>Pool6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t=900s )</td>
<td>518</td>
<td>20.19</td>
<td>13.36</td>
<td>-34.65</td>
<td>-42.73</td>
<td>-48.24</td>
</tr>
</tbody>
</table>

Q = 300 MGD after 900s (Particle size = 1mm)
CONCLUSIONS:

- Out of all the flow training devices tested, **Option 5**, continuous guiding baffle following the south-side lateral wall of approach channel with triangular steps at the wrist, shows the most improvement in terms of grit distribution in each pool for most of the discharges considered.

- This is an easily applicable option in terms of structure geometry considered.
GATE OPENING SOLUTION SCENARIOS...

The different cases were tested for three discharge values of 250, 350 and 450 MGD.

- Alternative 0 (A0) considers the case in which all the gates are open.
- Alternative 1 (A1) considers the case in which gates 11 and 12 are fully closed.
- Alternative 2 (A2) considers the case in which gates 1 and 2 are fully closed.
- Alternative 3 (A3) considers the case in which gates 1 and 2 are 2/3 open.
- Alternative 4 (A4) considers the case in which gates 1 and 2 are 1/3 open.
- Alternative 5 (A5) considers the case in which gates 11 and 12 are 2/3 open.
- Alternative 6 (A6) considers the case in which gates 11 and 12 are 1/3 open.
ALTERNATIVE 1: GATE 11 & 12 FULLY CLOSED

(Video Simulation)
CONCLUSIONS AND RECOMMENDATIONS FROM GATE OPERATION SIMULATIONS

- Changing the openings on north side extreme for gates 1 and 2 does not affect the flow distribution to conduits 7 to 12 significantly.

- Similarly changing openings of gates 11 and 12 does not affect the flow distribution to conduits 1 to 6.

- Shutting the gates 11 and 12 fully, causes formation of a dead zone considerably large, almost over the full length of distribution conduits 11 and 12. This dead zone is prone to accumulate solid material of all sizes since the flow velocity in the region is much slower than the fall velocity of grit sizes that are observed in the system (75μm to 1mm).

- Fully shutting gates 11 and 12 could also overload gates 9 and 10 in high inflow times.

- In the high flow times (Q~450MGD) keeping the gates 11 and 12 2/3 open instead of fully shut and at the low flow times (Q~250MGD) keeping the gates 1/3 open will prevent accumulation of solid material in the distribution conduit 11 and 12 while reducing the loading to Pool 6.
CFD goal of the preliminary simulations is to reproduce the hydrodynamics of a final settling tank for two different discharge conditions so that the mechanics of sedimentation can be observed. Two preliminary simulations are conducted with 2-MGD (low flow) and 6-MGD (high flow) inflow discharges.
3D Simulation results are presented in two planes cutting through the middle of the tank.

Plane, D1, Cutting Diagonally Through Settling Tank

Plane, X1, Cutting Through Middle of the Settling Tank
The streamlines show recirculation zones near the tank bottom. The suspended material plunges towards the tank bottom and should settle there. However, these strong recirculation zones may resuspend the solids, promoting their transport towards the outlet of the tank.
POSSIBLE SOLUTION SCENARIOS

- Increasing the depth of the settling tanks (Solution Scenario 1)
POSSIBLE SOLUTION SCENARIOS

- Increasing the diameter of the central skirt might reduce the amount of interaction between two jets entering the domain. (Solution Scenario 2)

- Decreasing the clearance of central skirt from the tank bottom (bringing the mouth of the ring closer to the tank bottom). (Solution Scenario 3)

**Original Domain**

\[ D_r = D = 2.25\text{m (7'-4 1/2")} \]

\[ h = 2.2\text{m (7'-2")} \]

**Scenario 2**

\[ D_r = 2D = 4.5\text{m (14'-9")} \]

\[ h = 2.2\text{m (7'-2")} \]

**Scenario 3**

\[ D_r \sim D = 2.25\text{m (7'-4 1/2")} \]

\[ h = 0.9\text{m (2'-11")} \]
Note much improvement is observed between scenarios.
The figure shows that TKE values are higher near the bottom of the tank and these high values penetrate closer to the sidewall of the tanks in the original domain. Deepening the tank in Scenario 1 reduces the high TKE area near the tank bottom and confines the penetration distance of high TKE. Similarly, changing the diameter and the clearance of the central ring from the bottom of the tank affects the size of the area of high TKE.

AVERAGE CONCENTRATION OF THE EFFLUENT LEAVING THE SYSTEM
POSSIBLE SOLUTION SCENARIOS

- Locate a round plate to spread the flow laterally and away for the sludge hopper (Solution Scenario 4)

Particles clump at the center of the tank bottom when a plate is placed under influent well.
SIMULATION DOMAINS WITH AND WITHOUT PLATES

a) original domain

b) - plate diameter=4m, distance from central skirt=35cm

c) - plate diameter=4m, distance from central skirt=50cm

d) - plate diameter=6m, distance from central skirt=35cm
AVG. SOLID CONCENTRATION AT THE OUTLET
CONCLUSIONS AND RECOMMENDATIONS

- Installation of a plate under the influent well is an economical alteration of the final settling tanks.
  - This alteration will direct flow to lateral walls of the tank
  - This will greatly reduce disturbance of already settled particles near the sludge hopper at the tank bottom, allowing for more efficient solids collection in the hopper
  - The solids concentrations in the effluent will be considerably reduced

- Based on simulation results, a plate with diameter of 5m placed about 35cm below the influent well is recommended.
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Protecting Our Water Environment
Metropolitan Water Reclamation District of Greater Chicago
Thank You