Innovative Lock Design: The In-Chamber Longitudinal Culvert System

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ABSTRACT

Many navigation projects on the Upper Mississippi River and Ohio River systems are proposing lock additions, enlargements and/or repairs to meet the predicted increases in tow traffic. Innovative designs are being considered for project components to save construction, operation, and maintenance costs. A large savings in lock-wall construction costs can be realized if the lock filling and emptying culverts are placed inside the lock chamber rather than within the lock wall, as in traditional practice. Culverts placed inside the chamber can also accommodate the innovative lift-in and float-in construction techniques under consideration. This filling and emptying system, with the culverts in the lock chamber, was designated the In-Chamber Longitudinal Culvert System (ILCS). This paper describes the applicability of the ILCS concept to both 1270-ft (387-m) and 870-ft (265-m) long lock chambers, which has been demonstrated by site-specific model studies conducted by the U.S. Army Engineer Waterways Experiment Station. Synthesis of these experimental results has led to general guidance suitable to design of this innovative lock system, providing a safe and efficient hydraulic configuration that is less costly than conventional systems.

INTRODUCTION

As the nation's steward of the inland waterway system, the U.S. Army Corps of Engineers (USACE) takes pride in the planning, engineering, construction, and operation of the navigation projects in the system. Like any transportation system, portions may deteriorate with time or become outdated in the face of advancing technologies. Locks and dam facilities are no exceptions. As a project becomes less reliable due to age, or a congestion point due to inadequate capacity, the overall efficiency of the system diminishes. Therefore, the Corps of Engineers' job is twofold: to operate existing projects at their highest level of efficiency, and to plan for tomorrow's needs, thereby maximizing benefits to the nation from waterway use.

In September 1992, the director of civil works formed a task force to investigate design and construction innovations for locks and dams. The work of the task force formed the basis for *Engineer Pamphlet (EP) 1110-1-14*, titled Report of the USACE Task Force on Design and Construction Innovations for Locks and Dams (DCILD). That report recommended a full study be performed and completed in four phases. Phase 1 determined the feasibility of the approach and provided a plan for completing Phase 2—Guidance and Design Tools, Phase 3—Demonstration, and Phase 4—Research and Development. The status of Phases 2-4—was reported in *EP 1110-1-20*, titled Future Directions for Design and Construction Innovations in Navigation Structures. Prior to these innovative efforts, navigation projects were conceived, designed, and built using the philosophy that the structures have to rely on traditional methods and approaches in order to be rugged and reliable. This has proven to be a very successful philosophy that needs to be kept in mind since the existing USACE navigation projects have served the nation well.

It is generally accepted that a large Civil Works project will have a design life of 50 years; however, this is really the economic design life. Infrastructure, as a rule, has a useful service life, much longer than the economic design life. Many existing projects are well past their economic design life, but still provide benefits to the nation. As progress is made in the DCILD, it is realistic to expect the same kind of performance from our new projects. This should be the baseline for comparison of alternatives. If USACE proposes a project that cannot be expected to perform to this level, the customers will be made aware of this. It may be completely acceptable to construct a project with a 25- or 30-year life. However, this has to enter into life-cycle costs of the project, and there has to be a buy-in to this concept by all interested parties (USACE, the waterway users, and the public). This new philosophy says it is acceptable to explore concepts that have not been applied traditionally in this field. Engineers are empowered to seek out innovative methods to solve problems of building and maintaining navigation projects with limited resources. The challenge is to maintain the excellent record the Corps of Engineers has for designing and building quality projects while changing the way it is done.

To ensure that all technologies applicable to modernization of the inland waterways navigation systems are effectively evaluated in the interest of achieving modernization at the lowest practical cost, the Regional Navigation Design Team (RNDT) was formed. The RNDT was composed of representatives from the Ohio River Division (currently within the Lakes and Rivers Division), North Central Division (which is currently within the Lakes and Rivers Division and the Mississippi Valley Division), and the Lower Mississippi Valley Division (presently within the Mississippi Valley Division). The specific goals of the RNDT are to

- Share information on innovative design experience, and meet periodically at districts to be briefed on their projects;
- Communicate with industry regarding how and why changes are being made in the way navigation structures are being designed;
- Evaluate design quality assurance/quality control (QA/QC) procedures; and
- Challenge design criteria, and support engineers in promoting good design ideas that require changes and exemptions to civil works policies and criteria.

The RNDT recognized research and development (R&D) as a critical component of advancing the concepts of design and construction innovations. R&D priorities were identified in *EP 1110-1-20*. The highest-priority areas were float-in-structures, in-the-wet/underwater construction, high-performance materials, and physical and analytical models. The following discussions relate to R&D directed toward the modeling efforts identified in the priority areas.

INNOVATIVE LOCK DESIGN BACKGROUND

A physical modeling effort was initiated in 1994 by several Corps districts to investigate the feasibility of innovative designs for lock intakes and lock filling and emptying systems. The physical model experiments were necessary to determine the hydraulic performance of the proposed designs and to make modifications, if needed or applicable, to achieve an acceptable design. The initial modeling program involved four different sites where new locks are proposed for construction. These four sites are McAlpine Lock and Dam (L&D), Louisville District; Marmet L&D, Huntington District; Monongahela River No. 4 L&D, Pittsburgh District; and a representative lock from the Upper Mississippi lock replacement Study, St. Louis District.

The new McAlpine Lock model study was the first to investigate the use of an ILCS. The navigation improvements planned for the McAlpine project provided a desirable site to investigate the ILCS. The filling and emptying system originally proposed also included a through-the-sill intake and discharge outlet with the ILCS. The lock study's principal objective was to develop an innovative hydraulic filling and emptying system design for the navigation lock that was efficient yet less costly than standard systems, while ensuring safe conditions during lock operations. Specifically, the study was to determine the

- Filling and emptying times for various valve speeds at the design lift of 37 ft;
- Flow conditions and motion characteristics of unmoored barges in the lock chamber during filling and emptying operations;
- Hawser forces exerted on barges moored in the lock chamber; and
- Pressures in the culverts.

A laboratory model was used to evaluate the ILCS.

NEW McALPINE LOCK MODEL

The 1:25-scale model reproduced 275 ft of the upstream approach; the entire filling and emptying system, including portions of the upper guide and guard walls, intakes, valves, culverts, lock chamber, outlets, and lower guide and guard walls; and about 550 ft of the downstream approach. The approach areas and the lock chamber were constructed of plywood and the intakes, culverts, and discharge outlets were constructed of plastic. The eight rotating disk valves were constructed of sheet metal. Six sheet-metal barges, each simulating a length of 195 ft and a width of 35 ft, were loaded with weights to achieve the desired 9-ft draft. A hawser-pull (force-links) device that measured the longitudinal and transverse forces acting on a tow in the lock chamber during filling and emptying operations was used to help evaluate lock chamber performance for varying valve operations. Three such devices were used: One measured longitudinal forces, and the other two measured transverse forces on the downstream and upstream ends of the tow, respectively. These links were machined from aluminum and had SR-4 strain gages cemented to the inner and outer edges. When the device was mounted on the tow, one end of the link was pin-connected to the tow, while the other end was engaged to a fixed vertical rod. While connected to the tow, the link was free to move up and down with changes in the water-surface elevation in the lock. Any horizontal motion of the tow caused the links to deform and vary the signal, which was recorded with a personal computer using an analog-to-digital converter. The links were calibrated by inducing deflection with known weights. All data obtained from the pressure cells used to measure instantaneous pressures, and data obtained from the strain gages used to measure hawser forces, were recorded digitally with a personal computer.

Pressures throughout the systems were measured with piezometers (open-air manometers). Pressures obtained in this manner are considered average pressures because of the reduction in frequency response resulting from the use of nylon tubing.

Experimental Procedures

Evaluation of the various elements of the lock system was based on data obtained during typical filling and emptying operations. Performance was based primarily on hawser forces on tows in lockage, movement of unmoored (free) tows in the lock chamber, roughness of the water surface, pressures, and time required for filling and emptying. Quantification of energy-loss coefficients was made using fixed-head (steady-flow) conditions with the culvert valve and/or miter gates fully opened or closed.

Experimental Results

The primary elements of the new McAlpine system consist of four 12-ft-by-12-ft intakes at the upper miter sill face, transitioning to two 16-ft-by-18-ft culverts located on the lock floor between the lock walls; rotating disk valves of the same size as the intakes; about 32 pairs (actual number varied with design) of 3.5-ft-by-1.25-ft ports located in each culvert and four 12-ft by 12-ft outlets positioned at the downstream face of the lower miter sill where the flow is controlled by rotating disk valves.

Type 1 Design

Numerous designs having various port arrangements were evaluated beginning with the Type 1 design, which had 33 pairs of ports (a sum of port-area-to-culvert-area ratio of 1.0) centered about the midlength of the lock (Figure 1). The ports in opposite culverts were staggered; therefore, the jet impact distance was the distance between the culverts. Port spacing was selected such that jet interaction between opposite manifolds would not produce bulking of the water surface. The appropriate port spacing was computed based on the idealized description of a submerged two-dimensional momentum jet, following the method proposed by Albertson et al. (1950), and later extended by Fisher et al. (1979). The jet boundary was taken as that distance from the jet centerline where the jet velocity was negligible (0.01 fps). This boundary set the jet's effective width. The port spacing of 12 ft was set equal to the jet's effective width at the largest impact distance. This impact distance, mentioned previously, was the distance between the manifold culverts (29.42 ft, Figure 1).

Observation of an unmoored 18-barge tow in the lock chamber during filling indicated rapid movement of the tows toward the upstream miter gate and contact with the miter gate, occurred early in the filling cycle. These observations were made with a 2-min filling valve operation and a 37-ft lift. These experiments are commonly referred to as free-tow-drift patterns and provide a good indicator of lock chamber performance. Minimal free tow drift would mean flow entering the lock chamber during filling is welldistributed, and no large water-surface gradients exist. Since movement of the tows was not acceptable with the Type 1 design for the 2-min valve operation and the 37-ft lift, modifications were made to the lock chamber to try to improve performance.

Type 11 Design

Numerous modifications were made. The location of the ports was changed, and several types of baffling devices were evaluated. The Type 11 design provided close to the desired performance. This design consisted of 16 pairs of ports in each culvert, in both halves of the lock chamber. The upstream and downstream ports were centered in the vicinity of the lock quarter points. Wall baffles were placed on the lock walls adjacent to the ported sections of the manifolds, and port extensions were installed on the upstream ports only.

Type 17 (Recommended) Design

The lock chamber floor was raised outside the manifold sections, as requested by the Louisville District, to reduce excavation costs. This configuration was designated the Type 17 design and is shown in Figure 2. The Type 17 design filling and emptying system produced maximum longitudinal hawser forces during filling, ranging from 13.8 tons using a 2-min valve time, to 2.5 tons using an 8-min valve time. A 5-min filling valve resulted in maximum hawser forces of 4.5 tons, and a lock filling time of about 10.7 min. These maximum hawser forces were acceptable and were very similar to those produced by the Type 11 design, in which the entire lock chamber floor was at the same elevation.

Flow conditions in the lock chamber during filling with the Type 17 design were acceptable, and an unmoored tow rises almost vertically. Unmoored tows during lock filling and emptying should not occur in locks, but this performance provides a good indication of how uniform the flow distribution is in the lock chamber during a fill operation. A series of experiments were performed to determine the performance of the Type 17 McAlpine ILCS with a much higher head than is anticipated at the project. Hawser measurements were obtained with a 47-ft lift for filling valve operations of 4 and 10 min. The maximum longitudinal hawser forces measured with the 4-min valve were 25.5 tons in the upstream direction and 7.3 tons in the downstream direction. The maximum upstream longitudinal hawser forces were measured approximately 4.5 min after the valve began opening, or slightly after the valve was completely open. These results indicate that a higher water surface occurs in the downstream end of the lock just after the valve is completely open and contributes to the large upstream hawser forces. The maximum downstream hawser forces occur approximately 1 min into the filling cycle.

The longitudinal hawser forces measured with the Type 17 design, the 47-ft lift, and the 10-min filling valve operation revealed that the maximum upstream hawser forces were 6.7 tons, and maximum downstream hawsers were 2.7 tons. Both the maximum upstream and downstream hawsers occurred around the time the filling valves were completely open.

The results with the higher lift indicated the Type 17 design would need to be modified to achieve the same filling and emptying performance as determined with the 37-ft lift. The filling and emptying characteristics of ILCS are similar to the side port filling and emptying system. Corps design guidance (*EM 1110-2-1604*) suggests the side port filling and emptying system is best suited for lifts below 30 ft, and these results suggest this may also be the case for the ILCS.

This laboratory investigation of the new McAlpine Lock demonstrated that construction of the filling and emptying culverts on the lock floor between the lock walls is a viable design. These findings were based on one design, and should be applied with caution to other sites having different chamber or culvert sizes. The following general conclusions drawn from this study can serve as a basis on design guidance for the ILCS:

- The port-to-culvert area ratio should be about 0.97
- The port spacing in each manifold should be staggered
- Two groups of ports should be centered about the one third points of the lock length
- Port extensions on the upstream group of ports decreased the flow rate issuing from this group (especially early in the filling cycle), thereby making the distribution of flow along the length of the chamber more uniform.
- Port extensions also train the jets issuing from these ports in a direction normal to the longitudinal culvert.
- Wall baffles are beneficial because they diffuse the port jets at the lock chamber floor.

MARMET ILCS MODEL

A second ILCS model investigation was performed for a new lock proposed for construction at the Marmet navigation project in the Huntington District of the Corps of Engineers. Improvements to the project to enhance navigation include construction of an additional lock (870 ft from pintle to pintle, and 110.08 ft wide) that will be located on the east side of the existing locks. The design lift is 24.0 ft elevation which occurs with the normal upper pool elevation of 590 and a normal lower pool el of 566. The new lock design features a through-the-sill intake, a longitudinal in-chamber filling and emptying system, and a conventional sidewall discharge manifold similar to the design used on the Red River Lock 1.

The purpose of the model study was to evaluate and make modifications to the filling and emptying system, if necessary, to provide a design acceptable to the Huntington District and the towing industry. As discussed previously, an ILCS filling and emptying design with features similar to Marmet Lock was modeled for the McAlpine Lock project. Since the length of the Marmet Lock was smaller than the McAlpine design, model experiments were necessary to check the adequacy of this design with a shorter length, and to determine the operational characteristics.

A laboratory model was also used for this investigation. The 1:25-scale model reproduced 600 ft of the upstream approach, including a portion of the right guide wall and the left guard wall. The intakes; miter gates; the entire filling and emptying system, including culverts and valves; discharge outlet manifold; and approximately 300 ft of the topography downstream from the outlet were also reproduced.

The filling and emptying system begins with a multi-ported intake located in the upstream face of the miter gate sill. Each port is 9.84 ft wide by 14.76 ft high at the face of the intake. Each half of the intake transitions to 13.12-ft-wide-by-14.76-ft-high culverts located outside the lock walls where the filling valves and bulkheads are located. Downstream from the filling valve, the culverts curve back into the lock chamber and continue to the filling and emptying manifold. The filling and emptying manifold consists of the two 13.12-ft-wide-by-14.76-ft-high culverts with 11 pairs of ports located in both the upstream and downstream portions of the lock chamber. The upstream ports contain additional port extensions to direct the filling jets normal to the culverts. Downstream from the filling and emptying manifold, the culverts turn back outside the lock walls to accommodate the emptying valves and bulkheads. The discharge outlet is a multi-ported type with the face of the outlet located along the lock wall in the lower approach.

Type 1 Design, Free-Tow Experiments

Free-tow longitudinal drift patterns were observed during filling and emptying for 3-, 4-, and 8-min valve operations. The patterns indicated there were no rapid accelerations. Results of the free-tow drift patterns indicated the performance of the original design filling and emptying was good enough to proceed with the hawser measurements without modifying the system.

Hawser Force Measurements, Filling Operations

The longitudinal hawsers measured with a 2-min valve operation indicate that immediately after the valve begins to open, the barges inside the lock experience an upstream hawser force for a few seconds, and then begin to experience a downstream hawser force, which generally was the maximum hawser force experienced during the filling operation. Between 1 and 2 min into the filling cycle, the longitudinal hawser force changes from downstream to upstream and the maximum upstream hawser force was experienced around 1.5 min. into the filling operation. The longitudinal hawser force then begins to fluctuate between downstream and upstream direction, and the magnitude is greatly reduced. The average of the maximum longitudinal hawser forces measured with the 2-min valve was 9.9 tons in the downstream direction, and 7.0 tons in the upstream direction. These longitudinal hawser forces were higher than the 5.0-ton limit provided in Corps of Engineer design guidance.

The average of the maximum longitudinal hawser forces measured with the 4-min valve was 6.3 tons in the downstream direction, and 4.5 tons in the upstream direction. The average of the maximum transverse hawser forces measured on the upstream end of the lock valve was 1.8 tons on the right side, and 3.4 tons on the left side. The average of the maximum transverse hawser forces measured on the downstream end of the lock valve was 1.5 tons on the right side, and 3.1 tons on the left side. These hawser forces were considered marginally acceptable since the maximum hawser force measured was very close to the 5.0-ton limit suggested in the Corps design guidance.

Marmet-Model conclusions-model experiments with the Type 1 design (original design) filling and emptying system revealed the performance was acceptable for the 4-min valve operation, which the system was designed for, with the upper pool elevation of 590, and the lower pool elevation of 566 ft. The maximum longitudinal hawser forces with the Type 1 design filling and emptying system were above the desired limit of 5.0 tons for this lift with the 2-min valve operation. Minor modifications to the baffling arrangement and the port extensions inside the lock chamber were made in an attempt to reduce longitudinal hawsers during filling operations with the 2-min valve operation. No significant reductions were observed and since the performance was satisfactory with the 4-min valve, the type 1 design filling and emptying was considered acceptable. No changes were made to the discharge outlet design.

SECOND NEW McALPINE MODEL STUDY

Another laboratory investigation was conducted for the 1,200-ft lock addition planned at the McAlpine navigation project. In the previous model study for the new McAlpine project, the intakes and outlets were located in the upper and lower miter gate sills, respectively. Evaluation by the Louisville District of the valve maintenance requirements (since they would have to be located underwater), and the risk of excessive downtime, made a second model study necessary. The intakes and outlets were changed from the through-the-sill type to more conventional designs, with the valve wells located in concrete monoliths. The culvert manifolds for the filling and emptying system inside the chamber were the same as the Type 17 design of the previous study. The culverts upstream and downstream from the manifolds contained curved sections between the chamber and the valve wells.

The results from this model study indicated that a two-speed valve operation was required to obtain the fastest filling time and still maintain acceptable hawser forces. Also, port extensions were necessary on some of the downstream ports to prevent excessive water-surface turbulence during filling, and the width of the wall baffles was increased by 1 ft. The modifications were designated the Type 11 design and are shown in Figure 3. The two-speed valve operation allowed the lock to fill in 11.3 min and maintain longitudinal hawsers less than 5 tons for the 37-ft lift design condition. These changes were minimal, but they do demonstrate the need for additional research to better understand the ILCS design.

ILCS RESEARCH

Research is currently being performed in the Locks and Conduits Group at the Waterways Experiment Station to investigate and develop the additional design guidance for the ILCS. The objective of this work unit is to provide design information necessary to develop design details for the ILCS for the low- and medium-lift locks.

Laboratory and numerical models are being used to evaluate the hydraulic performance of the ILCS. The research program is a four-year effort that began in fiscal year 1998.

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