Summary Report
Mel Price Lock and Dam Physical Model, Upstream Scour

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Executive Summary

In April 2007, a routine bathymetric survey at Mel Price Lock and Dam detected scour holes immediately upstream of the dam piers. Additional surveys revealed that some of the scour holes were up to 22 ft deep and presented a serious risk of undermining the dam. Repairs were attempted twice at the total cost of over a million dollars. However, the scour holes reoccurred within a year of each repair. Similar surveys conducted at two other locks and dams within the St. Louis District revealed that the upstream scour issue was not limited to Mel Price. Significant upstream scour and exposed piles were found at Locks and Dams 24 and 25. Currently, Lock and Dam 25 is undergoing repair for these issues while Lock and Dam 24's repairs are planned to start in fiscal year 2012.

The decision was made to investigate the mechanism of upstream scour using scale physical and numerical models of Mel Price Lock and Dam. The physical model was constructed at the U.S. Army Corps of Engineers Engineer Research and Development Center (ERDC) in Vicksburg, MS. The numerical models were developed at the U.S. Army's Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH.

Numerical modeling supported the assertion of the Mel Price staff that ice thickness at the dam gates reaches 20 feet. Applying this information to the physical model revealed that ice cover is a significant factor in causing upstream scour, and that ice approaching thicknesses greater than 13 feet is capable of scouring an armored bed similar to the scour found at the prototype location. Physical modeling also showed that gate operations at and above the 12 foot opening can cause scour with the necessary ice cover. Tests demonstrated that operation of multiple adjacent gates reduces bed velocity. Numerous methods to prevent further scour at the design elevation were tested, but none were found to be satisfactory (including 14,000 lb grout-filled bags). Use of a new lower design elevation for the stone bed protection (370 ft. in place of 375 ft.) was tested and found to be stable for the placement of multiple stone gradations

Contents

Figures and Tables

Preface

The model investigation reported herein was performed for the U.S. Army Corps of Engineers, St. Louis District (MVS). This study was authorized by MVS on December 17th, 2008 and Mr. David Gordon from MVS directed the study.

Model experiments were performed by the personnel of the Coastal and Hydraulics Laboratory (CHL) of the U.S. Army Engineer Research and Development Center (ERDC) under the general supervision of Dr. William Martin, Director, CHL; Mr. Jose E. Sanchez, Deputy Director; Dr. Jackie S. Pettway, Chief, Harbors, Entrances and Structures Branch, CHL, and Mr. Jeff Lillycrop and Mr. Jack Davis, Technical Directors, CHL.

The experimental program was led by Mr. Donald C. Wilson. Model tests were performed by Mr. Larry Tolliver, Mr. Kevin Pigg, and Mr. Eric Carpenter.

At the time of this report, COL Gary E. Johnston was Commander and Executive Director of ERDC. Dr. Jeffrey P. Holland was Director.

Acknowledgments

Beyond the numerical modeling, the expertise that Mr. Andrew Tuthill and Dr. Meredith Carr contributed was beneficial to the development of the simulated ice and expectations of ice behavior.

Unit Conversion Factors

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
feet per second	0.3048	meters per second
cubic feet per second	0.02831685	cubic meters per second

Introduction

Mel Price Lock and Dam is located on the Mississippi River near Alton, IL, approximately 17 miles north of St. Louis (Figure 1). Construction began in 1979 and was completed in 1994. The Mel Price Lock and Dam has two locks, a 1,200 ft. long main lock controlled with a miter gate and a lift gate, and a 600 ft. long auxiliary lock controlled with two miter gates (Figure 2). The dam is 1,160 feet long and water level is controlled by the manipulation of nine 110-ft-wide tainter gates. Over 56 million tons of cargo was locked through Mel Price in 2009, and over 6,600 lockages were completed. As part of the network of locks and dams operated by the Corps of Engineers (COE) to maintain navigation on the Mississippi, Mel Price is sometimes referred to as Lock #26, its number relative to the other locks and dams on the Upper Mississippi River. Mel Price Lock and Dam replaced the previous Lock and Dam #26 that was located upstream. The structure maintains a pool 40.6 miles long that covers 31,000 acres. Typical pool elevation in the vicinity upstream of the dam is 418.4 ft. To protect the dam, a stone bed armor layer with a D_{50} = 1 ft. extends approximately 64 ft upstream from the dam sill.

In April 2007, a routine bathymetric survey was performed at Mel Price Lock and Dam that included the areas immediately adjacent to the upriver piers. The survey revealed the presence of scour holes adjacent to all of upriver piers in the stone bed armor area, with some of the holes having scoured to considerable depth (up to 22 ft deep) and presenting a possible risk of undermining the structure. An attempt was made to fill in the scour holes with 5,000 lb max size stone (Appendix A). (Mean weight for stone ≈ 500 lbs,). This repair, hereafter referred to as the first repair, was awarded in May of 2007 at a cost of approximately $1.4 million dollars. Follow-up surveys performed in May and July 2008 revealed that the scour holes had started to re-develop. The scour holes were then re-filled in September of 2008 using a 5,000 lb max size stone with a gradation favoring larger stone. This repair, hereafter referred to as the 2nd repair, cost roughly $230,000. Follow-up surveys showed that the 2nd repair also failed to stop the scour from re-occurring.

After the initial pier scour was discovered at Mel Price, two locks and dams in the district (Lock and Dam 24 and 25) were surveyed to determine if the problem was localized to Mel Price. Scouring of varying degrees was discovered at both dams, severe enough at Lock and Dam 25 to prompt an extensive repair that included grouting below parts of the lock and dam structure. With the upstream scour present at multiple sites, along with the high cost of the repairs that proved to be temporary, it was decided that funding was warranted for research and testing to determine the cause leading to the upriver pier scour. This testing was also planned to lead to a solution that would protect the lock & dams. The decision was made to investigate the issue using a two-pronged approach: 1) a scale physical model to be built at the US Army Corps of Engineers' Engineer Research and Development Center (ERDC) in Vicksburg, MS, and 2) numerical models developed at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH. The focus of this report is to detail the development and testing efforts with the scale physical model; the efforts of the numerical models will be mentioned as they pertained to support of the physical model.

Follow-up discussions and survey analysis have revealed that upriver pier scour is not isolated to the St. Louis District. Similar surveys of the upriver sections of locks & dams within the Rock Island District also suggest the occurrence of upriver scour. Because of this, the emphasis of this report was placed more on a general solution to the problem of upstream lock & dam scour instead of site-specific solutions, with the ultimate goal of developing a guideline for all applicable locations.

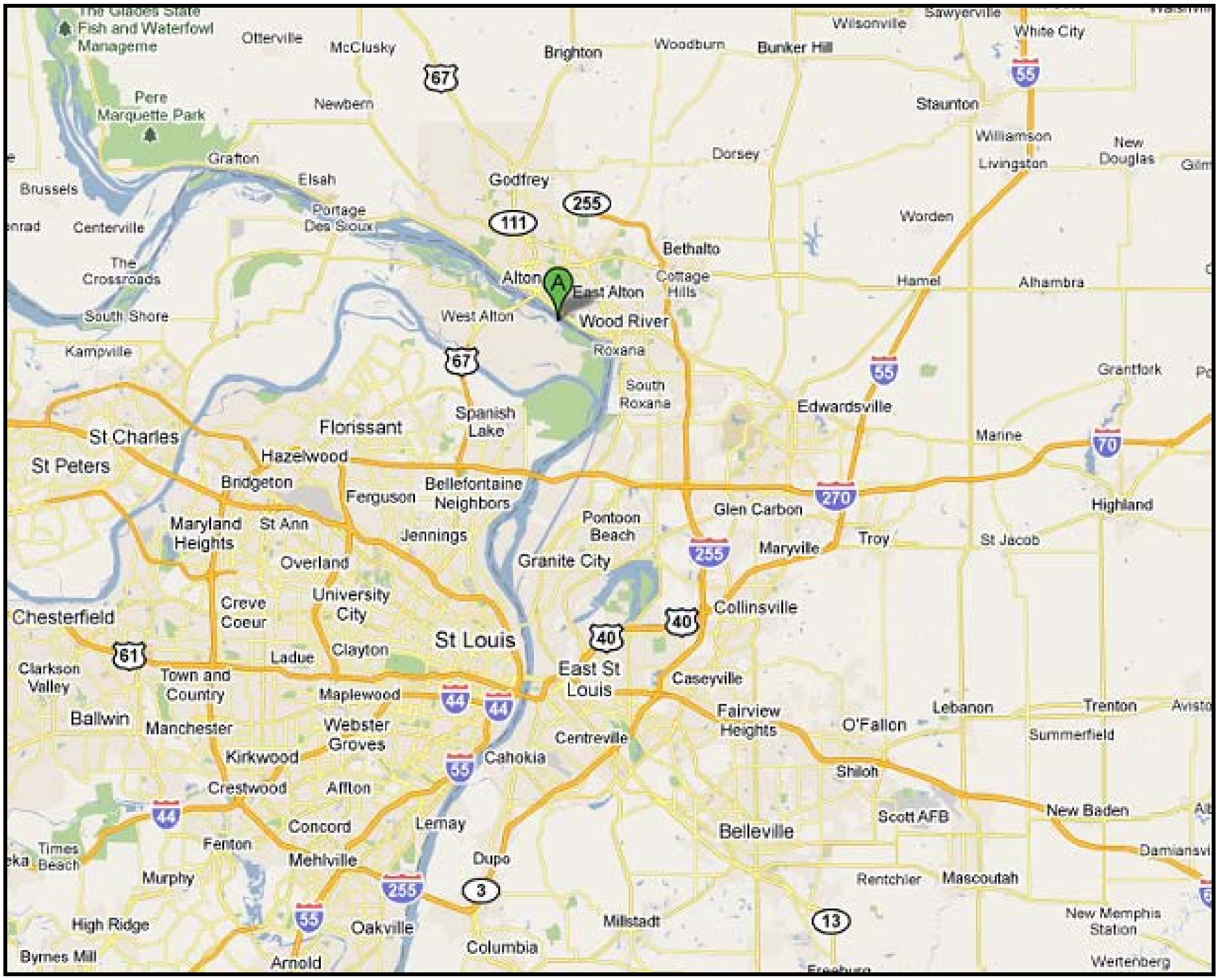


Figure 1 - Vicinity Map

Figure 2 - Aerial photograph of Mel Price Lock and Dam

Analysis of Upstream Bathymetry

As part of the investigation of the upstream scour issue, the record of the upstream surveys of the Mel Price Lock and Dam was reviewed. The images included in Appendix B are 3-dimensional renderings of the bathymetric surveys developed using Fledermaus software. The color scale was held constant for all surveys, and is shown in Appendix B. All images are displayed with the upstream to the north; therefore Illinois is shown on the right and Missouri on the left. The gate numbers are provided on the first image and will be used as a reference for discussion. Below is the survey chronology, followed by the effects in bathymetry since the previous survey

1. April 2007 – A bathymetric survey first reveals the scour issue at Mel Price. The scour holes are evident in front of every pier, and at times the holes span the length of an entire gate (as at Gate 4). The holes reached a maximum depth of up to 22 ft (between Gate 1 and Gate 2) which put the structure at risk for undermining, as the concrete sill of the dam extends down only 20 ft.
2. September 25, 2007 – The pre-repair construction survey was taken in the fall of 2007. Both scour and deposition have continued to occur since the previous survey; the area adjacent to the right downstream pier of Gate 5 has scoured multiple feet since last surveyed, whereas deposition has occurred adjacent to the Gate 4 sill. The scour damage remains extensive; the right downstream pier of Gate 6 is the only pier not undergoing double-digit losses in stone bed protection elevation (the pier has lost 7 ft of protection).
3. November 1, 2007– The stone bed protection elevations in this post-1st repair construction survey suggests that the repair largely returned protection to within ± 2 ft of the design elevation of the original design (375 ft.).
4. May 11, 2008 - Little scour (less than 1 ft) had occurred in the month since the last survey.
5. July 8, 2008 - All pier-adjacent piers exhibited scour in this survey from between 3 ft to 7 ft below the design elevation. The left pier of Gate 4 exhibited the most scour while the right exhibited the least. Less than 1 ft of scour of scour was common in the sill-adjacent stone bed protection, with the bed in the vicinity of Gates 1 and 2 being slightly deeper.
6. August 28, 2008 – All areas adjacent to piers exhibits scour ranging from 4 ft to 6 ft below the design elevation, with 4 ft of scour being most frequent. Gate sill- adjacent scour has remained below 1 ft past the design elevation except for Gates 1 and 2, which have scoured an additional foot.
7. March 18, 2009 – The right downstream pier of Gate 4 had already reached 4 ft of scour from the design elevation by the time this survey was taken. The remaining gates were within 1 ft of the design elevation, with the stone bed protection frequently raised to an elevation above the design elevation.
8. July 21, 2009 – The stone bed protection adjacent to the right pier of Gate 4 continues to slowly lose material, now at 6 ft of scour from the design elevation; in no other place has more than 2 ft of material below the design elevation been lost.
9. December 17, 2009 – Conditions are similar to the last survey; less than 1 ft of change in elevation is typical. The lone exception is the area adjacent to the pier between Gates 1 and 2, which has lost approximately 2 ft of material

10. April 28, 2010 – After the 2009-2010 winter, the upstream face of the dam was surveyed again. The protection immediately adjacent to the piers had at this point scoured approximately 4 ft or less from the design condition; the gate sill-adjacent protection had scoured 2 ft or less.
11. October 3, 2010 – The survey was similar to the previous survey; the gate sill-adjacent scour was between 0 ft to approximately 2 ft, and the pier adjacent scour was up to 4 ft deep.
12. December 2, 2010 – Pier-adjacent scour has gone beyond 4 ft deep at the pier between Gates 1 & 2 and the piers flanking Gate 4; the other pier-adjacent areas all show evidence of scour but within 1 ft -3 ft deep. Sill-adjacent scour remains within 1 ft of the design elevation and is frequently about the design elevation.
13. March 2, 2011 - The most recent bathymetric survey again displayed similar scour to the previous survey. All stone bed protection in the immediate vicinity of the piers has undergone between 1 ft to 5 ft of scour, with the deepest scour occurring at the pier between Gates 1 and 2 and the piers flanking Gate 4. No more than 2 ft of scour has occurred in the sill-adjacent stone bed protection.

Purpose and Scope of Model Investigation

A physical model was used to determine the cause of the upriver scour at lock and dam sites by simulating a similar scour occurrence under known conditions. Once the cause of the upriver scour was determined, additional testing was conducted to determine if scour reoccurrence could be prevented with a combination of operational practices and constructible physical changes. A 1:25-scale model simulating three of the tainter gates and the upper bed structure was used in the investigation.

Currently, the Corps of Engineers has neither a design guide for resolving the issue of upstream scour at locks and dams, nor a standard practice for the passing of ice through locks and dams operating. It is the intention of those involved that this report may serve as at least the impetus for such guidance, if not the actual basis for guidance.

Physical Model Development

The Mel Price physical model was built at the Engineer Research and Development Center (ERDC) Coastal and Hydraulics Laboratory in Vicksburg, MS. Model development began in January 2009. The 1 ft to 25 ft scale model was constructed in a 69 ft long, 21.1 ft wide flume. Three tainter gates were simulated in the flume instead of the full upriver dam face (Figure 3), due to size and cost limitations and to better isolate the flow occurring in front of individual piers. To lower cost and reduce fabrication time, the majority of the gate structure was re-used from the Olmsted Lock & Dam physical model. This was possible because of the large degree of similarity between the geometries of the two dams. The upriver sand bed section of the model (Figure 4) consisted of up to a bench in front of the gate structure to better replicate the approach geometry for the upstream. As in the prototype, an armor layer of stone bed protection rests immediately in front of the upstream section of gate structure. This stone has been sized to replicate the in-situ stone at the prototype, for the original stone place, the first repair, and the second repair. Underneath the bed stone armor, filter cloth was used to provide a better simulation of bedding material, with the main objective of reducing piping.

A stilling basin was not constructed since it would have no effect on the upstream scour. Stone cobbles were used below the gate outlet to dissipate the velocity of the flow through the gates (Figure 5). The tailwater and upriver pool elevations were determined with rulers set to scale in both portions of the model. The flow into the flume is supplied by a 12-inch diameter pipe and a 20-inch diameter pipe from a constant head tank fed by multiple pumps. The maximum flow possible into the flume from this system is 40 cfs. At the end of the flume, a gate was used maintain tailwater pool elevation. Two drains below the tailgate empty the flume into the building’s sump.

A walkway was built over the gates to provide better access to the gates’ winch controls. A second, moveable walkway was used to assist with taking measurements and recording video. The gates were outfitted with scaled rulers indicating the equivalent feet opening of the gate setting. Markings were placed on the upstream face of the model to aid with the placement of stone bed armor and with setting the gate openings for tests involving the use of underwater video.

Figure 3 - The model gate structure and walkway viewed from upstream

Figure 4 - The bed upstream of the model gate structure

Figure 5 - The model gate structure and walkway viewed from downstream

Ice Development Simulation

Ice development was simulated using a 21ft x 4ft x 1ft wooden raft built in four sections to facilitate installation and removal (Figure 6). Draft was controlled by adding or removing lead weights and the bottom of a raft was sloped and lined with chicken wire to simulate the natural friction of real ice. To facilitate the use of a 2D acoustic Doppler velocimeter (ADV) to take velocity measurements, three holes aligned parallel to the flow were drilled in the raft and lined with PVC to prevent the raft from flooding. Later, a fourth hole and a box were added for additional instrumentation use. The walls of the raft were raised during testing to accommodate deeper drafting of the raft.

Ice development was also modeled using cubes cut from sheets of 0.375 in. thick polyethylene (Figure 7). Based on CRREL's recommendations for ice size distribution, the sheets were cut into five different size squares: 0.75 in., 1.25 in., 2.00 in., 2.75 in., and 4.00 in. Because of its volume and weight, the acrylic ice was dumped by skid steer into the flume after the flume had been filled but before test conditions had been established for each test. To prevent the acrylic pieces from getting into the sump, metal cages were installed over the flume drains and the acrylic ice cleared out of the flume after the completion of a test.

Figure 6 - Wooden raft used to simulate upstream ice

Figure 7 - 0.75 in. thick pieces of acrylic ice

Numerical Model Development

Concurrent with the development of the physical model, a numerical model was developed by Andrew Tuthill, P.E. and Meredith Carr, PhD at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). The DynaRICE 2-dimensional dynamic ice model was used for testing because of its ability to simulate ice transport, thickening, and jamming. Two different meshes were created in SMS 10.1 for the model: the first mesh simulated the prototype dimensions, and the second model simulated the physical model dimensions. These numerical models were used to check and support the multiple assumptions and findings made in the physical-modeling process. Testing results from the numerical models supported multiple assumptions and results of the physical model: maximum velocities measured with ice cover were found to be similar, ice thicknesses used in the physical model were corroborated by ice growth numerical model scenarios, and areas of high bed activity were the same.

Details of the development and results of the numerical modeling can be found in “Numerical Modeling of Ice Passage at Mel Price Lock and Dam” by Meredith Carr and Andrew Tuthill.

Similitude

Establishing similitude between the model and prototype units and dimensions is required to ensure an accurate transfer of model data to prototype quantities. Dimensional analysis indicates the dominant forces in a free-surface flow are inertial and gravitational. Similitude requires the ratio of these two forces be equal in the model and prototype. This is referred to as Froudian similitude, where the Froude number in the model is equal to the Froude number in the prototype for a given flow condition.

Similitude also requires the Reynolds number in the model be equal to the Reynolds number in the prototype. That is, the ratio of inertial forces to viscous forces be equal for a given flow condition. However, it is impossible to simultaneously meet Froudian and Reynolds criteria in a scaled model. The solution is to scale a model such that, for the flow conditions to be investigated, the Reynolds number in the model is greater than 5000. At Reynolds numbers of 5000 or greater, scale effects associated with viscosity are negligible. By using a scale at which viscous effects are negligible, Froudian criteria can be used to develop scale relationships.

The accepted equations of hydraulic similitude, based on the Froudian criteria, were used to express the mathematical relations between the dimensions and hydraulic quantities of the model and the prototype. The general relations expressed in terms of the model’s scale or length ratio, L_r, are shown in Table 1.

Measurements of each of the dimensions or variables can be transferred quantitatively from model to prototype equivalents by means of the above scale relations. All model data are presented in terms of prototype equivalents.

:

Scale Relations

Dimension	Ratio	Scale Relation
Length	Lr	1:25
Area	Ar = Lr 2	1:625
Velocity	Vr = Lr 1/2	1:5
Discharge	Qr = Lr 5/2	1:3,125
Time	Tr = Lr 1/2	1:5
Force	Fr = Lr 3	1:15,625
Frequency	fr = 1/Lr 1/2	1:0.2

Table 1 - Scale Relations

Physical Model Testing

The testing conducted with the Mel Price physical model had two main goals: 1) determine the driving mechanism for the upriver scour, and 2) develop measures to protect the lock and dams of the St. Louis District and potentially other districts in the future. Because of the goal-specific nature of the investigation as well as the unknown mechanism driving the upriver scour, the testing schedule was often evolutionary as compared to regimented. A standard test would begin with the setting of initial test conditions: filter cloth, if used, placed underneath the stone bed protection, the sand bed re-graded to design conditions, stone bed protection screened to gradation, reset depending on which repair condition was being tested, the initial ice condition set (if ice is being used, acrylic ice or ice raft), and a decision would be made as to gate conditions for the test. Once the initial conditions were set, the water level in the flume was slowly raised, first in the upper pool, and then by slightly opening the gates, the lower pool. To increase gate conditions, the flow into the flume was raised in conjunction with the gates as to maintain pool levels. As necessary while reaching flow conditions, ice conditions would be set as desired for testing. Once at the proper gate conditions, the test would be run for the desired length of time, and then the model gates and flow were lowered simultaneously to avoid overfilling the flume and disrupting the bed.

The initial tests in July 2009 attempted to determine if the scour would occur under normal operating conditions. The test was run with a center gate opening of 23 ft (the largest gate opening used by the lock staff when not at open river conditions) and simulating a 419 ft prototype upper pool elevation and a 395 ft. prototype lower pool elevation. The upper pool was almost always kept at 419 ft. or 420 ft. depending on test water demands and the lower pool was always run at a prototype elevation of 395 ft. Neither the original stone bed armor nor the first repair stone underwent any considerable scour (Figure 8 – Figure 13).

Figure 8 - Upstream pre-test conditions for a 23 ft. center gate opening

Upper pool = 419 ft., original stone placement test

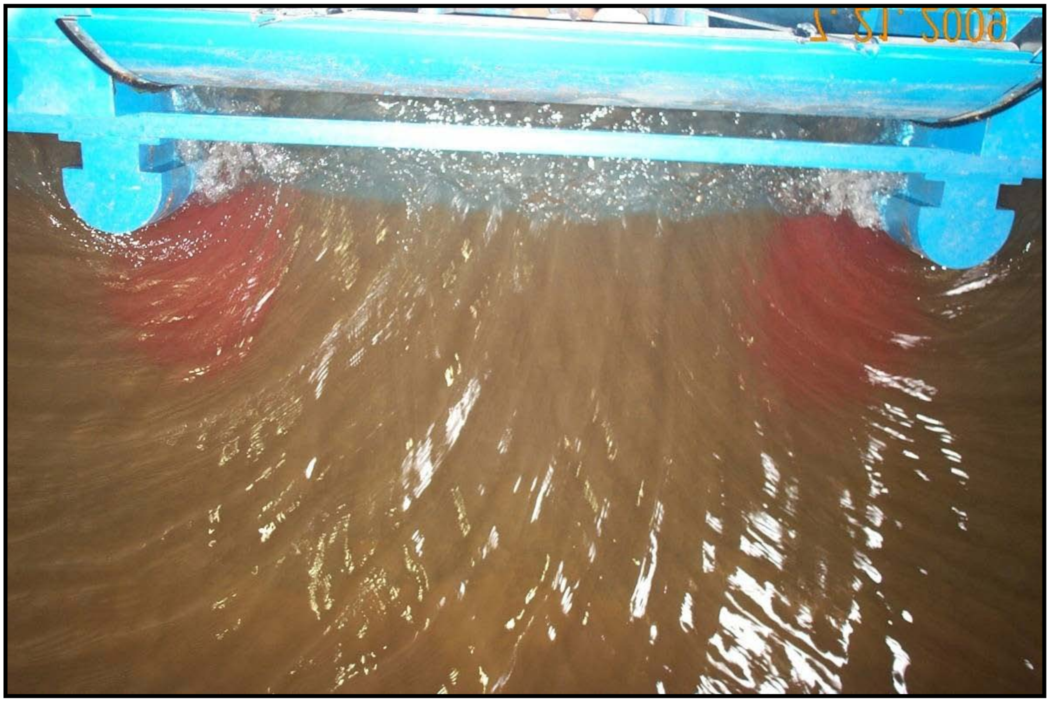


Figure 9 - Upstream view of the center gate during testing

Figure 10 - Post-test conditions for a 23 ft. center gate opening

Upper pool = 419 ft., original stone placement test

Figure 11 - The post-test 23 ft center gate opening, original stone, filter cloth, no ice

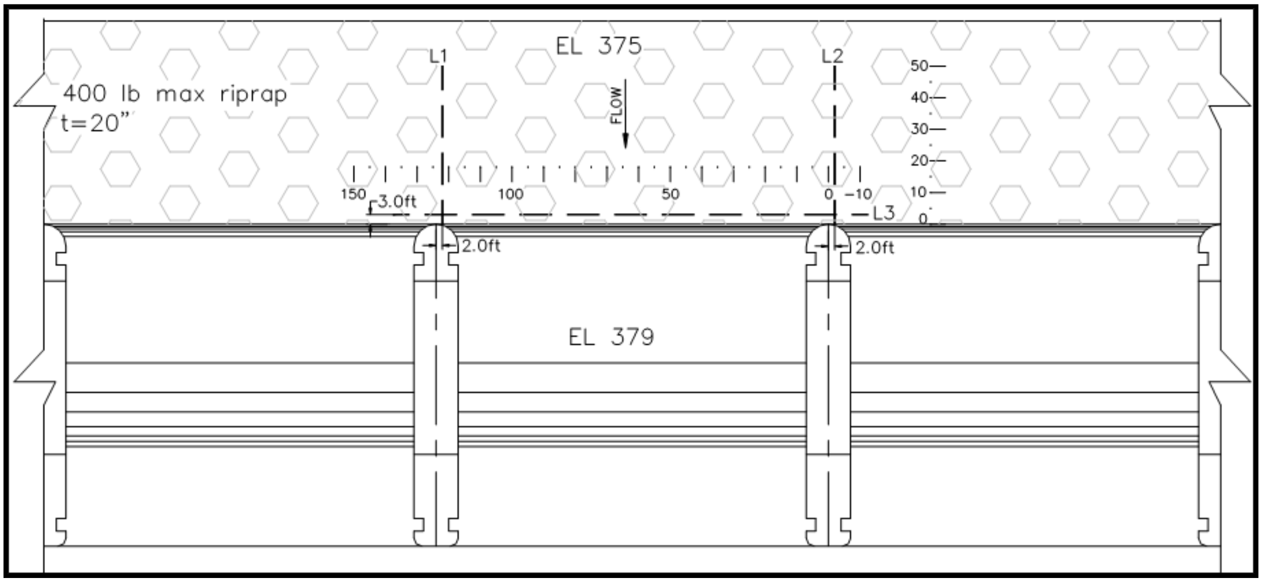


Figure 12 - Bed survey frame of reference

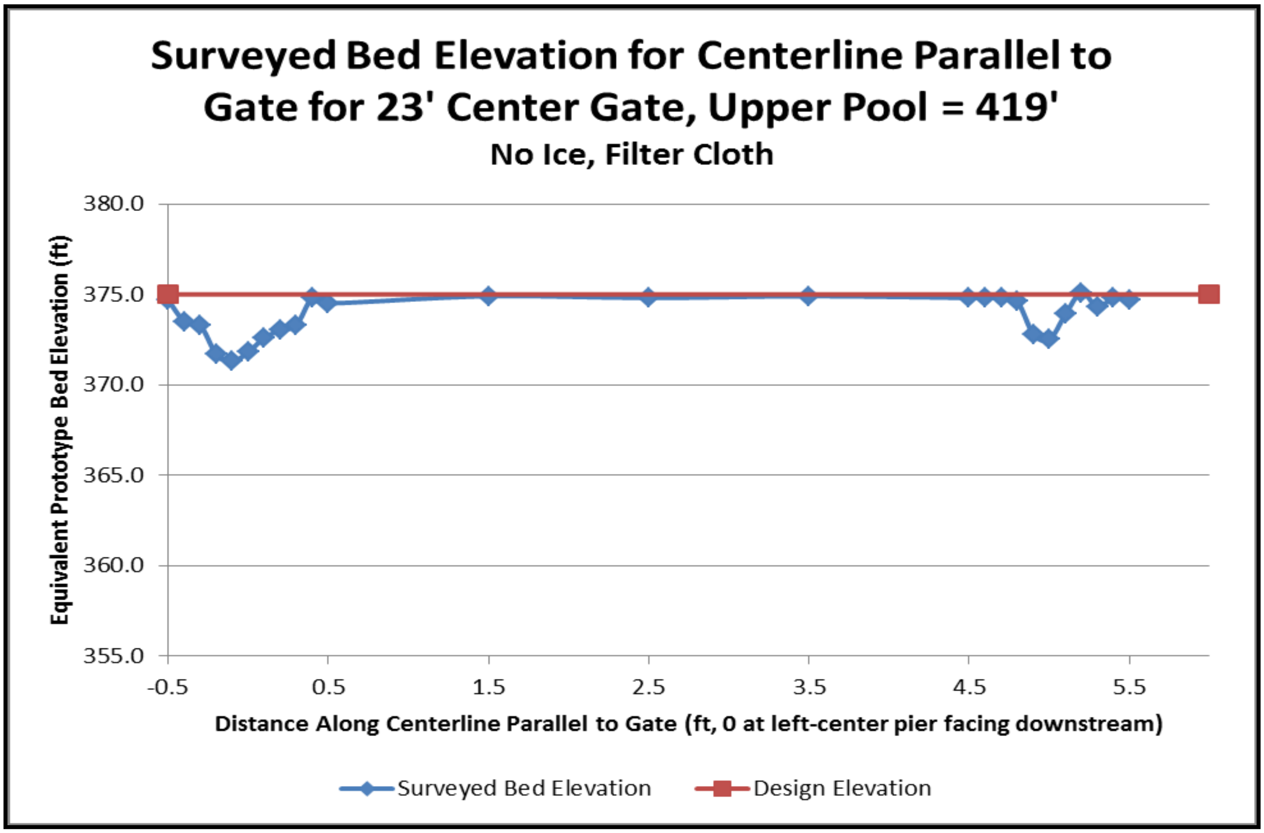


Figure 13 - Bed Survey of Test Conducted 6-23-09

After the testing of normal operating conditions was concluded, testing focused on a possible cause suggested by lock and project staff: the buildup of ice in front of the dam during the winter. It was theorized that ice build-up occurs along the gates of the locks and dam into the upper pool and serves as a constriction to the flow, which in turn increases flow velocities and bed shear stress. This theory was supported by the findings of the numerical model. Based on conversations with CRREL staff, the ice raft was designed to simulate the thickness and roughness that could be expected from natural ice. The initial ice tests focused on different gate openings on the main gate, the use of filter cloth, the ice raft (drafting at 10 ft), and stone type. The tests conducted revealed that ice causing scour was possible and that the use of filter cloth and gate opening affected the rate of scour occurring. However, the level of scour occurring was not representative of the scour seen occurring of the prototype (the model scour was significantly less than seen in the prototype). During these tests, the open river condition was modeled as it was considered a unique condition of river operation. However, minimal scour was observed (Figure 14 – 15), and all ADV measurements revealed relatively low velocities of approximately 5 fps.


10.13.2009

Figure 14 - 23 ft center gate opening, original stone, no filter cloth, with ice raft

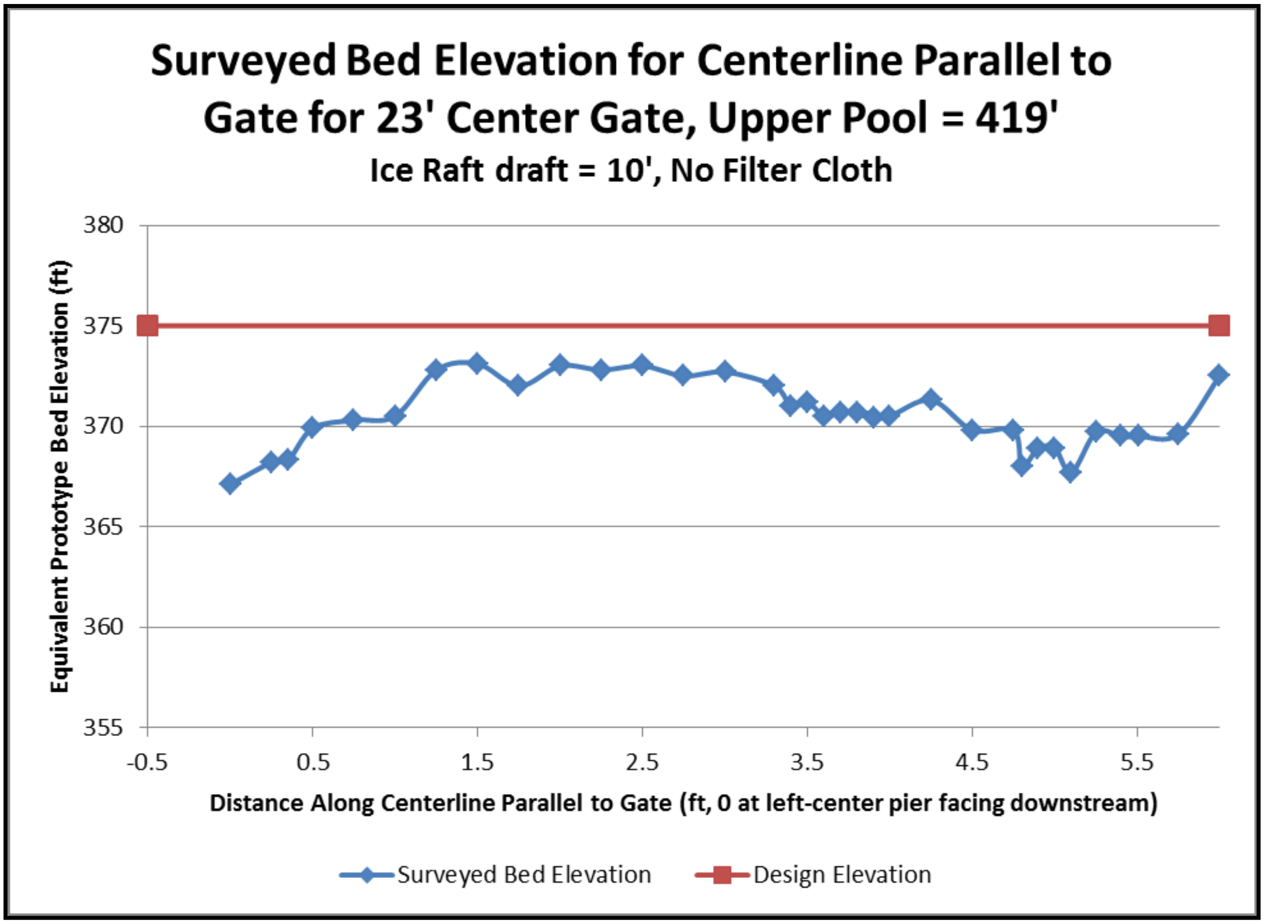


Figure 15 - Bed scour survey taken after test run 10-13-09

To this point in the testing, the buildup of ice around the piers was simulated using the wood raft. The project team questioned whether the raft represented a legitimate simulation of the effects of ice on scour. The project team decided to model the ice using the polyethylene cubes described above. The polyethylene ice had the advantage over the ice raft in that it, like the river ice, consisted of a multitude of different chunks that could pack. The initial tests with the polyethylene ice focused on getting the ice to pack and tighten like real ice (Figure 16). These tests quickly revealed that the polyethylene was a poor proxy for real ice; the polyethylene lacked the variable shape and thickness of real ice. Because of the geometry differences, the polyethylene formed a single-piece-thick matrix on the water surface, unlike real ice, which can slide, stick, and tighten into a mass with other pieces. Higher flows were used in an attempt to get the ice to pack, but these flows led to a flushing passage of the polyethylene. With the polyethylene ice failing to pack on its own, manual packing was initiated a broom to agitate the upstream water surface bed with a stirring motion to submerge and layer the ice (Figure 17). Tests utilizing manually-packed polyethylene were run, but as before, no scour occurred before high flows passed the polyethylene through the model gates.

Figure 16 - Acrylic ice pieces in the flume upstream of the gates

Figure 17 - Mechanically packed acrylic ice upstream of the gates

The hydraulic model was next used to test the lock and dam operators' statement that ice was growing as thick as 13 ft – 14 ft. thick based on the gate openings necessary to pass large pieces of ice. These ice thickness estimates were also supported by numerical model tests. A test was run using the following parameters: the ice raft drafting 13-14 ft.; the original bed rock armor in place; the polyethylene ice manually packed to a 4-6 ft. thickness upriver of the ice raft; the filter cloth in place; the center gate open to 20 ft; and the side gates open to approximately 2.5 ft (to avoid filling and submerging the ice raft). The test was run for six hours, during which a minor amount of artificial ice passed under through the center gate bay under the gate.

The test showed a significant amount of scouring had occurred immediately adjacent to the pier heads; the scour depth reached to an equivalent of a 10 ft prototype depth (Figure 18 - 19). Sand from underneath the filter cloth was pulled out through the gates. There was also scour directly in front of the gate, again with both rock and sand moving. The scour around the center gate appeared similar to prototype scour, suggesting that a case had been found that mirrored the real-world. The test was repeated with similar results recorded. The stone was then switched to the first repair to insure that the scour was not specific to the rock size or the particular rock placement, and again similar results occurred.

Figure 18 - Pier Scour after testing with a 13 - 14 ft ice raft draft

Figure 19 - Close up on right pier scour after testing with a 13 - 14 ft ice raft draft

Once the scouring conditions were established in the prototype and physical model, the focus of the testing shifted to finding a measurable distinction when scouring did and did not occur in the model. Tests were conducted to determine the effects of operating with: a center gate opening between 16 ft. and a 20ft.; an additional gate open at different heights; and one gate open to a set height versus two gates open to the same height. Flow velocities were measured using an Acoustic Doppler Velocimeter (ADV) and velocity profiles graphed to determine the change in velocity representative of scour occurring and not occurring.

The ADV measurements revealed two important findings: 1) the maximum possible velocity obtained with multiple testing configurations was approximately 24 fps; and 2) variable side gate tests suggest that opening a side gate and the center gate to 16 ft. open at the same time reduces bed velocity (Figures 20 - 24). The velocity measurements taken during the multiple open gate simulations demonstrate the correlation of dam operations with shear stress and scour. The tests suggest a combination of operations-based and design base improvements should be considered to decrease the shear stress and scour.

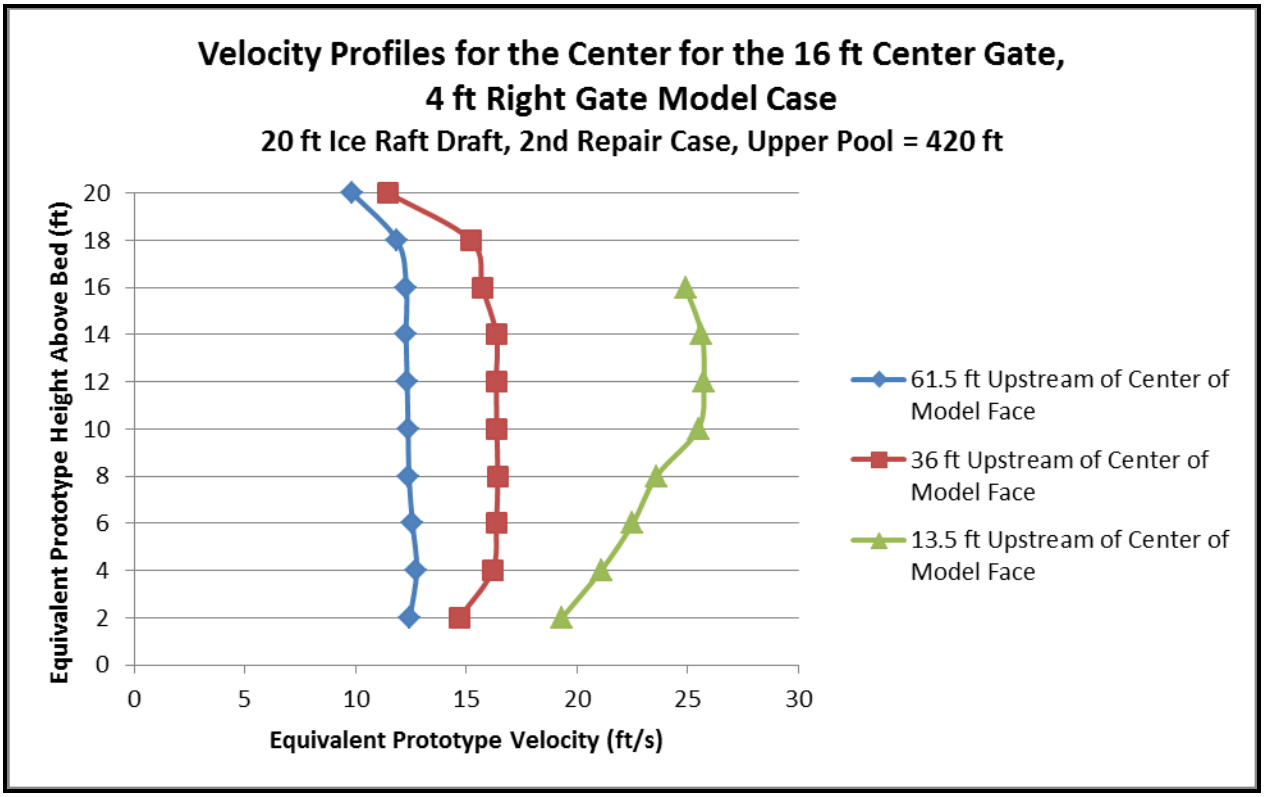


Figure 20

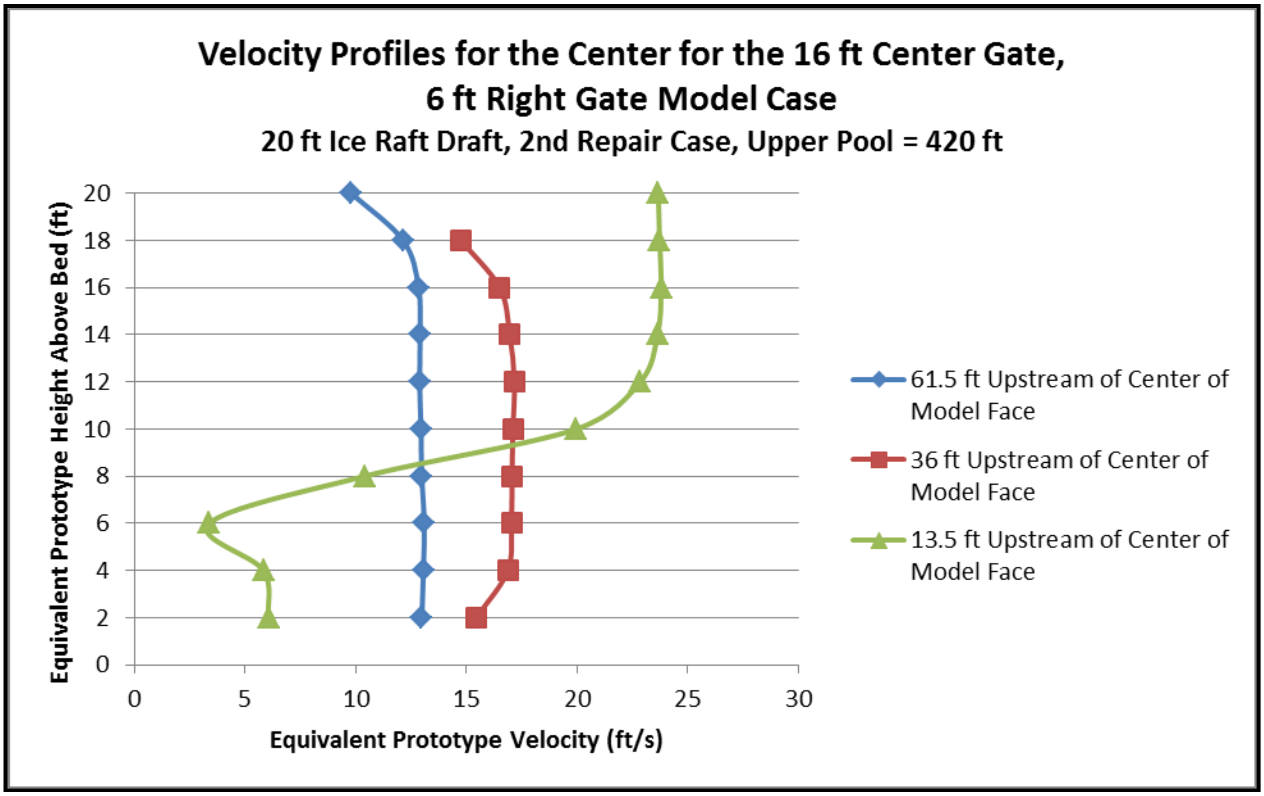


Figure 21

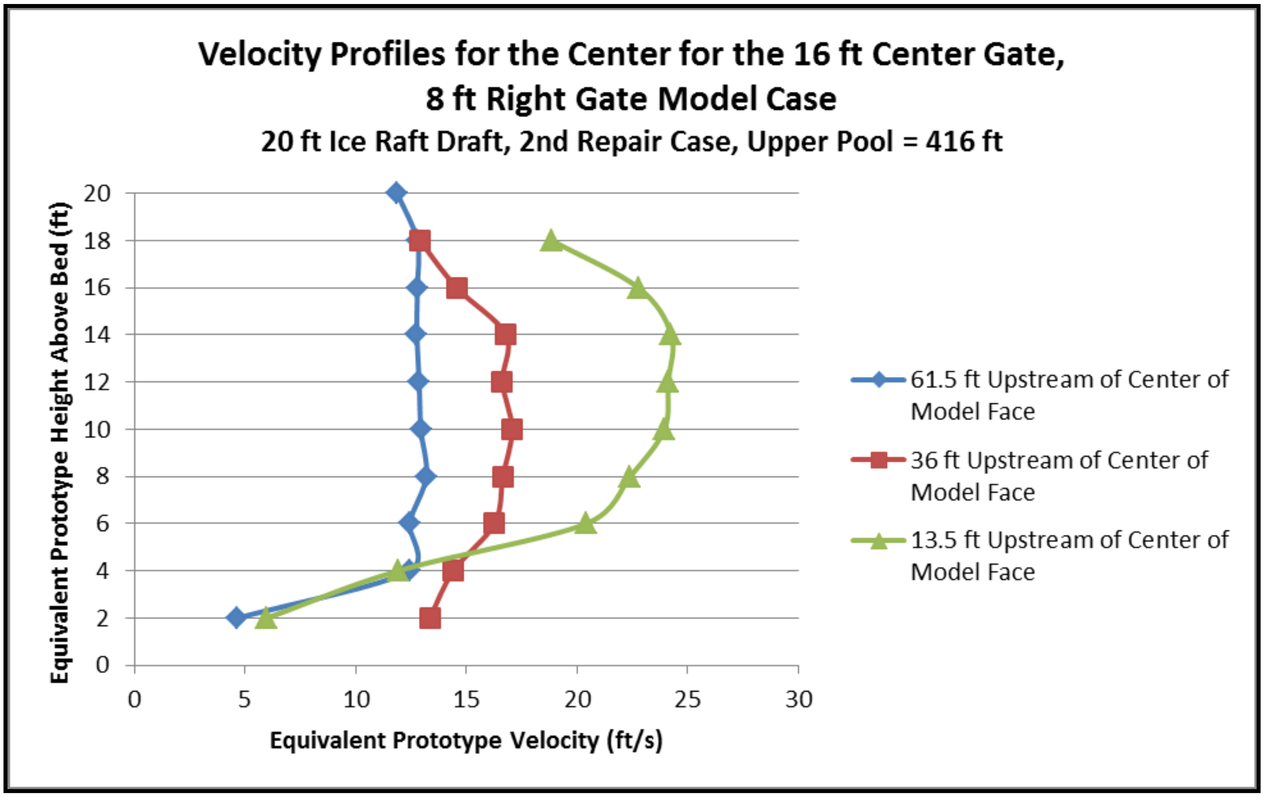

Velocity Profiles for the Center for the 16 ft Center Gate, 8 ft Right Gate Model Case
20 ft Ice Raft Draft, 2nd Repair Case, Upper Pool = 416 ft
Equivalent Prototype Height Above Bed (ft)
Equivalent Prototype Velocity (ft/s)
0
2
4
6
8
10
12
14
16
18
20
0
5
10
15
20
25
30
61.5 ft Upstream of Center of Model Face
36 ft Upstream of Center of Model Face
13.5 ft Upstream of Center of Model Face

Figure 22

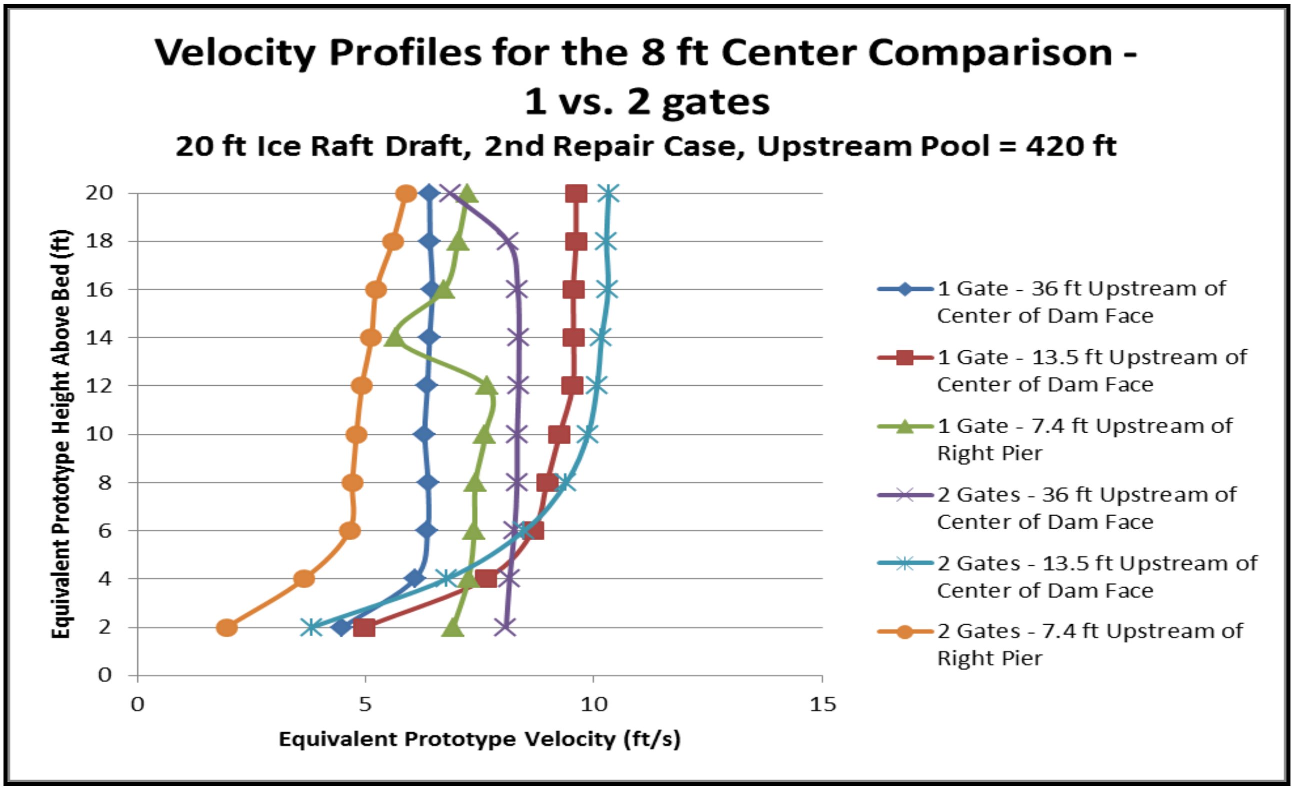

Velocity Profiles for the 8 ft Center Comparison - 1 vs. 2 gates
20 ft Ice Raft Draft, 2nd Repair Case, Upstream Pool = 420 ft
Equivalent Prototype Height Above Bed (ft)
Equivalent Prototype Velocity (ft/s)
0
2
4
6
8
10
12
14
16
18
20
0
5
10
15
1 Gate - 36 ft Upstream of Center of Dam Face
1 Gate - 13.5 ft Upstream of Center of Dam Face
1 Gate - 7.4 ft Upstream of Right Pier
2 Gates - 36 ft Upstream of Center of Dam Face
2 Gates - 13.5 ft Upstream of Center of Dam Face
2 Gates - 7.4 ft Upstream of Right Pier

Figure 23

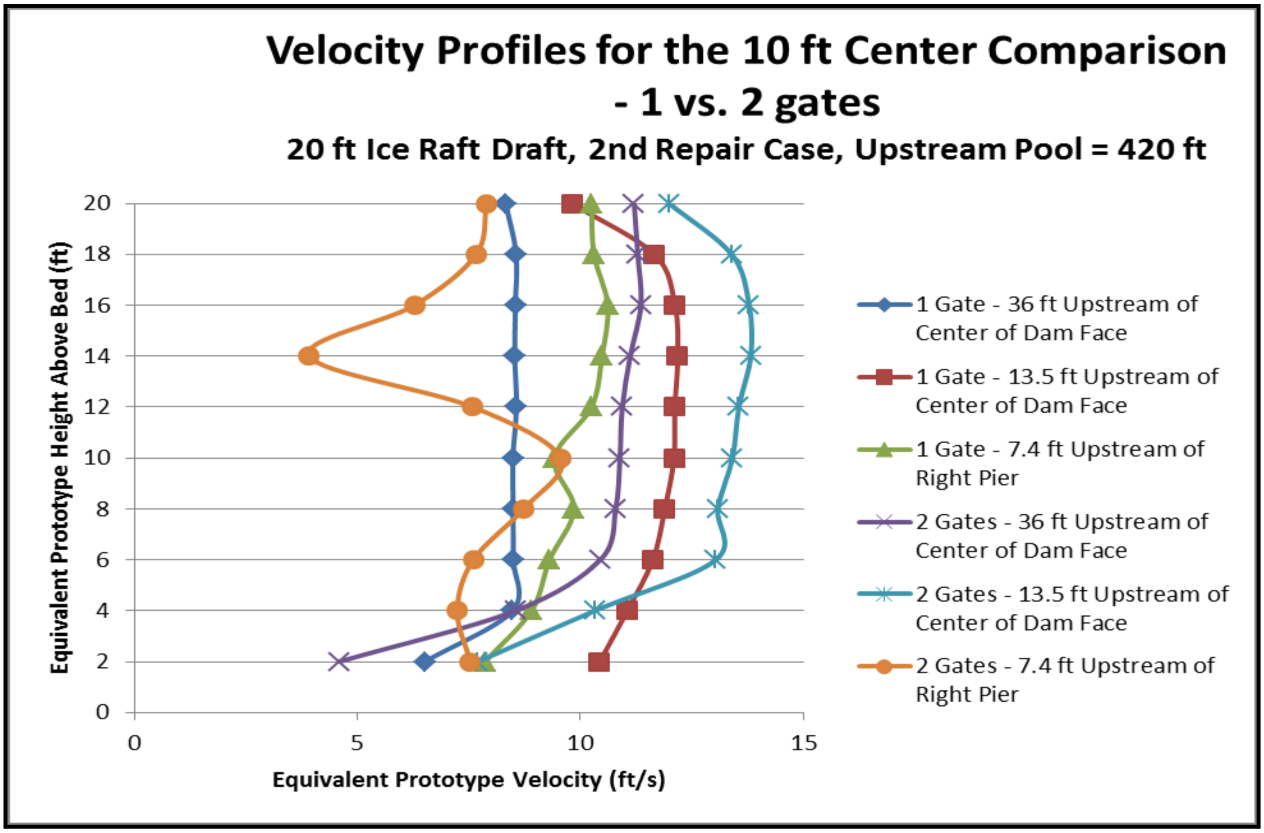


Figure 24

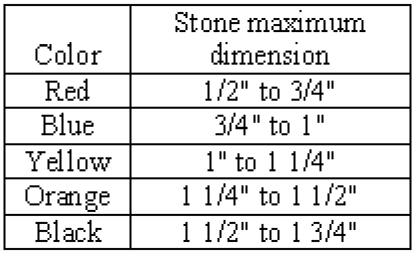
It was observed during the previous tests that low amounts of bed scour were occurring despite model conditions considered beyond normal operations for the prototype. A test was run with a 20 ft ice raft draft and pool conditions set at 420 ft upper and 395 ft lower to examine the scouring of 2nd repair stone bed protection. The bed was sorted in this test to re-create the repair stone conditions. The center gate was initially set at an 8 ft opening and slowly opened at 2 ft intervals to 20 ft.

During the gate opening process, underwater video taken of the bed activity recorded stone ejection starting at a 14 ft center gate opening with movement continuing sporadically until the end of the test. The video along with close-up photographs taken at the end of the test showed that scour was evident under the high flow conditions but was limited to the area in close proximity to the pier. The test was repeated with the stone gradations painted different colors (Table 3) to improve stone recognition. A section of the stone bed armor protection immediately in front of the right model pier was replaced with the painted stones mixed to replicate the 2nd repair gradation. Repeating the test with the painted stones revealed that the flow was mobilizing typically only the smallest size stones (Figure 25).

The modeling team tested different alternatives to determine if a capping layer of stone would prevent scour using the same parameters outlined above except for the make-up of the painted stone section of the bed. Instead of matching the 2nd gradation, the painted stones were prepared in two layers: a bottom layer consisting of the red and blue stones (the smallest stones in the gradation) and a single top layer of yellow and orange stones. Movement and stone ejection in the 14 ft. – 16 ft. center gate opening range again occurred, with six yellow stones and one orange stone ejecting during the test (Figure 26).

Because of the failure of the yellow and orange top layer, a test was run with a bottom layer of yellow, red, and blue stone and a single thickness top layer of black and orange stone (believing the orange stone ejection from the previous test to potentially be an outlier). For this test condition, rock movement again began at a 14 ft. center gate opening. Ejection of two orange rocks occurred with the center gate open 18 ft. and the right gate just beginning to be opened to 2 ft. (Figure 27).

Due to the ejection of the two orange stones, the next test was conducted to determine if a confining layer of stone was feasible using the same bottom layer, but with a top layer comprised exclusively of black stones (5,000 lb stones in the prototype). Tests revealed that black stones could be ejected at flows corresponding to gate openings as low as 16 ft. under the right initial placement conditions and without packing or organizing the stones (Figure 28). Given the likely method of placement large stone would be off of a barge, larger stone sizes were not tested for the corresponding prototype flow.



Color	Stone maximum dimension
Red	1/2" to 3/4"
Blue	3/4" to 1"
Yellow	1" to 1 1/4"
Orange	1 1/4" to 1 1/2"
Black	1 1/2" to 1 3/4"

Table 2 - Model painted stone gradation

Figure 25 - Movement of painted 2nd repair stone

Figure 26 - Orange and yellow stone cap layer movement

Figure 27 - Black and orange stone cap layer movement

Figure 28 - Black stone cap layer movement

Because of the movement of the black stone, several alternatives were discussed for the capping layer in the model. The use of stone larger than 5,000 lb. prototype was ruled out due to the high cost of acquisition and the need for a means of effectively placing such large stone in front of the dam. A concrete pad was discussed but dismissed due to potential cost. Concrete blocks were dismissed in favor of grout-filled bags which could possibly be constructed on-site and placed with a closer spacing. Two sizes of bags were tested: 1) 2.25 ft. by 4.25 ft. by 8.5 ft. weighing approximately 9,000 lbs. and 2) 2 ft. by 4.25 ft. by 12.5 ft. weighing approximately 14,000 lbs.

The smaller sized bags were tested first and were placed on top of the stone bed armor repaired to the design elevation with the 2nd repair stone and with the long dimension oriented parallel to the flow. During the test, five of the grout-filled bags were lifted from the bed and ejected through the gate bay, with two of the bags lifting off as the gate transitioned to a 14 ft. center gate opening (Figure 29).

The larger grout-filled bags were tested next but with the bags positioned perpendicular to the flow. During the test, six grout filled bags were lifted and ejected through the gate bay, the first when the gate was at a 12 ft. gate opening (Figure 30**)**. It should be noted that movement below the 14 ft. – 16 ft. threshold was frequently seen in the underwater video tests. Because of concerns that the grout-filled bags protruded from the bed, the test was rerun with the top of the bags level with design bed elevation. The bags were again ejected starting at the transition to a 14 ft. center gate opening (Figure 31).

Figure 29 - Movement of model 9,000 lb grout-filled bags during testing

Figure 30 - Movement of model 14,000 lb grout-filled bag during testing

Figure 31 - Movement of model 14,000 lb grout-filled bag during testing

The movement of the larger grout-filled bags shifted the emphasis of the possible solutions testing away from the use of a capping layer to changing the design elevation of the stone bed protection. Changing the elevation of the stone bed protection potentially does two things to alleviate scour: 1) it increases the cross-sectional area, reducing velocity and bed shear stress, and 2) it lowers the stone bed protection away from near-sill turbulence. The stone bed protection was lowered to an elevation of 370 ft. and the 14,000 lb bags were buried in the immediate vicinity of the sill and piers to match the design top elevation of the stone bed protection. This test was run with center gate starting at an 8 ft. opening and incrementally increasing to an 18 ft. opening. During this test, none of the grout-filled bags moved (Figure 32**).**

Figure 32 - 14,000 lb grout-filled bags in place after testing at 370 ft. elevation

The initial test at the lowered stone bed protection elevation proved promising so the test was reconfigured to account for more of the in-situ environment. The next test was run with a 370 ft stone bed protection and the 2nd repair stone at 370 ft elevation for 20 ft in front of the sill. The bed was then transitioned to a 1V:6H slope for 30 ft., and leveled off at 375 ft elevation for 25 ft. This test was repeated with incremental gate conditions starting at an 8 ft. opening and increasing to an 18 ft. opening. The near sill bed proved to be stable in this test, but the lower end of the transition slope moved significantly.

The bed was then set to a single configuration based on a top stone bed protection elevation of 370 ft. and the 2nd repair stone placed 20 ft deep from the sill to approximately 85 ft from the face of the dam. Multiple flow conditions were run for this bed configuration. During the first run, the center gate was held at a 14 ft. opening and the test run overnight with the ice raft drafting 20 ft. No scour occurred during this test. The test was repeated with an 18 ft. center gate opening. Again, after running overnight, no scour occurred. The third flow condition was run with the center gate set at a 10 ft. opening. The gate was opened incrementally to 18 ft and then fluctuated between a 10 ft. and 18 ft. center gate opening. The right gate was also open to 8 ft. for both center gate conditions. Once again, there was no movement of stone during testing.

The last set of tests was similar to the previous three with the exception of the stone gradation. Instead of using a 20 ft. deep layer of 2nd repair stone for the entire length of the stone bed protection, the 2nd repair stone was placed only within a 20 ft. proximity of the dam, with the original stone gradation used for the remaining upstream stone bed protection. Once again, overnight tests run with 10 ft. and 20 ft. center gate openings showed no evidence of movement in the post-test bed photographs. A test was also run with the center gate opening incrementally from 10 ft. to 20 ft. and then varied between 10 ft. and 20 ft. The test continued with the 20 ft. center gate opening, the right gate opening incrementally from 0 ft. to 10 ft., and then the right gate varied between 2 ft. and 10 ft. open with the same center gate opening. No movement was recorded throughout this test.

Data Considerations

One shortcoming of the physical model testing was the quality of the simulation of the ice. The methods used to simulate ice in the physical model were at the two extremes of the natural cohesion of ice with the acrylic ice pieces exhibiting no cohesion and the ice raft exhibiting complete cohesion. The only interactions the pieces of acrylic ice exhibited were bumping and sliding; they did not tighten to a point to reflect the confinement of cross-sectional area and elements of pipe flow that natural ice exhibits. The ice raft performed in an opposite manner by not allowing any break up and creating unnatural situations like the ice controlling the depth in the upper pool. A second major failing of the river ice simulations more pertinent to the use of the acrylic ice was the downriver pressure exerted by the upriver ice sheet, which would have potentially affected packing, could not be modeled.

A second deficiency of the physical model was the scalability of the Mississippi River bed versus the flume bed, particularly sand. Scaling the bed of the Mississippi River for rock gradations smaller than those used in the stone bed armor section would have required using particles 1:25 the size of sand grains and would have been both inordinately expensive and difficult to work with. Instead, a clean sand was used with the understanding that the model fails to properly model the effect small sediments have on scour.

Summary

Normal flow conditions and high water conditions were tested to see if they resulted in upstream stone bed protection scour. Neither case resulted in scour mirroring the prototype.

Ice was the next major variable considered in an attempt to generate scour similar to the prototype. Ice was initially modeled using a raft built to simulate ice conditions in front of a dam. The raft was drafted 10 ft for multiple tests to mimic a corresponding ice growth built up in front of the dam gates. Scour occurred, but not to depths representative of the prototype.

Further testing the assumption that upstream ice buildup was the source of the scour issue, ice was modeled with polyethylene as an alternative to the ice raft. The polyethylene was cut into size fractions mimicking the actual gradation of frazil ice. Despite multiple gate configurations, the polyethylene did not stack to grow in thickness as natural river ice does, nor did it act as a confining layer for the flow.

Tests were conducted with the draft of the ice raft drafting approximately 13 ft – 14 ft instead of the original 10 ft. This slight increase in depth was found to significantly change the scour effects on the bed; unlike the 10 ft. draft, the 13 – 14 ft. draft was found to produce scour similar to scour identified in the prototype. A series of tests performed with different gate openings revealed that the use of smaller gate openings and the opening of multiple adjacent gates reduced the bed velocity, leading to a lower bed shear stress and less scour.

Tests were performed to find a constructible solution to the upstream scour problem. Initial tests focused on increasing the size of the surface stone bed protection, but an effective capping layer size was not found. The use of grout-filled bags as a capping layer immediately adjacent to the dam was tested but resulted in less than favorable results.

Lowering the design elevation of the stone bed protection from 375 ft. to 370 ft. was tested for stone bed protection consisting entirely of the 2nd repair gradation. No recordable movement was observed in both high opening and variable opening gate conditions. The tests were repeated with the stone bed protection simulating the current stone conditions of the prototype at the 370 ft. elevation with similar results.

RECOMMENDATIONS

The findings of this study is that the upstream stone bed protection at Mel Price Lock and Dam be constructed to a new elevation of 370 ft. Lowering the top elevation of the stone bed protection from 375 ft. to 370 ft. increases the cross-sectional area in the immediate vicinity of the dam gate bays, and distances the stone bed protection from entrance turbulence at the dam sill.

It is recognized that lowering the design elevation of the stone bed protection is not a viable solution at all sites undergoing upstream scour due to ice. In addition to the lower design elevation for the stone bed protection, the results of this study recommend a change in lock and dam operations at sites where ice scour presents a threat. Passing ice more frequently through the gates would lower ice thickness which would lead to less restriction of the upstream cross section in the area immediately adjacent to the dam and require lower gate openings for flushing ice. However, flushing ice more frequently conflicts with the need to maintain the pool level upstream of the lock and dam. Trial and error at each site along with a means of estimating ice thickness would be needed to determine new guidance for gate operations.

A second operations recommendation from this study is the collection of regular upstream scour surveys of the lock and dam. At Mel Price, scour holes have developed in the immediate vicinity of multiple dam piers that already reach down to the recommended stone bed protection elevation of 370 ft. It is recommended that these holes be monitored with periodic surveys, as the scour holes are believed to have a higher potential for further scour than if the new design elevation were implemented for the entire stone bed protection.