Chicago uses hydraulic and CFD modeling to assess the effect of future water demands

Presented by:
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Robert Butterworth, P.E., AECOM

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Overview

• Background

• Modeling Efforts
  o Tunnel Model
  o Surge Model
  o CFD Model

• Conclusions
Project Team

- **AECOM**
  - Tom Weber
  - Liaqat Khan
  - Lindle Willnow

- **Chicago Department of Water Management**
  - Michael Sturtevant
  - Burt Rezko
  - Ross Sweeney, CTR
Background

• CDWM supplies purified Lake Michigan water to about 5.4 million people in the City of Chicago and its suburbs

• Two of CDWM’s largest suburban consumers:
  o Major water purveyors served by Southwest Pumping Station
  o Expect significant growth within their supply area
Project Understanding & Issues Map

• Concerns
  - Tunnel capacity
  - Station capacity
  - Station hydraulic deficiencies
  - Reliability

• Solutions
  - Hydraulic & CFD models to determine capacities
  - Improvements necessary to meet demands
  - Concept design for redundant pump station
Study Objectives

• Determine how much water is available from SWPS and tunnel system
  o Both current and future water demand conditions

• Determine improvements to SWPS and South Tunnel System required to meet water demands of future suburban growth
  o Prepare estimate of cost for these improvements

• Evaluate whether current and projected SWPS operating conditions adhere to the Hydraulic Institute (HI) Guidelines
Tunnel System Modeling Summary
Southern Tunnel System

- Supplied from South Water Purification Plant
  - 2000 Peak Hour = 827 mgd
  - 2030 Peak Hour = 700 mgd

- Provides water to four pumping stations
  - Station 1 (105 mgd)
  - Station 2 (190 mgd)
  - Station 3 (154 mgd)
  - Southwest (300 mgd)

- Nine Main Tunnel Sections
  - 190,000 feet total length
  - 8 ft diameter to 16 ft x 15.1 ft high arch
Tunnel Model Development

• AECOM developed and calibrated a new computer based hydraulic model
  o As-built drawings, pump curves & SCADA data
  o Modeling Software: H2O Map Version 8
Water Demand Data

- Water demands based on historical data and estimated projections
  - SWPS is only pump station expected to experience significant increases in water demand

<table>
<thead>
<tr>
<th></th>
<th>(Calibration)</th>
<th>Avg An Year</th>
<th>An Av Year</th>
<th>Max Day Year</th>
<th>Peak Hr Year</th>
<th>Max Day Year</th>
<th>Peak Hr Year</th>
<th>Max Day Year</th>
<th>Peak Hr Year</th>
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<tbody>
<tr>
<td>Note 1</td>
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<td>Note 3</td>
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<td>Note 4</td>
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<td>Western - Total</td>
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<td>75.90</td>
<td>82.00</td>
<td>155.00</td>
<td>200.00</td>
<td>117.00</td>
<td>154.00</td>
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<td>64.50</td>
<td>75.00</td>
<td>117.00</td>
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<td>83.00</td>
<td>105.00</td>
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<td>105.00</td>
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<tr>
<td>Southwest</td>
<td>102.00</td>
<td>114.00</td>
<td>113.00</td>
<td>178.00</td>
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<td>174.00</td>
<td>192.00</td>
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<td>136.40</td>
<td>130.00</td>
<td>218.00</td>
<td>279.00</td>
<td>165.00</td>
<td>187.00</td>
<td>165.00</td>
<td>190.00</td>
</tr>
</tbody>
</table>
Southwest Pump Station (Geometry)

- Station built in 1963
- 12-foot-dia. inflow tunnel
- 17-foot-dia. vertical shaft
- Two horseshoe shaped channels
  - 9 ft wide and 9 ft high
  - 151 feet long (each)
- Six 6-foot-dia. wet wells
- Six pumps with suction pipe dia. of 3.33 and 2.33 ft
Southwest Pump Station (Pump Capacity)

<table>
<thead>
<tr>
<th>No.</th>
<th>Rated Q (MGD)</th>
<th>Modeled Q (MGD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>60</td>
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<tr>
<td>3</td>
<td>50</td>
<td>60</td>
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<tr>
<td>4</td>
<td>25</td>
<td>30</td>
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<tr>
<td>5</td>
<td>50</td>
<td>60</td>
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<tr>
<td>6</td>
<td>25</td>
<td>30</td>
</tr>
</tbody>
</table>
Tunnel Modeling Results

Two Analyses were Performed for Tunnel System:

1) Fixed Demands
   - Water demands are input into the model to determine the resultant head losses in the system
   - As water demand increases, the head losses through the system are also increased and water levels in suction wells are dropped

2) Fixed Head
   - Amount of flow that can be provided to SWPS based on maintaining a fixed pressure head discharge
Tunnel Modeling Results

• Fixed Demands Analysis
  
  o Results for all scenarios indicate that drawdown of water levels in SWPS suction wells are adequate for safe operation of the pumps
  
  o Suction well levels for all scenarios are significantly above minimum well elevations (-27.0 feet for SWPS)
  
  o Most extreme scenario is all six 60 MGD pumps with drawdown in SWPS wet well to -10.71 feet
Tunnel Modeling Results - Fixed Demands

• 2030 Maximum Day Demand – Future Conditions

<table>
<thead>
<tr>
<th>Pump Station</th>
<th>Pumpage (MGD)</th>
<th>Min. Suction Well Level (ft)</th>
<th>Modeled Well (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southwest</td>
<td>225</td>
<td>-27.0</td>
<td>-4.10</td>
</tr>
<tr>
<td>Western</td>
<td>117</td>
<td>-25.0</td>
<td>-2.63</td>
</tr>
<tr>
<td>Roseland</td>
<td>165</td>
<td>-16.0</td>
<td>-4.09</td>
</tr>
<tr>
<td>68th Street</td>
<td>83</td>
<td>-9.5</td>
<td>-0.20</td>
</tr>
</tbody>
</table>

• 2030 Peak Hour Demand – Future Conditions

<table>
<thead>
<tr>
<th>Pump Station</th>
<th>Pumpage (MGD)</th>
<th>Min. Suction Well Level (ft)</th>
<th>Modeled Well (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southwest</td>
<td>300</td>
<td>-27.0</td>
<td>-7.98</td>
</tr>
<tr>
<td>Western</td>
<td>154</td>
<td>-25.0</td>
<td>-5.66</td>
</tr>
<tr>
<td>Roseland</td>
<td>190</td>
<td>-16.0</td>
<td>-6.71</td>
</tr>
<tr>
<td>68th Street</td>
<td>105</td>
<td>-9.5</td>
<td>-1.27</td>
</tr>
</tbody>
</table>
Tunnel Modeling Results - Fixed Head

• Amount of flow that can be provided to SWPS based on maintaining a fixed pressure head discharge

• SWPS under future conditions with all six pumps nominal rated at 50 MGD (actual discharge 60 MGD)
  o Firm capacity approx. 283 MGD while maintaining downstream pressure of 50 psi with well elevation of -7.46 feet
  o Firm capacity approx. 306 MGD while maintaining downstream pressure of 40 psi with well elevation of -8.17 feet
### Tunnel Modeling Results - Fixed Head

#### Fixed Head at 50 psi; 2030 Peak Hour Demand

<table>
<thead>
<tr>
<th>Pump Condition</th>
<th>SWPS Pumpage (MGD)</th>
<th>SWPS Well Level (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Pumps @60 MGD</td>
<td>233</td>
<td>-6.03</td>
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<tr>
<td>5 Pumps @60 MGD</td>
<td>283</td>
<td>-7.46</td>
</tr>
</tbody>
</table>

#### Fixed Head at 40 psi; 2030 Peak Hour Demand

<table>
<thead>
<tr>
<th>Pump Condition</th>
<th>SWPS Pumpage (MGD)</th>
<th>SWPS Well Level (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Pumps @60 MGD</td>
<td>251</td>
<td>-6.55</td>
</tr>
<tr>
<td>5 Pumps @60 MGD</td>
<td>306</td>
<td>-8.17</td>
</tr>
</tbody>
</table>

DWM required 2030 peak hour flow of 250 MGD with one pump out of service
Summary and Conclusions

• South Tunnel System has sufficient capacity to meet anticipated population growth and corresponding increased water demands
  o Contingent on future replacement of existing 25 MGD pumps with larger 50 MGD nominal rated pumps

• AECOM recommends that SWPS discharge piping and feeder mains be evaluated prior to committing to meet future flows
Surge Modeling Summary
Surge Model Development

• AECOM used hydraulic tunnel base model to develop surge model
  o Pump start-up scenario
  o Pump trip scenario

• Assess impact at SWPS pumps and suction wells
  o Impact in tunnel system and other pump stations

• Discharge conditions not reviewed

• HAMMER and H2O Surge programs used
Transient Analyses: Pump Start-up Results

- No excessive lowering of wet well levels
- No adverse effects of concern due to relatively small pressure fluctuations
Surge Modeling - Pump Trip Findings

- No vacuum pressures or major pressure spikes

- Water level surge at SWPS
  - Higher than gate shaft operator platform at ceiling elevation +21
  - Higher than pump shaft cap at elevation +31

- Additional venting mitigates surge levels in pump shafts and gate shaft

- Minimal impacts at other stations

- Recommend additional monitoring for surge conditions
  - Compare to modeled surge results
Computational Fluid Dynamics Modeling Summary
CFD Modeling

- CFD modeling investigates hydraulic performance of pump station intakes
  - AECOM utilized STAR-CCM+ software by Computational Dynamics, Ltd.
  - Numerically solve fundamental equations of fluid flow, conservation of mass and momentum
  - Solves appropriate equations to quantify turbulent characteristics
  - Three-dimensional rendering of existing SWPS geometry grid

- Valuable tool for developing modifications to address performance deficiencies
CFD Model Development (Geometry)

- 12-foot-dia. inflow tunnel
- 17-foot-dia. vertical shaft
- Two horseshoe shaped tunnels
  - 9 ft wide and 9 ft high
  - 151 feet long (each)
- Six 6-foot-dia. wet wells
- Six pumps with suction pipe dia. of 3.33 and 2.33 ft
CFD Model Development (Pump Capacity)

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<td>6</td>
<td>25</td>
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</table>
Performance Evaluation Criteria

• Modeled hydraulic parameters were compared against Hydraulic Institute (HI) guidelines

• Standard industry reference for pump design, pump inlet configuration and pump testing

• Hydraulic Phenomena Investigated
  o Surface and subsurface vortices
  o Swirling flow at the pump bell
  o Non-uniform approach velocity
  o Highly turbulent flow
Performance Evaluation Criteria

• Resulting Consequences
  o Reduced pump efficiency / flow capacity
  o Cavitation at impeller
  o Unbalanced load on impeller / reduced bearing life
  o Vibration problems / reduced bearing life
  o In combination, deterioration of pump performance or pump life
CFD Modeling Findings

- Results of model runs suggest that deviations of axial velocity from the mean are within HI guidelines (10% variance) at all pumps.

- For the existing condition, maximum swirl angle at Pump 2 is close to the limiting value (5 deg.).

- For future condition, maximum swirl angle at Pump 1 marginally exceeds the limiting value by 0.5 deg.
Findings: Model Runs with High Swirl Angle (~5 degrees)

<table>
<thead>
<tr>
<th>Pump #</th>
<th>Pump Q</th>
<th>Velocity</th>
<th>Swirl Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Wmin/Wav</td>
<td>Wmax/Wav</td>
</tr>
<tr>
<td>Run 1: 300 MGD (6 pumps running – existing conditions)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-2</td>
<td>60</td>
<td>0.979</td>
<td>1.022</td>
</tr>
<tr>
<td>Run 2: 240 MGD (5 pumps running – existing conditions)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-2</td>
<td>60</td>
<td>0.986</td>
<td>1.024</td>
</tr>
<tr>
<td>Run 6: 300 MGD (pumps 1, 2, 4, 5, and 6 running – future conditions)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>P-1</td>
<td>60</td>
<td>0.99</td>
<td>1.02</td>
</tr>
<tr>
<td>Run 7: 300 MGD (pumps 1, 2, 3, 5, and 6 running – future conditions)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-2</td>
<td>60</td>
<td>0.99</td>
<td>1.02</td>
</tr>
<tr>
<td>Run 8: 180 MGD (pumps 1,2, and 5 running – existing conditions)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-2</td>
<td>60</td>
<td>0.97</td>
<td>1.01</td>
</tr>
</tbody>
</table>
Possible Solutions

• Common Solutions:
  o Floor and side wall splitters
  o Flow Dividers or Vanes
  o Baffles or Baskets
  o Increase suction pipe diameter
  o Increase pump bell diameter
Possible Solutions

Picture of Basket

Basket Attached to Pump 2

80% Porosity
Flow Characteristics Around Pump 2 Bell: With and Without Basket for 300 MGD

<table>
<thead>
<tr>
<th>Pump #</th>
<th>Pump Q</th>
<th>Velocity</th>
<th>Swirl Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Wmin/Wav</td>
<td>Wmax/Wav</td>
</tr>
<tr>
<td>Run 1: 300 MGD (6 pumps running)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-2</td>
<td>60</td>
<td>0.979</td>
<td>1.022</td>
</tr>
<tr>
<td>Run 4: 300 MGD (6 pumps running; basket at Pump 2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-2</td>
<td>60</td>
<td>1.009</td>
<td>1.015</td>
</tr>
</tbody>
</table>
Flow Characteristics Around Pump 2 Bell: With and Without Basket for 300 MGD

Without Basket

With Basket

Velocity Magnitude

Turbulent Kinetic Energy

Vorticity (Swirl Angle)
Flow Characteristics at Pump 2 Bell Throat: With and Without Basket for 300 MGD

**Without Basket**

- **X-velocity component**
- **Y-velocity component**
- **Z-velocity component**
- **Turbulent kinetic energy**

**With Basket**

- **X-velocity component**
- **Y-velocity component**
- **Z-velocity component**
- **Turbulent kinetic energy**

**Vorticity (Swirl Angle)**

**Velocity Ratios:**
- \( W_{max}/W_{avg} = 1.022 \)
- \( W_{min}/W_{avg} = 0.979 \)

**Swirl Angles:**
- \( \alpha_{z_{max}} = 0^\circ \)
- \( \alpha_{yz_{max}} = 4.95^\circ \)

**Pump Flow = 60 MGD**

**Velocity Ratios:**
- \( W_{max}/W_{avg} = 1.015 \)
- \( W_{min}/W_{avg} = 1.009 \)

**Swirl Angles:**
- \( \alpha_{z_{max}} = 0^\circ \)
- \( \alpha_{yz_{max}} = 1.25^\circ \)

**Pump Flow = 60 MGD**
Summary and Conclusions

• For the existing condition, maximum swirl angle at Pump 2 is close to the limiting value (5 deg.)

• For future condition, maximum swirl angle at Pump 1 marginally exceeds the limiting value by 0.5 deg.

• To remain within HI guidelines, with respect to swirl angle, consider adding baskets at Pumps 1 and 2

• Physical modeling is firmly recommended when 25-mgd pumps are to be replaced with 50-mgd pumps
  o Adding inlet baskets should be modeled at this time
Conclusions
Conclusions

• South Tunnel System has sufficient capacity to meet anticipated 2030 peak hour water demands of 250 MGD

• Replacement of existing 25 MGD rated pumps with larger 50 MGD rated capacity pumps

• Additional monitoring for surge conditions is recommended

• Consider adding baskets at Pumps 1 and 2, especially if deterioration of pump flow rate or excessive vibration is observed
Thank You

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