Simulating Control-Structure Ratings using Computational Fluid Dynamics: The case of Lockport Powerhouse, Illinois

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Outline

- Introduction /motivation
- Materials & methods
- Results
- Conclusions
Chicago Area Waterway System

- includes ~ 130-mile\(^1\) array of natural and constructed rivers, canals, locks and other structures in Chicago and northwest Indiana

- 5 million residents & additional industrial load of ~ 4.5 million population equivalents\(^2\)

\(^1\)GLC (2012)
\(^2\)https://wiki.epa.gov
### Connections to Lake Michigan

- **Wilmette Pumping Station**
  - 3 gates

- **Chicago River Controlling Works**
  - 4 sluice gates at north side & navigation lock
  - 4 sluice gates at the south side

- **O’Brien Lock and Dam**

### Connections to Illinois River / Mississippi River watershed

- **Lockport Controlling Works**
  - 7 sluice gates

- **Lockport Power House**
  - 9 sluice gates
  - 2 turbines
Control-structures’ operation

Gates/Lock operations during an event

Wilmette Pumping Station

Lockport PH

CRCW

O'Brien Lock & Dam

Lockport CW

Credits: A.R. Waratuke

1Zhu et al (2017)

2S. Santacruz (2014)
But what about control-structures rating?

- diversion accounting
- flooding protection/planning
- hydraulic/water quality modeling
- and more…
Predictive 1D, 2D & 3D models for CAWS

1D HEC-RAS modeling: S. Santacruz & A. Rojas

Telemac-2D modeling: Z. Li

3D EFDC modeling: Dr Z. Zhu

Quijano et al (2017)
LOCKPORT POWER HOUSE
Structure description
Structure description

photo credits: Dr B. Landry

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Lockport PH

source: MWRD
Structure description - turbines

- two turbines
- produce 40 million kilowatt-hours per year (110,000 KWH/day) ($1 million worth of electricity)
- maximum flow capacity ~2500 cfs each (5000 cfs in total)
there are nine sluice gates (14 ft × 9 ft), three each in pits identified as #3ABC, #4ABC and #7ABC.
Structure operation

- “Normally open the available gates in the pits farthest from the generators, i.e. pit #7, then pit #4, then pit #3.”
- “If only one gate is to be opened, typically this would be the center (B) gates in each pit.”
- “If two gates in each pit are needed, it is preferred to open the outer (A and C) gates as they are not adjacent and thereby reduces the turbulence.”
- “All three gates in each pit will be used only after all seven LCW gates have been opened or if authorized by the Canal Operations Engineer or higher supervisor.”

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Straub et al (2012)
Surrounding structures

Fenderwalls

4 cylinders

Straub et al (2012)
Previous studies

Muga (1961) – University of Illinois

Hart and McGee (1985)

Kiefer (1994)

Straub et al (2012)

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Methodology

Materials & methods

Digital Data, Engineering drawings & bathymetry data

AutoCAD 2018

GRASS GIS 7

Blender

Andrew Waratuke’s MatLab scripts

Python scripts

Geometry reconstruction

FLOW-3D®

CFD solver

Computational Grid

Numerical results
Computational approach

- Flow 3D® solver was used for the solution of the non-hydrostatic Unsteady Reynolds-Averaged Navier-Stokes equations

- RNG k-ε model was applied for the turbulence closure

- Flow discharge boundary conditions were imposed at the upstream end and stage discharge at the downstream pool
Computational domain & grid

Computational domain:

~ 680 m long
~ 250 m wide

Cartesian Computational grid of ~ 11 million cells was used with enhanced resolution close to the structure in order to resolve the gates/structure details.

Materials & methods

- Mesh sensitivity test for:
  - coarse (~7 mil)
  - medium (~11 mil) &
  - fine grid (~ 15 mil)

A mean error of < 5 % was observed for the final selected grid.
Numerical results

10,000 cfs with 6 gates open (2 / chamber)
Numerical results – Flow structure

Flow accelerates around cylinders, and fenderwall arches.

Flow accelerates inside the structure’s chamber and draft tubes.

Strong recirculation zone at the downstream pool.
1 gate open per chamber

4000 cfs

6000 cfs

7500 cfs

8500 cfs

10000 cfs

Streamwise velocity component (m/sec)

-8.0 -6.9 -5.7 -4.6 -3.4 -2.3 -1.1 0.0 1.1 2.3 3.4 4.6 5.7 6.9 8.0
2 gate open per chamber

7000 cfs

10000 cfs

13000 cfs

15000 cfs

18000 cfs

Streamwise velocity component (m/sec)
3 gate open per chamber

10000 cfs

16000 cfs

20000 cfs

23000 cfs

25000 cfs

Streamwise velocity component (m/sec)

-8.0 -6.9 -5.7 -4.6 -3.4 -2.3 -1.1 0.0 1.1 2.3 3.4 4.6 5.7 6.9 8.0
Flowrate convergence
Rating curve development

\[ Q = C_d A \sqrt{2gh'} \]

where:

- \( Q \) is the discharge in m³/s
- \( A \) is the cross-sectional area in m²
- \( 2gh' \) represents the energy head
- \( C_d \) is the discharge coefficient

- \( C_d = 0.591 \) (CFD based rating)
- \( C_d = 0.613 \) (Kiefer 1994)

The relationship between discharge and energy head can be expressed as:

\[ y = 0.5911x \]

with \( R^2 = 0.9601 \).
Comparison with previous studies

- CFD results (dashed)
- Kiefer (1994)
- Hart & McGee (1985)

Results

n= 3 gates
n= 2 gates
n= 1 gates

Q in cfs

water surface elevation in ft CCD

n= 3 gates
n= 2 gates
n= 1 gates

10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
-15.00
-10.00
-5.00
0.00
2.00

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An example – Rating evaluation using HPGs

Hydraulic Performance Graphs (Yen & González 2000)
An example – Rating evaluation using HPGs

CRCW gates open?
2 options:

- Flow reversal
- Flow towards LPH
Conclusions

• Computational Fluid Dynamics modeling was proven to be a useful and efficient tool for the development of Control Structures Rating.

• HPGs can be used to evaluate whether rating curve results are realizable or not at steady state.

• Lockport Power House has enough capacity to convey the flow of CAWS. However, the water surface gradient required to convey this flow within Chicago Sanitary and Ship canal may become the bottleneck factor of the system conveyance.
Future work

- Study the effect of the unsteadiness of the flow on Lockport rating

- Include the effect of CSOs in the HPG analysis ("leaky channel" HPGs)

- Try to find a way to improve control structure operation in CAWS system in an “optimum” way taking into consideration both hydraulic and water quality criteria.
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