Sediment Transport in the Intake Area of the Cardinal Plant: Field Study and Physical Model

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Abstract

Sedimentation is a chronic problem in many riverside water intakes. As part of US EPA rule 316(b) of the Clean Water Act, American Electrical Power and Buckeye Power Inc. are considering the installation of submerged cylindrical wedge-wire screens in the intake area of the Cardinal Plant. A study was performed to evaluate the sediment transport to the intake area and deposition near the screens. This study was comprised of three primary activities: perform on-site field work, construct and perform tests with a 1/24 reduced-scale laboratory model, and develop and perform simulations with a CFD model. This paper describes the field work and physical model. The model, based on Froude scaling, replicates a range of river flows and intake flows. Sediments were modeled using reduced-scale particles based on field samples. The model was calibrated against velocity data collected in the river upstream and near the intake. Deposition rates and deposition regions predicted with the physical model agree well with the CFD model. According to the models, sediment deposition could negatively affect intake operation with the cylindrical screens for existing conditions. Model results indicate that mitigation measures can be effectively implemented to reduce sedimentation near the intakes. Mitigation measures designed in attempts to mitigate sediment deposition around the screens were evaluated and are discussed.

Introduction

The Cardinal Power Plant (Cardinal) is located on the Ohio River near Brilliant, Ohio and has been in operation since 1967. American Electrical Power and Buckeye Power Inc. (the Owners) are investigating options to comply with U.S. EPA Rule 316(b) for fish impingement and entrainment at their cooling water intakes. Cardinal is unique in that the cooling water intakes are set back from the main bank of the river, in a side pool or forebay, created by excavation at the time of plant construction. Under existing conditions, significant sedimentation occurs in the forebay, requiring dredging every 3 to 5 years. Field measurements, physical modeling, and numerical modeling were utilized in a comprehensive study to help determine the feasibility of replacing the existing traveling water screens (TWS) with a static array of submerged cylindrical wedge-wire screens (screens). Ideally, the screens will be located entirely within the forebay, extending some distance from the intakes, to avoid frequent barge traffic in the main river channel. This paper focuses on the field data collection (Firoozfar et al. 2016a) and physical modeling portions of the work (Firoozfar et al. 2016b). Part 2 of this study is a sister paper and focuses on the numerical portion of the work (Politano et al. 2016).
Field Work

Overview

IIHR collected bathymetric data, velocity data, and sediment samples in the vicinity of the plant during two field programs with special focus on the forebay (Figure 1). The data was used to develop, construct, calibrate, and validate the physical and numerical models used in the study. The data was collected using an 18-ft research vessel, specially outfitted with the appropriate instrumentation and equipment.

Figure 1. Aerial view of the Cardinal Plant forebay (IIHR, September 21, 2015)

Bathymetric Data

An area of the Ohio River and the forebay bed elevations were measured from the research vessel using a single-beam sonar system with GPS tracking. Horizontal and vertical position of the sonar were measured with Real Time Kinematic (RTK) and Global Navigation Satellite System (GNSS) receivers, with correlations from a temporary ground-based reference station. The equipment setup provided riverbed elevation accuracies of approximately +/- 1 inch. Measurements were concentrated within and near the forebay to capture a higher level of detail required for the modeling.

Hydrographic survey software was used to aid in navigation, integrate system components, store measured data, and post-process the data. Elevation points were used to create a triangulated irregular network (TIN) surface model of the surveyed area. Available topographic data of the overbank areas was incorporated to create a final digital elevation model (DEM) of the study area (Figure 2).
Figure 2. Digital elevation model developed from the bathymetric surface and overbank topographic data

**Velocity Data**

River discharge and velocity were measured using a vessel-mounted Acoustic Doppler Current Profiler (ADCP). This instrument uses the sound wave reflections generated by four transducers off particles in the water to measure three-dimensional velocities in the water column. The location of each measurement was resolved using the GNSS data streams integrated with the ADCP data collection software, allowing real-time visualization and adjustments for vessel movement.

ADCP measurements were collected along river transects to determine river discharge and at stationary locations to develop accurate vertical velocity profiles at specific locations. Depth-averaged velocity vectors were calculated along each transect over the study reach (Figure 3).
Sediment Data

River bed sediment samples were collected in the river channel and within the forebay. Samples were collected using a winch-deployed clamshell bucket from the research vessel. Sample locations were measured with the GNSS.

Sediment grain size distribution was determined by sieve and SediGraph analysis of each sample in IIHR’s sediment laboratory according to ASTM standards (ASTM, 2006 and ASTM, 2013). Sediment size distribution and characteristic particle sizes $D_{10}$, $D_{50}$, and $D_{90}$ were determined, representing the particle sizes in which 10, 50, and 90% of the particles in the sample are smaller in diameter.

Results showed that sediments collected upstream of the forebay ranged from silt to sand along the right bank to gravel and cobble towards the main channel centerline. Sediments collected in front of the forebay ranged from clay and silt to sand near the forebay to gravel and cobble towards the main channel. Sediments collected inside the forebay were finer, ranging from clay to silt and sand. Sediments collected further out in the main channel ranged from sand to cobble. Sediment sample locations were plotted on an aerial view of the project site and colored by the $D_{50}$ sediment particle size (Figure 4).
Physical Model

Model Overview

A geometrically undistorted physical model of the cooling water intakes, forebay, and a 2,300-foot portion of the Ohio River channel was constructed at a 1:24 scale (Figure 5). The main river channel was constructed of concrete with an erodible bed in the vicinity of the forebay and intakes. River bathymetry and overbank topography from the field survey were integrated in the model using cross-sectional templates cut with a computer numerically controlled (CNC) gantry router.

The model simulated river flows up to 283,000 cubic feet per second (cfs) and cooling water intake flows up to 800,000 gallons per minute (gpm). The model recirculated river flows from a below-grade sump to the model headbox using pumps. A flow-conditioned headbox distributed flows uniformly across the river width. Flowrates were established with calibrated flow meters. Cooling water intake flows were set with a pump, valves, and flow meters. River water surface elevation was controlled with an adjustable tailgate weir.
In sediment laboratory studies like this one, the sediment sizes measured in the field cannot usually be scaled based on the geometric scale factor due to the effect of gravitational and inter-particle electrostatic forces (i.e., model particles would clump together). Therefore, other scaling relationships must be considered. The two most significant dimensionless parameters of sediment movement in a channel are the Shields parameter and the particle Reynolds number. In order to achieve sediment movement similarity, the values of these parameters must be matched in the model and prototype. However, this strategy usually requires a combination of a geometrically distorted model and/or lightweight particles to achieve a match. Because the use of a geometrically distorted model is not encouraged for complex flow scenarios such as the present study (Ettema, 2000), using lightweight particles in the model was the best way to achieve similarity. Consequently, lightweight Acrylic particles were chosen for the sediment in the model because they provided acceptable movement in the model and matched the Shields parameter and Reynolds number as closely as possible. Acrylic particles have similar specific gravity as coal and walnut shells, which are typically used in mobile bed models (Bettess, 1990; Ho et al., 2010; Frostick et al., 2011; Gorrick and Rodríguez, 2014), but are advantageous since they don’t biodegrade and are readily available in specific sizes.
The model sediment was mechanically mixed to the target particle size distribution and artificially fed into the model at a precisely controlled rate to simulate suspended and bed load in the river. This was the same sediment used in the erodible bed portion of the model. The sediment slurry was distributed through a custom fabricated feeder located upstream of the mobile bed area along the right bank. This provided sediment-laden flows in the river for deposition within the forebay and along the right bank.

Figure 6. Model sediment and screens

**Velocity Calibration**

A series of tests were conducted to assess the capability of the model to replicate the flow velocities and directions measured during the field campaigns. The calibration initially focused on matching the velocity and flow direction in the main channel and then in the forebay. River flowrate, tailwater elevation, barge configuration, and intake flow conditions from the specific dates of the field campaigns were replicated on the model prior to measurement. Over the course of calibration, modification and adjustments to the model headbox and inlet conditions were made to achieve proper flow behavior in the main channel. Field data from the first field campaign was associated with much lower river flows, and therefore had low water velocities, which proved difficult to match within the target range of +/-10% of flow magnitude and +/-10 degrees of flow angle. Field data from the second field campaign was associated with higher river flows, had higher velocities, and was able to be matched more closely on the model. For both conditions, barges were in various configurations and moved throughout the day, adding some uncertainty to the field measurements. However, the comparisons showed that, overall, the flow patterns in the main channel and along the right bank matched well with the field data, with all data points falling within the established criteria. Calibration inside the forebay was more challenging, with factors such as lower velocity magnitudes, influence from physical structures (e.g. moorings and barges), and thermal influences from the discharge canal contributing to uncertainties between model and field data. However, the model forebay flow patterns and velocities were consistent with field measurements and matched reasonably well (Figure 7).
Sediment Calibration

An additional test was undertaken to determine the models capability of producing a sediment deposit in the forebay similar to what was measured during the field campaign. Prior to the test, the forebay area was flattened to a “dredged” condition. Then an 85-hour model test was run while continually feeding sediment upstream at a known rate. The test resulted in a total volume of sediment deposited in the forebay within 2% of the target known quantity in the field. In the model, the sediment bar deposit was more uniform than observed in the field (Figure 8). This is most likely due to more controlled and constant flow and sediment conditions in the laboratory than experienced in the field. In the field, the sediment deposit was formed over decades, with portions of it dredged out over time to create channels for water to reach the intakes. In addition, the field deposit formed with transient influences from natural hydrologic cycles and highly variable sediment loads that cannot be quantified for comparison. It was concluded that the physical model showed good replication of the overall shape and pattern of the deposition in the forebay based on the existing sediment deposition in the field, given the practical limitations in the laboratory and the unquantifiable field conditions.
Sediment Mitigation Testing

To make valid comparisons between each sediment test, the model was run at the same prescribed river flowrates and sediment feed rates for the duration of each test. The model flowrates were selected based on analysis of relationships between the historical river flows and total suspended sediment (TSS) data and observations of sediment transport on the model.

After the completion of each test, the model was slowly drained to minimize sediment disturbance. A terrestrial laser scanner (Plenner et al. 2016) was then used to measure the bed surface in order to quantify the amount of sediment deposited and create elevation maps of the resultant bed (Figure 9) and difference plots of the bed from before and after the test.

Several shorter exploratory tests were conducted first with different sediment mitigation approaches in an effort to determine the most effective means to reduce the amount of sediment depositing in the forebay. Several combinations of various structures including submerged
skimmer walls, full height walls, and submerged vanes were tested. Observations revealed that submerged skimmer walls were not effective at reducing sedimentation but rather full height walls and strategic placement of vanes could potentially provide the desired improvements. Based on observations of the initial tests, nineteen preliminary concepts were developed for consideration.

Through further testing, analysis, and discussion with the Owners, nine concepts were selected for full testing. The majority of these scenarios included a full height wall that was used to alter the flow patterns near the entrance forebay and within the forebay. Other scenarios included walls, vane arrays, re-contouring the right bank, or various combinations thereof.

Test results showed that re-contouring of the right bank was effective, but was not pursued due to concerns with handling river debris and higher-than-expected costs to remove the bank material. For the remaining tests, the results showed that deposition from suspended sediments, rather than bedload, was the dominant process for most of the concepts. Therefore, the concepts involving full-height walls rather than skimmer walls or vanes were more effective at reducing sediment deposition within the forebay. The two best performing wall concepts were referred to as option 2B and option 10. Option 2B was an angled wall originating from the right bank at the upstream end of the forebay that directed river flows outward and away from the forebay. Option 10 was an expanded version of option 2B and included the option 2B wall and an additional wall across the forebay face that created a narrow entrance into the forebay (Figure 10). Due to the orientation and extent of the full-height walls, option 10 created a settling region outside of the forebay and downstream of the angled wall in which a significant amount of the sediment particles in the water column deposited. This caused a significant reduction in suspended load entering the forebay and resulted in very little deposition of the total material fed into the model inside the forebay.

Figure 10. Option 10 test results
**Final Testing**

Because option 10 would be expensive to implement in the field, the Owner's preferred approach is to install the option 2B wall first and add the additional wall across the forebay to create option 10 at a later date if the option 2B wall alone performs unsatisfactorily. Due to this phased approach, several additional tests were conducted to further explore the performance of the option 2B wall independently. Tests included sensitivity tests on the wall angle, the influence of barges moored across the forebay entrance (as frequently occurs), and operation with unit 1 offline.

The final tests showed that the original wall angle of 25 degrees was optimal. Changing it plus or minus 5 degrees from the original orientation slightly increased the volume of sediment deposited in the forebay, but only by a few percentage points.

Tests to determine the influence of six fully loaded barges (two long and three wide) moored across the forebay entrance showed that the barges increased the amount of sediment deposited in the forebay. Most of the additional sediment was determined to be due to mobilization of the erodible bed beneath the barges, which created locally higher velocities beneath the barges due to the reduced water column from the barge draft. However, even with the barges, the sediment reduction was still better than most other options tested.

Tests with unit 1 offline showed a tendency for more sediment to deposit in front of unit 1 and less to deposit in front of unit 2, with a slight overall increase in deposition over the entire forebay.

**Conclusions**

The following conclusions were drawn from the study:

- Without mitigation measures, submerged screens in the forebay would encounter significant sedimentation over time, requiring periodic dredging around the screens.
- Sedimentation in the forebay and around the screens can be significantly reduced with implementation of mitigation measures.
- Full-height walls that cause significant changes to the forebay and near-shore river hydraulics are most effective at reducing sedimentation in the forebay.
- Altering the angle of the option 2B wall by five degrees or less does not significantly alter the forebay deposition patterns.
- Mooring barges in front of the forebay with the option 2B wall in place does not significantly alter the forebay deposition patterns.
- Taking unit 1 offline with the option 2B wall in place results in more deposition in front of unit 1 but less deposition in front of unit 2.
- Sediment mitigation option 10 performed most favorably from a flow and sediment perspective. The Owners' plan to implement option 10 incrementally by first installing the option 2B wall and then later installing the wall across the forebay to create option 10 is a reasonable approach. If satisfactory performance is achieved with option 2B, then further improvements provided by the secondary option 10 wall may not be necessary.
References


