Summary Report
Lock and Dam 24 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. This prompted a survey at Lock and Dam 24which revealed the formation of multiple scour holes; the deepest occurring at Pier 4 reaching approximately 4 ft below the pier base (8.5 ft below the design elevation of the stone bed protection). Due to the reoccurring nature of the scour at Mel Price Lock and Dam and the discovery of similar scour problems at Locks and Dams 24 and 25, physical and numerical modeling efforts were conducted in an attempt to determine the cause and to test possible solutions.

Testing was done using a scale hydraulic model located at the Corps of Engineer's Engineering Research and Development Center (ERDC) Coastal and Hydraulics Lab (CHL). The physical testing identified the buildup of ice in front of the lock gates as the primary cause of the upstream scour. The primary recommendation from the model testing was to lower the design elevation of the upstream stone bed protection 5 feet. The solution found from the Mel Price lock and dam testing was not constructible at Lock and Dam 24 because the dam sill at Mel Price is 14 feet thicker than at Lock and Dam 24.

A scale hydraulic model was constructed to examine the upstream scour conditions with respect to ice buildup upstream of Lock and Dam 24. The physical modeling again supported the assertion that the buildup of ice upstream of the dam gates is a significant factor in causing upstream scour. The test results indicated that opening the two gates adjacent to the three center gates used for ice passage 5 ft would alleviate scour adjacent to the piers. A second recommendation of the model testing is to extend the upstream scour protection 30 ft to reduce both upstream and near-pier scour. Two additional recommendations are to conduct regular surveys of the upstream stone bed protection and to minimize upstream ice buildup.

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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 July 19, 2011, and Mr. Timothy Lauth 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. William Curtis, 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 Kevin Wilson was Commander and Executive Director of ERDC. Dr. Jeffrey P. Holland was Director.

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

Lock and Dam 24 is located on the Mississippi River at River Mile 273.4 near Clarksville, MO. It is approximately 64 miles northwest of St. Louis, MO (**Figure 1**). Construction began in July 1936 and was finished in March 1940. A major rehabilitation project was completed in 2005. Lock and Dam 24 has one 600 ft long lock chamber controlled with two miter gates (**Figure 2**). The dam is 1,340 feet long and water level is controlled by the manipulation of fifteen 80-ft-wide tainter gates. There is a 2,720 ft auxiliary spillway adjacent to the dam on the Illinois side. Over 24 million tons of cargo was locked through in 2010 when over 3,800 lockages were completed. The structure maintains a pool that is 27.8 miles long covering 13,000 acres. The pool elevation in the vicinity upstream of the dam is typically 448.58 ft. The dam has a stone bed armor layer of 5 ton stone that extends approximately 24 ft from the dam sill.

In April 2007, a routine bathymetric survey at Mel Price Lock and Dam revealed the presence of scour holes in the stone bed armor adjacent to all of the upriver piers. Some of the holes were scoured up to 22 ft deep, and presented a risk of possibly undermining the structure. A subsequent survey at Lock and Dam 24 (LD 24) on April 20, 2007 revealed multiple scour holes in front of piers; the deepest reaching a depth of 8.5 ft in front of Pier 4. At this depth, the scour was 4 ft below the pier base and exposed part of the sheet pile cutoff wall and the upstream timber piling. Further erosion past the sheet pile cutoff wall could cause the dam foundation to erode. Less scour was revealed at Piers 5 through 11.

After the discovery of the upstream scouring at LD 24 and the re-occurring scour at Mel Price Lock and Dam, physical and numerical modeling was conducted to determine a possible cause and a solution to the scour. Ice buildup upstream of the dam was found to be the primary cause of upstream scour in the physical model, and the construction solution that proved successful was to lower the design elevation of the stone bed protection from its design elevation of 375 ft to a position 5 ft lower at 370 ft. However, lowering of the stone bed protection was not a solution that would apply to all situations (additional information is available in **Summary Report - Mel Price Lock and Dam Physical Model, Upstream Scour)**. At Locks and Dams 24 and 25, where the sill thickness is much less than at Mel Price, lowering the stone bed protection 5 ft would lower the design elevation for the protection below the pier base elevation. This would result in some of the wooden piles that support the pier being exposed and potentially the exposure of the sheet pile cutoff wall. To investigate a second solution for upstream scour at lock and dam sites, additional modeling at the Coastal Hydraulics Laboratory (CHL) in Vicksburg was approved.

Scour was identified at Lock and Dam 25 (LD25) in the same time frame as the discovery of upstream scour at Mel Price Lock and Dam and Lock and Dam 24. The scour at LD25 was worse than that at LD 24, with the deepest scour hole exposing 11 ft beneath the dam pier base. The severity of the scour at LD25 prompted the design and construction of a repair initiated in May 2008. The repair consisted of: 1) filling the holes in the vicinity of the piers with a combination of sand and grout held in place with permanent formwork and 2) re-establishing the upstream stone bed protection. A survey taken in August 2011 revealed that the stone bed protection near the piers was within 2 ft of the design elevation.

Scour holes were previously discovered immediately upstream of LD 24 in August of 1977. These scour holes were upstream of Piers 5 through 9 and ranged from 4 to 8 ft deep. The holes were filled with 42 inches of 1000 lb. riprap placed on graded stone 'C' as part of a stone protection replacement contract at the lock and dam in 1978.

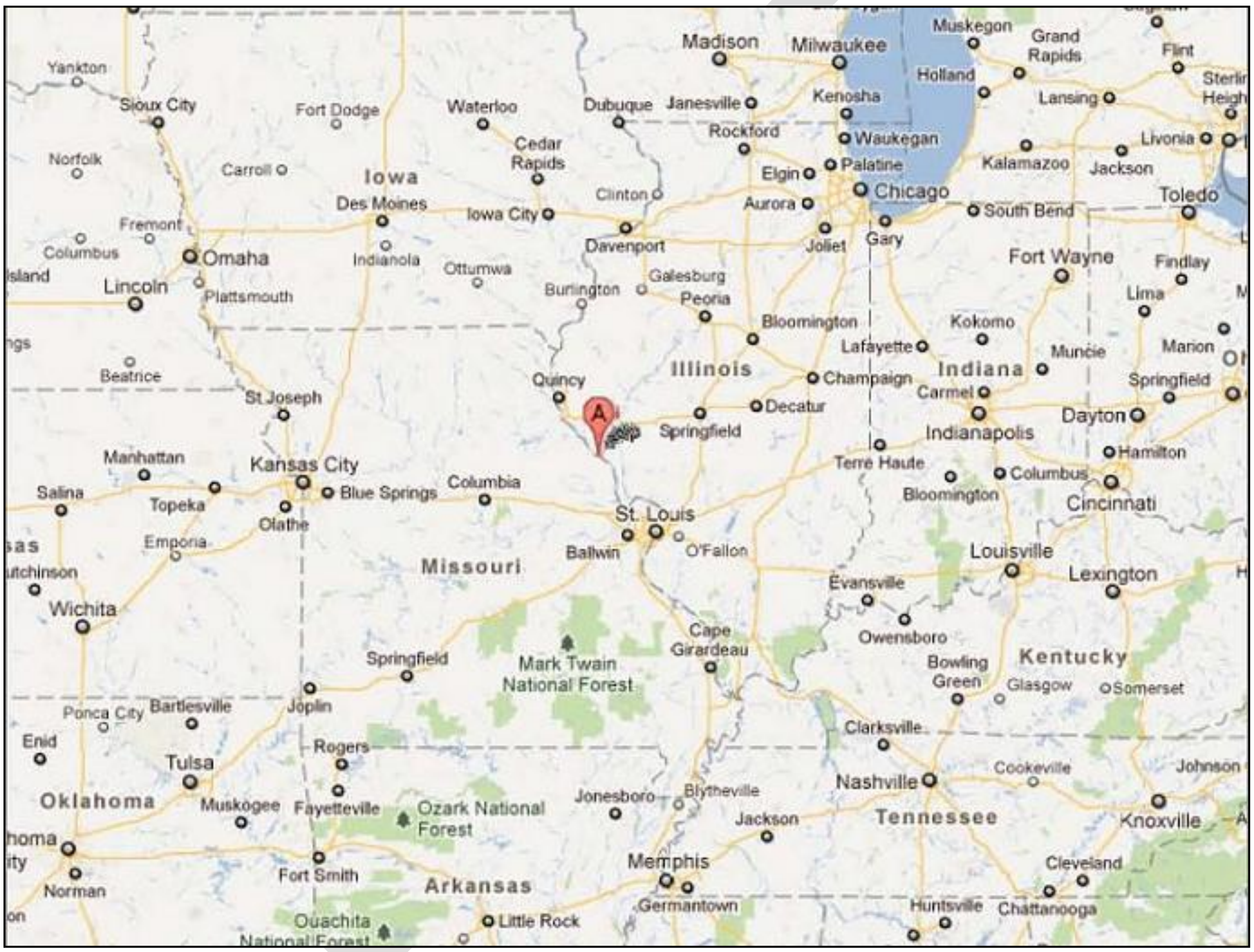


Figure 1 - Vicinity Map

Figure 2 - Aerial photograph of Lock and Dam 24

Analysis of Upstream Bathymetry

As part of the investigation of the upstream scour issue, 3-dimensional renderings of the previous bathymetric surveys conducted at Lock and Dam 24 were reviewed. The images included in **Appendix A** are 3-dimensional renderings of the bathymetric surveys developed using Fledermaus software. The color scale was held constant for all surveys and all images are displayed with the upstream to the north; the Illinois bankline is to the right and Missouri bankline to the left. The gate numbers on the first image are used as a reference for discussion. Below is the survey chronology, followed by the effects in bathymetry since the previous survey

1. December 4, 2007 – Scour holes are evident at Piers 4 thru 11, with no scour hole extending completely across a gate bay. The holes reached a maximum depth of approximately 10 ft (adjacent to Pier 4) which put the structure at a risk of undermining, as the concrete sill of the dam extends down only 6 ft.
2. July 9, 2008 – In the 7 months since the last survey, 1-2 ft of material were deposited in large areas upstream of the lock and dam. Further upstream, deeper deposition occurred upstream of gates 1 and 3 thru 12; scour occurred upstream of gates 13 and 14.
3. December 8, 2008 – Five months later, the majority of the stone bed protection had changed ± 1 ft; what change outside of that occurred was a loss of material of -1 to -2 ft. Immediately upstream of the stone bed protection, losses of elevation up to -9 ft had occurred in multiple locations, though this was likely due to the passing of sand waves.
4. April 1, 2009 – The first survey of the location performed in 2009 revealed little change in the stone bed protection in the preceding 4 months, and the change that did occur was typically +1 to +2 ft of aggregation. Upstream of the stone bed protection, the losses of elevation previously were once again gaining material, with gains of approximately +10 ft occurring in front of Gates 2 and 3.
5. May 3, 2010 – No significant change was evident in the stone bed protection. Upstream of the protection, both areas of erosion and deposition were evident, with erosion prominent in the center and on the right descending bank side of the channel and deposition on the left descending bank of the channel.
6. September 8, 2011 – In the 16 months since the previous survey, the stone bed protection exhibited little to no change; what change did occur was largely a loss of material of -1 to -2 ft. Changes upstream of the stone bed protection are split between deposition and erosion.
7. February 15, 2012 – Almost no change occurred in the 5 months between surveys; the single aberration is scour up to -6 ft in front of Gate 7 and Pier 8.

Purpose and Scope of Model Investigation

A physical model was used to test the assertion that the buildup of ice upstream of the lock and dam was the driving mechanism of the upstream scour by re-creating the scour under known conditions. Once the upstream scour was successfully simulated, additional testing was conducted to determine a means of relieving or eliminating the upstream scour with a combination of operational practices and constructible physical changes. A 1:25-scale model simulating five of the tainter gates and the upper bed structure was used in the investigation.

The Corps of Engineers currently does not have a design guide that addresses the issue of upstream scour or a standard of practice for the passing of ice at the locks and dams. It is the desire of everyone involved with this project that the results of this model investigation will serve as the impetus for such guidance.

Mel Price Lock and Dam Model Investigation

A 1:25-scale section model of three of the tainter gates and the upper bed structure of the Mel Price Lock and Dam was previously developed to investigate the occurrence upstream scour. After the initial tests ruled out normal operating conditions as a cause of the scouring, the investigation focused on the build-up of ice along the gates of the locks and dam. Based on input from the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), an ice raft was constructed to replicate the displacement and roughness of ice. Different gate openings, the wooden raft replicating ice drafting 10 ft, and filter cloth simulating a stone bedding material were tested in different combinations to re-create the scouring found in the surveys.

Scour did occur, but the amount of scour occurring in the model was significantly less than what was measured at the prototype (the actual Lock and Dam). During these tests, the open river condition was also modeled as it was considered a unique condition of river operation, but the scour produced was minimal.

After the initial ice testing proved unsuccessful at replicating the prototype, cut sheets of polyethylene were used to simulate various types of ice packs. It was discovered the polyethylene did not act as a confining layer, wouldn't stack, and lacked cohesiveness. It was decided to return to the use of the ice raft, but to draft to a deeper depth representing an increased ice build-up in front of the dam. The deeper draft created the desired representative scour, and the level of ice buildup tested was confirmed both with numerical simulations and operations practices at the lock and dam.

Once the cause of the upriver scour was determined, tests were conducted to determine if scour could be prevented by changing the gradation of the stone bed protection upstream of the dam. This proved not to be a viable alternative as rocks as large as 5,000 lb as well as 9,000 lb and 14,000 lb grout-filled bags were found to move well below the test flow condition.

Having eliminated the use of larger stone as a solution, the next testing possibility was lowering the design elevation of the stone bed protection. These tests were successful and showed that by lowering the design elevation of the stone bed protection 5 ft, the second repair stone would be stable under multiple gate conditions. This was taken as the solution for the prototype. The upstream stone bed protection has scoured to approximately 5 ft below the original design elevation to the current recommended design elevation at select piers. The stone protection is surveyed once a year to monitor scour progress.

Physical Model Development

The Lock and Dam 24 physical model was built at the Engineer Research and Development Center (ERDC) Coastal and Hydraulics Laboratory in Vicksburg, MS. A 1 ft to 25 ft scale model of five tainter gates was constructed inside a 69 ft long, 21.1 ft wide flume. The five tainter gates were used 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.

The upriver sand bed section of the model sloped up to a bench in front of the gate structure to better replicate the upstream approach geometry. 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 both the original stone placement and the 1977-78 repairs. The prototype stone gradations are presented in **Appendix B**. Filter cloth was used underneath the bed stone armor to provide a better simulation of bedding material and to reducing piping.

Stone cobbles were used below the spillway to dissipate the velocity of the flow through the gates (**Figure 4**). The tailwater and upriver pool elevations were measured with rulers set to scale in both portions of the model. The flow into the flume is supplied by 12-inch and 20-inch diameter pipes from a constant head tank fed by multiple pumps. The maximum flow possible into the flume is 40 cfs. A gate was used at the end of the flume to maintain the tailwater pool elevation.

A walkway was built over the gates to provide better access to the gates' worm-drive controls and a second, moveable walkway was used to assist with taking measurements and recording video. The gates were outfitted with scaled rods 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 model gate structure and walkway viewed from downstream

Ice Development

Ice development was simulated using a 21ft x 4ft x 1.2 ft wooden raft built in three sections to facilitate installation and removal (**Figure 5**). The bottom of a raft was sloped and lined with chicken wire to simulate the natural friction of the ice. The draft was controlled by adding or removing lead weights. Initially, walled cutouts were made in three of the sections to allow use of an underwater camera, lighting, and a 2D acoustic Doppler velocimeter (ADV) used to take velocity measurements underneath the ice raft. After later tests suggested that the panels were exaggerating the scour, the cutouts were covered and PVC shafts were installed in the raft to allow for the continued use of the ADV.

Figure 5 - Wooden raft used to simulate upstream ice

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 must 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.

Table 1 - Scale Relations

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

Testing

The main objective of the Lock and Dam 24 physical model testing was to develop a means of reducing or eliminating scouring of the upstream stone bed protection. Because of the goal-specific nature of the investigation, the testing schedule was often evolutionary as compared to regimented. To develop a means of reducing or eliminating scour, conditions representative of the scour occurring at the prototype needed to be generated in the model. Two different scour patterns were required for the model scour to be considered representative: 1) scour hole development around the piers, and 2) unraveling of the upstream edge of the stone bed protection leading to protection failing forward (**Figure 6**).

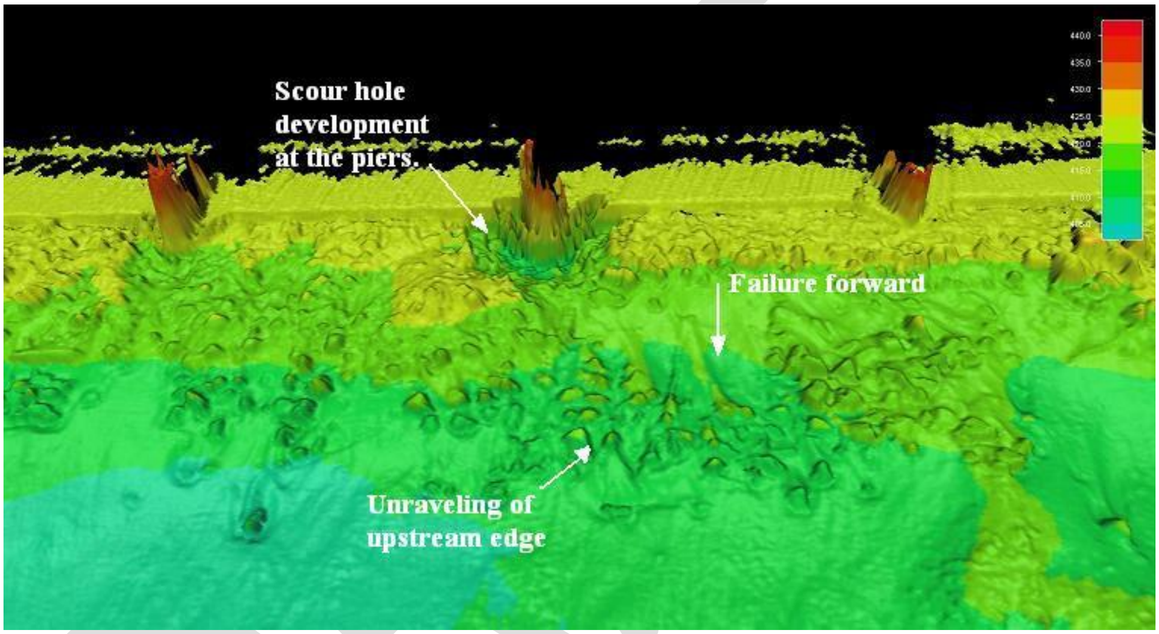


Figure 6 - February 15, 2012 Hydrographic survey

Testing began with the setting of initial test conditions: filter cloth was placed underneath the stone bed protection, the sand bed graded to design conditions, the stone bed protection screened to gradation, the stone bed protection was set depending on the repair condition being tested, and a decision made as to gate conditions for the test. Once the initial conditions were set, the water levels in the upper and lower pools where slowly raised by slightly opening the gates. The pool levels were maintained by opening or closing the gates in conjunction with adjusting flow rate of water in the flume. . .

At prescribed gate conditions, the model would be run with the model gates and flow rates lowered simultaneously to avoid overfilling the flume and disrupting the bed. With the flow reduced, the ice raft was floated upstream of the model as to not disturb the bed with the low clearance of the ice draft.

The initial tests in December 2011 were run to determine if the scour was occurring without the presence of ice. The tests were run with variable gate openings up to 17 ft simulating a 449 ft prototype upper pool elevation and a 434 ft prototype lower pool elevation. The upper pool elevation would be set at 449 ft for all following tests; the lower pool was set at a prototype elevation of 434 ft for conditions with no ice present, and 438 ft for conditions where upstream ice was simulated. For these tests without simulated ice, the stone bed protection did not undergo any considerable scour. The open river condition was run next, with Gates 2, 3, and 4 completely opened and with an upper pool elevation of 460 ft and a lower pool elevation of 457 ft. No scour was evident for this case.

The testing proceeded with the modeling of the build-up of ice using the ice raft as done in the Mel Price Scour modeling. Testing was conducted with the ice raft drafting 10 ft and gates 1, 2, and 3 open at multiple heights starting at 5 ft and increasing in 2 ft increments. The filter cloth was buried 6 inches below the sand elevation. This test format, with a slightly increased draft, successfully replicated the scour occurring at Mel Price Lock and Dam during the Mel Price model testing. These tests for the Lock and Dam 24 model led to little scour, and the scour that did occur was not indicative of the scour adjacent to the piers at the prototype (**Figure 7**).

Figure 7 - Variable 3 center gates, 10 ft ice raft draft

The tests were repeated with the draft of the ice raft increased to 15 ft. Additional scour occurred, but the scour was once again not representative of the scour occurring in the prototype, where the scour was focused in front of the gates instead of the piers. This test with three gates open scoured away nearly all of the protection in front of Gate 3 with the little rock remaining in front of the adjacent piers (**Figure 8)**.

Figure 8 - Variable 3 center gates, 15 ft ice raft draft

The 10 ft draft tests were repeated with the filter cloth directly below the stone protection instead of 6 inches below the surface. These tests also resulted in scour in front of the gates, and suggested failure due to the surface presences of the filter cloth. A modification was made by folding the filter cloth back around the pier to promote the stone settling instead of launching but this resulted in exaggerated scour upstream of the center gate due to the surface presences of the filter cloth (**Figure 9**).

Figure 9 - Variable 3 center gates, 10 ft ice raft draft, filter cloth removed around piers

The next attempt to generate scour representative of the prototype was performed using a smaller draft. Initially, a 5ft draft was tested with 1 gate and then 2 gates opened incrementally wider as per previous testing. These both led to non-representative center gate scour. At this time, acrylic plates were installed in the ice raft to close the main cutouts; these plates would be kept in for all additional testing.

Given the lack of success to this point in the testing, the modeling team decided to switch from varying the gate openings during tests to setting a constant gate condition and running at that condition for a longer period of time. A gate opening of 7 ft was selected based on discussions with lock and dam staff about ice passage operations (**Figure 10**). Ice drafts of 5 ft, 10 ft, 15ft, and 20 ft were tested at time intervals of 5 hours and overnight due to lab operational hours.

These tests did lead to representative scour along the leading edge of the scour protection and immediately adjacent to the pier. Comparing the results, a greater ice draft led to increased scour both upstream of the stone bed protection and at the dam piers.

Figure 10 - 7 ft center gates, 20 ft ice raft draft

Once the prototype conditions were successfully re-created, extending the upstream stone bed protection was tested with the 5, 10, 15 and 20 foot ice drafts. The gate openings were increased from 7ft to 9ft to reflect a worse case of ice passage. While the tests resulted in bed scour upstream of the stone protection, the leading edge of the stone remained intact at each ice draft. The pier scour, however, was present at all draft conditions (**Figure 11**).

Figure 11 - 7 ft center gates, 20 ft ice raft draft, 30 ft stone protection extension

The pier scour was tested using different stone placements in the immediate vicinity of the piers. The first placement was based on the Lock and Dam 25 repair. This placement tested two conditions; 1) a pier location where 8 ft of scour had occurred, allowing for placement of both the “A” and “C” stone, and 2) a pier location where 4 ft of scour had occurred, allowing for placement of only “A” stone. For all tests with two placement conditions, a successful possible solution was determined to be a solution where a maximum of 4 ft of scour occurred at the pier on either placement condition. With the ice draft set to 15 ft, the maximum scour depth observed in the first condition was approximately 6 ft (**Figure 12**); the maximum observed in the second condition was approximately 8 ft. Both conditions were more than enough to potentially reach the pier base.

Figure 12 - 9 ft center gates, modified “A” stone over modified “C” stone

The second placement tested was based on using derrick stone as the top layer of stone protection. Two conditions were again tested: 1) a pier location a pier location where 8 ft of scour had occurred, allowing for placement of both the derrick stone and modified “C” stone, and 2) a pier location where 4 ft of scour had occurred, allowing for placement of only derrick stone. The tests for these two conditions both yielded a maximum scour depth of 5-6 ft at the piers (**Figure 13**).

Figure 13 – 9 ft center gates, derrick stone over modified “C” stone

After the stone placements were tested, the model was run with the gates adjacent to the main ice passage gates open. For these tests, the three center gates of the model were held open 9 ft with the two outer gates opened 1, 3 and 5 feet. These openings were tested for two stone placements: 1) an 8 ft scour hole filled with the L&D 25 repair and 2) a 4 ft scour hole filled with modified “A” stone. The side gates open 1ft produced a maximum of 9 ft scour in the immediate vicinity of the pier and the 3 ft open tests produced a maximum of 8 ft scour. The 5 ft side gate open tests, however, produced a maximum scour depth of 3-4 ft at one gate with the other gates experiencing less than 3 ft of scour (**Figure 14**).

Figure 14 - 9 ft center gates, 5 ft side gates, modified "A" stone over modified "C" stone

With the side gate openings identified as a possible means of alleviating pier scour, tests were performed with the side gates open to determine if additional upstream stone bed protection was needed. The design length of the stone bed protection tested with the side gates open 5 ft produced pier scour with depths between 6 and 9 feet deep. This pier scour was also accompanied by scour that unraveled large portions of the upstream edge of the stone bed protection in front of Gate 3.

A test with a 15 ft extension of the stone bed protection produced 5 ft of pier scour and, although the upstream protection edge again unraveled, the stone protection in front of the gates was more stable than in previous tests (**Figure 15**). A re-testing of the 30 ft extension produced a scour depth of approximately 3-4 ft with little unraveling of the upstream edge of protection.

A test was conducted using only modified “A” stone on top of the filter cloth in the vicinity of the piers instead of a layering of modified “C” underneath modified “A” stone. This test led to up to 9 ft of scour immediately adjacent to the piers, reiterating the importance of the multiple gradations of stone.

Figure 15 - 9 ft center gates, 5 ft side gates, 15 ft protection extension

Data Considerations

One shortcoming of the physical model testing was the simulation of ice. The ice raft, as constructed, could only re-create the ice in complete cohesion. Because the raft could not simulate any ice break-up, it led to the possibility of unnatural situations like the ice potentially controlling the depth in the upper pool.

A second deficiency of the physical model was the scaling of the Mississippi River bed in the flume, particularly the bedding material and river 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 difficult to work with and expensive. Clean sand was used with the understanding that the model fails to properly model the effect small sediments have on scour.

Summary

Flows with the maximum head differential and at the open river condition 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 simulated 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 (the scour that occurred was centered in front of the gate, and not at the piers). The draft was increased to 15 ft, but the scour was still not representative. Changes were made to the filter cloth to no improvement.

Representative scour began occurring with the transition from variable gate openings to longer tests held at a constant gate opening. This scour increased or decreased based on the draft, prompting the 9 ft center gate opening and 15 ft ice raft draft to be set for following tests attempting to discover a solution.

The first testing avenue explored to alleviate or eliminate upstream scour was the extension upstream of the stone bed protection. The extension of the stone bed protection did lessen the scour at the upstream edge of the protection, but did not reduce the occurrence of upstream scour.

The second attempt to reach a solution was to try different stone placements along with an extension of the stone bed protection. Two different stone placements were attempted: the first based on the Lock and Dam 25 repair, the second using a top layer of derrick stone. Both placements experienced at least a maximum of 6 ft a scour, which would reach the pier base elevation in the prototype.

The third path to a solution investigated was opening the gates adjacent to the main ice passage gates. The side gates were opened 1 ft, 3 ft, and then 5 ft. The 5 ft side gate opening was found to be successful at reducing scour to a level where the pier bases would not be exposed. Once the success of opening the side gates to alleviate scour was validated, testing examined the need for the length extension of the stone bed protection. The use of a shorter extension (15 ft) and the complete removal of the extension were both tested; the 30 ft extension was found to perform better than both. The use of only modified “A” stone without modified “C” stone underneath was also tested; the test without the smaller stone underneath experienced far more scour.

Recommendations

The first recommendation of this study is to open the gates adjacent to the main ice passage gates at least 5 ft during ice passage situations. Opening the adjacent gates limits the formation of vortices around the piers as the river flows through the open gates and lowers the near-bed velocity which will reduce the transport of sands and protection stone. This was found to reduce scour to a maximum of 3-4 ft in the model, a depth above the pier base elevation not threatening the sheet pile cutoff wall.

The second recommendation of this study is to extend the stone bed protection an additional 30 ft upstream of the Lock and Dam. The original design length for the stone bed protection was 21 ft; at this length, the upstream edge of protection nearly scoured enough to connect to the pier scour. Model testing supports that a longer length of stone bed protection both lessens the unraveling the leading edge of the upstream protection and supports lowered scour at the piers. This extension was found to be critical to the successful implementation of the side gate openings as a solution to scour reduction.

A third recommendation of this study is to routinely conduct hydrographic surveys upstream of the lock and dam. Routine surveying is necessary to monitor scour progression and increases the likelihood of recognizing and correcting problems before they become critical and expensive to repair.

Appendix A: Survey Comparison

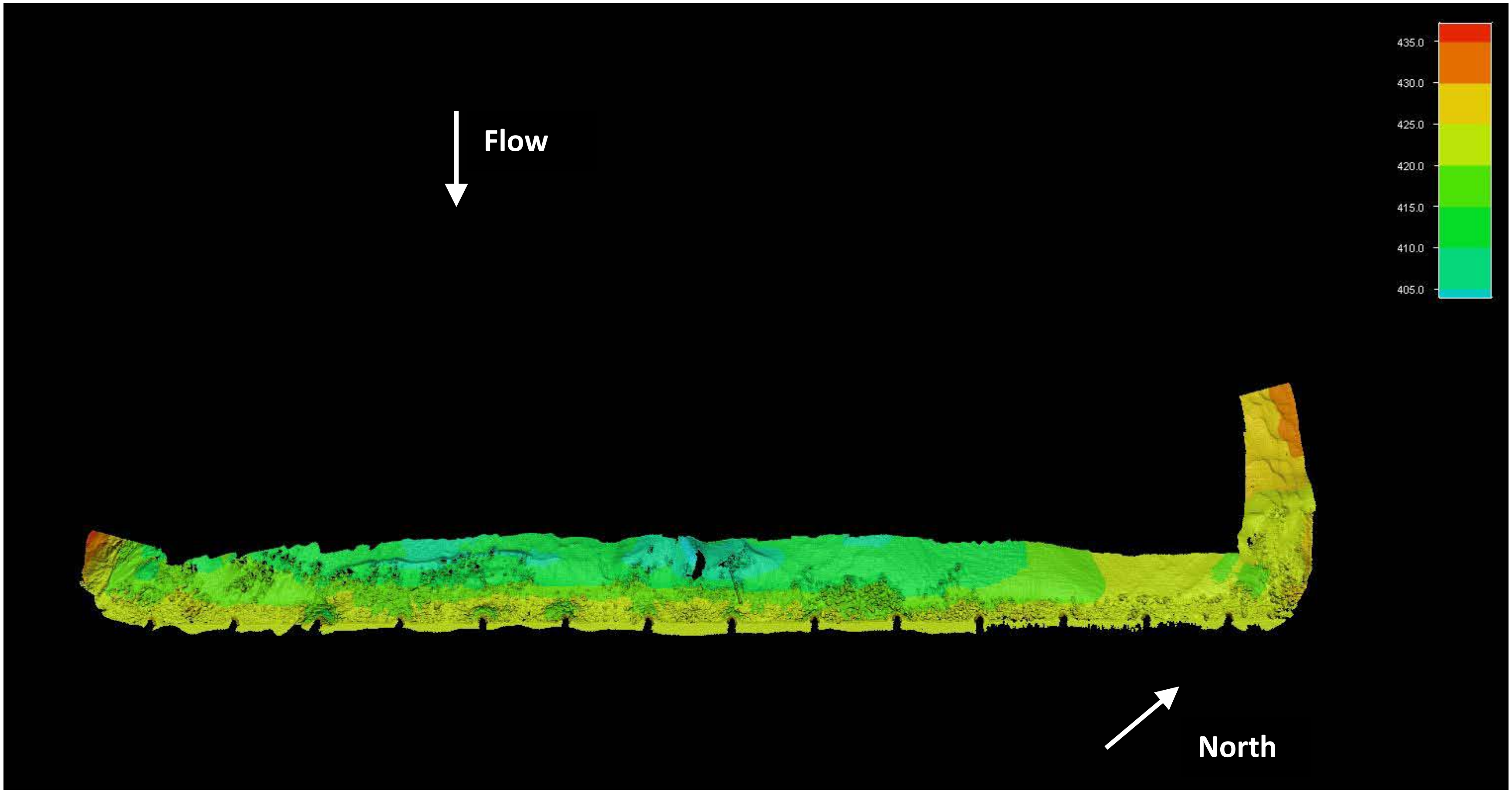


Figure 1 - 12-4-2007 Survey

North and flow direction consistent between surveys

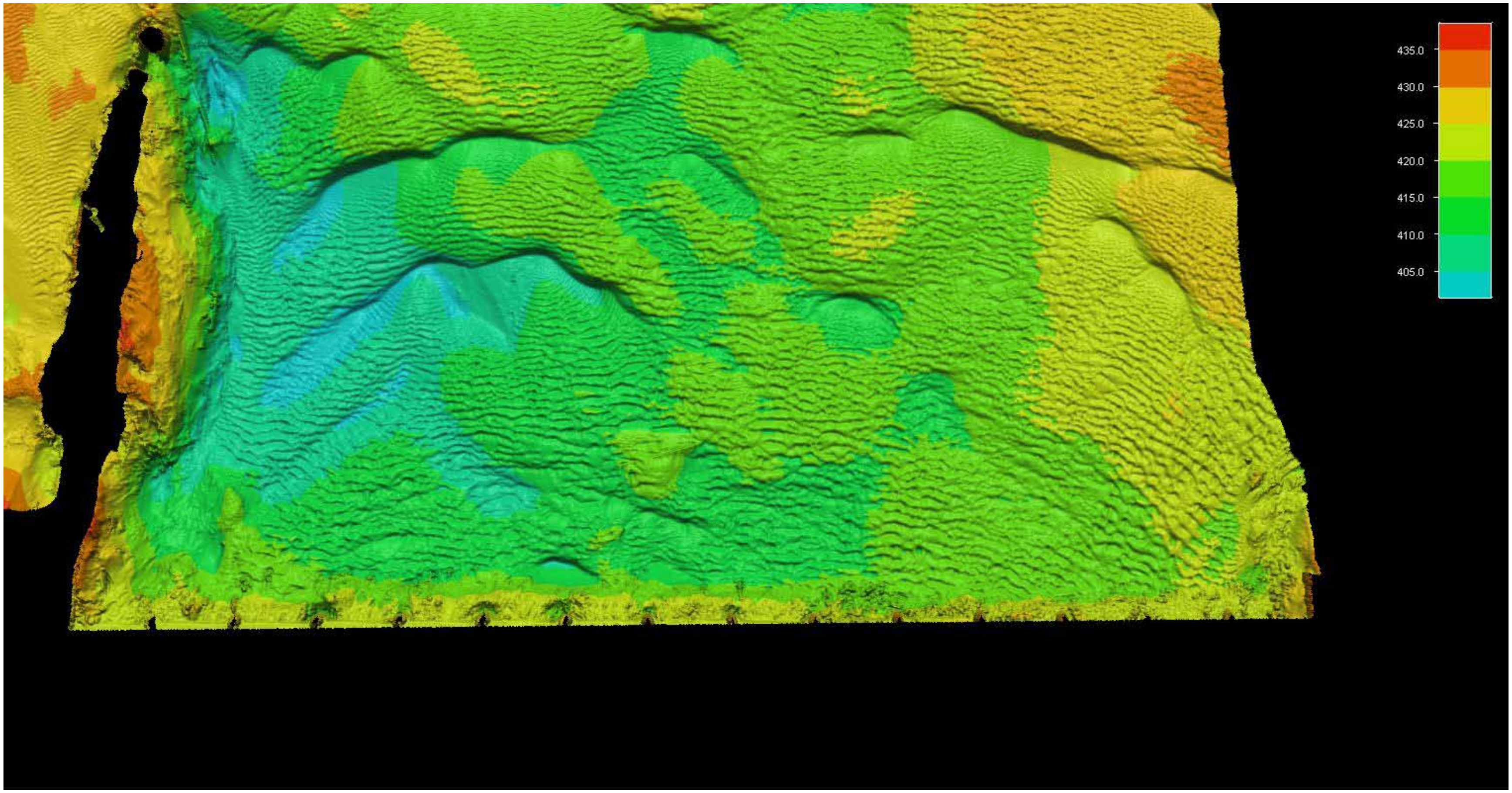


Figure 2 - 7-9-2008 Survey

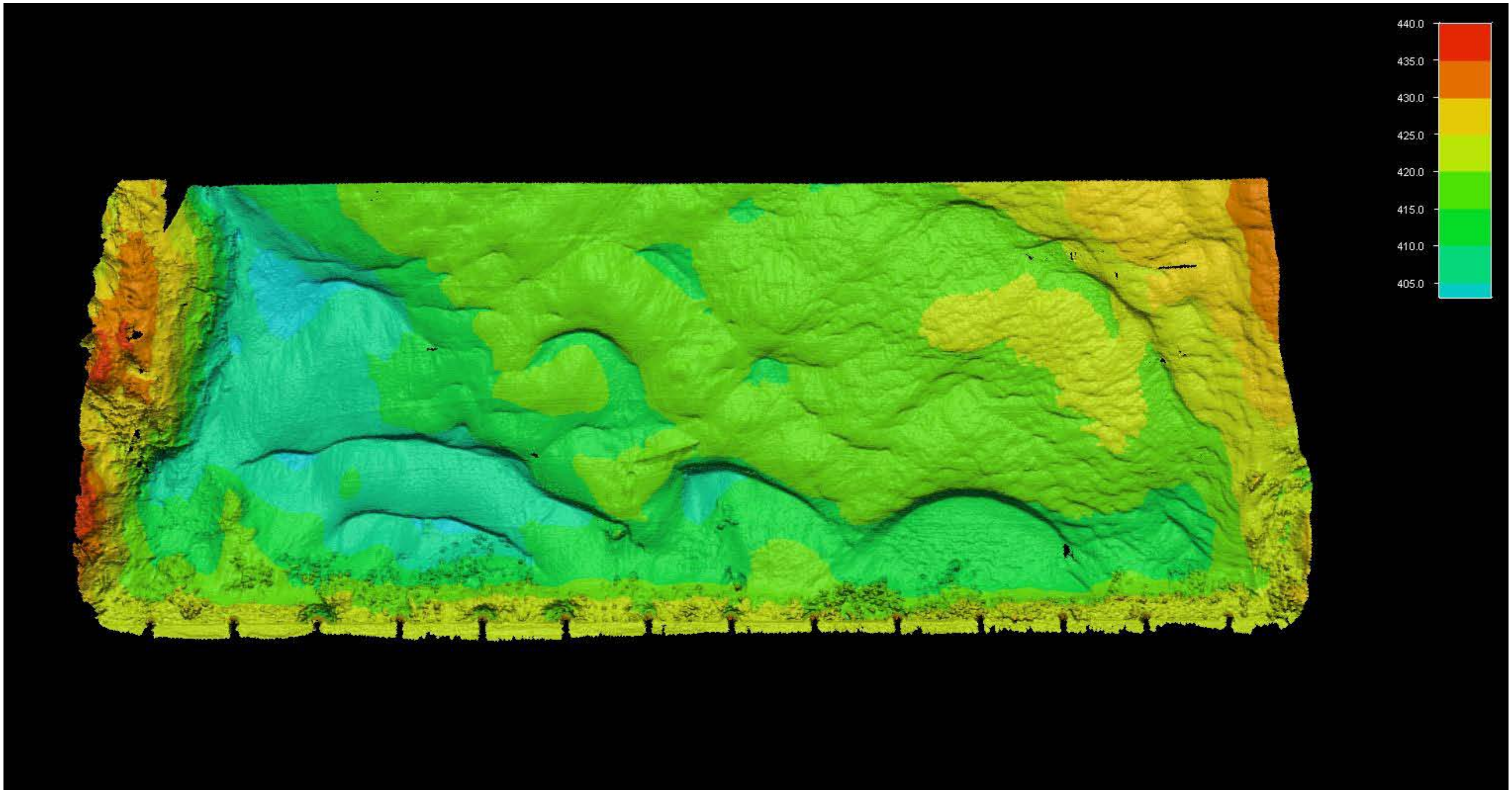


Figure 3 - 12-8-2008 Survey

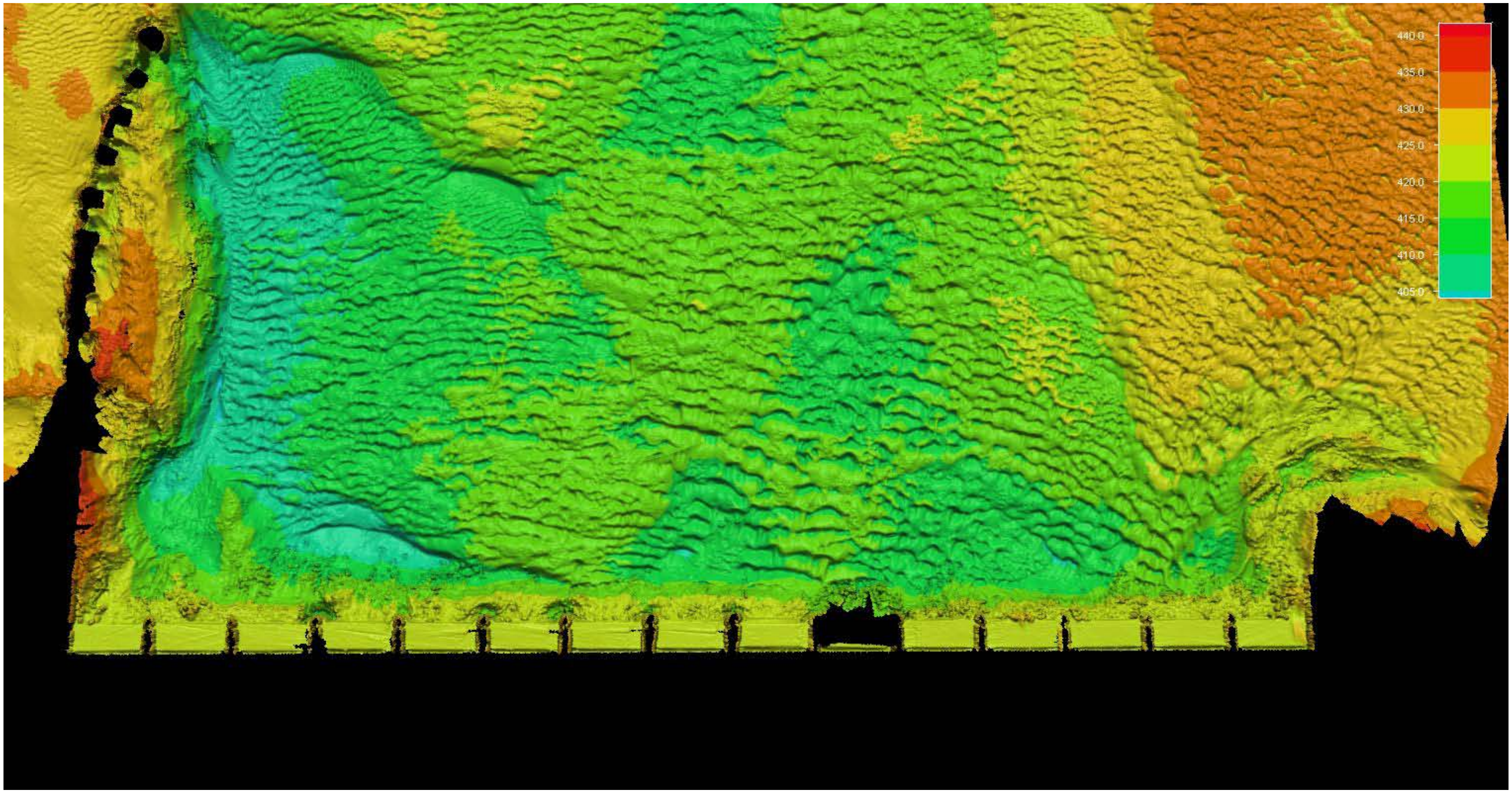


Figure 4 - 4-1-2009 Survey

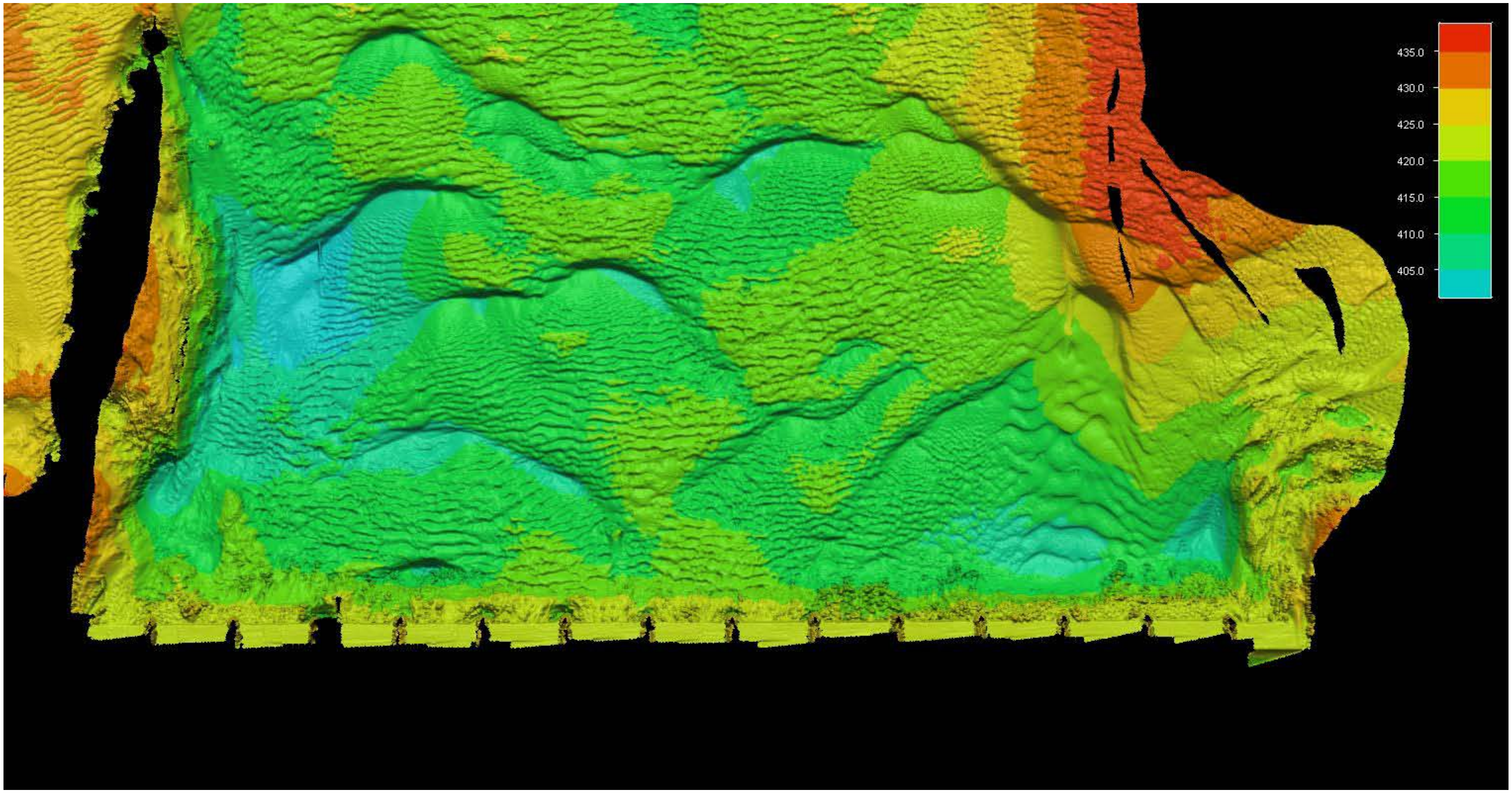


Figure 5 - 5-3-10 Survey

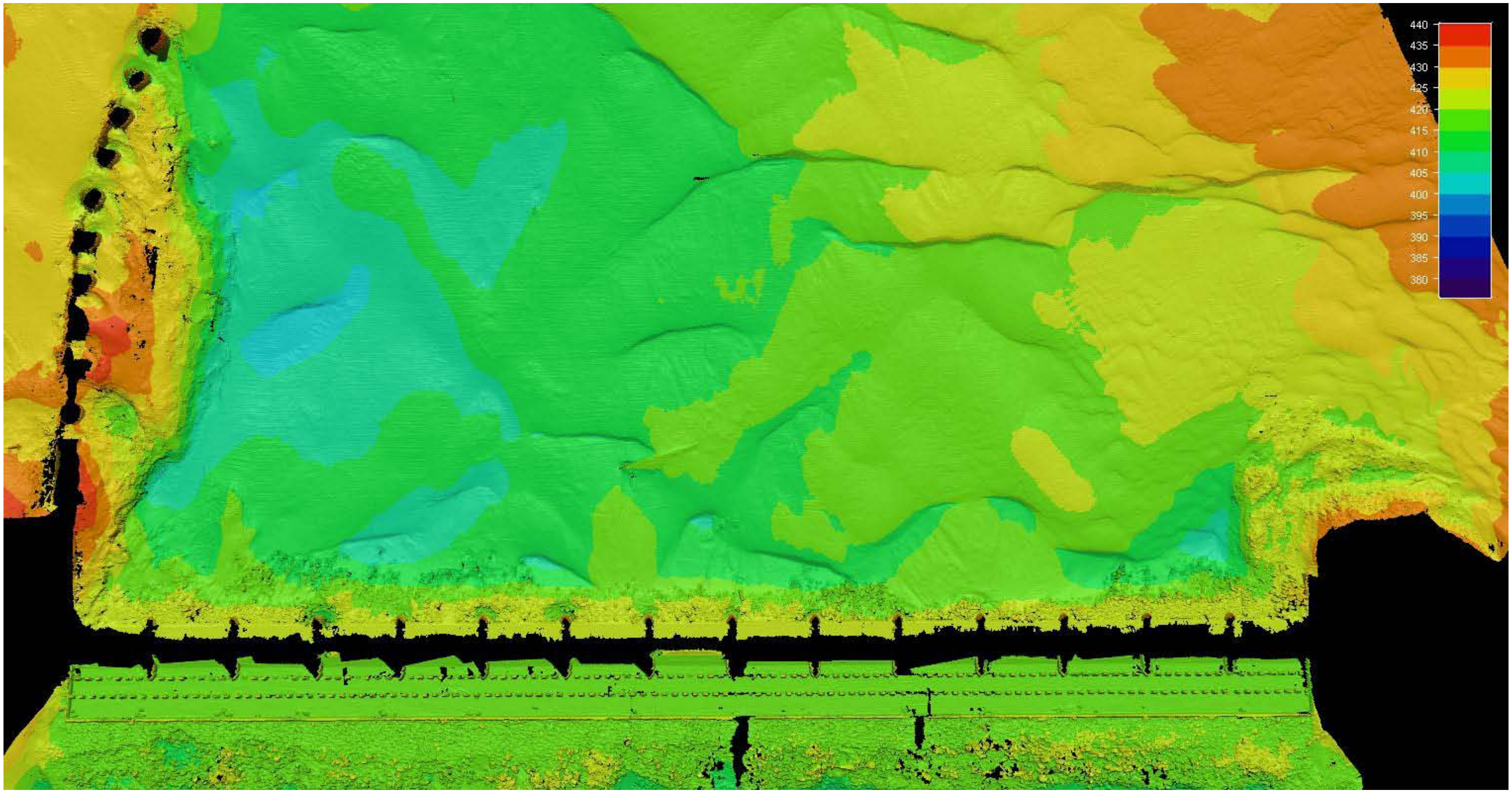


Figure 6 - 9-8-11 Survey

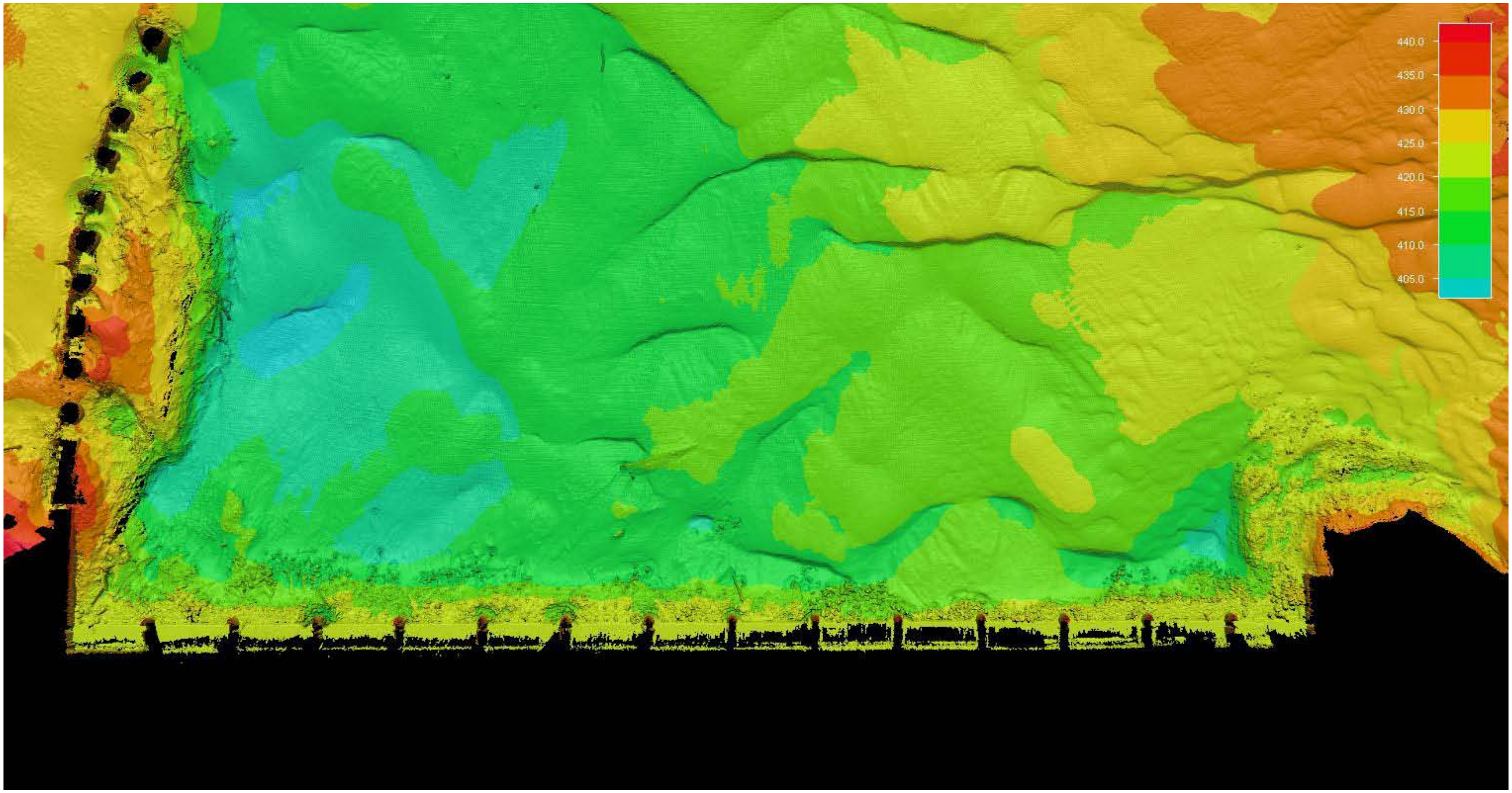
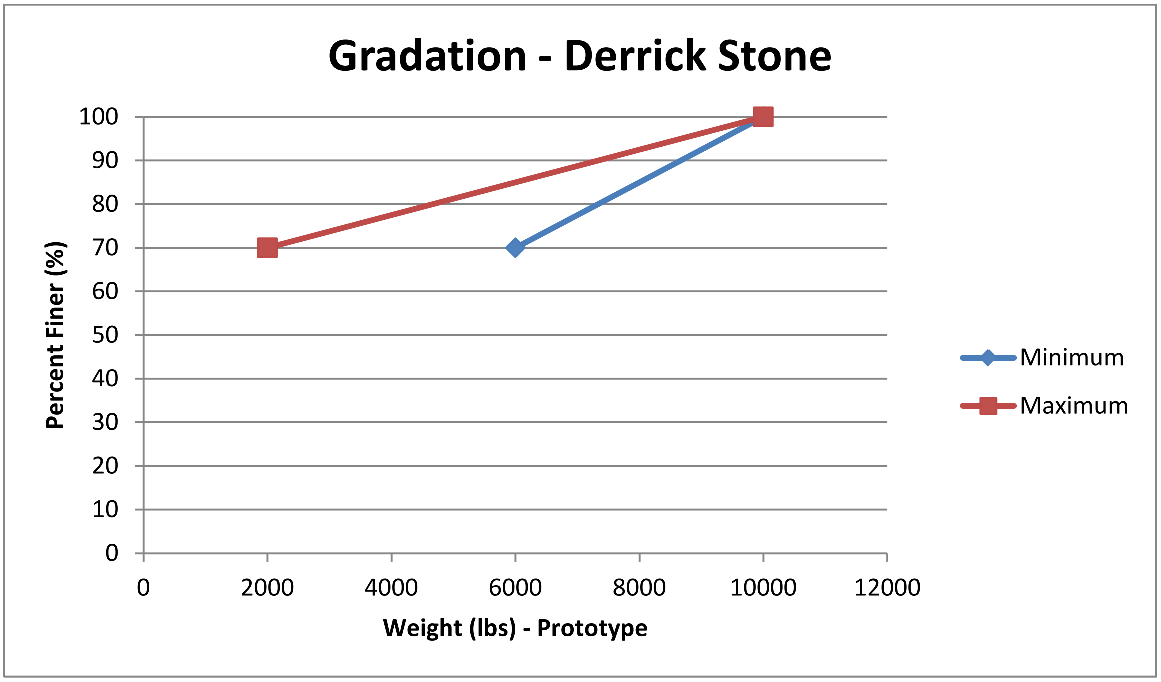
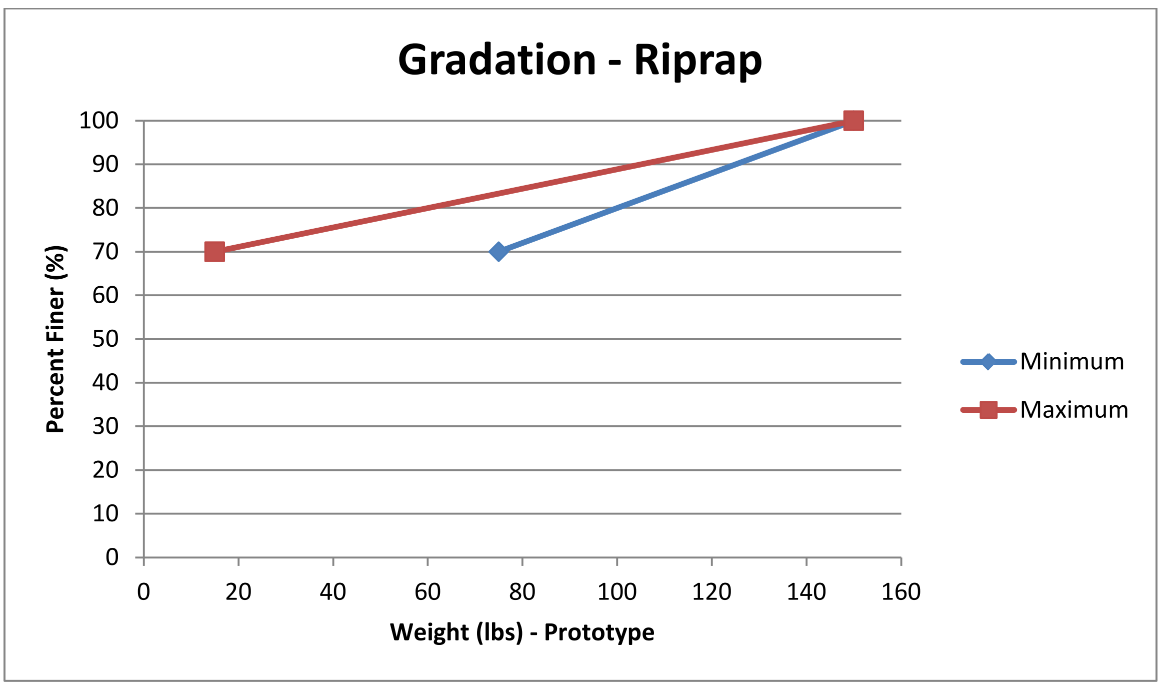


Figure 7 - 2-15-12 Survey

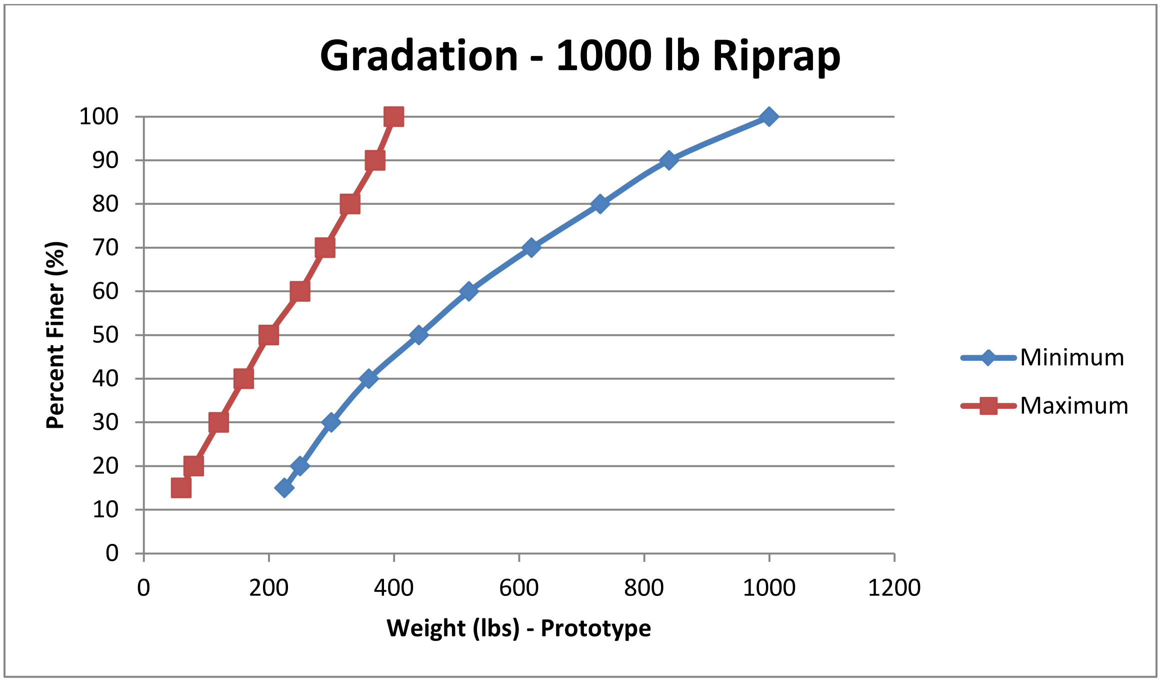
Appendix B: Stone Gradations

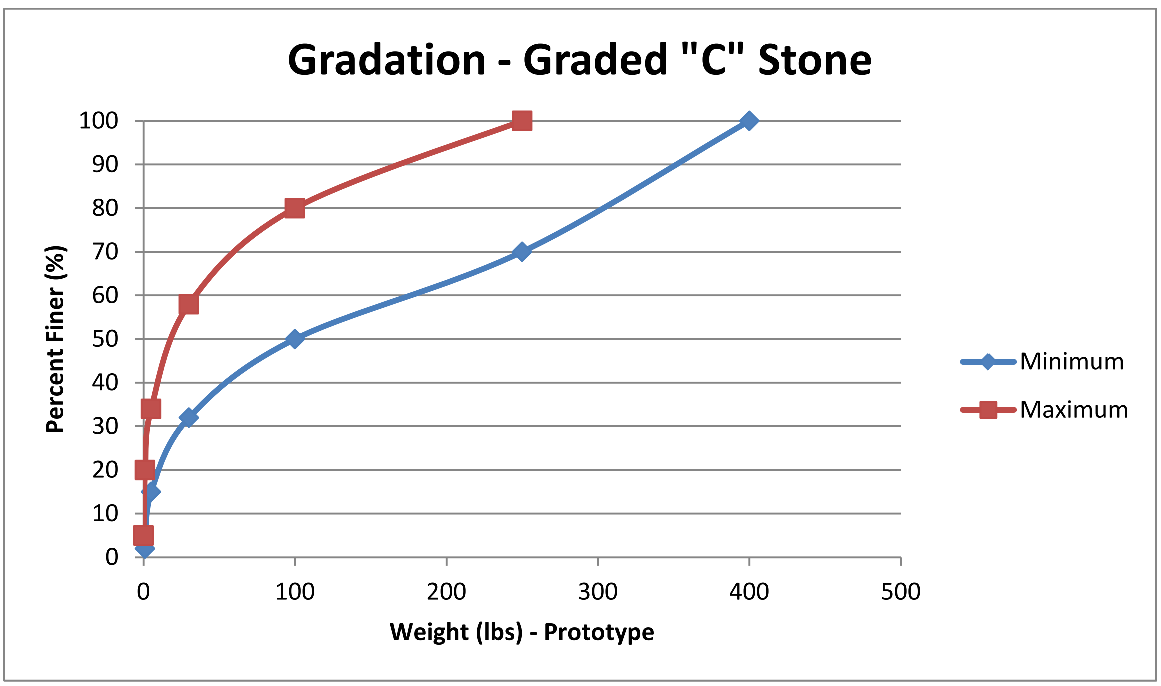
Original Stone Gradations





1977-8 Repair Gradations





Modeling Gradations