ERDC/CRREL TR-03-2

Cold Regions Research and Engineering Laboratory

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Ice and Debris Passage for Innovative Lock Designs

Andrew M. Tuthill

January 2003

Abstract: Physical and numerical models were used to assess ice and debris passage at navigation locks, focusing on key factors such as the configuration of the upper approach, the design of the lock filling and emptying system, and the location and design of culvert intakes and outlets. Unconventional ice passage techniques such as manifolds in the miter gates were also evaluated. Physical model results were compared to field observations and a parallel series of tests using the DynaRICE ice-hydraulic numerical model. Ice processes modeled included upper approach ice accumulation during lock filling, drawing ice into the lock chamber, and flushing ice out of the lock. Initial ice thickness was found to be the most important parameter affecting ice passage. Physical and numerical model results compared reasonably well, proving DynaRICE to be a useful tool for assessing ice passage for new lock designs.

COVER: Tow breaking through frozen brash ice on the Ohio River.

Technical Report
ERDC/CRREL TR-03-2

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January 2003

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by Andrew M. Tuthill, Research Hydraulic Engineer, Ice Engineering Research Group, RS/GIS Water Resources Branch, U.S. Army Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire.

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The author thanks John Hite and Jose Sanchez of ERDC-CHL for their assistance with the plastic ice tests, as well as Hung Tao Shen and Lianwu Liu of Clarkson University, who did the DynaRICE numerical modeling work. Thanks also go to John Gagnon, Carrie Vuyovich, and Thomas Morgan, who assisted with the physical model tests at CRREL.

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CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	By	To obtain
inch	25.4	millimeter
foot	0.3048	meter
$foot^3$	0.02831865	$meter^3$
mile	1609.347	meter
$mile^2$	2,589,998	$meter^2$
$foot^3$/second (cfs)	0.0004719474	$meter^3$/second
foot-pound	1.335818	newton-meter
pound	4.448222	newton
$pound/inch^2$ (psi)	6894.757	pascal
Btu/lb_m	2326.000	joule/kilogram
Btu/lb_m ºF	4186.800	joule/kilogram kelvin
Btu/ft^3 ºF	67,066	$joule/meter^3$ kelvin
Btu/ft^3	37,259	$joule/meter^3$
degrees Fahrenheit	$t_C = (t_F - 32)/1.8$	degrees Celsius

Ice and Debris Passage for Innovative Lock Designs

ANDREW M. TUTHILL

1 INTRODUCTION

Ice interferes with navigation on many of the major inland waterways in the northern United States. Rivers most affected are the upper Mississippi, the Illinois, the upper Ohio and Monongahela, as well as portions of the Great Lakes and connecting channels (Fig. 1).

Figure 1. Major ice-affected inland waterways in the United States.

Figure 2. Tow breaking through frozen brash ice on the Ohio River.

Difficulties arise as vessel traffic continually rebreaks the ice cover on the navigation channel, forming accumulations of ice pieces ranging in size from inches to several feet, known as brash ice (Fig. 2). The upper approaches to many Corps navigation locks naturally collect brash ice and debris as a result of water current, wind, and vessel movement. Downbound tows push this ice into lock chambers, thereby leading to other problems, such as ice interference with miter gates and ice congestion of miter gate recesses. Often there is not enough space in the lock chamber for both the brash ice and the tow, thus requiring separate ice lockages before the tow can lock through.

Some Corps projects have submergible lift gates or emergency bulkheads at the upper ends of their locks that act as overflow weirs to sluice brash ice directly through the chamber. The majority of projects, however, rely on time-consuming ice lockages to clear the upper approach during periods of heavy ice, delaying barge traffic on the river. The design of a project; the layout of the upper approach, guardwall* configuration, culvert intake and outlet location; and the

* Guardwalls are continuous barriers between the lock approach on the river side of a navigation project. They typically extend above and below the lock and are about the same length as the lock chamber. Their primary purposes are to help tows line up on the lock and keep tows away from the dam gates. Similar structures called guidewalls are located on the landward side of lock approaches.

filling and emptying (F/E) system design all affect the capability of a project to pass brash ice and debris. For this reason it is critical to consider ice and debris passage in the planning and design of new locks.

The Innovations for Navigation Projects (INP) Research Program, funded by the U.S. Army Corps of Engineers, has developed cost-saving new lock designs and lock construction methods. This report describes research on ice passage issues associated with the new lock designs. The approach involves physical modeling of locks using plastic ice, as well as the use of ice-hydraulic computer models to simulate ice passage at locks and dams. In addition to assessing the ice passage performance of INP new lock designs, a more general goal was to improve the available tools for modeling ice and debris passage in and around locks and dams.

2 BACKGROUND

Approximately one-third of the 230 navigation projects operated by the Corps of Engineers are affected by ice (Zufelt and Calkins 1985, Tuthill 2002). Many of these structures have reached or exceeded their design life and a number of lock and dam rehabs and planned replacements will incorporate INP designs and methods. A major INP focus was in-the-wet construction methods that avoid the cost of cofferdams. This involves casting large project components off site, towing them into place, sinking them, and filling them with tremie concrete.

In addition to cost-saving construction methods, INP developed designs to simplify lock design, reduce concrete quantities, and ultimately reduce structure cost. One alternative is an in-chamber longitudinal culvert (ICLC) filling and emptying system (Stockstill 1998, Hite 2000) in which the F/E culverts are located beneath the lock floor instead of their conventional location in the lock walls (Fig. 3). As a result, the lock walls are thinner, so less concrete is required. Locating the F/E ports along the culverts simplifies the design compared to conventional F/E designs such as bottom lateral port systems. Locating the lock filling intakes beneath the upper miter gate sill instead of in the sidewalls upstream of the gates further reduces concrete volumes and construction costs.

The INP also examined alternatives for extending 600-ft-long locks to 1200 ft to reduce delays and increase waterway capacity. The lower locks on the Ohio River and the two lowest locks on the Mississippi are 1200 ft by 110 ft to accommodate standard 12-barge tows. However, the locks on the Illinois River, and most lock chambers on the upper Mississippi and upper Ohio Rivers, are 600 ft long by 110 ft wide. To transit these projects, a 12-barge tow must break into two 6-barge cuts, lock through separately, and remake on the other side before continuing. The simplest lock extension alternative considered was adding 600 ft on the downstream end of the existing lock and using the existing F/E system (Fig. 4) (Hite 2001). A number of more costly alternatives under consideration would extend the lock and add supplemental filling and emptying capacity in the form of additional culverts and lateral systems.

Extending a lock chamber from 600 to 1200 ft requires lengthening the river guardwall, which increases the ice and debris accumulation area of the upper approach. In order to align tows and keep them away from dam spillway gates, river guardwalls are usually at least as long as the tows entering the lock. For this reason, plans for extending 600-ft locks to 1200 ft requires doubling the length of the river guardwall and significantly increasing the brash ice and debris-capturing area of the upper lock approach (Fig. 5). It is therefore important to incorporate efficient ice and debris-clearing alternatives in INP lock extension designs.

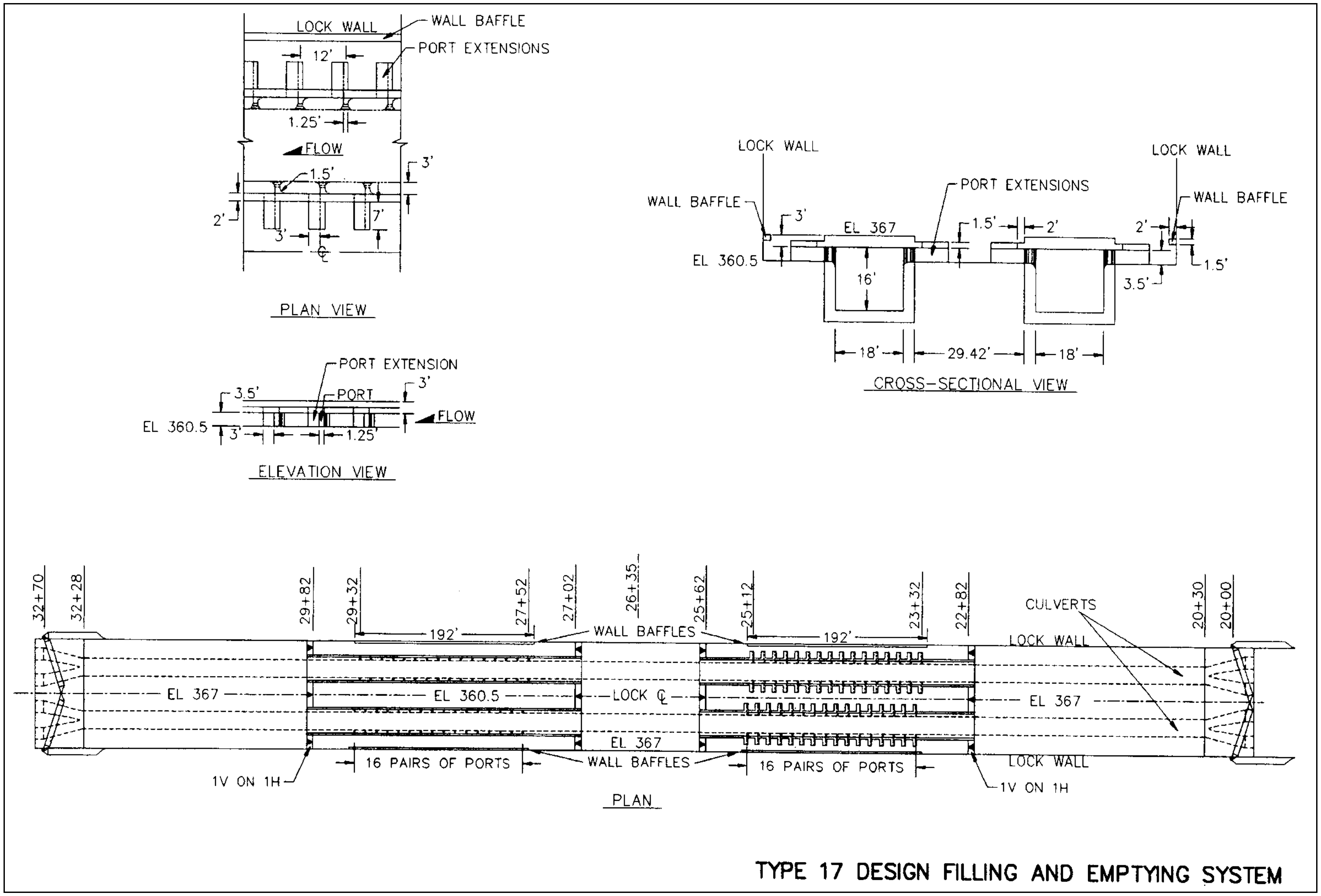


Figure 3. Layout of Coastal and Hydraulics Laboratory (CHL) McAlpine Lock model, an example of an in-chamber-longitudinal-culvert (ICLC) filling and emptying system. (From Stockstill 1998.)

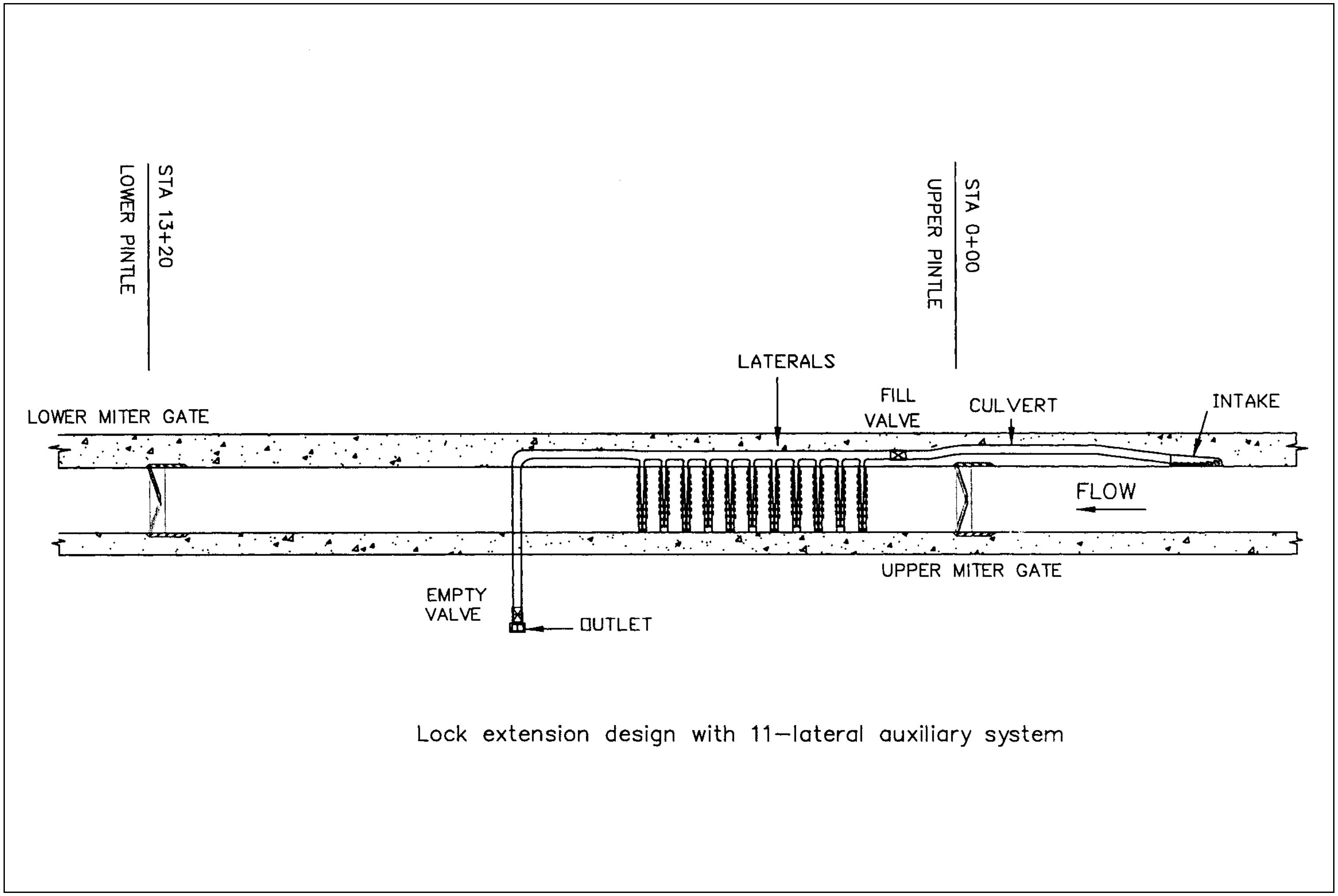


Figure 4. 600-ft × 110-ft lock extended to 1200 ft with no additional filling and emptying capacity. (From Hite 2001.)

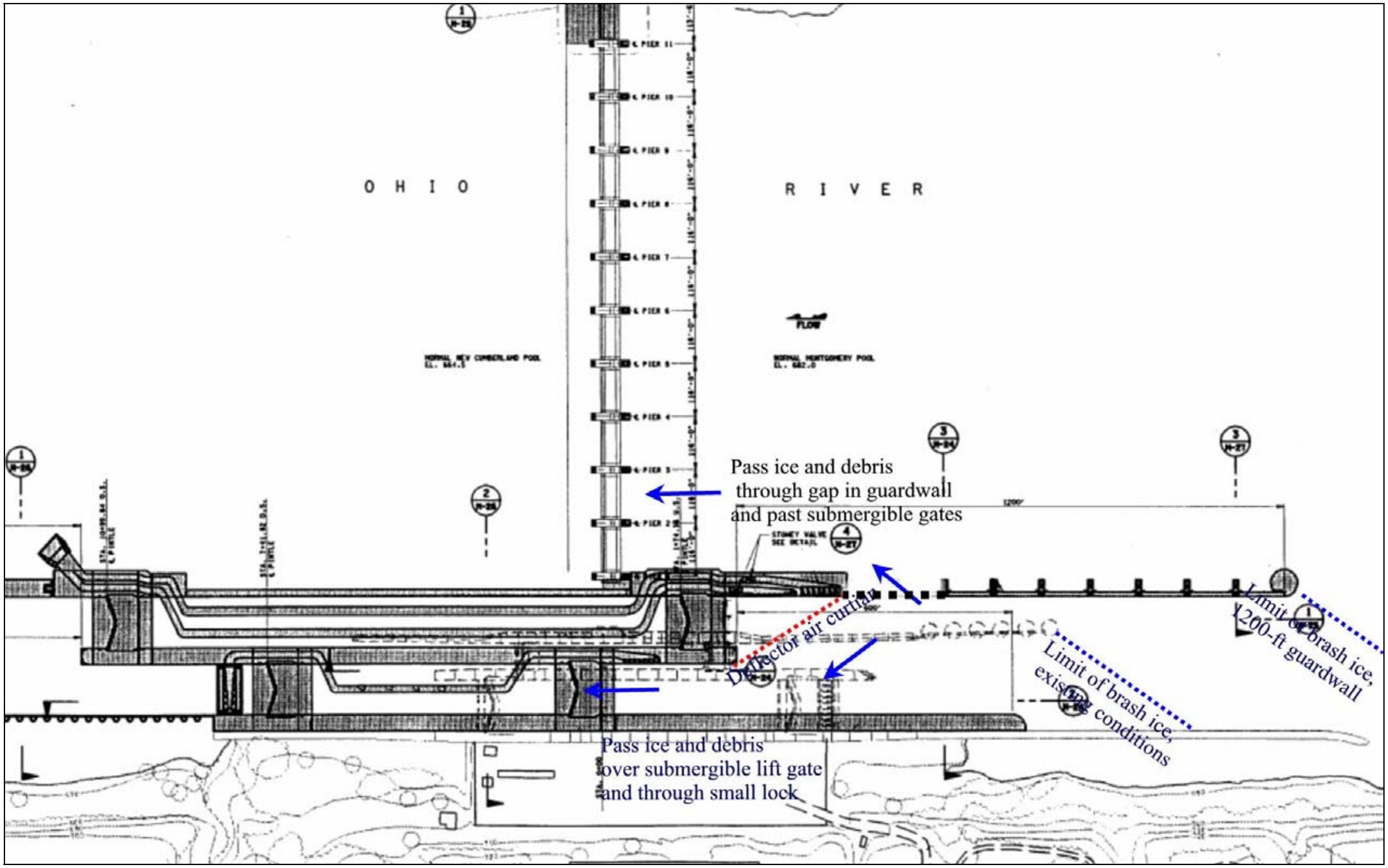


Figure 5. Proposed 600- to 1200-ft lock rehab for the upper Ohio River showing longer river guardwall and larger ice and debris collection area in upper approach.

A number of physical model studies at CRREL have examined ice passage at Corps locks and dams using natural ice. Gooch et al. (1990) and Tuthill and Gooch (1997) describe physical model studies with real ice that investigated the use of submergible tainter gates to pass brash ice at Starved Rock Lock and Dam on the Illinois River. Physical model studies of Lock and Dam 20 on the Mississippi River (Zufelt et al. 1993) and the Soo Locks (Tuthill 2000) examined the use of submergible lock gates of high-flow point source bubblers for passing ice.

Tuthill et al. (1999) reviewed pre-engineering designs of lock replacement projects on the upper Ohio River for the Pittsburgh District, identifying potential ice problems and suggesting solutions (Fig. 5). Liu et al. (2001) used the DynaRICE ice hydraulic numerical model to evaluate these alternatives using the existing Montgomery Lock and Dam as a baseline case. The study simulated ice accumulation in the upper lock approach and ice passage through dam gates. Also investigated in the study were methods for clearing and deflecting ice from the upper approach, such as high-flow bubblers, submergible lock gates, and gaps in the upper guardwall. Qualitatively, DynaRICE results compared well with field-observed ice processes.

3 APPROACH

The current study combined physical modeling of ice passage in locks with the use of ice-hydraulic numerical models. Where possible, physical model results were compared to field observations. The goal was to validate the numerical models with the physical model results and use the numerical models to assess the ice passage performance of selected INP lock designs.

Physical model tests were done in the CRREL 1:36-scale Soo Locks model and the Coastal and Hydraulics Laboratory (CHL) 1:25-scale Kentucky Lock model. A plastic ice material was scaled to field-observed piece size distributions. Three processes were modeled: 1) Ice accumulation in the upper approach near the culvert intakes during lock filling, 2) drawing ice from the upper approach into the lock chamber, and 3) flushing ice from the lock chamber into the lower approach.

Ice passage in and around locks was simulated using the DynaRICE model, developed in collaboration with Clarkson University (Liu et al. 1999, Liu and Shen 2000, Shen et al. 2000, Liu et al. 2001). DynaRICE has two-dimensional, depth-averaged, unsteady hydrodynamics, solved on a fixed finite element mesh. The hydrodynamics are coupled with ice dynamics that lump ice accumulation parameters such as ice concentration thickness and roughness into larger “discrete parcels.” DynaRICE computes depth-averaged two-dimensional water velocity distributions, which in many situations can be used to approximate the near-surface water velocity, particularly if the water-depth-to-channel-width ratio is small. Near lock intakes, where the depth-to-width ratio is high and flow is unsteady and three-dimensional, depth-averaged hydrodynamics proved unsuitable for estimating surface currents. Initial comparisons found the DynaRICE depth-averaged water velocities in the upper approach to be greater in magnitude and duration than the surface velocities observed in the physical model. Empirical methods were therefore used to adjust the calculated depth-averaged velocities to approximate the observed surface velocities. In the ice lockage tests, following an initial ramp-up period, the calculated depth-averaged velocities were similar to the observed surface velocities, so the DynaRICE velocities were used without adjustment.

4 PHYSICAL MODELS

CRREL Soo Locks model

The majority of the tests were done in the CRREL 1:36-scale Soo Locks physical model. Unless noted otherwise, all units for length, time, and velocity are converted to prototype using Froude similitude laws. The modeled area included the 110-ft-wide Poe Lock, which has a split-bottom lateral FE system extending over 65% of the 1200-ft-long chamber, and the parallel 80-ft-wide MacArthur Lock with an interlaced-bottom lateral FE system covering 74% of the lock's 950-ft-long chamber (Fig. 6). Lift is 21 ft, and the depth in the upper approach and in the lock chamber (at low pool) is about 33 ft. For both locks, under existing conditions, the culverts are located in the lock walls and the culvert intakes are in the upper approach walls, just upstream of the upper miter gates.

CHL Kentucky Lock model

The CHL 1:25-scale Kentucky Lock model was selected for plastic ice tests because the model area includes a significant portion of the upper approach. Also, its through-the-sill intake is similar to designs developed under the INP (Fig. 7). The Kentucky Lock has chamber dimensions of 1275 ft by 110 ft with a lift of 50 ft and a multi-port F/E system fed by culverts in the lock walls. The 398 15-inch-diameter ports extend over 57% of the chamber length. This type of F/E system design, unique to Tennessee Valley Authority locks, has longer filling and emptying time than more conventional side port or bottom lateral filling and emptying systems (Sanchez 2001).

Plastic ice

Previous physical model studies with ice showed the importance of accurately reproducing the scaled piece size distributions of the ice observed in the field (Tuthill and Gooch 1998). A representative piece size distribution for brash ice was estimated from observed ice runs on the St. Claire River (Daly and Arcone 1989) and analysis of photos of brash ice in the Poe Lock in March 1999. These data are plotted in Figure 8 and a curve fitted empirically. A crushed polyurethane plastic ice material successfully simulated ice jam processes in a 1:120 jam physical model study of the upper Niagara River sponsored in part by the New York Power Authority (NYPA) (New York Power Authority 1998). The size distribution of this "NYPA" ice matches reasonably well with the less than or equal to 50 percent and finer portion of the field-observed ice piece size. The larger size fractions were sawn 1/4-inch-thick polyethylene squares (Table 1). The specific gravity of the plastics was 0.92, similar to 0.916 for freshwater ice.

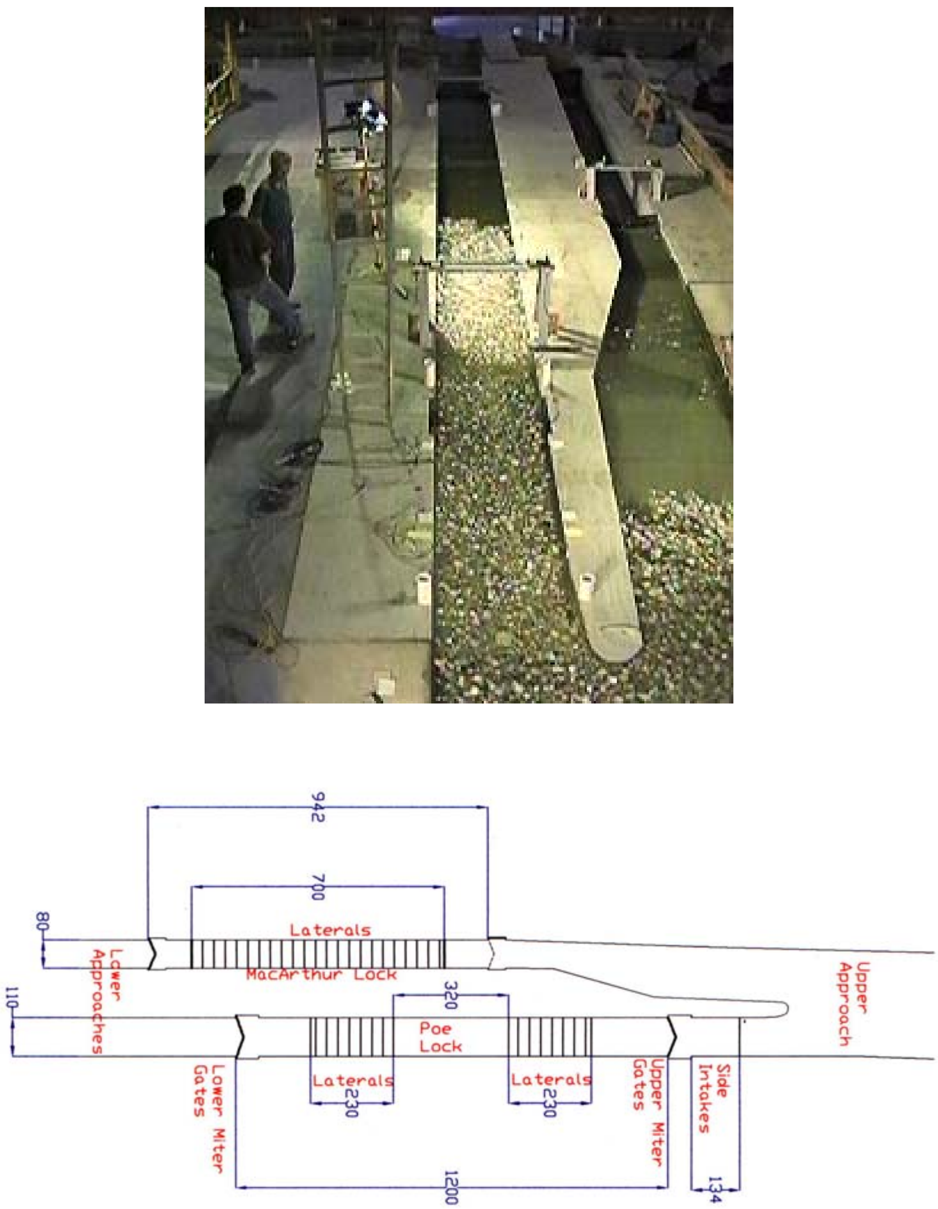


Figure 6. CRREL Soo Locks physical model.

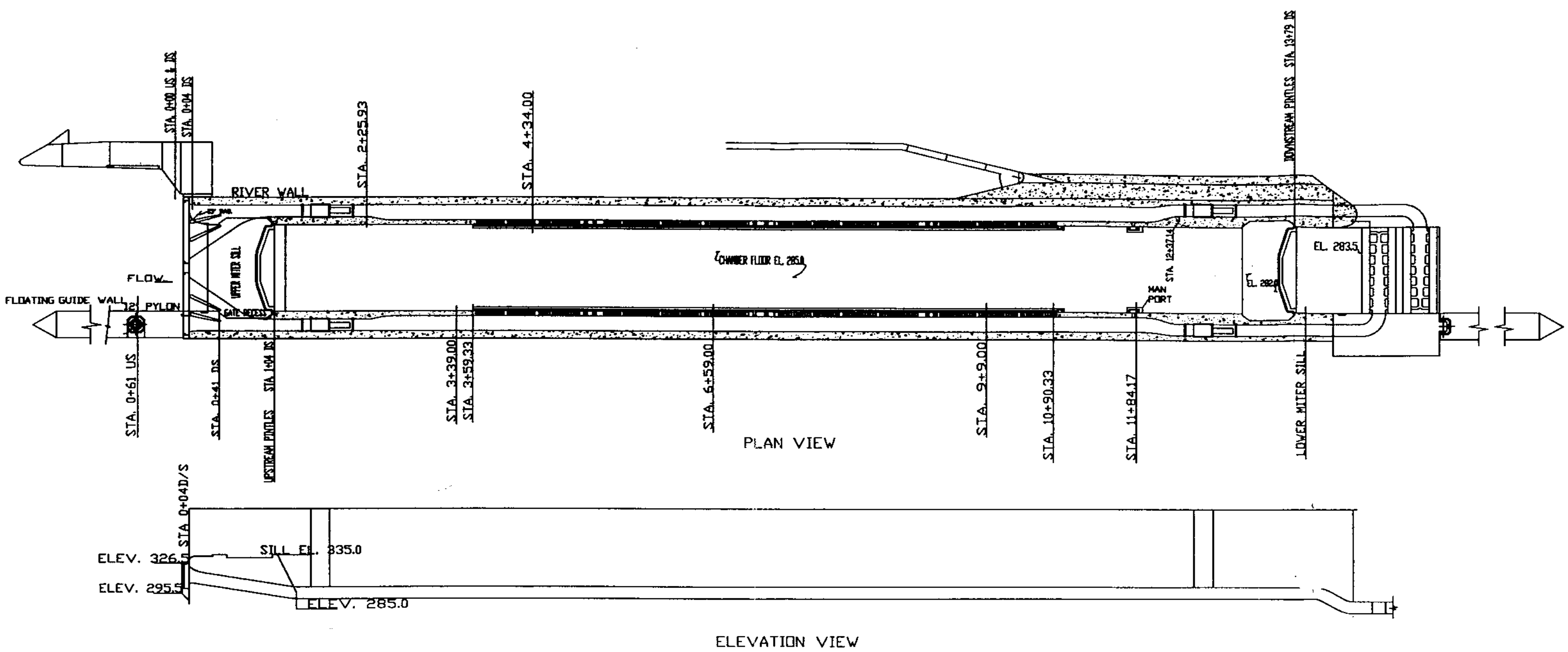


Figure 7. 1:25-scale CHL Kentucky Lock model showing multi-port filling and emptying system. (From Sanchez 2001.)

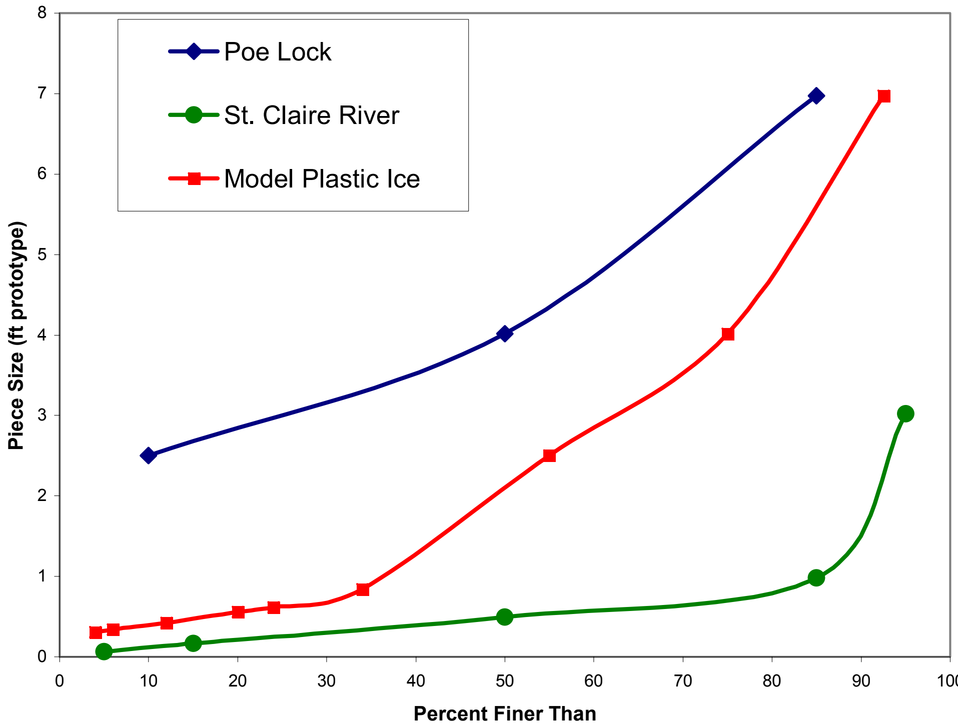


Figure 8. Ice piece size distributions. Field observations from the Poe Lock and St. Claire River as well as the plastic ice used in the physical model tests.

Table 1. Piece size distribution for plastic ice used in physical models.

Percent finer by weight	Piece diameter (ft prot)	Model ice type
90	6.5	Sawn ¼-inch-thick polyethylene squares
80	4.7	
70	3.6	
60	2.8	
50	2.1	Crushed polypropylene NYPA ice
40	1.3	
30	0.7	
20	0.6	
10	0.4	

Physical model tests

Table 2 summarizes the physical model tests with plastic ice.

Table 2. Physical model tests with plastic ice.		
Test	**Model**	**Description**
1. Upper approach ice accumulation during lock filling		
1a	CRREL Soo Poe Lock	Existing conditions: intakes in side walls
1b		INP through-the-sill intakes
1c	CHL Kentucky Lock	Through-the-sill intakes, upstream of gates
2. Drawing ice into lock chamber		
2a	CRREL Soo Poe Lock	Existing split-lateral F/E system
2b		INP 600- to 1200-ft lock extension
2c		Existing F/E, w/ports in lower miter gates
2d	CRREL MacArthur Lock	Existing interlaced-bottom lateral system
3. Flushing ice from lock chamber		
3a	CRREL Soo Poe Lock	Existing split-lateral F/E system
3b		Existing F/E system w/ports in upper miter gates
3c	CRREL MacArthur Lock	Existing interlaced-bottom lateral system

Surface water velocity measurements

Surface water velocity distributions and vertical water velocity profiles were measured in the physical models under open water conditions. In the relatively quiescent hydraulic conditions in the vicinity of locks, water slopes are mild and near-surface water velocity is the most important parameter influencing brash ice movement.

Water velocity was measured by three different methods. The simplest way of measuring surface velocity was to visually track drogues with respect to range markers. Two-dimensional surface velocity distributions were also obtained through analysis of down-looking Hi-8 video of drifting confetti and plastic ice pieces. This method proved the most useful in unsteady flow situations because it provided progressive horizontal velocity distributions during lock filling and ice locking operations. A miniature Marsh McBirney electromagnetic velocity probe and a two-dimensional acoustic Doppler probe supplemented the surface velocity data and also provided vertical velocity profile data.

Ice accumulation near intakes during lock filling

Upper approach ice accumulation tests were done in CRREL and CHL physical models, representing three types of intake designs. The first case used the existing Soo Poe Lock design with eight 10-ft × 10-ft intake ports spaced along each wall for 138 ft, starting 70 ft upstream of the upper miter gates (Fig. 9). Because the side intake design is widespread at Corps locks, it was considered the baseline case. A through-the-sill intake was constructed in the Soo Poe Lock, allowing direct comparisons to the existing intakes in the upper approach walls (Fig. 9). Finally, upper approach ice accumulation was observed during the filling of the CHL Kentucky Lock, where the intakes are built into the face of the upper miter gate bay, 100 ft upstream of the miter gates (Fig. 5).

CRREL Soo Locks model

Plastic ice movement in the upper approach was observed in the Poe Lock model for existing conditions for intakes located in the sides of the upper approach (Case 1a), and the through-the-sill intake case developed in the INP (Case 1b). Both tests used a filling curve based on staff gage measurements made during normal fills at the prototype Poe Lock in 1999. The filling curve is highly unsteady, increasing from 0 to 6500 ft^3/s in the first 3.5 minutes (Fig. 10). During the first half of the hydrograph rise, water currents in the upper approach are more or less uniform with depth. By the time of the hydrograph peak, surface velocity in front of the intakes has significantly declined as an increasing portion of the flow occurs at depth. By mid-fall on the hydrograph, surface currents are practically zero and all flow into the intakes is occurring at depth. Figure 11 compares measured water velocity profiles for the two types of intakes for a total flow of 6000 cfs.

As an initial condition, the upper approach was filled with a single-layer accumulation of plastic ice at an approximate surface concentration of about 70 percent and an average thickness of 1.5 ft. A boom located 320 ft upstream of the miter gates kept the ice out of the intake area until the start of the test. Before opening the filling valves, the boom was removed, allowing the ice to drift freely into the intake area. A down-looking video camera tracked the ice movement during lock filling.

Figure 10 shows the filling curve and compares the position of the leading edge of the ice accumulation with time for the side intakes and the through-the-sill intakes cases. In the side intakes case, the final ice edge position is near the downstream end of the intakes while for the through-the-sill case the ice accumulation reaches the face of the miter gates.

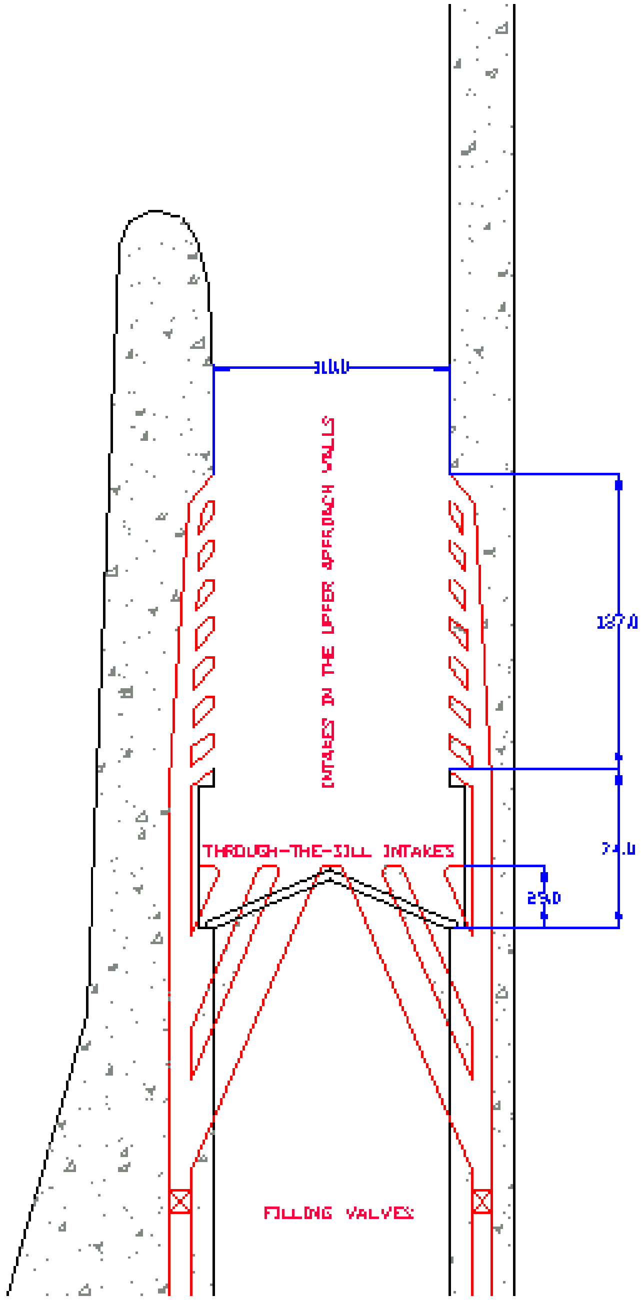


Figure 9. CRREL Poe Lock model modified to include through-the-sill intakes, in addition to the existing intakes in the upper approach walls. To test one intake type, the other type was blocked off. Both intakes feed culverts in the lock walls, controlled by the filling valves.

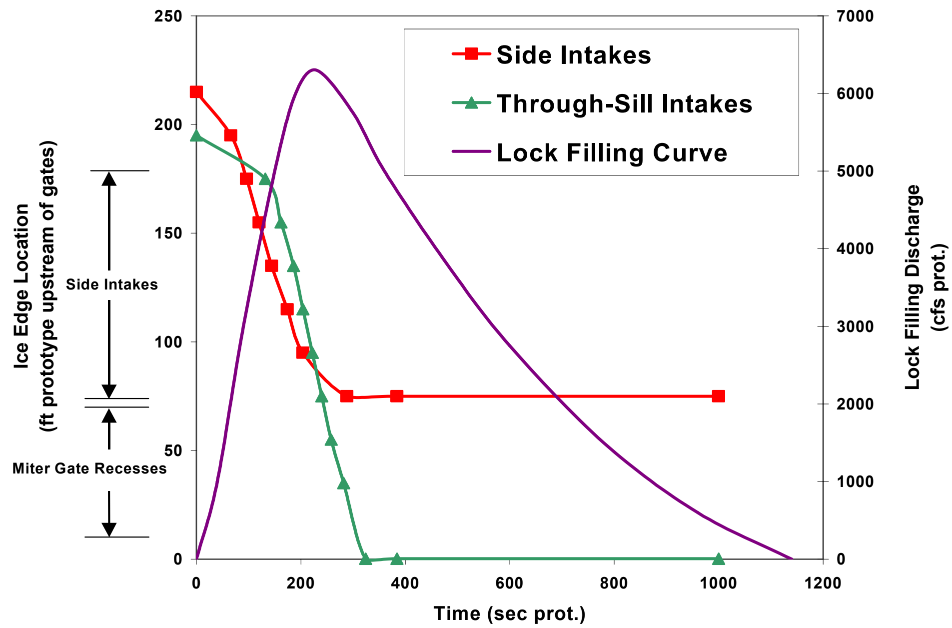
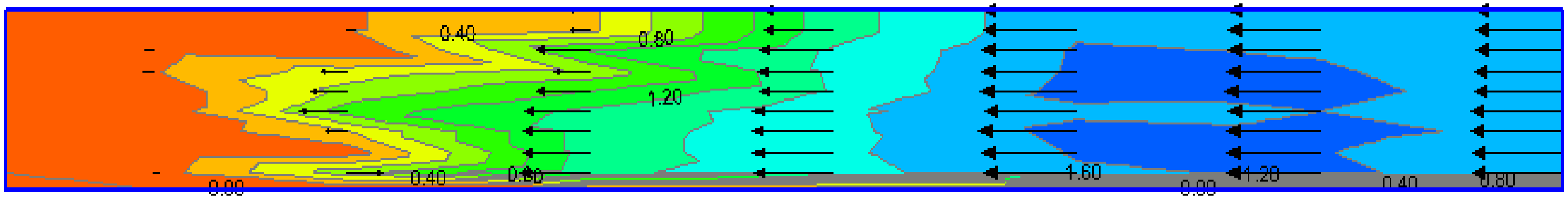


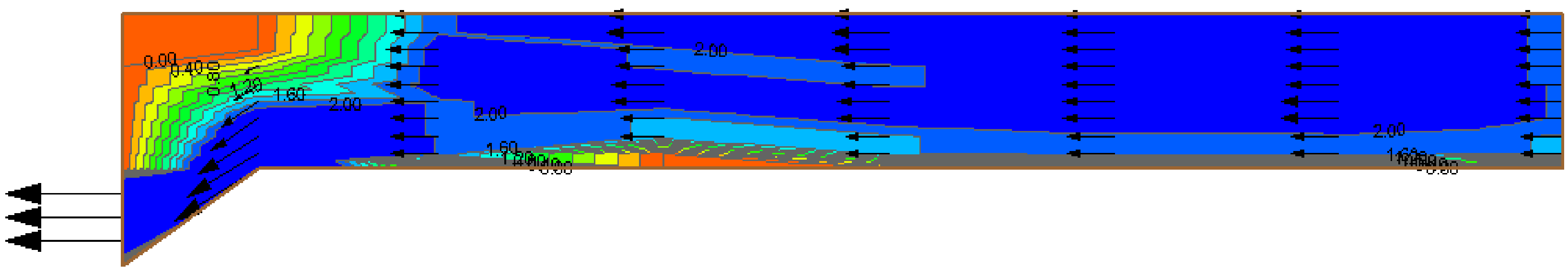
Figure 10. Filling curve and ice edge position for the side intakes and the through-the-sill intakes.

Kentucky Lock model

Plastic ice accumulation was observed in the upper approach of the 1:25-scale CHL Kentucky Lock (Case 1c). The upper approach of the Kentucky Lock model is similar in layout and size to that of the Poe Lock. An important difference is the floating approach walls that allow flow underneath, unlike the bottom-founded walls of the Poe Lock upper approach. Also, a shallower over-sill depth (25 ft compared to 32 ft for the Poe Lock) and a higher peak filling discharge (14,000 cfs compared to 6500 cfs) result in higher water velocities in the upper approach. The intakes are located in the front face of the upper miter gate bay 100 ft upstream of the miter gates, while the Poe Lock model through-the-sill intakes are located directly in front of the miter gates. Figure 12 shows the filling curve and a series of photographs of the plastic ice accumulating in front of the miter gates during lock filling.



a. Case 2a: 6000 cfs passing through side intakes.



b. Case 2b: 6000 cfs passing through-the-sill intakes.

Figure 11. Measured water velocity along the centerline of the Poe Lock model upper approach.

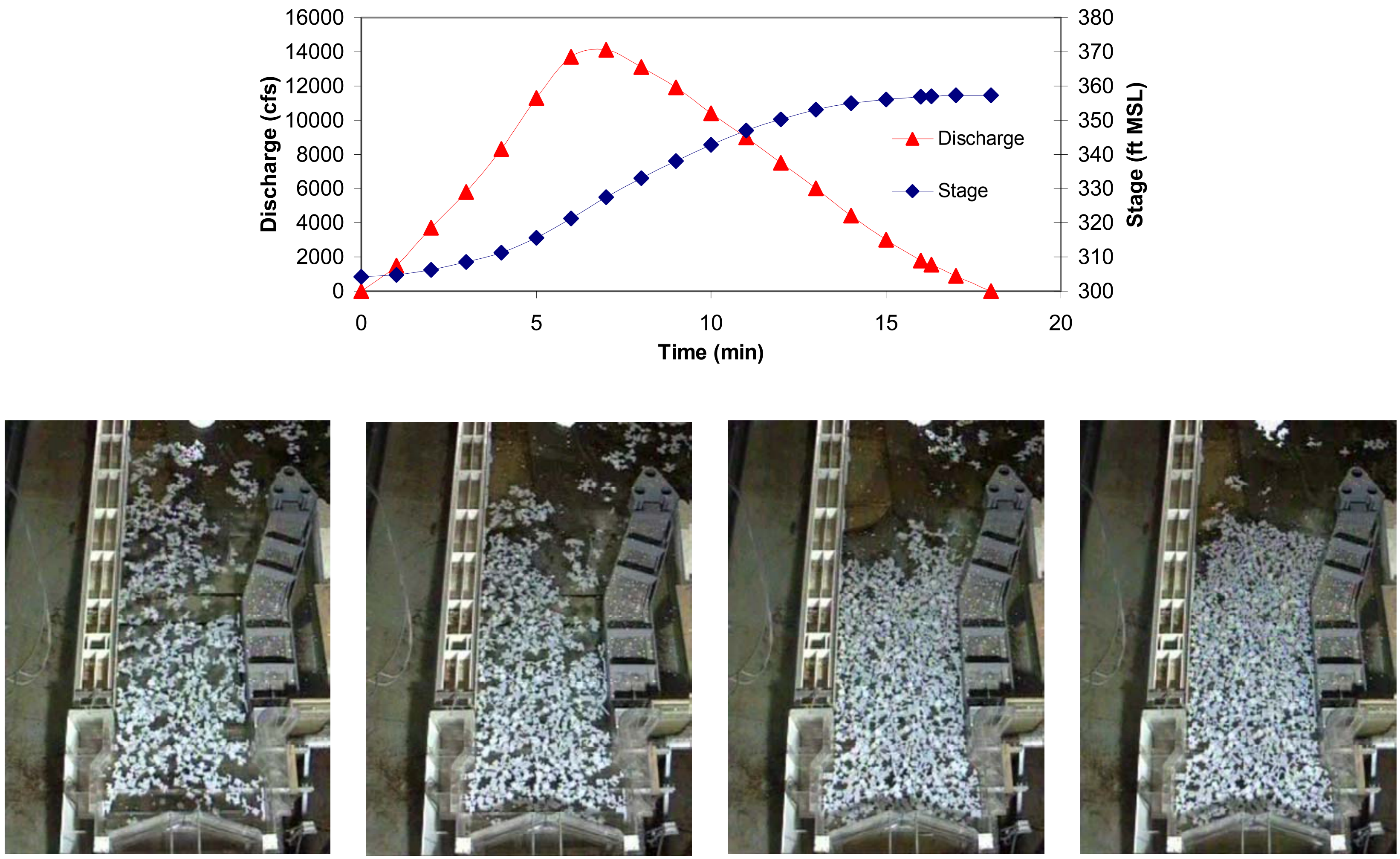


Figure 12. Lock filling. Curve and plastic ice movement in the upper approach of the Kentury Lock model during filling.

Drawing ice into the lock chamber

Ice drawing tests were done for three different types of filling and emptying systems: the split-bottom lateral F/E system of the model Poe Lock (Case 2a), the 600 to 1200 lock extension case (2b), and the interlaced bottom lateral system of the model MacArthur Lock (Case 2d). For these tests, the lock is at high pool with the upper miter gates open and the lower miter gates closed. An additional test (2c) examined the effect of ports in the lower miter gates of the Poe Lock model to create surface currents to draw ice into the lower portion of the lock chamber.

Model Poe Lock

In the model Poe Lock, opening the emptying valves 100% creates a surface flow field that decreases from an average surface velocity of 1.3 ft/s in the upper approach to nearly zero at a location about two-thirds of the way down the lock chamber (Fig. 13). Total flow from the emptying valves is 6000 ft^3/s, slightly less than the peak flow during lock filling.

Initially a 1.5-ft-thick accumulation of plastic ice was retained behind a boom located 320 ft upstream of the open upper miter gates. The empty valves were opened, and once steady flow established, the boom was removed, allowing the plastic ice to drift into the lock chamber (Case 2a). In Case 2b, only the upper set of laterals was used, in order to simulate a 600- to 1200-ft lock extension case. Flow from the upper laterals was 3000 ft^3/s, about half of the Case 2a discharge of 6000 ft^3/s. Surface water velocity declined from 1.0 ft/s in the upper approach to zero by about one-third of the way down the chamber (Fig. 14). In Case 2c, four 3.6-ft-diameter ports in the face of the lower miter gates passed 670 ft^3/s in addition to the 6000 ft^3/s passing through the ports in the lock floor. With the ports in the lower gates open, surface velocities in the lower third of the chamber were about 0.2 ft/s (Fig. 15).

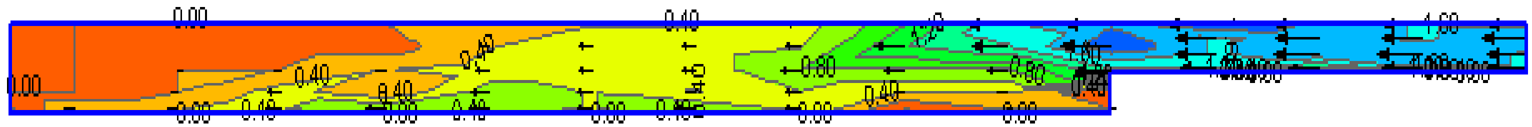


Figure 13. Vertical velocity profile along centerline of the model Poe Lock Case 2a: Drawing ice into chamber with existing split-bottom lateral F/E system.

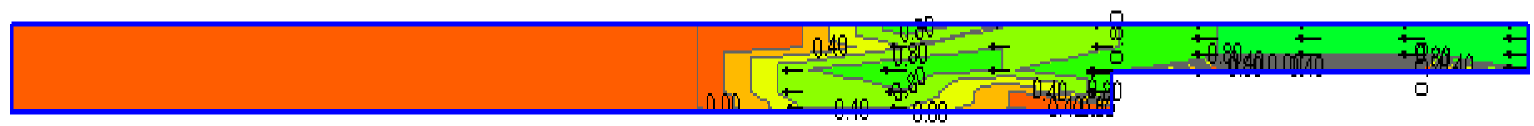


Figure 14. Vertical velocity profile along centerline of the model Poe Lock Case 2b: Drawing ice into chamber with upstream laterals only to simulate 600- to 1200-ft lock extension.

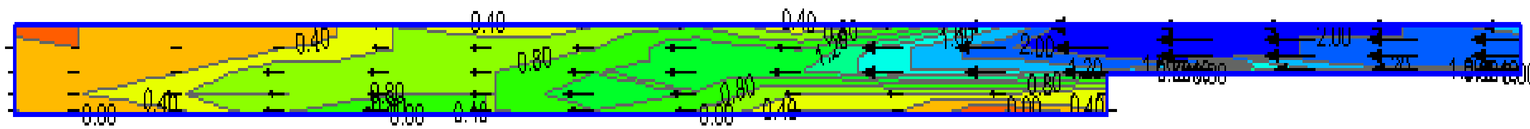


Figure 15. Vertical velocity profile along centerline of the model Poe Lock Case 2a: Drawing ice into chamber with existing split-bottom lateral F/E system plus ports in lower miter gates.

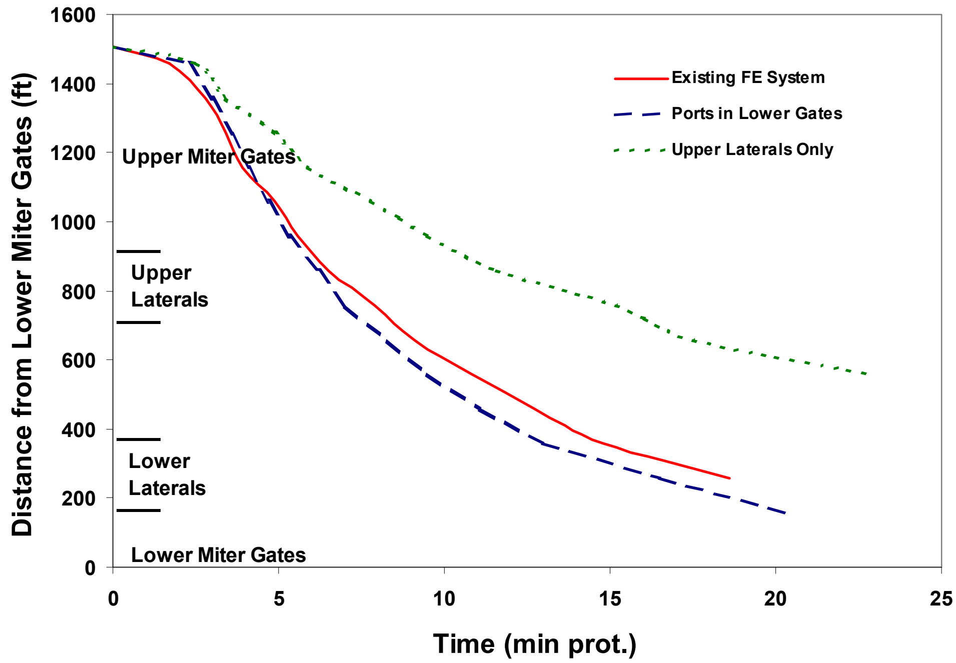


Figure 16. Position of ice edge vs. time, drawing ice into the model Poe Lock chamber.

Figure 16 compares the ice edge positions vs. time for the three cases. The existing FE system performed well, drawing ice to within 200 ft of the lower miter gates. Opening the ports in the lower miter gates resulted in only a slight improvement over existing conditions. Using only the upper laterals, it was possible to draw ice about halfway into the lock chamber.

Flushing ice from the lock chamber

For the ice flushing tests, the lock is at low pool with the lower miter gates open and the upper miter gates closed. Initially, the entire lock chamber is filled with an ice accumulation with an average thickness of 2.4 ft. Opening the filling valves 100% results in a total flow of 5000 ft^3/s out the ports in the lock floor. The resulting surface flow field increases from near zero at a location about 200 ft downstream of the upper miter gates to about 2 ft/s in the lower third of the lock chamber (Fig. 17). The ice was allowed to drift from the lock chamber into the lower approach (Case 3a). In Case 3b, four 3.6-ft-diameter manifolds in the face of the upper miter gates added 600 ft^3/s to the flow from the ports in the lock floor. With the manifolds in the upper gates open, surface velocities in the upstream one-third of the chamber were at or above 1.0 ft/s (Fig. 18).

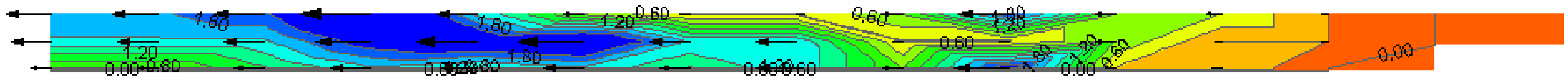


Figure 17. Vertical velocity profile along centerline of the model Poe Lock Case 2a: Flushing ice from lock chamber with existing split-bottom lateral F/E system.

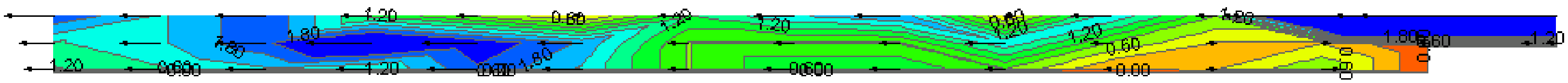


Figure 18. Vertical velocity profile along centerline of the model Poe Lock Case 2a: Flushing ice from chamber with existing split-bottom lateral F/E system plus ports in lower miter gates.

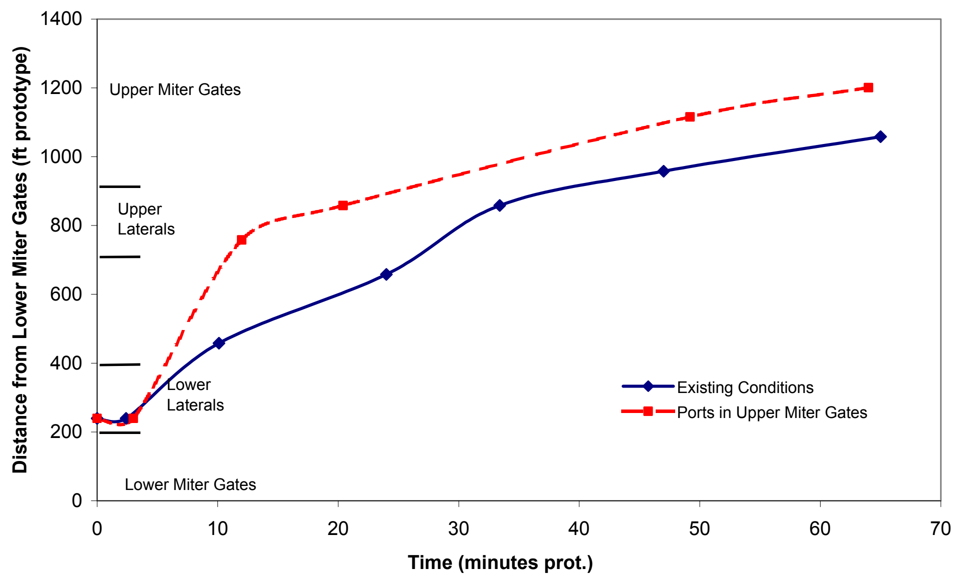


Figure 19. Ice edge positions vs. time for the two Poe Lock ice flushing cases.

Figure 19 compares the ice edge positions vs. time for the two ice flushing cases, showing a significant improvement with the ports in the upper miter gates.

MacArthur Lock ice lockage tests

Ice lockage tests were repeated for the MacArthur Lock model to compare ice passage performance for the two different types of filling and emptying systems. The split-bottom lateral FE system of the Poe Lock, which extends over 65% of the lock's 1200-ft-length, consists of two 230-ft-long bays separated by 320 ft. The MacArthur Lock's interlaced-bottom lateral FE system is continuous over 73% of the lock's 950-ft-length (Fig. 5).

Figure 20 compares ice movement into and out of the two lock models with respect to time. Units are normalized by dividing time by total time and location of the downstream edge of the ice accumulation by the length of the lock chamber. The results show no significant difference in performance between the two types of filling and emptying systems, although the ice accumulation moves faster initially in the MacArthur Lock.

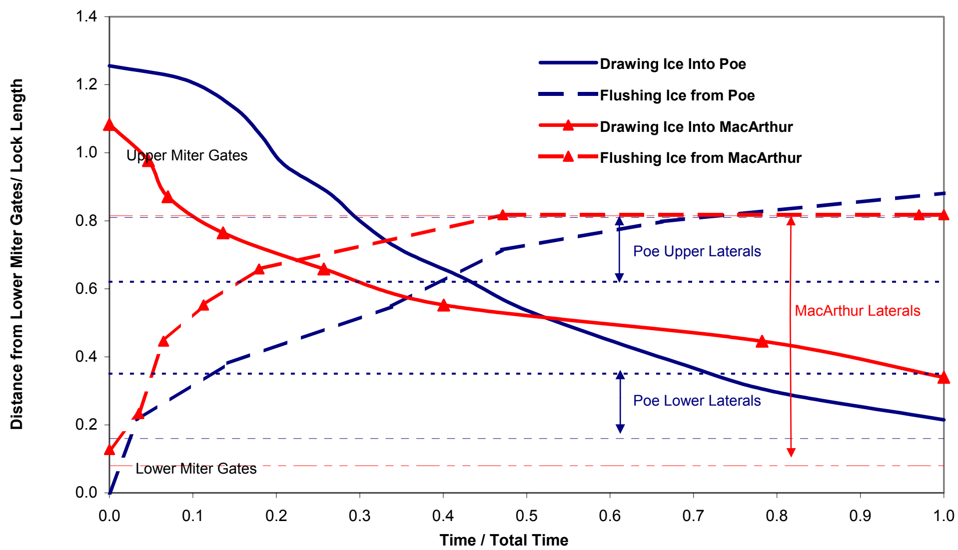


Figure 20. Comparison of ice lockage performance of Poe and MacArthur Locks.

Model–prototype comparison

Web camera images of an ice lockage on 31 March 2002 at the Soo Poe Lock were compared to physical model data. The Web camera saved an image every two minutes as loose brash ice was drawn into and flushed from the Poe Lock chamber. Prototype ice thickness was about 1.5 ft, similar to the scaled thickness of the plastic ice in the physical model. Ice edge location compared well between prototype and model as the ice was drawn into the lock chamber (Fig. 21). Figure 22 plots percent ice coverage in the Poe Lock chamber as ice is flushed to the lower pool. Differences in ice movement are attributed to different initial conditions and valve settings. The model started with 80-percent ice coverage, while the prototype started with 60 percent. The model ice cleared more quickly than the prototype because the model filling valves were opened 100 percent compared to the prototype valve opening of 50 percent.

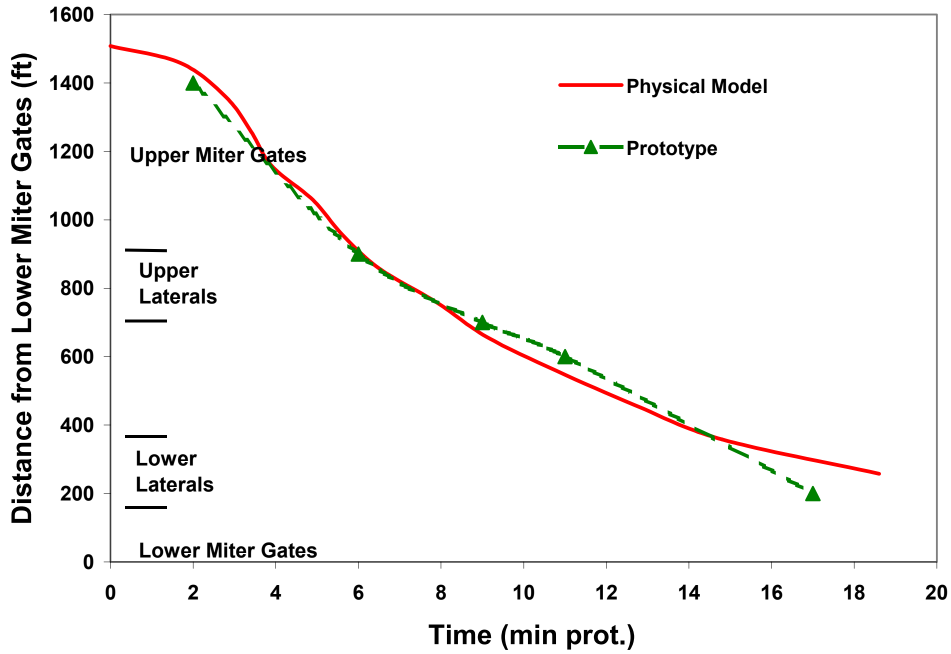


Figure 21. Drawing ice into the Poe Lock. Comparison of physical model and prototype.

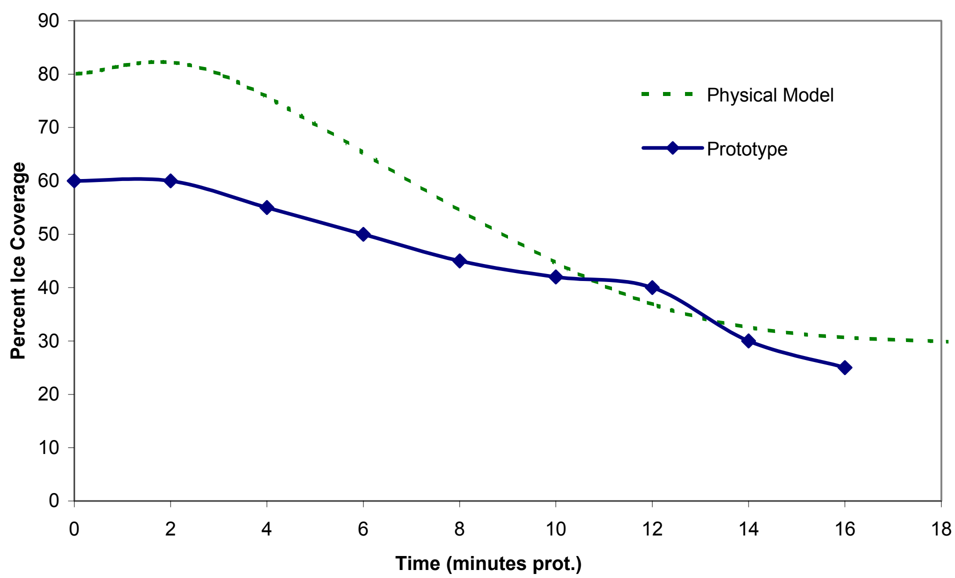


Figure 22. Flushing ice from Poe Lock. Comparison of physical model and prototype.

Numerical simulations

The DynaRICE model was set up to simulate the ice passage cases listed in Table 3.

Table 3. DynaRICE simulations of ice passage in the Poe Lock.

Case	Description
1. Upper approach ice accumulation during lock filling	
1a	Existing conditions: intakes in side walls
1b	INP through-the-sill intakes
2. Drawing ice into lock chamber	
2a	Existing split-lateral F/E system, initial ice 1.5 ft thick
2b	Upper laterals only to simulate INP 600- to 1200 ft-lock extension
2c	Existing split-lateral F/E system, initial ice 2.6 ft thick
3. Flushing ice from lock chamber	
3a	Existing split-lateral F/E system
3b	Existing split-lateral F/E system with ports in upper miter gates

5 MODEL DOMAIN AND BOUNDARY CONDITIONS

Three different model domains were used: the first for the upper approach ice accumulation tests (1a, b), the second for ice drawing tests (2a, b, c), and the third for ice flushing tests (3a, b). Model features and boundaries are shown in Figure 23.

For the upper approach ice-accumulation tests and the drawing-ice-into-the-lock-chamber tests, the upper pool stage was held nearly constant by maintaining a steady through-flow of 6400 ft^3/s at the upper end of the domain (Fig. 23). The upper miter gates of the Poe Lock defined the downstream limit of the domain. The existing side intakes were modeled as 138-ft-long lateral outflow boundaries along the upper approach walls, beginning 70 ft upstream of the miter gates. The through-the-sill intakes were modeled as a 110-ft-wide lateral outflow boundary along the face of the upper miter gates. The actual filling curve for the prototype Poe Lock was used in both intake cases. As an initial ice condition, an accumulation with an average thickness of 2 ft was retained behind a boom located 320 ft upstream of the miter gates.

For the drawing-ice-into-the-lock tests, the lower miter gates defined the downstream limit of the model domain. The Poe Lock's split-bottom lateral FE system was modeled as four 230-ft-long lateral outflow boundaries, separated by 320 ft, centered about the chamber mid-point. For the existing conditions case, a steady discharge of 6000 ft^3/s was evenly distributed along the four lateral outflow boundaries. For the lock extension case, a total discharge of 3000 ft^3/s was distributed along the upstream two outflow boundaries. The initial ice accumulation was in the same location as in the upper approach ice accumulation tests, with an average thickness of 1.6 ft.

For the ice flushing simulations, the upper miter gates defined the upstream limit of the domain and a lower pool stage outflow boundary marked the downstream end of the modeled area. For the existing conditions case, a steady discharge of 5000 ft^3/s was evenly distributed along the four lateral inflow boundaries. Four manifolds in the upper miter gates were modeled by adding 600 ft/s of inflow at the upper end of the lock chamber. Initially, ice covered all but the downstream 20 percent of the lock chamber length, with an average thickness of 2.0 ft.

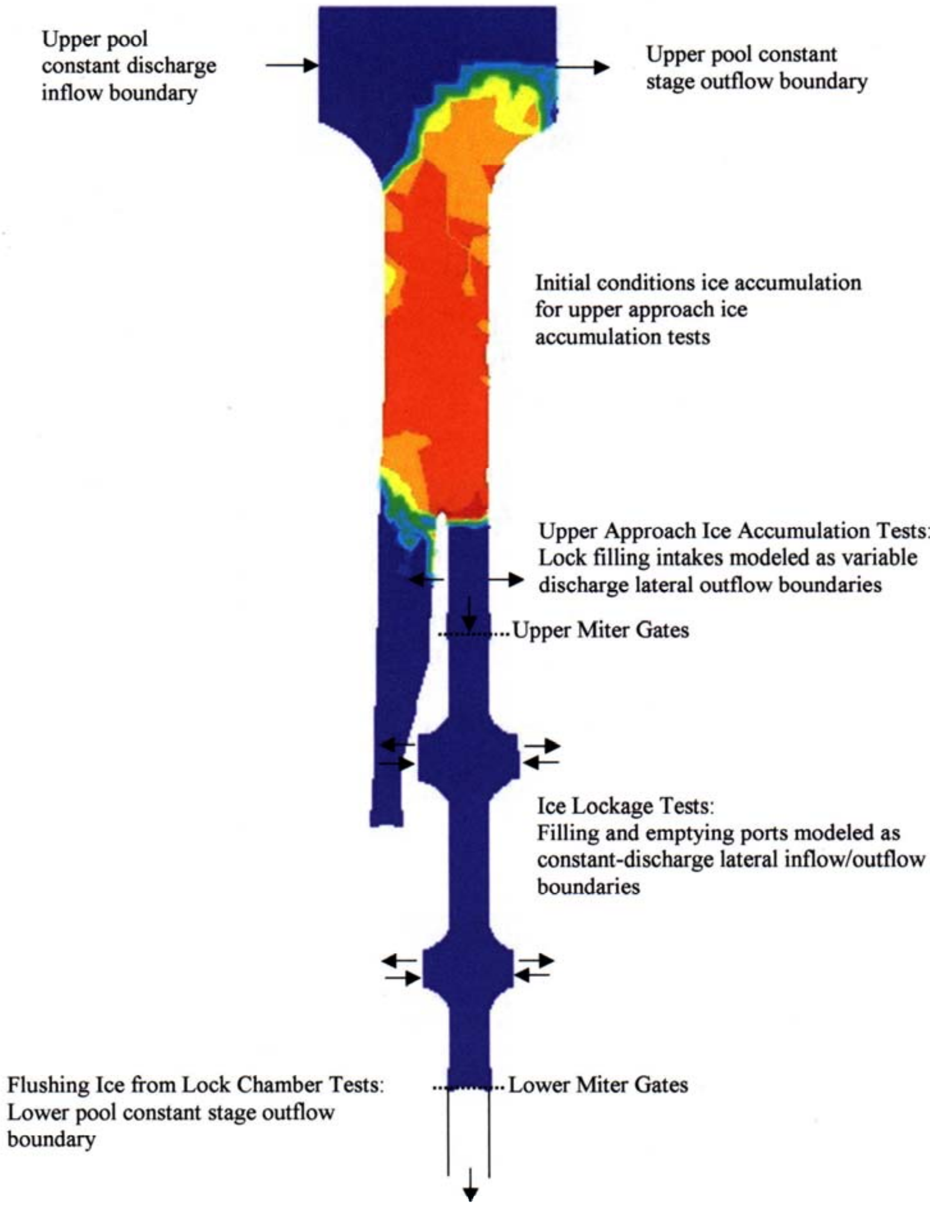


Figure 23. Plan view of modeled area, showing inflow and outflow boundaries and initial ice conditions for upper approach ice accumulation tests.

6 SIMULATION RESULTS

Ice accumulation in the upper approach during lock filling

Figure 24 compares observed and simulated ice movement for the existing and through-the-sill intake cases. The leading edge positions with respect to time compare reasonably well. In the through-the-sill intake case, the calculated ice position reached its maximum downstream extent after four minutes, then retreated slightly as flow into the intakes declined to zero. This phenomenon was not observed in the physical model.

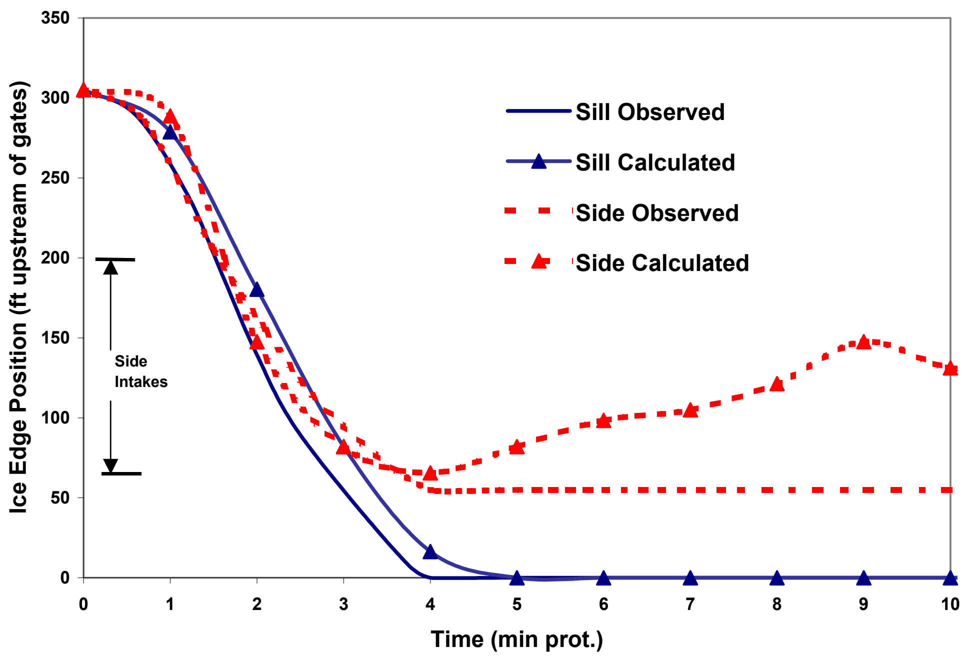


Figure 24. Position of ice edge in upper approach during lock filling. Intakes in upper approach walls and through-the-sill intakes cases, DynaRICE-calculated vs. results from physical model.

Drawing ice into the lock chamber

Figure 25 shows a reasonable comparison between observed and simulated results for the drawing-ice-into-the-lock tests. The second test used only the upper laterals to simulate the effect of doubling the length of an existing 600-ft-long lock without adding any FE capacity. The initial average ice thickness in the upper approach was 1.6 ft in the simulation, slightly higher than the average initial ice thickness of 1.5 ft observed in the physical model.

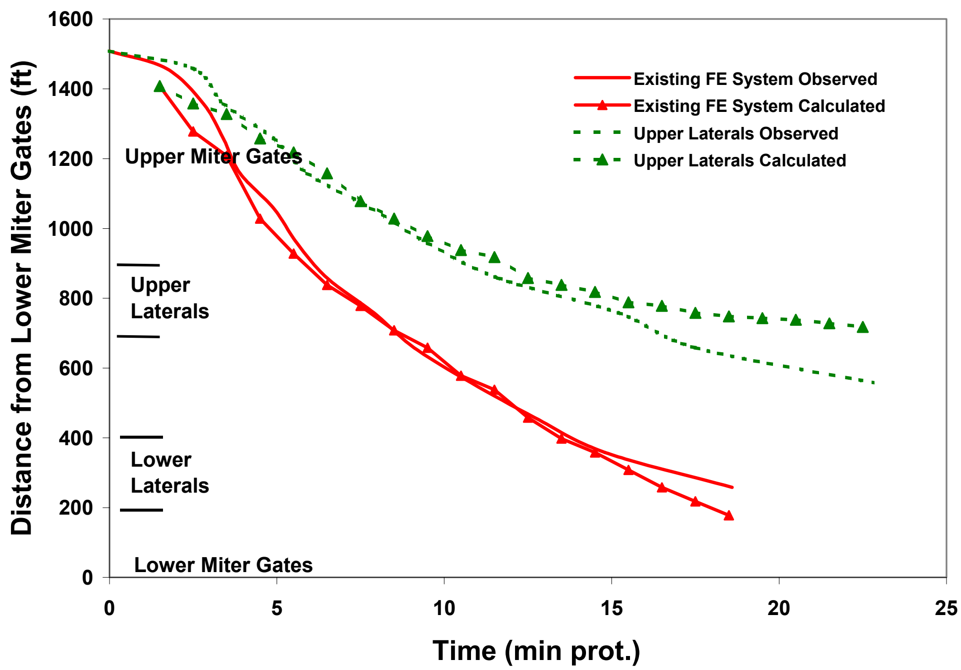


Figure 25. Drawing ice from the upper approach into the lock chamber; position of ice edge vs. time.

Flushing ice from the lock chamber

Ice flushing from the lock chamber is more difficult to define in terms of movement of a leading edge of the ice cover. In the physical model existing conditions case, the ice accumulation narrowed at the downstream end and moved out of the chamber in a swath about half the chamber width, leaving behind an ice cover upstream of the upper lateral bays. In the simulations, the ice cleared by the same process, but more quickly. Figure 26 plots observed and calculated percent ice coverage in the lock chamber with respect to time for the existing conditions case and with manifolds in the upper miter gates. In both the physical and numerical models, addition of the manifolds in the upper miter gates caused all the ice to clear out.

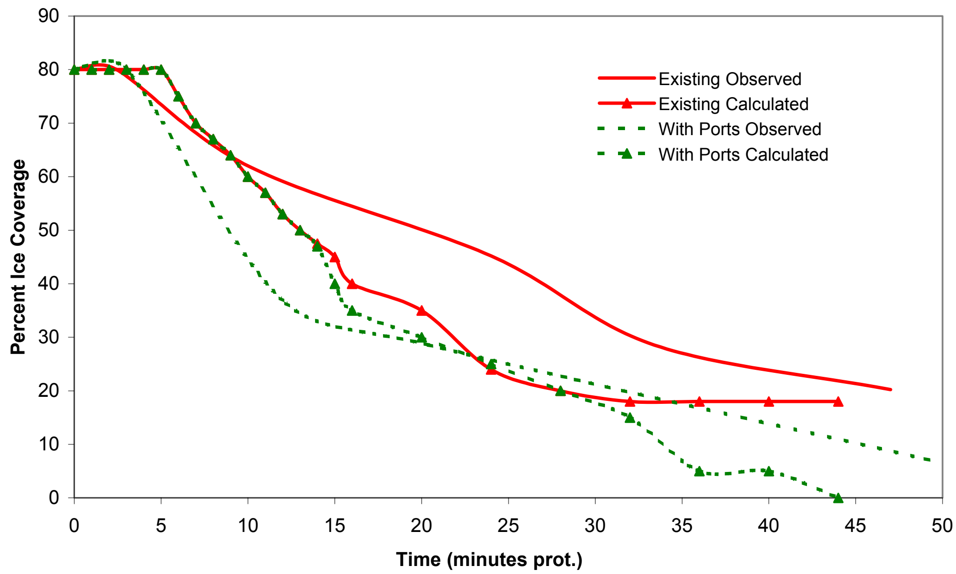


Figure 26. Percent ice coverage on the Poe Lock chamber during ice flushing.

Effect of initial ice thickness on ice movement into the lock

Initial ice thickness strongly influenced physical and numerical model tests results. Figure 27 compares the final position of the ice drawn into the lock chamber for initial upper approach ice thicknesses of 1.6 ft and 2.6 ft. In the thinner ice case, the ice traveled to within 130 ft of the lower miter gates while in the thicker ice case, the ice reached a point only about 330 ft upstream of the lower gates, appearing to jam near the upper laterals.

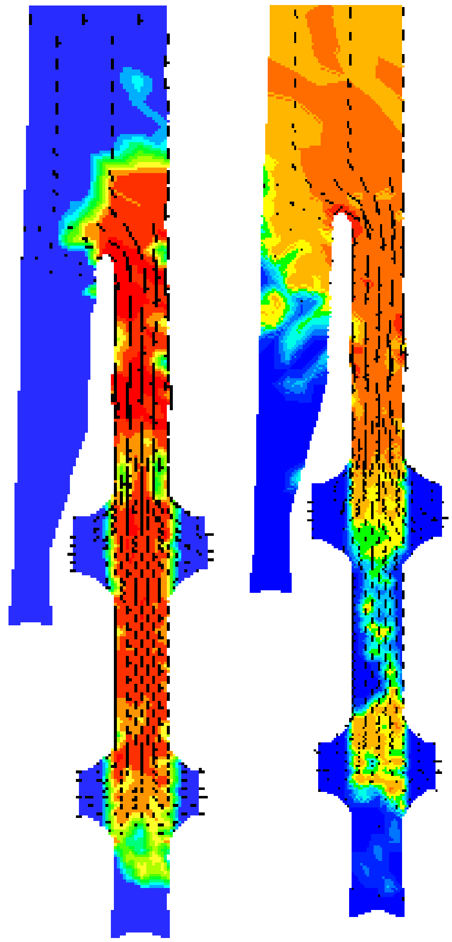


Figure 27. Effect of initial ice accumulation thickness in the upper approach on final ice cover extent in the lock chamber. In the case shown on the left, the initial ice thickness was 50 cm. In the right-hand case, the initial ice cover was 80 cm thick.

7 SUMMARY AND CONCLUSIONS

Physical and numerical models were used to investigate the relationship between lock design features and ice passage performance. Topics investigated included the effect of culvert intake design on ice movement in the upper approach and the relationship between filling and emptying system design and ice lockage performance.

During lock filling, the through-the-sill-type intakes drew ice into contact with the upper miter gates while the maximum ice position for the conventional side intakes was about 100 ft away. Based on this result, at sites where heavy ice or debris is expected, the cost advantage of the through-the-sill intake should be weighed against possible operational disadvantages.

Addition of manifolds in the lower miter gates produced a very slight improvement in terms of drawing ice into the chamber. The addition of ports in the upper miter gates significantly improved the model lock's ice-flushing capability. Observations of full-scale ice-flushing ports at the Soo Poe Lock support the model results.

Based on limited model testing, there appears to be no significant difference between the ice lockage performance of the MacArthur and Poe Lock models in spite of their different filling and emptying system designs. This suggests that total discharge into and out of the lock chamber and the resulting surface water velocity distributions outweigh the design of the F/E system in terms of ability to pass ice and debris.

Parallel simulations were done using the DynaRICE ice-hydraulic numerical model. Without extensive calibration, the observed and calculated results were reasonably close. Both the physical and numerical models were found to be very sensitive to initial ice accumulation thickness. The study proved DynaRICE to be a useful tool for assessing ice passage for new lock designs.

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14. ABSTRACT

Physical and numerical models were used to assess ice and debris passage at navigation locks, focusing on key factors such as the configuration of the upper approach, the design of the lock filling and emptying system, and the location and design of culvert intakes and outlets. Unconventional ice passage techniques such as manifolds in the miter gates were also evaluated. Physical model results were compared to field observations and a parallel series of tests using the DynaRICE ice-hydraulic numerical model. Ice processes modeled included upper approach ice accumulation during lock filling, drawing ice into the lock chamber, and flushing ice out of the lock. Initial ice thickness was found to be the most important parameter affecting ice passage. Physical and numerical model results compared reasonably well, proving DynaRICE to be a useful tool for assessing ice passage for new lock designs.

15. SUBJECT TERMS

Brash ice	Lock and dam	Navigation lock	Plastic ice
Culvert intakes	Lock culverts	Numerical ice-hydraulic model	Upper lock approach
Ice passage	Lock filling and emptying system	Physical model	

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