How U.S. Locks and Dam Power Developers are Meeting Army Corps Navigation and Sediment Transport Requirements

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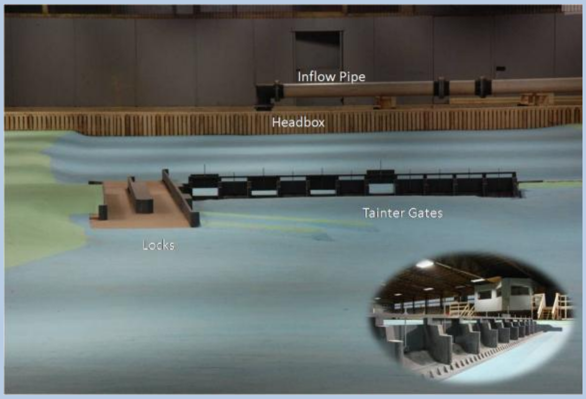
Introduction

Many of the large rivers in the United States were not originally navigable throughout the year because of shallow water conditions during low flow seasons. While the U.S. Army Corps of Engineers' (USACOE) first civil works project involved clearing snags and debris on the Ohio River in 1824, it was later in the nineteenth century that they built their first dam and accompanying locks for large vessel transport at Davis Island in 1885. This was followed in the 1930's by extensive locks and dam development on the Ohio, the Mississippi, and other large rivers[i]. In the 1950's the USACOE began the Ohio River modernization program which started replacing the outdated wicket gate dams with larger lock chambers and dams[ii]. While the available head at these facilities was generally too low to make hydropower development economically feasible at the time, the USACOE incorporated features in the dams to accommodate such development.

The oil shortage of the 1970's resulted in federal and state legislation to encourage development of alternative energy sources. Many communities, utilities and developers began looking at the existing dams as opportunities to develop hydropower at a reasonable cost. Several projects were licensed and constructed in this period. Licenses for many of the unconstructed sites have been maintained as the energy situation has changed. More recently, with renewable energy tax credits being made available for powerhouse installation at existing dams, developers and towns have been actively vying for the Federal Energy Regulatory Commission (FERC) licenses at these sites and moving forward with design and construction. The USACOE builds and maintains navigable waterways and it is their responsibility for the safe, reliable, and economically efficient transport of vessels. Satisfying their operational concerns is a key design requirement. The USACOE's interest has many elements including maintaining river navigation, maintaining the stability of the structures, and complying with environmental and regulatory requirements that dictate certain operations. Maintaining navigability requires: ensuring that boat navigation in the river and the locks is not negatively impacted by powerhouse operations and avoiding the need for additional dredging due to changes in sediment deposition patterns.

This white paper describes how physical and computational modeling are being used to satisfy USACOE requirements associated with navigation and sediment transport at locks and dam powerhouse projects throughout the United States.



Smithland Locks and Dam physical model looking upstream

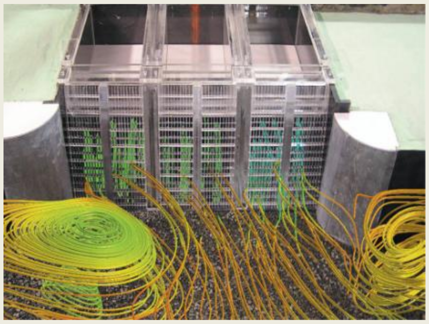
Navigational Concerns and Requirements

A tremendous amount of industrial materials are transported on the large rivers of the world. As an example, about one sixth of the United States intercity freight is carried on inland waterways[iii]. The Mississippi River alone, not including tributaries such as the Ohio and Missouri Rivers, has 335 industrial facilities and terminals[iv]. Even minor collisions costing hundreds of thousands of dollars to repair can close traffic for a week, causing much more costly supply problems. In addition, many of the barges traveling these corridors contain fuels and other industrial materials that are toxic or hazardous to the environment. The navigable channels, locks, and dam operations on these rivers have been developed and are maintained by the USACOE to facilitate the passage of commercial navigation. The channels and lock approaches and exits have been designed to provide safe and efficient operation.

Optimizing the Intake Channel

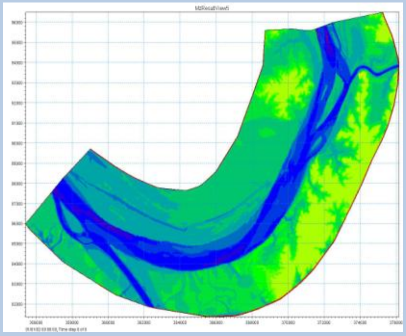
One major operational concern when developing power at an existing locks and dam structure is making sure that power from the turbines is maximized so that profitable operation is achieved. Turbine manufacturers generally require that the velocity profile at the powerhouse intake meet strict uniformity requirements in order to ensure turbine performance guarantees. The design of the intake channel usually involves the coupled use of a three-dimensional numeric model and a detailed physical model.

While the USACOE generally is not concerned with powerhouse performance, it often makes sense to perform the navigation model and the intake channel physical model in parallel. The navigation model provides information on river currents at the boundaries of the intake sectional model that can be used to provide accurate intake modeling. Unfortunately, the studies cannot be performed in the same space, because the scale requirements are quite different. In order to model free surface vortices accurately, the intake channel model must have a significantly larger scale, typically including only partial river width, but including significant detail of the intake channel and intake structure.



Combined CFD and physical modeling of an intake channel

Construction and operation of a hydroelectric project generally changes the currents in the vicinity of the nearby locks and has the potential to affect the navigation traffic. Additionally, modification of the currents can affect the erosion and settling of bed materials which may deposit in navigable channels and reduce the available draft. Other potential sedimentation impacts include the erosion of stream banks as well as erosion or deposition of bars and islands. Because of these concerns, The USACOE generally requires scaled physical hydraulic model studies for the purpose of developing acceptable approach and tailrace flow conditions that will have minimal impact on sediment and navigation. Computational Fluid Dynamics (CFD) is also being adopted for the study of sedimentation. The physical model scale is typically on the order of 1:100 to 1:150, depending on specific flow conditions and river depths. The model is first constructed without any proposed powerhouse or modifications, then is validated and calibrated with field velocity data. A team consisting of engineers, towboat pilots and lock personnel from the USACOE having experience with the locks in question use a scaled remote controlled towboat and barge and qualitatively compare the characteristics of navigating into and out of the model locks with the actual site. The powerhouse, tailrace, intake and related grading are then incorporated in the model. Velocity changes are quantitatively observed and mapped for comparison to the existing site conditions. At this stage, the approach or tailrace grading as well as dam operation may be modified from the initial design in order to provide acceptable flow patterns to navigation. Once an optimum is believed to be achieved, the USACOE's team will again use the remote control towboat and barge to make qualitative comparisons of ease of navigation.



Transient numerical sediment transport model showing unsteady elevations downstream of Smithland Locks and Dam

Dredging Concerns

Related to navigation is the issue of possible increased dredging requirements due to the presence of the tailrace and powerhouse. The addition of a powerhouse changes the flow distribution at the dam and inevitably has at least some impact on sediment transport and deposition. The USACOE requires modeling be performed in order to show that dredging frequency will not need to be increased in order to maintain sufficient depth for barge traffic. Modifications to project geometry and operations may be required to achieve this goal. The USACOE also has the option of modifying operations of the dam spillway gates for the same purpose.

Two types of sediment modeling are generally utilized: qualitative physical modeling in conjunction with the navigation model, and detailed quantitative numeric modeling. A third option, detailed physical modeling using a moveable bed may be required if the other types of studies are inconclusive. In the first case, a small amount of simulated sediment (appropriately scaled) is laid out on the bottom of the physical fixed bed navigation model in a simple pattern in key areas and regions where scour potential is expected to change. As the model runs at varying flows, the sediment motion is observed. These observations are made in the model of existing conditions and compared to similar observations in the "with project" model. In the second case, a very detailed two dimensional numeric model is validated against existing velocity and sedimentation data. The powerhouse and tailrace are then added to the model, and the results are compared to the validation case. Interpretation of the impacts is generally provided by an expert from the USACOE Engineering Research and Development Center (ERDC).

The following case study provides an example of how these concerns were addressed for a recent project.

Case Study: Smithland Locks and Dam

Lockages at the Smithland facility on the Ohio River, about sixty miles upstream of the Ohio and Mississippi River confluence, average twenty-one per day and the hydro plant proposed by American Municipal Power (AMP) had the potential to impact that traffic. During normal river conditions the hydro plant will divert the first 55,000 cfs, flow normally passing over the spillway. The plant discharges the flow through a 2000 ft long tailrace oriented at approximately 45 degrees to the river channel and directed toward the lower approach to the navigation locks on the opposite bank.

"Stop action" digital photography showing barge movement into the lower lock approach

A comprehensive Froude scale model of the river reach potentially affected by the project was constructed (see figure on Page 1). As discussed above, acceptable scales range from 1:100 to 1:150. A scale of 1:120 was used in this case. The model extents included 2 miles upstream of the dam and almost 2.5 miles downstream. The downstream reach included the confluence of the Cumberland River, several large islands, and a bend, all of which added complexity. The model was constructed to simulate the baseline (existing) operation as well as future conditions including the project as proposed. The fixed bed physical model was calibrated/validated to recorded river velocity distributions obtained with an Acoustic Doppler Current Profiler (ADCP) as well as to historic water surface profiles by modifying channel roughness. The Smithland locks and dam has resulted in significant sediment deposition and the formation of an "Unnamed" island downstream of the fixed weir. The tailrace will pass through the island. Therefore, a comprehensive numeric model of the river reach downstream was used to evaluate project impacts on river bed movement. Results of the numeric model were also used to determine the flow distribution around the major downstream island.

The physical model was developed to evaluate potential project impacts over the entire range of project operations, river flow rates from approximately 18,000 cfs up to approximately 600,000 cfs. Seven flow conditions, ranging from a single unit operating to the maximum navigable river flow were selected for testing in the physical model. These conditions were simulated for two possible conditions of the tributary Cumberland River as the flow from this river affects the tailwater levels at the locks and dam. Flow in the Cumberland River is controlled at a USACOE dam which also generates hydropower.

The USACOE visited the physical model at the completion of the validation process to evaluate navigation under the existing conditions. The team included the lockmaster, the lead hydraulic engineer from the Louisville District and navigation/sedimentation experts from the ERDC. They evaluated the scaled towboat and barge movement into and out of the upper and lower lock approaches and recorded the simulations with "stop action" digital photography (see figure below). The lockmaster consulted with the ERDC towboat operator regarding the appropriate navigation line and expected behavior. The towboat operator developed a "feel" for the vessel's interaction with the river. The ship tracks were then compiled to provide a visual record of the effects of river currents on the vessels and the operator made extensive notes to document his findings for comparison to later "with project" tests. Detailed records of river velocities and currents were prepared by tracking the paths of drogues with digital imaging equipment and custom software.

The model was then modified to include the project facilities (powerhouse, tailrace, and approach channels) and a program was undertaken to develop the optimum tailrace geometry. Emphasis is placed on the tailrace geometry because of the higher downstream velocities resulting from the shallower depth. The project design engineer worked with Alden to develop a geometry that considers impacts on energy generation (head loss), construction cost, and acceptable navigation conditions. As the USACOE is not present at these development tests, the impacts on navigation were estimated based on certain key flow conditions.

The development of the tailrace geometry at the Smithland Project resulted in a significant improvement in project economics. The tailrace must be cut through a large island that developed through sediment deposited downstream of the dam over the last 20 years. The physical model was used to develop a tailrace that minimized its length without impacting navigation. The USACOE revisited the model after the tailrace design had been developed and retested using the same flow conditions, but with the power plant operating. The tailrace design was modified slightly to improve navigation impacts and project constructability. The physical model modifications were possible because they could be made quickly with available materials and the towboat operator was able to assess their impact based on his experience.

Other USACOE concerns were also evaluated in the physical model. Studies of "tracer" materials representing sediment were used to simulate patterns of bed sediment movement under baseline and "with project" conditions. Waves resulting from powerhouse load rejections were also simulated to determine the impacts on the barge flotilla in critical lock areas. The model was also used to evaluate alternatives to mitigate potential impacts to an endangered mussel species that inhabits an area near the project tailrace.

A 2D numerical mod study was also completed for the site to quantify the effect of sedimentation on the navigation channels. A two dimensional sediment transport model was developed including approximately 19 miles of the Ohio River from the lock and dam to Paducah, Kentucky. Model simulations were conducted for the baseline geometry to determine the location where sediment deposition currently occurs. The powerhouse geometry and flow characteristics were added to the model and the same flow rates were simulated. An evaluation of the change in sedimentation patterns was completed. In addition to the steady state simulations, two continuous hydrographs of 100 to 130 days were run. The hydrograph simulations were used to quantify how the sediment deposited in the tailrace during periods of high flow is eroded during periods of low flow. Alternative tailrace geometries, guide vanes and groins were considered to modify currents and deposition patterns. The dam gate operation was proposed to be modified based on the steady state simulations and the hydrograph simulations to find an acceptable operating procedure that did not increase sedimentation in the navigation channel.

Timothy Sassaman is a project manager at Alden Research Laboratory where he is responsible for large scale topographic models involving open channel flow related to navigation and pump discharge capacity. Current hydraulic modeling efforts include lock and dam navigation studies as well as pump and turbine intake studies where the formation of vortices and approach flow configurations could affect performance.

Summary

This white paper has provided an overview of how modeling is used to address U.S. Army Corps of Engineers requirements when developing hydropower at existing locks and dam facilities. The organization must be satisfied that operation of a newly constructed hydropower facility will not negatively impact the commercial river traffic on the large rivers of the U.S. Physical and numeric modeling has been successful in addressing such concerns, in addition to providing valuable operational and environmental data.

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[i] http://www.lrp.usace.army.mil/nav/ohioback.htm
[ii] http://en.wikipedia.org/wiki/List_of_locks_and_dams_of_the_Ohio_River
[iii] http://en.wikipedia.org/wiki/United_States_Army_Corps_of_Engineers
[iv] http://www.industrialinfo.com