CFD for Sedimentation: Modeling Calibration and Verification

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Presentation Outline

• Introduction
  • Clarifier Modeling Options
  • Role of Models
  • Calibration and Verification Definitions
• 2-D and 3-D Modeling
  • General Modeling Process
  • Model Calibration
• 2-D Case Study
  • 2Dc Model
• 3-D Case Study
  • Square Clarifier Field Test and CFD
  • Radial clarifier EDI Evaluation Case Histories
Introduction

Clarifier Modeling Options

- Box models
- 1-D models
- 2-D models
- 3-D models
- Effective use of all levels of models

Increasing rigor

<table>
<thead>
<tr>
<th>Level</th>
<th>Strength</th>
<th>Application</th>
<th>Weakness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hazen</td>
<td>Simple</td>
<td>Discrete settling (Grit)</td>
<td>Ignores hydrodynamics</td>
</tr>
<tr>
<td>Limit State</td>
<td>Simple</td>
<td>Zone settling (SST preliminary design and operational)</td>
<td>Ignores hydrodynamics</td>
</tr>
<tr>
<td>1D</td>
<td>Computation speed</td>
<td>All types of settling including 2 phase flows</td>
<td>Ignores hydrodynamics</td>
</tr>
<tr>
<td>2D</td>
<td>Computation speed compared to 3D; runs on laptop.</td>
<td>All clarifiers where there is a dominant flow direction; dynamic simulations.</td>
<td>Ignores lateral non-uniformity in solids and momentum.</td>
</tr>
<tr>
<td>3D</td>
<td>Completeness of governing equations; high spatial resolution.</td>
<td>All clarifiers. Steady state simulations where a dominant flow direction cannot be assumed.</td>
<td>Long execution times; high level of expertise required.</td>
</tr>
</tbody>
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Calibration or Verification/Validation? Definitions

**Calibration**: Initial trials to adjust model parameters to reproduce field conditions (either long term data or field testing data).

**Verification/Validation**: Tests to confirm that a model is representing field conditions. For example by independent stress tests with different flow or settling conditions or operating data.

2-D and 3-D Clarifier Modeling
CFD: General Modeling Process

- Calibration depends on model configuration (sub-models) and data collection
- Special sampling/data collection may be required for model calibration/verification

Based on:
- Influent parameters (Influent flow and MLSS)
- Operational parameters (Units in service, RAS flow)
- Sludge characteristics (settling, flocculation)

CFD Modeling of Clarifiers

General Purpose:
- Predict clarifier performance and capacity

Based on:
- Influent parameters (Influent flow and MLSS)
- Operational parameters (Units in service, RAS flow)
- Sludge characteristics (settling, flocculation)
Input and operation parameters:
Flow measurements; SOR, RAS, MLSS

Performance parameters:
Effluent TSS; Blanket depth
Solids profile; Internal Hydrodynamics

Sludge characteristics:
Settling and compression properties
Flocculation and fractionation properties

Input and Output Parameters for Model Calibration and Verification

CFD Modeling of Clarifiers:

Field Testing – Data Gathered for CFD Modeling Calibration

- Flocculation parameters
- Sludge Volume Index (SVI)
- Flocculated suspended solids (FSS) and dispersed suspended solids (DSS)
- Settling properties of the sludge: zone, and compression rates
- Discrete settling parameters
Typical CFD Settling Model Approaches

- Vesilind Equation
  \[ V_s = V_o e^{-kX} \]

- Takac’s equation
  \[ V_s = V_o \left[ e^{-k_1(X-x_{ma})} - e^{-k_2(X-x_{ma})} \right] \]

- McCorquodale’s five-component model

Modeling Flocculation (McCorquodale et al. 2004)

- Differential settling flocculation:
  \[
  \frac{dC_1}{dt} = -\frac{3}{2} k_{ds} \frac{C_1 C_2}{\rho_1 \rho_2} \left( 1 + 2 \frac{d_1}{d_2} \right)^2 \left( V_{s2} - V_{s1} \right)
  \]

- Shear-induced flocculation
  \[
  \frac{dn}{dt} = K_B X G^n - K_A X n G
  \]

  - Floc Breakup
  - Floc Aggregation
Field Testing: Determination of Settling Properties

\[ V_s = V_0 \cdot e^{-K \cdot X_{TSS}} \]

Field Data

\[ y = 46.963e^{-0.653x} \]

\[ R^2 = 0.9427 \]

Daily Average - SVI

<table>
<thead>
<tr>
<th>Date</th>
<th>Average SVI</th>
<th>mL/g</th>
</tr>
</thead>
<tbody>
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<td>9/8/2012</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>9/9/2012</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td>9/10/2012</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>150</td>
<td></td>
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Dye Testing

- Dye tests provide an estimate of field performance of secondary clarifiers
- Compare to an “ideal” plug flow reactor
- Evidence of short-circuiting and density currents
Calibration of the flocculation sub-model

- Collect a MLSS sample (About 15.0 Liters)
- Use a six-paddle stirrer and fill each jar with 2.0 L of mixed liquor (avoiding unnecessary delays)
- Assign a flocculation time to each jar, e.g., 0, 2.5, 5, 10, 20, 30 minutes
- Mix the samples at a G of approximately 40 s\(^{-1}\)
- Allow the sample to settle for 30 minutes
- Take a supernatant sample from each jar
- Measure the TSS

Equation 2.39

\[
C = a+(C_0-a)\cdot e^{-kG\cdot t}
\]

\[
C = 4.3 + (60.7)\cdot e^{-0.49728\cdot t}
\]

\[
n_t = \frac{K_B\cdot G}{K_A}\cdot \left( n_0 - \frac{K_B\cdot G}{K_A}\right)\cdot e^{-K_A\cdot X\cdot G\cdot t}
\]

\[
C=a+(C_0-a)\cdot e^{-kG\cdot X}
\]

Wahlberg et al. (1994)

La Motta et al. (2003)

\[
K_A = 7.4 \times 10^{-5} \text{ L/g SS}
\]

\[
K_B = 8.00 \times 10^{-9} \text{ s}
\]

\[
X = 2,800 \text{ mg/L}
\]

\[
G = 40 \text{ s}^{-1}
\]
Clarifier Sampling – Stress Testing

- If possible, stress testing provides information on how the clarifiers react at maximum flow conditions
  - When does failure occur?
  - Useful information for modeling

2-D Modeling – Case Study
Developed at the University of New Orleans in 2004, 2Dc is a 2-D CFD model customized for clarifiers. It accounts for all the major processes occurring in settling tanks (e.g., hydrodynamics, flocculation, environmental impacts). It accounts for the dynamics of the sludge inventory. It can predict effluent quality and RAS concentration. It allows visualization of the internal conditions in the clarifier, like the position of the sludge blanket and flow pattern. It incorporates the geometry and other internal features of the clarifiers.
2-D Case Study: City of San Francisco Wastewater Enterprise Southeast Water Pollution Control Plant (SEP)

- 57 mgd ADWF HPOAS facility
- Design WW Flow = 250 mgd
  - (150 mgd through secondary treatment)
- Sixteen (16) – 120 ft Diameter Circular Center Feed Peripheral Overflow SCs
- SC reaching end of useful life

An extensive field investigation was conducted at the SEP WPCP

- Field testing performed to understand
  - How the SEP clarifiers respond to stress conditions
  - Determine MLSS settling, flocculation and settleability parameters
Field testing at SEP WPCP

The following data were collected and analyzed:

- **Stress Testing:**
  - Influent and effluent flows
  - Return activated sludge flow rate
  - MLSS, RAS SS, Effluent SS
  - Sludge Blanket
  - Sludge Volume Index
  - Flocculation parameters
  - Flocculated suspended solids (FSS)
  - Dispersed suspended solids (DSS)
  - Discrete settling parameters
  - Settling properties of the sludge: zone, and compression rates

- **Follow up testing**
  - Dye Studies
  - RAS drawdown testing
  - Stamford Baffle stress testing
  - Microscopy

Stress testing demonstrated performance limitation with the existing clarifiers

Clouds of solids are an indication of poor clarifier hydrodynamics (strong internal currents)

Cloudiness observed with four clarifiers online → SOR = 850 gpd/ft²

Significant cloudiness observed with three clarifiers online → SOR = 1,000 gpd/ft²
Before design, clarifier optimization was conducted using the 2Dc Model

- A computational fluid dynamics (CFD) model was developed and calibrated and validated against stress testing data
- Model used to evaluate potential upgrades to be incorporated during clarifier rehab, including:
  - Removal of inlet target baffles *(were resulting in floc breakup)*
  - Center well diameter *(existing too small)*
  - Stamford baffle position

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Recommended improvements resulted in increased capacity and reliability of the secondary clarifiers

2-D Case Study

- Secondary Clarifier Capacity
  - MLSS = 2,800 mg/L, SVI = 85 mL/g, RAS = 30%

- 45 mg/L – Weekly average Outfall effluent limitation during dry weather
3-D Modeling – Case Studies

Case Study: Square Clarifier Calibration and Verification

Samstag et al. (2010)
Field Tests for Calibration and Verification

Settling Velocity Tests

Dye Tests

Comparison of Field to CFD

Solids Profile Field Test

CFD Simulation Velocity and Solids Profile
Case Study: Activated Sludge Clarifier Optimization

- Radial flow clarifier
- Questions:
  - Optimum Depth?
  - Optimum Inlet?
  - Optimum Feedwell?
  - Optimum Effluent Zone?

Samstag and Wicklein (2014)

Radial Flow Clarifier CFD Model

- 3D Fluent CFD
- 1,100,000 hexahedral cells
- K-epsilon turbulence model
- User defined functions (UDF) to implement
  - Solids settling and transport
  - Density coupling
Verification test of CFD Model

Case Study: Activated Sludge Clarifier Alternative Inlet Configurations
Case Study: Activated Sludge Clarifier Alternative Velocity Vector Plans

Case Study: Activated Sludge Clarifier Alternative Velocity Plans
Case Study: Activated Sludge Clarifier Alternative Velocity Profiles

Case Study: Activated Sludge Clarifier Comparison Solids Profiles
Conclusions

- It is still necessary to perform calibration and verification tests for CFD evaluation of sedimentation.
- Calibration test examples:
  - Settling tests
  - Floc tests
- Verification test examples:
  - Solids profile tests
  - Dye tests
- CFD can uncover significant potential capacity and performance improvements